Topics on Archery Mechanics

Joe Tapley

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Introduction

The basic physics of archery has in principle been understood for around 80 years. The last topic to be theoretically described was vortex shedding (aerodynamics) in the 1920's related to developments in the aircraft industry. While the principles of archery are understood, in practice the behaviour of the bow/arrow/archer system (termed 'interior ballistics') and the arrow in flight (termed 'exterior ballistics') are somewhat complicated. In order to understand the mechanics of archery computer models are required.

Models related to interior ballistics have been developed over the years becoming more realistic (and complex). A few related papers are listed below:

Kooi, B.W. 1994. The Design of the Bow. *Proc.Kon.Ned.Akad. v. Wetensch* , 97(3), 283-309
The design and construction of various bow types is investigated and a mathematical model is used to assess the resulting effects on the (point mass) shot arrow.

Kooi, B.W. & Bergman, C.A. 1997. An approach to the study of Ancient Archery using Mathematical Modelling. *Antiquity*, 71:124-134.
Interesting comparison between the characteristics and performance of various historical and current bow designs.

Kooi, B.W. & Sparenberg, J. A. 1997. On the Mechanics of the Arrow: Archer's Paradox. *Journal of Engineering Mathematics* 31(4):285-306
A mathematical model of the behaviour of the arrow when being shot from a bow including the effects of the pressure button and bow torsional rigidity. The string forces applied to the arrow are derived from the bow model referenced above.

You can download most of the archery papers by Bob Kooi et al (in PDF/Postscript format) from the following link Archery Mechanics Papers. While inevitably many of the papers have a highly technical content there are non-mathematical versions which cover the general concepts and conclusions.

Realistic mathematical models for the exterior ballistics of arrow flight, while simpler than the interior ballistics, are as far as I know non-existant. You can at least download a couple of (incomplete) models from this site.

I have attempted here to put together a basic (laymans) guide to the bow/arrow system and arrow flight. The guide is not complete and comprises bits and pieces added when and if I have the time and inclination.

Joe Tapley June 2000

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BOW MECHANICS

Bow Efficiency And The Concept Of Virtual Mass

Defining Virtual Mass

Starting with a stationary bow at the brace height position, as you draw it back you store energy in the bow. The area under the force draw curve equals the total energy stored (E_t). When the arrow is released the bow ends up stationary again at the bracing height. The total energy stored has gone somewhere. Most of this energy ends up where you want it as arrow linear kinetic energy (E_a) but the rest (E_w)is wasted.

The energy equation for the bow is thus:
$E_t = E_a + E_w$

The energy efficiency of the bow (F) is defined as the ratio of the arrow energy to the total stored energy. i.e.
$F = E_a/E_t$

Supposing the arrow leaves the bow with a particular speed (S) then you can write the total stored energy in the bow as being equal to some imaginary mass (M) travelling at the same speed as the arrow. i.e.
$E_t = MS^2/2$

The value "M" includes the mass of the arrow (m) with the remaining mass (v) called the Virtual Mass. i.e.
$M = m + v$

This gives you that $E_t = MS^2/2 = (m + v)S^2/2 = mS^2/2 + vS^2/2$
$mS^2/2$ is just the kinetic energy of the arrow and $vS^2/2$ is the wasted energy E_w in tems of the kinetic energy of an imaginary Virtual Mass.

The bow energy efficiency $F = E_a/E_t$ thus becomes:
$F = (mS^2/2)/((m + v)S^2/2) = m/(m + v)$

The bow energy efficiency can be defined in terms of the arrow mass and the value of the virtual mass. What makes this useful is that it is found by experiment that for a given bow the value of the virtual mass is a constant over a sensible range of arrow mass.

Note that this expression for bow energy efficiency and the value of v being constant indicates that the heavier the arrow then the more energy efficient the bow becomes. We'll look at the practical effects of this later on.

Finding the Value of the Virtual Mass

In order to see how varying arrow weight effects bow efficiency or arrow speed we need to know value of the (constant) virtual mass for the bow. There are a number of ways you can do this.

The first method (maybe not recommended) is just to make a guess. Let's say a typical recurve bow has an energy efficiency between 70% and 80% and a typical arrow weight is 300 grains. Using the energy efficiency equation we have now got we get:

with 70% efficiency 0.7 = 300/(300+v) which gives a value of v = 128 grains

With 80% efficiency 0.8 = 300/(300+v) which gives a value of v = 75 grains

So lets take a typical value of virtual mass at somewhere around 100 grains

Probably the easiest method to measure the virtual mass reasonably accurately is shoot arrows of different weights and use a chrono to estimate the respective arrow speeds. Suppose we have two arrows of weight m1 and m2 and measure their respective speeds out of the bow at S1 and S2. The using the equation for total bow energy above we get:

$(m1 + v)S1^2/2 = (m2 + v)S2^2/2$

or tidying things up $(m1+v)/(m2+v) = S2^2/S1^2$

From which you can calculate the value of v

The third method that can be used, though a bit cumbersome, is to measure the speed out of the bow of an arrow of known weight and estimate the total energy stored in the bow from the force draw curve. You can then use the above equation to get the value of v:

$E_t = (m + v)S^2/2$

To get the value for the total energy you can either plot a draw weight - draw length curve on graph paper and measure the area under it (A), from which
$E_t = gA$ or assume the draw force curve is a straight line which gives $E_t = gLW/2$.

Where "L" is the draw length, "W" the draw weight and "g" the gravitational acceleration. Don't forget to include "g". In archery, energy is often quoted in foot-lbs which is not a unit of energy. To convert you need to multiply by "g".

Example of Estimating Arrow Speed

Suppose you have a 300 grain arrow (m1) and a measured speed of 210 feet per second (S1). What speed (S2) would you get with an increased pile weight say giving an overall 330 grain arrow (m2). Let's say the virtual mass value for the bow is 100 grains

If you ignore the effect of arrow mass on bow efficiency then the two arrows would have the same kinetic energy i.e.
S2 = S1*Squareroot(m1/m2) = 210*Sqrt(300/330) = 200 fps

With the 300 grain arrow the bow energy efficiency = 300/(300+100) = 0.75 (75%)

With a 330 grain arrow the bow energy efficiency = 330/(330+100) = 0.77 (77%)
so the extra arrow weight increases the bow efficiency by around 2%

The speed of the heavier arrow would be 210*Sqrt((300+100)/(330+100)) = 203 fps

So the speed effect of the heavier arrow on bow efficiency is in this case around 3 feet per second

How Well Does The Virtual Mass Approach Work

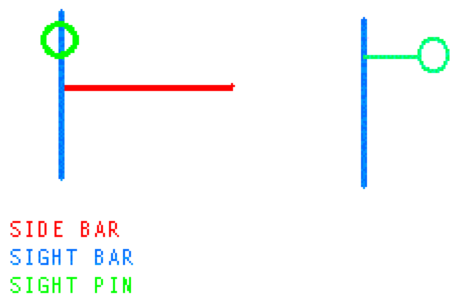
To test whether the virtual mass approach works in predicting speeds for arrows of different masses clearly we need to use the method to predict arrow speeds and compare the prediction with actually measured speeds. Bertil Olssen on his excellent site has produced numbers we can be confident about so we can make the comparison. The following table lists measured different arrow speeds for different mass arrows and compares the results with speeds calculated using the above virtual mass method.The first two arrows in the table are used for the virtual mass calculation.

Arrow Mass grams	Measured Speed m/s	Calculated Speed m/s	Calculated-Measured Speed Difference
16.5	60.80	60.80	0.00
19.4	57.21	57.21	0.00
22.6	53.81	53.90	0.09
27.8	49.41	49.57	0.16
30.6	47.41	47.63	0.22
33.5	45.61	45.85	0.24
42.1	41.31	41.54	0.23

As can be seen in this case when more than doubling the arrow mass the estimated speed is withing 0.25 m/s

BOW SIGHTS

Bow sights are used to aid the archer to align the vertical and horizontal position of the bow so that the arrow



hits the centre of the target.

The reference (sighting) line runs from the archer's eye through the sight pin to the target centre. By moving the sight pin up/down, side to side or backwards and forwards the orientation of the bow is changed consistently with respect to this reference line. The main elements of a bow sight are represented in the attached diagram.

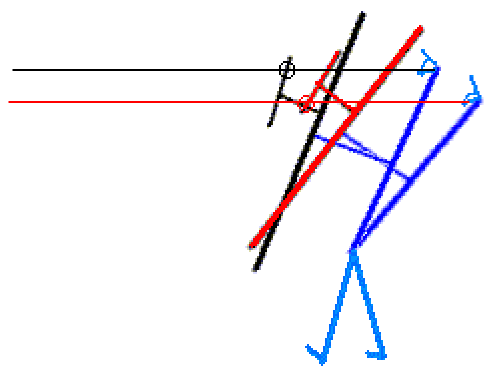
What recurve bow sights do not do is assist in keeping the axis of the bow in the vertical plane (or canted at some angle if required). Compound archers may use 'bubble levels' to help in this respect but their use is not legal for recurve archers. Recurve archers have to use skill to get a 'vertical' bow. It is the combination of the head position (tilt) and the angle a line running from the eye to the anchor point makes with the vertical that defines bow verticality. It think it helps if the eye-anchor point line is itself vertical but the position of the anchor point comes down to the shape of the archer's face as well as personal preference.

The aim of bow sight design is to enable a given sight pin position to be consistently reproduced, not to wander about from shot to shot and to enable controlled movement of the sight pin. Vertical and horizontal scales are usually built into the sight to assist with this as well as having a rigid sight assembly.

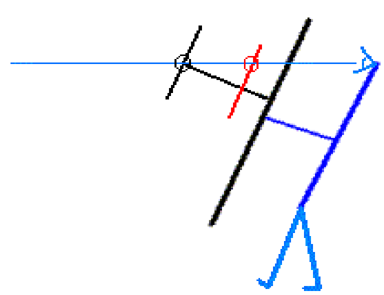
In order to hit a specific vertical point at some defined distance then you need to have the correct bow angle to the horizontal. By trial and error you find a suitable sight pin position for that distance so that when you line up your eye, the sight pin and the target you have the correct vertical bow angle. The two adjustments you can make are an up and down movement of the sight pin (on the sight bar) and to move the sight pin towards and away from the eye (vary the length of the side bar). It is the combination of up/down and forward/backwrds sight pin position that gives you the correct bow angle. Because it relies on a combination of two positions there are an infinite number of sight set ups that will give the correct vertical bow angle. They are not all equal as will be discussed later.

In order to define the bow position with respect to the eye/sight/target line you really need a second reference point on the bow, a 'backsight'. In principle you could keep the pin 'on the target' while rotating the bow any way you like with the sight pin being the axis of rotation.Compound archers often use a peep sight mounted in the string to provide a backsight so aiming becomes a mechanical operation. Recurve archers are not technically allowed to use two reference points. The second reference point is a combination of the head position/consistent anchor point and the 'sight picture'. In the sight picture you can subconciously (or maybe conciously) see the target, the pin, the bow limbs and the string. The archer learns to maintain the same sight picture from shot to shot e.g. the vertical position of the string with respect to the sight pin or bow limbs.

The following two diagrams illustrate how moving the sight pin up and down the sight bar or changing the length of the side bar (the eye to pin distance) affects the vertical bow angle.

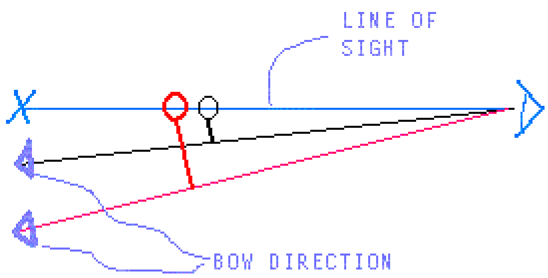


If the sight pin is moved down the sight bar (red bow) then the (blue) archer has to rotate his trunk to line up the sight pin with the eye to target line - the important effect resulting from this is that the bow angle with the vertical increases.

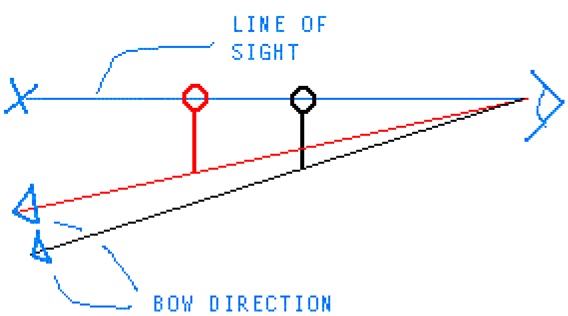


As the side bar is extended, to maintain the eye-pin-target alignment, the sight pin has to move downwards. For example with a reducing bow poundage (higher bow angle for a specific distance) the pin has to positioned lower and lower down on the sight bar ultimately causing a pin to arrow clearance problem. Reducing the length of the side bar projecting in front of the bow locates the required the pin position further up the sight bar regaining the required clearance.

Changes in the horizontal angle the bow makes with the direction of the target , the 'windage', is effected by moving the sight pin towards or away from the sight bar and or by changing the length of the side bar. The following two diagrams illustrate these effects:

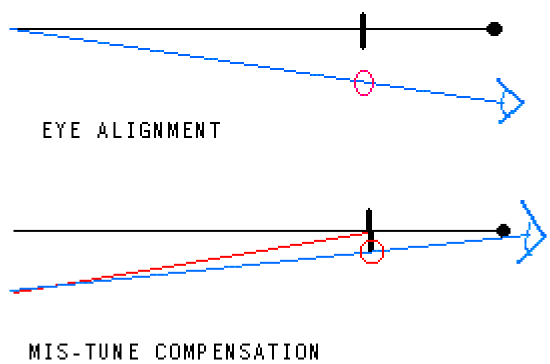


In the diagram moving the sight pin further away from the sight bar (black to red) has the effect (LH archer illustrated) of rotating the bow in the horizontal direction away from the target direction. (the two target pins illustrated should actually be in the same place).

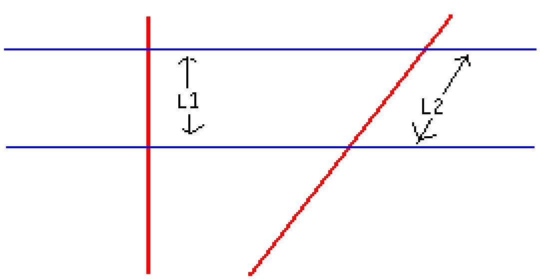


In the diagram the 'windage' has been kept the same while the side bar has been extended (black to red). As the side bar is extended, the angle between the bow direction and the eye-target line decreases. I.e. extending the side bar has the effect of increasing the sensitivity of the windage adjustment position.

The 'no wind' pin windage setting can be affected by how the archer's anchor point technique effects the eye position. The tuning of the bow will also effect the basic pin windage setting.



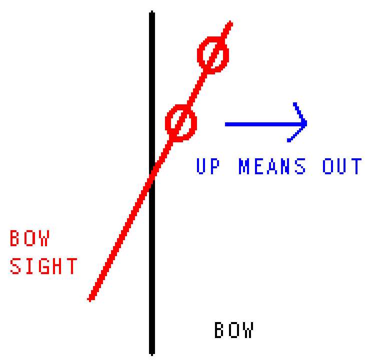
If say the archer anchors on the side of the face and the head is not tilted to compensate then the eye is offset to the line of the bow/arrow flight and the pin has to be moved away from the bow line to compensate. (eye alignment in the above diagram). If the bow is mistuned, e.g. stiff in the diagram, then again the pin windage position has to adjusted to compensate for the fact that the arrow does not travel in the same plane as the bow.



How about the geometry of the sight bar and side bar with respect to the bow? The sight bar is usually designed to be mounted so its long axis is parallel to the bow string both in the plane of the bow and at a right angle to this plane. If the bow is held so that the arrow is horizontal (give or take nocking point tillering) then the bow sight is vertical with respect to the ground. As the bow is raised with increasing target distance then the the angle the bow sight makes with the vertical increases. At the same time the line from the archer's eye to the target stays (on level ground) more or less horizontal. As the following diagram shows as this angle with the vertical increases the sensitivity of the pin position (up/down on the sight bar) changes (L2 is bigger than L1 for the same vertical varation in position). As you change the bow angle the sight mark gaps between distances will change. If the sight bar is fitted at an angle to the side bar then as you move the sight pin up and down you are at the same time moving it towards and away from the eye.

With target archers they are generally shooting on level ground so the bow angle for a given distance will always be the same. However with field archers and bow hunters (say shooting out of a tree stand) they can often be shooting uphill and downhill. With respect to shooting on level ground when shooting downhill the correct pin position will be higher on the sight bar and vice versa shooting uphill because the arrow trajectory becomes asymmetric. A variant on the bow sight is the pendulum sight where the sight bar remains vertical irrespective of bow angle. This to some degree compensates for the uphill/downhill effect because as say the bow is angled down the pin is effectively raised compared to the pin position on a fixed sight bar.

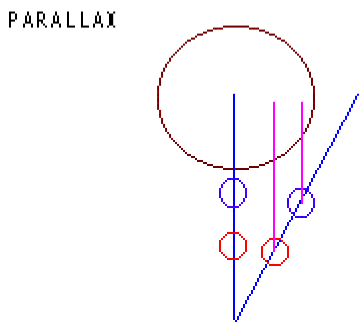
In the other plane keeping the sight bar aligned with the bow string means that any up/down movement of the pin position will not change the effective windage setting.



If the side bar is not aligned parallel to the plane of the bow then moving the bar forwards and backwards will have a similar effect on changing the windage setting as the sight bar misalignment illustrated above. Moving the side bar will change the windage setting. In the other plane if the side bar is not parallel to the arrow then you end up changing the angle of the sight bar to the vertical as described above.

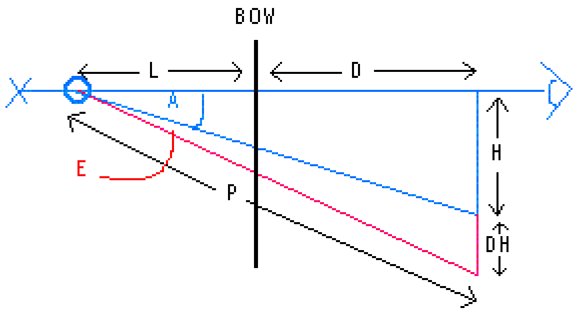
Whatever bow sight we use we do not want the arrow shaft or fletchings to hit any part of it on the way out of the bow. Most of this is catered for in the design. The bow sight is mounted on the opposite side of the riser to the arrow with sufficient clearance (we hope) that the only possible contact is with the sight pin itself or the pin support bar. As you go to longer distances the sight pin travels down the sight bar until it gets too close to shaft for comfort and the length of the side bar has to be reduced. It's not totally unheard of for an archer hitting low to lower the sight pin and then shoot the following arrow straight through the site pin (with catastrophic results - at least for the sight pin!). If you are seriously underpowered and run out of side bar length reduction then you can usually reverse the side bar in the mount moving the sight bar even closer to the archer's eye (between the bow and the archer) allowing the pin to be located even higher up the sight bar. In this situation in addition to contact with the arrow it's now worth thinking about possible contact between the bow string and the sight bar assembly. A bow string can move a significant amount forward of the bracing height position, maybe particularly for compound bows which have a lot of string wrapped round them wheels.

Can you 'optimise' the use of a bow sight? The answer is yes. Keeping the side bar as long as you can, while maintaining good arrow clearance, increases the distance between the front sight (the pin) and the back sight (your eye/anchor) and improves aiming because of the parallax effect. The length of the side bar also affects the amount of error in the arrow launch direction resulting from bad bow alignment e.g. variation in anchor point.



The diagram illustrates the parallax effect. If perfectly aligned on the target then both the near and far sight pins are aligned along the same line. If the alignment is off by some amount then because the 'radius' of rotation of the far pin is greater it moves further sideways appearing to track more across the face of the target. The longer the side bar then the more sensitive to movement the bow sight becomes - better feedback to the aiming process. There is a limit to this. If the side bar is so long that the pin is zooming about all over the target face this becomes more of a liability than an asset. As a general guide the side bar should be the length, at a specific distance, that the pin 'floats' around in the gold.

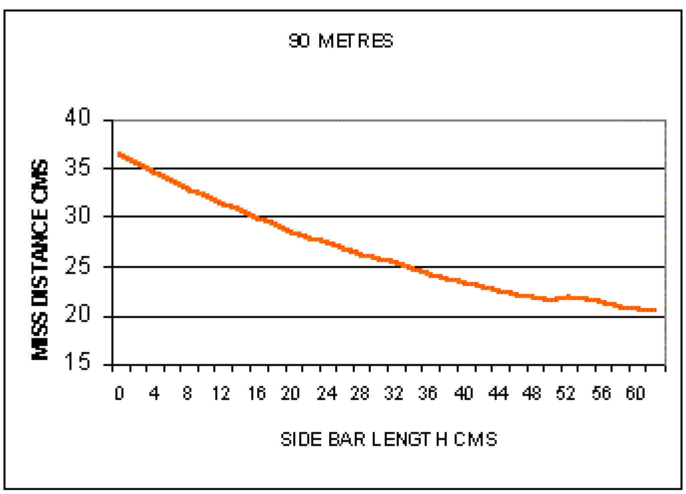
If when drawing a bow you end up with the anchor point at the wrong point, although the eye-pin-target line may be 'acquired' the bow is at the wrong angle and when shot the arrow will miss the target centre by some amount. How far the actual bow angle is from the correct angle, i.e. by how much the arrow will miss, depends on the length of the bow sight side bar.



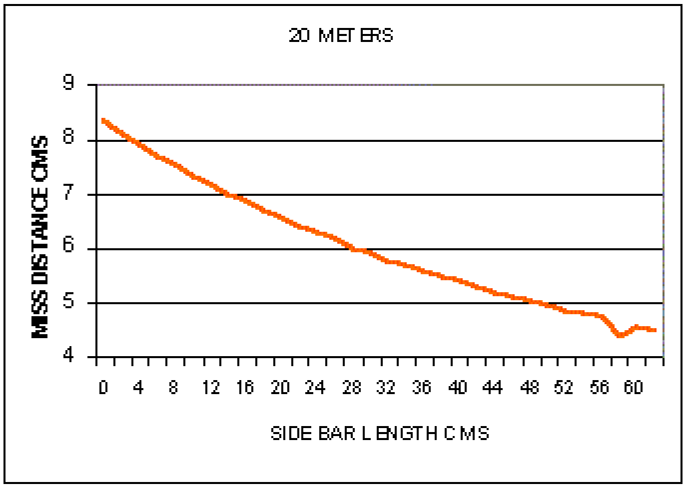
In the diagram 'L' is the length of the side bar, 'D' is the distance from the bow to a perpendicular dropped to the correct anchor point and 'H' is the length of this perpendicular. If the bow is drawn correctly (good anchor point) then when the eye, pin and target are aligned the angle 'A' is defined by the line from the eye to the pin to the anchor point. If say the anchor point is too low (by a distance 'DH') then this angle is increased by an amount 'E'. Any misalignment of the bow can be regarded as a rotation of the bow with the site pin being the axis of rotation. The angle 'E' is the error in the bow angle (how far it is from the correct bow angle).

If we assume (we hope!) that DH is small with respect to the length (L+D) then approximately E = DH/P

As P = Square Root of (H squared + (L+D) squared) and 'H' and 'D' are essentially fixed it can be seen that the value of 'E' for a given value of 'DH' decreases as the length of the side bar 'L' increases. The longer the side bar the more tolerance there will be to anchor point misalignment with respect to where the arrow hits the target.



The attached graphs estimate how far a 'typical' arrow will hit from the centre, with an incorrect anchor point, at 90 metres and 20 metres target distance as the length of the side bar increases. 'D' is assumed at 70 cms, 'H' at 12 cms and DH is assumed to be 0.3 cms. Bear in mind that there will be a maximum side bar length after which you will get arrow clearance problems. The maximum allowable value of 'L' will be greater at 20 metres than at 90 metres.



For example at 20 metres distance, using a 30 cm side bar the arrrow will hit about 1.25 cms closer to the target centre than if a 12 cm side bar was used.

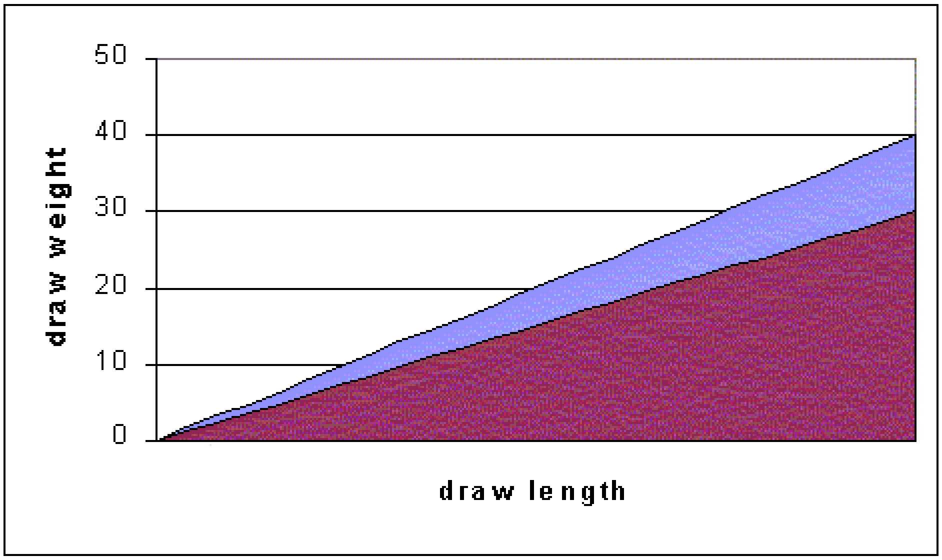
The basic approach to getting the best out of a bow sight is therefore straightforward. Use the longest length side bar you can at any specific distance. This occurs 'naturally' at long distances. At short distances, however, with many bowsights you end up with the pin up near the top of the bow window. If you shoot short distances get a bow sight with the longest side bar that it is practical to use (assuming it maintains adequate rigidity so it doesn't wobble about at full draw).

THE DRAW FORCE CURVE

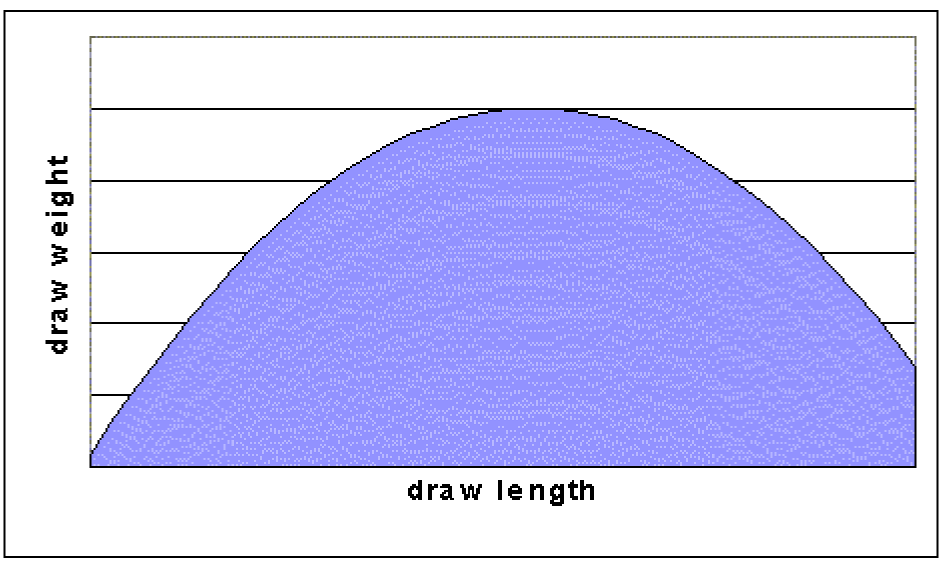
As you draw an arrow back on a recurve bow the force on the fingers steadily increases. How the weight on the fingers varies with the amount the arrow is pulled back is called the draw force curve. The draw force curve has the following important characteristics. Firstly the draw force curve determines what weight the archer has on the fingers at full draw. Secondly the draw force curve establishes how much energy is stored in the bow at full draw potentially available to go into the arrow speed off the bow. Thirdly the shape of the draw force curve near the full draw position determines the 'stacking' property of the bow i.e. at what rate the weight on the fingers varies with draw length.

What draw weight the archer is holding at full draw is down to archer preference and physique. This is basically determined by the riser/limb combination with some variation available to the archer via limb pocket adjustment or bracing height modification.

The following chart illustrates draw force curves for draw weights of 30 and 40 pounds at full draw.

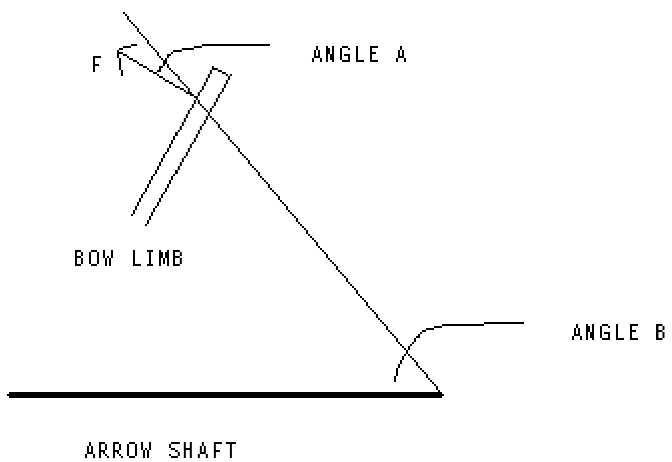


The energy stored in the bow limbs potentially available to go into arrow speed is represented by the area under the draw force line (brown for the 30#, blue for the 40# draw weights). The area under the 40# draw force curve is larger than under the 30# draw force curve i.e. more energy is potentially available for 40# weight bow. The blue area not covered by the brown area represents the difference in total area i.e. the difference in stored energy between the two draw weights. While a lot of this energy is wasted in limb movement, arrow vibration etc. on the shot the arrow will leave the bow faster with the 40# weight. The energy stored in the bow relates to the shape of the draw force curve.

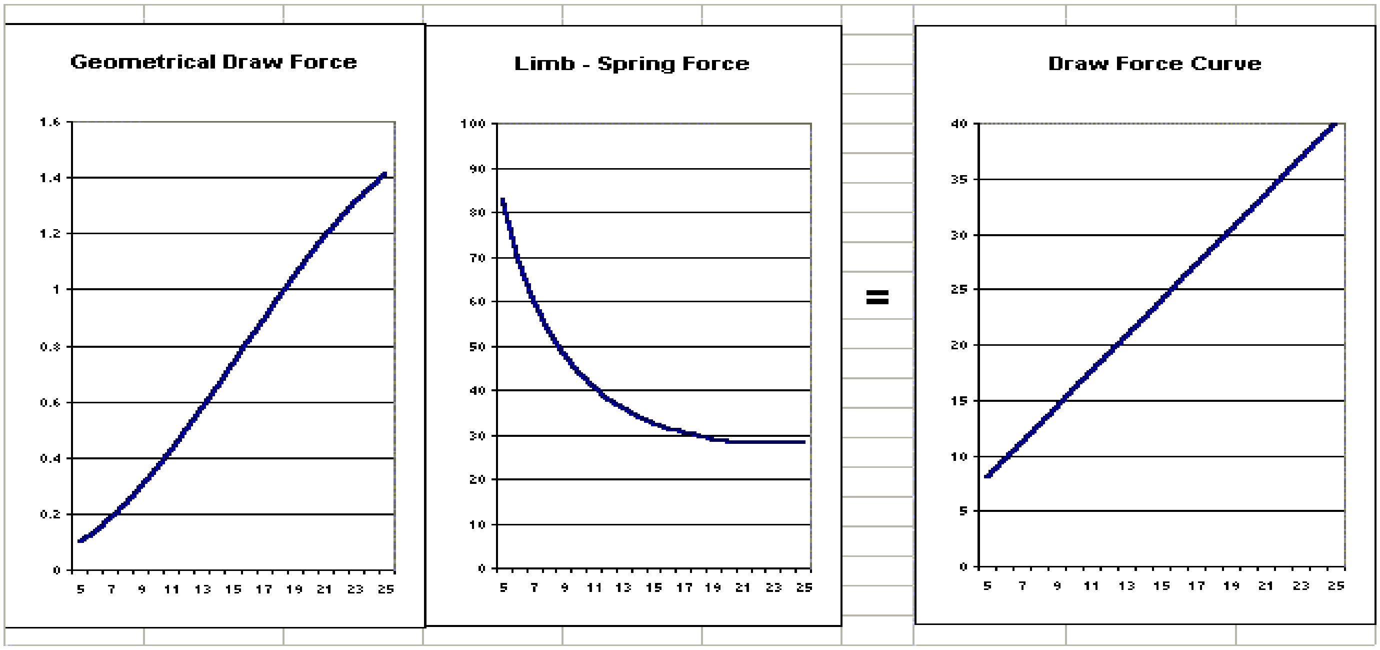


The representation of a compound bow draw force curve shows why much more energy (the blue area) is stored in the bow with a much lower weight at full draw.

The actual shape of the force draw curved is determined by the limb 'spring' characteristics and by the bow geometry. The bow limb is a complicated spring. With one end fixed as you draw the arrow and pull on the other end the limb shape changes and the spring force exerted by the limb changes. As you draw the arrow the angle the string makes with the direction of limb spring force and the angle the string makes with the arrow shaft change. The following diagram outlines what is going on at a specific point as the arrow is being drawn.



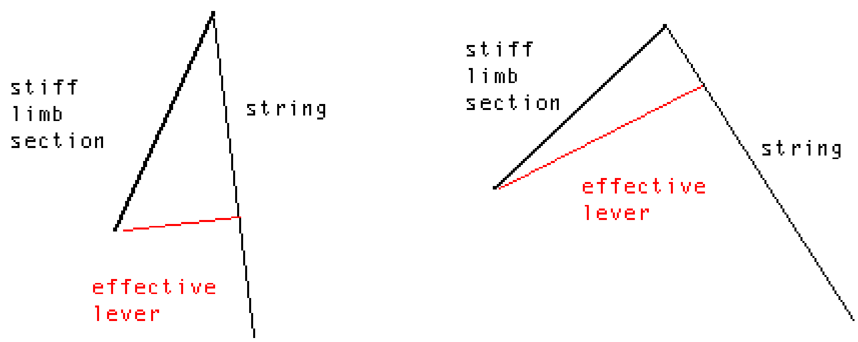
In the above diagram 'F' is the force exerted by the bow limb. The string is at an angle 'A' to the direction of the spring force. The tension in the bow string is FCos(A). Where Cos (cosine) is a mathematical function whose value depends on the angle 'A'. (Its value varies between 0 at 90 degrees to 1 at 0 degrees). The string is at angle 'B' to the arrow shaft. The weight on the fingers is 2FCos(A)Cos(B). (The factor 2 comes from having two, assumed identical, bow limbs). As the arrow is drawn back the values of F,A and B continually change as the draw length changes. e.g. angle B starts at 90 degrees at the bracing height position and decreases steadily as the arrow is drawn. The following charts illustrate how the string geometry and limb spring force vary over the draw length to produce the draw force curve.



The basic assumption in the above diagrams is that the force draw curve is a straight line and the draw weight is 40 pounds with the arrow drawn 25 inches. The initial few inches of draw are not shown as here the string is running around the bow limb so the geometry is more complicated and you also have string-limb friction operating. The recurve limb changes shape as the arrow is drawn and this affects the string geometry (angles 'A' and 'B'). The effect of this is ignored.

The Geometrical Draw Force graph shows how the value of 2Cos(A)Cos(B) typically varies over the draw length. The Limb-Spring Force graph shows how the value of 'F' varies over the draw length. You multiply these two values together to get the draw weight at any specific draw length. What is interesting about the spring force curve is that the force drops as the arrow is drawn and towards the latter part of the draw effectively becomes a constant tension spring. All done by clever limb construction, geometry and the reduction in material towards the limb tip.

An interesting approach to looking at bow draw force behaviour is presented by Ugo Bardi at the following link:



Look at the draw force curve for any recurve bow and what you see is, more or less, a straight line. The old rule of thumb of 2 pounds/inch for draw weight is based on the draw force curve being a straight line. Why straight? One could produce a bow limb having a draw force curve with a hump in it, something similar to a compound bow. This would give you a higher speed arrow with the same weight on the fingers. The way this can be done is in principle the same as for a compound bow i.e. the string tension is run through a lever which gets longer as you approach full draw. In the case of a recurve limb the lever is created by having a stiff section of limb towards the limb tip. As the limb bends and rotates and the angle between the limb and the string increases then the lever arm effectively gets longer and the required draw weight decreases as illustrated in the diagram.

The downside of this approach is that the limb section near the tip is not acting to store draw energy and is effectively 'dead weight'. Its rather like having a weight at each limb tip, it reduces the bow efficiency and can increase the shock loading on the bow from the shot. Overall you can still get a net gain. The traditional mongolian bow is an example of a bow using this approach. The practical problem in applying this approach to a modern recurve limb is torsional stability. Using a lever results in concentrating the stress in the bow limb below it making the limb more susceptible to twisting. The effect of any torque going into the limb from the string will be amplified because it acting through the limb lever. To get a significant weight let-off requires increasing the limb torsional rigidity by complex limb construction or by locally increasing the limb width. It is not currently economic to mass produce limbs having significant weight let-off.

Most archers prefer that the weight on the fingers increases smoothly up to the full draw position. When the draw weight rapidly increases near/up to the full draw position this is called 'stacking' and is viewed as a 'bad thing' (unless you are a compound archer and use a mechanical stop to generate 'infinite stacking' behaviour). Stacking can result from the spring characteristics of the limb, from the bow geometry or a combination of both. Usually if the limb and riser are bought as a package then stacking should not be a problem as the limb 'spring' and bow geometry are designed as a unit. With the advent of universal limb fitting however a problem has risen from one manufacturer's limbs being used with a different manufacturer's riser. Where this is done there is no guarantee that the limb spring properties and the overall bow geometry will produce a non stacking combination. If going the pick and mix route then you need to test before you buy.

While the area under the draw force curve represents the energy stored in the bow not all this energy will end up where we want it as arrow kinetic energy. The ratio of arrow kinetic energy to stored energy, expressed as a percentage, is what is called the bow efficiency. For recurve bows the efficiency is somewhere around 80% i.e. around a fifth of the energy stored in the bow is 'wasted'. You can have two bows with identical draw force curves but for a given draw length and arrow the arrow speeds off the bow can be different i.e. the two bows have different efficiencies. One reason for this could be that the two bows have diffferent geometrical and spring force characteristics contributing to the (overall same) draw force curve. For example suppose the bows have different limb lengths so one bow ends up longer than the other. The 'geometrical draw force' for the longer bow will be lower than for the shorter bow at all points during the draw because of the difference in bow geometry (the difference in the angles 'A' and 'B'). To have the overall same draw force then for the longer bow the 'spring force' must be correspondingly greater at all points during the draw. A typical way to get a stiffer spring force is to have more material in the limb, which makes it heavier. Accelerating a heavier limb with the same force results in a lower acceleration so the limbs (and hence the arrow) end up with a lower final speed. The longer bow is less efficient than the shorter bow although they both have the same draw force curve.

The design of the bow limb, its spring force characterisics, how it bends and the mass distribution in the limb will all effect the resulting efficiency of the bow. How the limb bends will also effect the bow 'geometrical draw force' characteristics. To pick a simple example the fastest moving part of the limb is the limb tip. The more mass there is in the limb towards the tip then the lower the resulting bow efficiency.

Another way the draw force curve influences bow efficiency is its shape/slope. Because the draw force increases as the bow is drawn the energy input per unit of draw length increases towards the end of the draw. The reverse is also true, the force on the arrow is highest at the point of the release and decreases as the arrow moves forward. One effect of a finger release is the Archers Paradox effect, the arrow bends. The higher the force on the arrow during the initial part of the shot then the more the arrow will bend . The energy that goes into the bending of the arrow is 'wasted' energy, it ends up as arrow vibration. The steeper the draw force curve or a draw force curve that bends upwards will result in more arrow bending and hence lower bower efficiency.

The other option is 'reverse' stacking i.e. the rate of increase of draw weight decreases as you approach full draw. This may be more comfortable for some archers. There is also the argument that with reverse stacking the arrow speed will be less sensitive to draw length as the variation of the area under the force draw curve with draw length will be reduced. True but a very marginal effect. The only practical way to get reverse stacking is to have the limb spring force reducing near to full draw. This can be done be reducing the amount of limb material towards the limb tip but this is limited by the strength, durability and stability requirements for the limb.

Dynamic Force Draw Curve

All the previous discussion relates to what is called the Static Draw Force Curve. When the static draw force is measured at different draw lengths nothing is moving. When the arrow is being shot everything is moving: bow, limbs, string, arrow, archer. The variation of the force exerted by the string on the nock of the arrow during the shot is called the Dynamic Force Draw Curve (even though the arrow is being shot rather than drawn). The dynamic force draw curve relates to the static force draw curve but is determined by the masses and accelerations of all the moving bits: bow, limbs arrow etc. A typical peak (static) draw weight for a recurve would be around 40 pounds. If you placed an arrow vertically on the ground and put a 40 pound weight on it then 'snap' the arrow would break. Over most of the shot the Dynamic Draw Force is lower than the Static Draw Force at any given draw length and follows an up-and-down variation tied in to the mechanical action of the bow and the Archers Paradox flexing of the arrow. Towards the latter end of the shot the Dynamic Draw Force is higher than the Static Draw Force as the momentum in the limbs feeds back into arrow acceleration.

It's the performance of the bow when being shot that matters so the Static Draw Force Curve should not be given to much weight when comparing one bow with another. e.g. if you replaced the working limb spacing material with mercury then although the Static Draw Force Curve would be much the same the performance of the bow would be considerably poorer.

BRACING HEIGHT

It is a well known effect that if you increase the bracing height of a bow the arrow speed out of the bow decreases and the arrow acts 'weaker'. Decreasing the bracing height has the reverse effect. Lowering the bracing height is sometimes used therefore to get more arrow speed. Increasing the bracing height is sometimes used to 'weaken' the arrow to get over arrow clearance problems. Playing about with bracing height as part of a bow tuning process is sometimes used as it varies the effective arrow dynamic spine.

The following describes how these two effects occur. The description is based on what happens if you increase the bracing height. For a decrease in bracing height just read the following backwards. 8-)

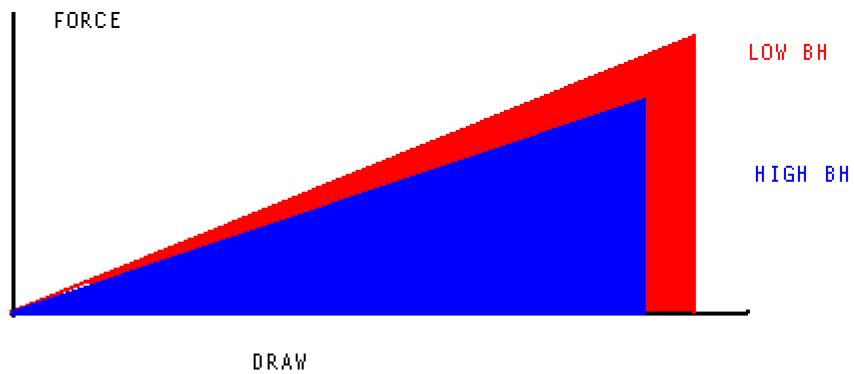
Effect on Arrow Speed

The speed at which the arrow leaves the bow depends on how much energy is stored in the bow when you draw it and what fraction of this energy goes into the arrow's kinetic energy. Increasing the bracing height affects how much energy is stored in the bow via two mechanisms, the slope of the draw force curve and the length the arrow is drawn against the string.

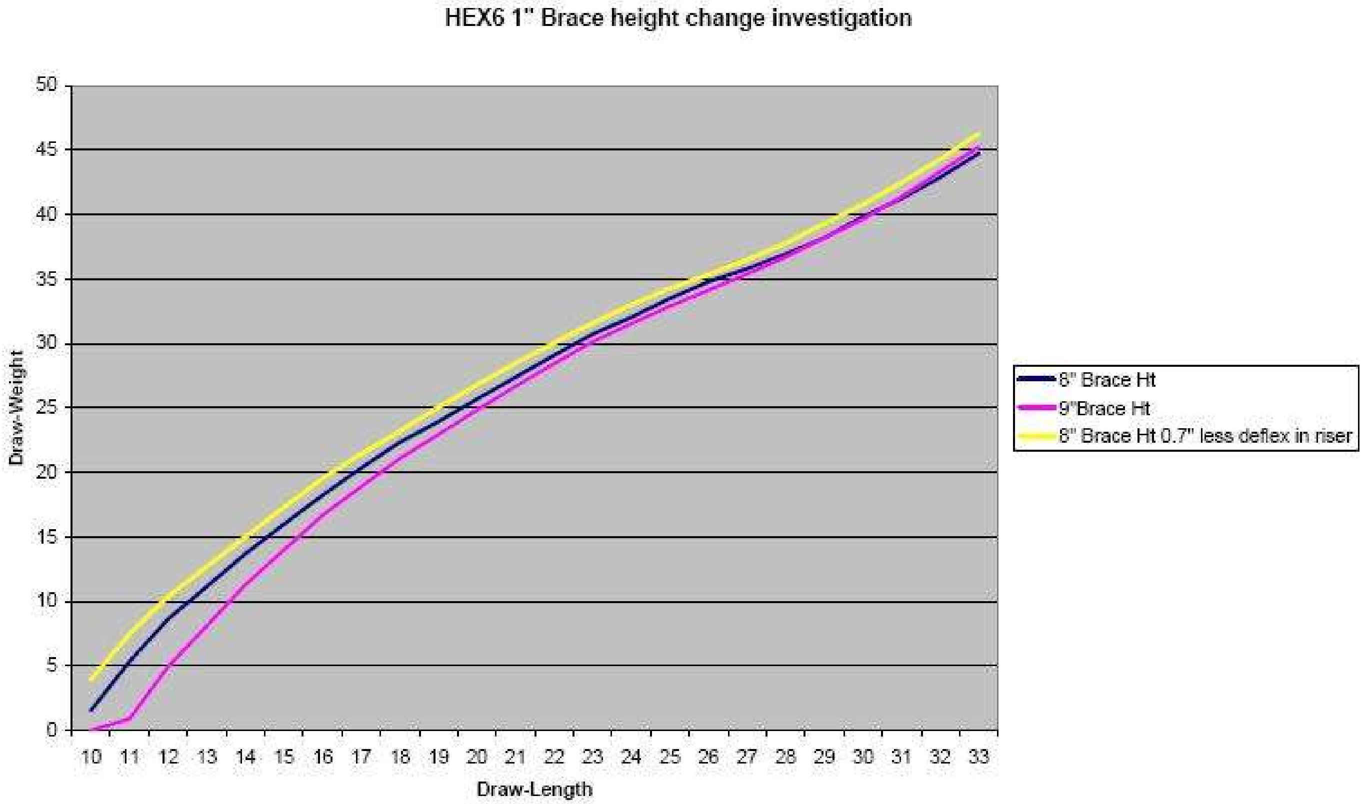
As described in the section on draw force the draw force curve is determined by the spring force the limb exerts as it is bent and the string geometry at the limb and the arrow nock. As the bow is drawn the spring force exerted by the limb decreases. If you increase the the bracing height the limb starts with more bend in it and so throughout the whole of the draw the limb spring force is lower having the effect of decreasing the slope of the draw force curve. Conversely if you increase the bracing height the angles the string makes with the limb and the arrow nock are changed through the draw to act to increase the slope of the draw force curve. These two effects therefore to a large extent cancel each other out. The resulting slope of the draw force curve may be steeper, less steep or much the same depending on the limb spring properties and the length of the bow. The shorter the bow and/or the stiffer the limbs the more likely it is that the slope of the draw force curve will increase. For a 68"/70" typical modern recurve the odds are that the slope of the draw force curve will remain much the same or decrease slightly. You can easily check the draw force variation at two different brace heights with a bow scale to see what is happening with a specific bow.

If the bracing height is increased by say 1" then when the bow is drawn the arrow is drawn 1" less against the string and so there will be less energy stored in the bow.(The loss of 1" of draw over the draw force curve you had with the original bracing height).

The following diagram illustrates the overall effect. The energy stored in the bow is represented by the area under the draw force curve.



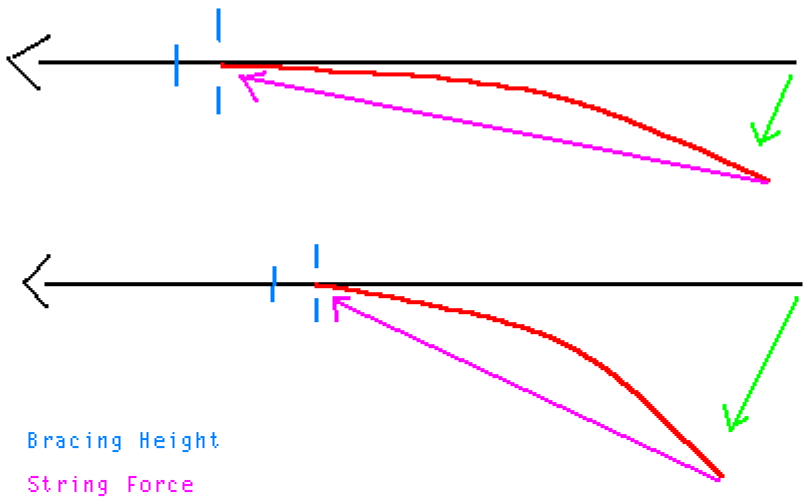
The increase in stored energy (hence higher arrow speed) for the lower bracing height in the above example comes partly from the difference in slope of the force draw curve and partly from the difference in draw lengths.



Here (from Border) is a practical example of how changing the brace height affects the draw force curve and hence the stored energy. Also included (the yellow curve) is an example of how the changing the brace height via modifying the riser (deflex) shape can be used to increase energy storage and hence increase arrow speed. The limitation on this approach is that bow torsional stability is reduced and the limbs are more likely to stack.

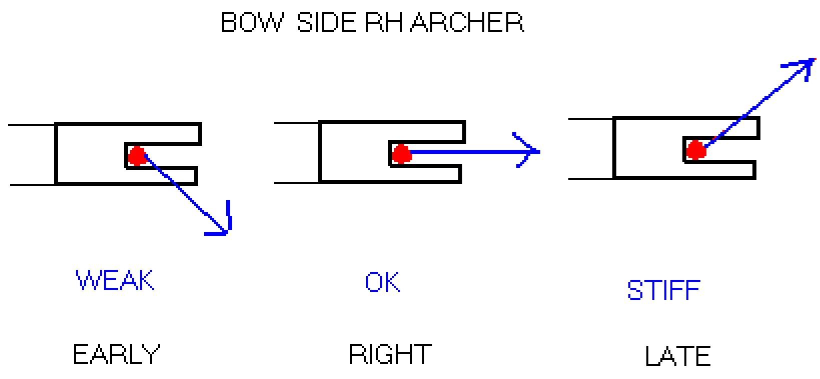
Effect on Dynamic Spine

Increasing the bracing height has two effects on the amount the arrow initially bends (its dynamic spine) when it is released. Firstly, as illustrated in the above diagram, it will in general lower the weight on the fingers at full draw. This will have the effect of reducing the amount the arrow bends (stiffer arrow). The second effect is that increasing the bracing height reduces the length of shaft over which this bending occurs and increasing the string force angle to the shaft which has the effect of increasing the amount the arrow bends (weaker arrow). In general the latter effect predominates and the overall effect is to 'weaken' the arrow.

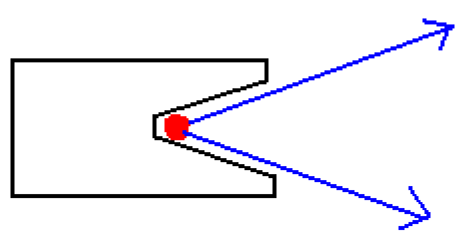


How the arrow bends on release is described in the section on Archers Paradox. The section of arrow shaft over which the 'nock end' bending occurs is from the nock end to a point a bit short of where the bracing height is located. (a 'bit short' as the arrow is moving forward as it bends). If you assume that the amount of 'spring energy' that builds in the shaft until the pile speed catches up with the nock speed is much the same for a small change in bracing height then although the length of bent shaft is a bit shorter, and hence stiffer, the angle between the string force and the shaft is bigger and overall the shaft bends more with the higher bracing height. Another way to put this is to say that as the bracing height increases a lower fraction of the string force goes into compressing the arrow shaft and a higher fraction into bending the arrow shaft.

The actual position of the bracing height will affect what effect the string has on the arrow at the point where the string separates from the nock. During the power stroke the bow string is accelerating, pushing the arrow. At some point, determined by the bracing height the string will start to decelerate and the arrow will leave the string behind. The string has to exit the nock groove. How it does this will effect the arrow rotation in the horizontal plane. The higher the bracing height then the earlier will the string exit the nock groove.



The ideal situation is when the string direction of travel (the blue arrows) runs straight down the string groove. The string has no effect on arrow rotation. If the brace height is too high the string will exit the nock too early and the direction of string deceleration runs through 'left hand side' of the nock groove. The consequent tweak on the arrow acts to increase arrow rotation in a clockwise direction (looking down on the bow) which makes the arrow act weak. If the brace height is too low you get the reverse and the arrow acts stiff. Generally, because of the way the arrow is flexing and moving, the consequences of having too late a string-nock separation will be worse than having one too early.



The tighter the string fit in the nock then the worse will be the consequences of the string not exiting the nock cleanly. The string-nock friction will add to the amount of rotation the arrow gets. This is why the nocking point should be just tight enough not to slide around in the nock groove during the draw. As the diagram illustrates having a short 'V' shaped nock provides a wider tolerance for the string to exit the nock cleanly.

In practice nocks are usually keyhole shape; the string is free to swivel inside the nock to prevent string/arrow torque while the "pinch" keeps the arrow from falling off the string during the draw process

The effect of bracing height on string-nock separation is not something that the archer need to be directly concerned with. When you select your arrow based on draw length and weight from the charts and use a bracing height in the recommended range this, by definition, gives you good nock-string separation. When you 'tune for groups' you are making small adjustments to how the arrow bends and rotates and getting the best nock-string separation is automatically included in the process.

The Relationship between Brace Height and Arrow Speed

If you make the assumptions that during the shot the time the arrow is on the bowstring equals the free-free shaft vibration time and that the arrow goes through 0.25 vibration cycles between the nock leaving the bow string and passing the pressure button then you get the relation that the bracing height equals the arrow launch kinetic energy divided by the peak draw force.

For example using data from Dennis Lieu
A tuned bow system with an ACC 3L-18 arrow had the following measured properties:
Arrow mass 341 grain (23.01 grams)
Draw Force 169N
Arrow launch speed 57.9 metres/second
Using the KE/Draw force method with the above data gives a bracing height requirement of 22.8 cms
The actual measured bracing height was 22.5 cms

Not in itself particularly useful perhaps but rearranging the equation gives you an estimate of arrow speed based on arrow mass, draw force and brace height which might be useful as it only needs numbers that any archer can easily measure.

i.e. Arrow Speed squared = twice brace height times draw force divided by arrow mass

With the above example and the measured brace height of 22.5 cms the estimated arrow speed is 57.5 m/s.

AN IDIOTS GUIDE TO BOW ROTATION

No offence is meant by the title. The topic of bow torque, bow rotation and stabilisation is on a realistic level such a can of worms that anyone with any sense avoids the subject like the plague. I'm happy to be included among this group. What I'll try to do here , based on some simplistic examples, is put across some basic concepts about how objects (e.g.. a bow) rotate when a force (torque) is applied. I shan't go through all the math just supply the relevant relationships.

Some Basic Concepts

The effect of a force on an object is to change it's momentum. In fact the definition of a force is the rate of change of momentum with time. It follows therefore that the change in momentum resulting from an applied force is the integral over time of the applied force i.e.put simply: **change of momentum = force x time**

In the following I'll use the symbol **F** for force with suffixes as appropriate.

The topic of Moment of Inertia has been covered on another page. The moment of inertia of an object around a particular axis can expressed as being equal to the object mass multiplied by the square of what is called the radius of gyration. The value of the radius of gyration of an object is dependant upon the position of the rotation axis. When you add stabilisers to a bow you to some extent increase the overall mass but what you are really trying to do is increase the value of the radius of gyration.

In the following I'll use the symbol **M** for object mass and **K** for the radius of gyration with suffixes as appropriate.

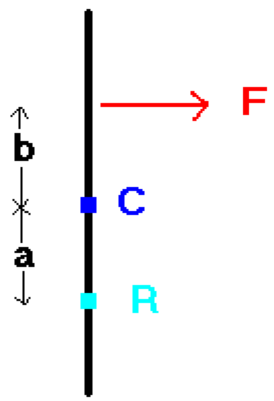
When you apply a torque to an object it rotates. The angle through which the bow rotates in a time **T** I'll represent by the symbol **A**.

When you apply a force to an object it changes it's momentum. There are two types of momentum, Linear Momentum and Angular Momentum. In general when you apply a force to an object both the linear and angular momentum are changed. There is a rule about momentum change called the 'Conservation of Momentum Principle' which is basically that momentum can't appear from nowhere or disappear down a black hole. The key to understanding how objects rotate under an applied force is that the changes in linear and angular momentum must **simultaneously** conform to the Conservation of Momentum Principle.

In the following discussion the bow is represented by a vertical black bar. It is assumed that the bow includes various appendages (sight, stabilisers etc.) so that the position of the bow centre of gravity is variable.

Free Bow

By Free Bow I mean that nothing other than a single applied force (which represents all the accelerating bits of the bow/arrow/string) acts on the bow. i.e. there is no bow hand. Only bow rotation in the vertical plane is considered.



A force **F** acts on the bow at a distance **b** from the centre of gravity at **C** and the assumed axis of the consequent rotation is at **R**. The distance from **R** to the bow centre of gravity is **a**. The centre of gravity is assumed to lie in the plane of the bow. The force is assumed to act for a time **T**, the time being short enough so we don't have to worry about the value and position of **F** etc. changing.

When you apply the Conservation of Momentum principle as defined above to the bow it defines the point about which the bow rotates and the rate of rotation about this point.

The distance **a** is given by:

$\mathbf{a} = \mathbf{K_g}^2/\mathbf{b}$ (further information)

Where $\mathbf{K_g}$ is the radius of gyration calculated at the centre of gravity **C**.

Several points follow from the definition of **a** above about the bow rotation axis. Firstly in this case (initially stationary riser and very small value of T) the 'natural' bow rotation axis can never be at the bow centre of gravity as this would contravene the Conservation of Momentum Principle. Secondly the closer the applied force is to bow centre of gravity the further away from **C** is the 'natural' rotation axis. Thirdly the higher the value of $\mathbf{K_g}$ the further away from **C** is the 'natural' rotation axis. (Here rotation axis is taken to mean a stationary point in the current reference frame around which the riser rotates.)

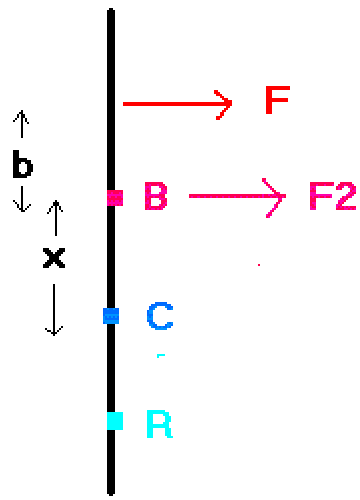
Assuming the force **F** is constant then the angle through which the bow rotates in time **T** is given by:

$\mathbf{A} = \mathbf{FT}^2(\mathbf{a}+\mathbf{b})/2\mathbf{M}(\mathbf{K_g}^2 + \mathbf{a}^2)$

No surprises here. The higher the bow mass and in particular the higher the value of $\mathbf{K_g}$ (lots of stabilisation) the less the bow will rotate in a given time. The closer the centre of gravity is to where the force **F** is applied then the less rotation you get. If the centre of mass is at the point where **F** is applied then there is no bow rotation.

Constrained Bow

This is the same situation as above but now a bow hand, located at a bow grip **B**, is introduced As is the usual situation the centre of gravity is located below the bow grip. The bow grip is located at a distance **x** above the bow centre of gravity. The bow grip is assumed to be located on the line between the applied force **F** and the centre of gravity **C**. This means that gravity has no effect on bow rotation.



When the arrow is shot and the force **F** is applied the bow 'tries' to rotate naturally in a clockwise direction with the rotation axis at **R** as in the first example but the bow hand prevents this. The bow 'leans' on the bow hand producing a force and reaction between the grip and the hand of value **F2**. Assuming that the bow hand doesn't move and the grip doesn't swivel about in the hand then the grip - hand pressure point acts like a horizontal spindle and the rotation axis of the bow is located at point **B**. The value of **F2** is that required to make **B** the rotation axis.

Applying the Conservation of Momentum Principle as defined above to the bow you get the expression for how much the bow rotates under the force **F** for a time **T**. i.e.

$$\mathbf{A} = \mathbf{FbT}^2/2\mathbf{M}(\mathbf{K}_g^{\,2}+\mathbf{x}^2)$$

Agan the higher the bow mass and the radius of gyration the less the bow will rotate. As far as the geometry of the bow goes, to reduce the amount of bow rotation we want a low value of **b** and a high value of **x**. The rotation angle is directly proportional to **b** and so is very sensitive to it. In practice the distance **b** relates to the gap between the pressure button (**F**) and the bow grip (**B**). This is the basis for it being said that the smaller this gap the more 'torque forgiving' is the bow. How small you can make **b** is determined by needing to have enough clearance to shoot the arrow and fletchings over the bow hand and arrow shelf. The value of **x** is limited by the bow design/construction, there is only so much weight you can add below **B** to lower the centre of gravity and keep a reasonable overall bow weight. The above equation illustrates the basic requirements for the barebow where stabilisers are not allowed. The arrow ideally rests on the bowhand knuckles (minimising **b**) and weight is added somehow to the bottom of the bow to increase **x** . Note that it is not possible in this case to have a bow set-up with a zero value of **A**, it is not possible to completely 'torque stabilise' the bow.

There are a couple of other considerations that may be worth a mention.

The reaction force **F2** at the bowhand is given by:

$$\mathbf{F2} = \mathbf{F}\,(1-\mathbf{xb}/(\mathbf{K}_g^{\,2}+\mathbf{x}^{\,2}))$$

If the centre of gravity is at the bow grip then **F2** = **F**. As the centre of gravity is lowered then the value of **F2** decreases. The friction between the hand and the grip depends on the force between them so as you lower the centre of gravity hand - grip friction decreases. As this friction opposes any movement of the grip in the hand during the shot it suggests that there is a benefit in having a low value of **x** i.e. having the centre of gravity near or at the bow grip. Many archers use shooting gloves to increase the hand - grip friction. There are probably also physiological and psychological effects on how the value of **F2** ultimately effects arrow groups.(On which I'm not qualified to comment).

Another consideration with respect to the centre of gravity position issue is energy. The energy in our revolving bow comes from the energy stored in the bow when drawing the arrow. So the more energy that ends up in the bow means less energy that goes into the arrow (less arrow speed). The energy **E** that ends up in bow due to the force **F** acting on it is given by:

$$\mathbf{E} = \mathbf{FAb}$$

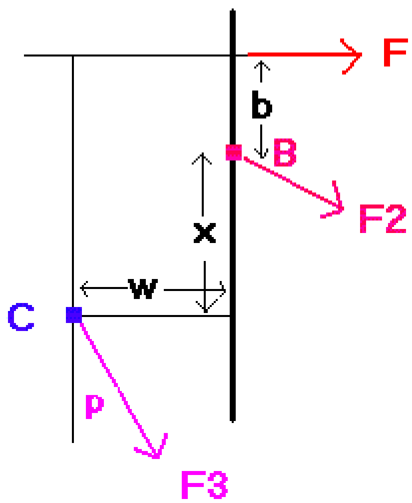
The value of **b** is defined by the bow manufacturer. The smaller we can make **A** (maximise torque stability) gives a side benefit of increasing the bow energy efficiency.

The tentative conclusions that can be made from the simple model above are that to make the bow 'torque forgiving' the archer should increase the bow mass and radius of gyration (moment of inertia) - well you all knew that anyway. The model also suggests that overall the stabilisers should be arranged so that the centre of gravity is located at the bow grip - hand pressure point, a suggestion that archers would invariably disagree with.

The big simplification in this model is that the bow is assumed to be vertical with **F**, **B**, **C** and **R** all in the plane of the riser. This results in gravity having no effect on the bow rotation. In practice when shooting any distance the bow has to be rotated in the vertical plane so this condition no longer holds and gravity does have an effect. Another consideration is that in general archers locate the centre of gravity vertically below the grip and in front of the riser. This raises the questions why do this and how far down and forward should the centre of gravity be. A model including the effect of gravity is required.

Constrained Bow - Gravity Affected

In this example the bow is elevated from the horizontal by an angle **p**. The distance from the button to the bow - hand pressure point is **b**. The centre of gravity **C** of the bow is located a vertical distance **x** below the pressure point and a horizontal distance forward **w** . In this case gravity has an effect on bow rotation. For convenience the viewpoint is rotated so that the bow appears to be vertical.



As in the previous example the bow is assumed to naturally rotate into the bow hand making **B** the rotation axis, which as previously acts like a horizontal spindle. In the earlier examples the fact that the bow hand had to support the weight of the bow was ignored as it had no effect on the bow rotation. In this case the weight does effect rotation so the value of **F2** is the total force on the bow hand resulting from the mechanical action of the bow (**F**) and the gravitational force (**F3**) on the bow.

There are now two torques, in opposite directions, acting to rotate the bow, the torque from the bow mechanical action and the torque from the bow mass. In principle then, if with the bow geometry these torques can be balanced we end up with a bow that doesn't rotate. We get a 'torque stabilised' bow.

Applying the Conservation of Momentum Principle as defined above to the bow and using **g** for the gravitational acceleration you get the expression for how much the bow rotates under the force **F** for a time **T**. i.e.

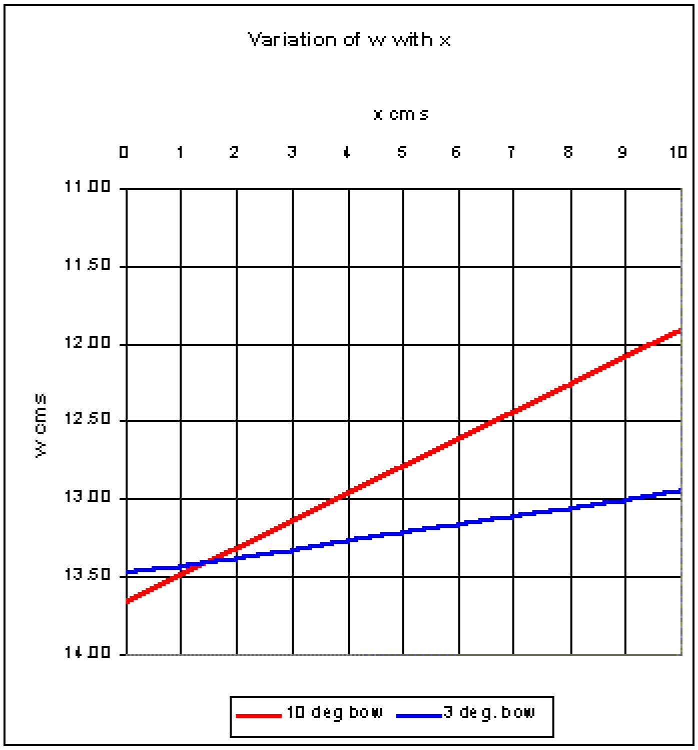
$$\mathbf{A} = \mathbf{T}^2(\mathbf{Fb}+\mathbf{Mg}(\ \mathbf{w}\mathrm{Cos}(\mathbf{p})+\mathbf{x}\mathrm{Sin}(\mathbf{p}))/(2\mathbf{M}(\ \mathbf{K}_g^{\ 2}+\mathbf{w}^2+\mathbf{x}^2\ ))$$

For a 'torque stabilised' bow **A** would be zero i.e. the terms in brackets in the numerator in the above equation

$(\mathbf{Fb}+\mathbf{Mg}(\mathbf{w}\mathrm{Cos}(\mathbf{p})+\mathbf{x}\mathrm{Sin}(\mathbf{p}))$ would equate to zero.

The term **Fb** is the (clockwise) torque from the action of the bow and is constant because the length of the lever arm doesn't depend on on the bow angle **p**. The term $\mathbf{Mg}(\mathbf{w}\mathrm{Cos}(\mathbf{p})+\mathbf{x}\mathrm{Sin}(\mathbf{p}))$ is the gravitational (anticlockwise) torque, **Mg** being the force and $(\mathbf{w}\mathrm{Cos}(\mathbf{p})+\mathbf{x}\mathrm{Sin}(\mathbf{p})$ being the length of the lever arm which does depend on the bow angle. For a specific bow angle **p** and value of **x** the value of **w** can be adusted to give a 'torque stabilised bow'. You can rearrange the net torque equals zero relationship to indicate how **w** depends on **x**. i.e. **w** = - **x**Tan(**p**)-**Fb**/**Mg**Cos(**p**)

This is just an equation of a straight line with slope -Tan(**p**). In other words for a given bow angle there a lots of positions of the centre gravity that will result in a 'torque stabilised' bow it's just a matter of getting the right combination of **x** and **w**.



The diagram illustrates the relationship between **x** and **w** for torque stabilisation for bow angles of 10 and 3 degrees (typical Fita round say).

The assumed properties of a 'typical' recurve bow are:

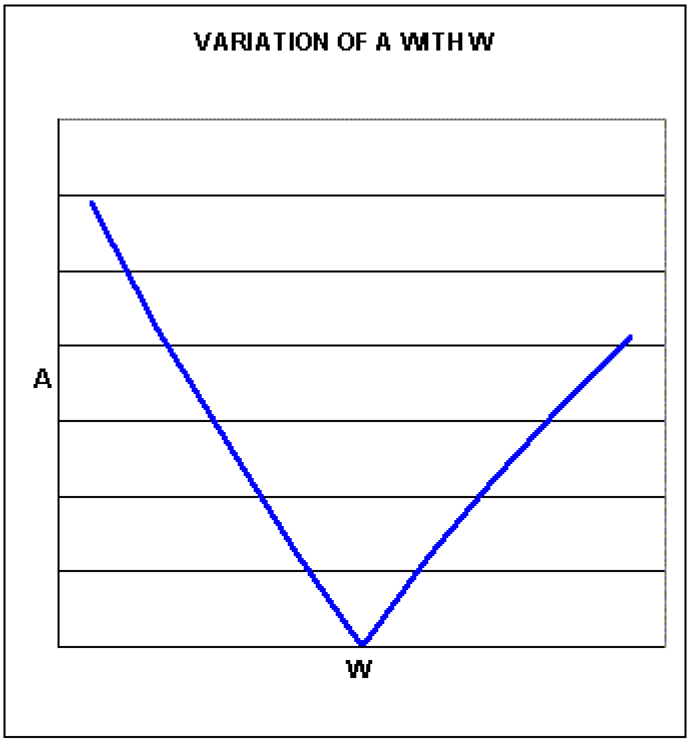
Mass **M** = 2.5 Kg
gap **b** = 5.5 cms
average **F** = 60 Newtons (guesstimated from typical draw weight)
x is assumed to vary from level with to 10 cms below position **B**

As **x** increases the required value of **w** decreases related to the bow angle and vice versa.

Torque stabilistation is related to the distance shot. You can only ever pick a compromise value for a range of distances.

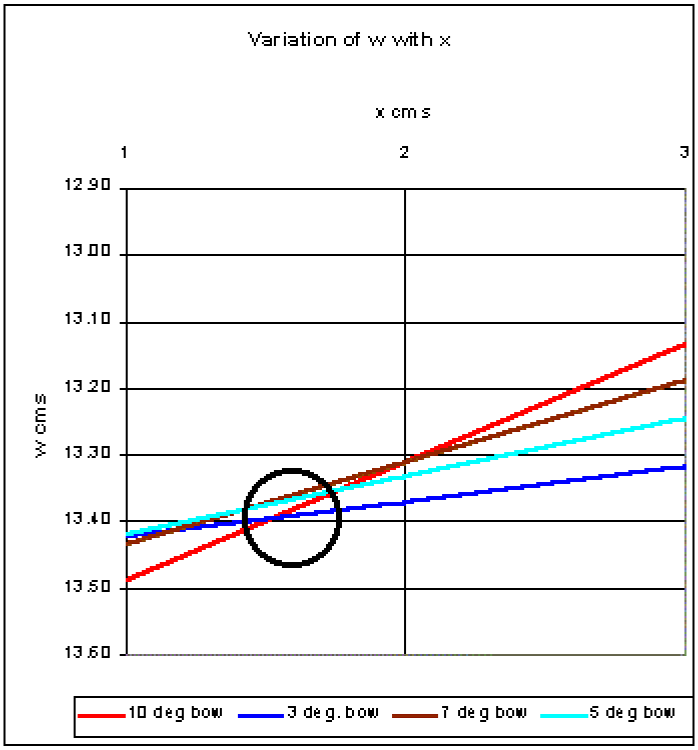
The slope is flatter the lower the bow angle which suggests that cranking up the bow draw weight gives some benefit with respect to overall bow torque stabilisation.

Perhaps the most relevent feature of the graph is that there is a specific value of **x** and **w** at which the bow is torque stabilised at both angles (both distances).



This diagram illustrates how much bow rotation (**A**) you get as **w** (or **x**) vary around the 'torque balance' situation. (the bow actually rotates in opposite directions either side of the optimum value but I've shown **A** as positive both sides)

What you get is a 'valley' shape. The closer you are to the optimum position of the bow centre of gravity (**A**=0) the less rotation you get.



If you plot the **w-x** curves for all the range of bow angles (distances) you shoot then you get a bunch of tramlines.

There is no single set of values of **x** and **w** which will give you a 'torque stabilsed' bow at all distances. All you can do is pick an area in which all the lines are relatively close (the black circle).

In reality for an actual bow the values of **x** and **w** (along with just about everything else) vary during the shooting process, so the best you can ever do is choose a compromise position which seems to work well overall.

The idea put forward in the previous example that reducing the value of **b** (the button to grip distance) makes the bow more torque forgiving in this case is no longer necessarily true because there are two torques affecting bow rotation. It's rather like a tug of war with the bow action at one end and gravity at the other. Reducing **b** means that at any given moment the 'bow' team is pulling less hard. The 'gravity' team's pull variation (**x** and **w** changing) can therefore result in more movement of the middle of the rope. i.e. reducing **b** can make the bow less torque forgiving.

The denominator in the formula for **A** includes the term $\mathbf{M}(\mathbf{K}_g^2+\mathbf{w}^2+\mathbf{x}^2)$ which is the Moment of Inertia of the bow with respect to rotation around the hand - grip pressure point. The bigger this term is then the less the bow rotates during the shot. The benefit of having a high bow mass is clear. The term $\mathbf{K}_g$ relates to the radius of gyration at the centre of gravity. The **x** and **w** values relate to how far the bow rotation axis is from the centre of gravity. The value of $\mathbf{K}_g$ will depend on the values of **x** and **w**.

The basic conclusion is that for a given bow mass the further the grip - bow hand rotation axis is from the centre of gravity and/or the higher the value of $\mathbf{K}_g$ the more 'torque forgiving' the bow will be. (And at the same time the values of **x** and **w** are selected to best obtain 'torque stabilisation').

How far the bow centre of gravity is from **B** is limited by mechanical effects on the bow. There are 3 principal limitations on this. The first obvious one is the overall bow weight. Too much weight will result in archer fatigue and the inability to hold the bow steady. (Bow Hand Loading) The second limitation is the stiffness of the stabiliser rods and the connections between rods and bow. As the length of a rod increases the stiffness drops rapidly (as the cube of the length). The more the rod bends when the riser twists then the less effective it's going to be in reducing the amount of riser twist. The third limitation is the effect on the bow tiller. If you can imagine pulling down on the end of a long rod of a bow at full draw then the effect will be to increase the bending of the top limb and reduce the bending of the bottom limb. When the string is released this differential bending disappears. So the further forward the bow centre of gravity is in front of the grip the more the bow tiller will require adjustment to compensate. As you can never completely compensate for bow tiller effects the higher the tiller the worse off you're going to end up.

Summary

To summarise a stabiliser system has two main functions

- Maximise the dynamic stabilisation of the bow, particularly with respect to the bow recoil.
- Establish a 'balanced bow' with the force on the bowhand running through the bow arm.

The above two criteria are to be met while keeping a 'manageable' force for the archer on the bowhand.

The first of the above criteria is met by use of a long rod pushing the bow centre of gravity forward of the grip. This property is enhanced by use of a very rigid extender which effectively increases the rod length.

The second of the above criteria is met by the extender, vbar and twin rod combination. As discussed in the section on bow hand loading the vertical bow mass load on the bowhand has to be adjusted to give the best biomechanical result. The V bar arrangement allows (twin rod) mass to be added at or close to a horizontal axis through the bow grip. This is the most efficient method of adding bow mass load to the bow hand bearing in mind the overall bow hand force needs to be within manageable limits.

Because the bow centre of gravity is in front of the grip, after the shot the bow rolls forward. It is sometimes suggested that this roll forward can affect the arrow while it's being shot. The arguments vary between this roll forward being a good thing or a bad thing. If you actually quantify the combined effect of the roll forward and the bow recoil backward it is clear that bow roll has no significant effect on the arrow.

The above models relate to bow rotation around a horizontal axis. Bow rotation around a vertical axis is more or less described by the 'constrained bow' model above. In this case in principle we can have both **b** and **x** equal to zero as **F**, **B** and **C** can be in the same vertical plane. There is only a torque problem if the bow hand centre of pressure (**B**) is horizontally shifted by incorrect hand placement. The archers paradox effect itself generates bow torque as it results in the horizontal direction of **F** changing (which results in a non zero varying value of **b**). This effect is essentially catered for in the 'bow tuning' process but as the buckling of the arrow on release depends on the loose a bad release can generate torque affecting where the arrow ends up.

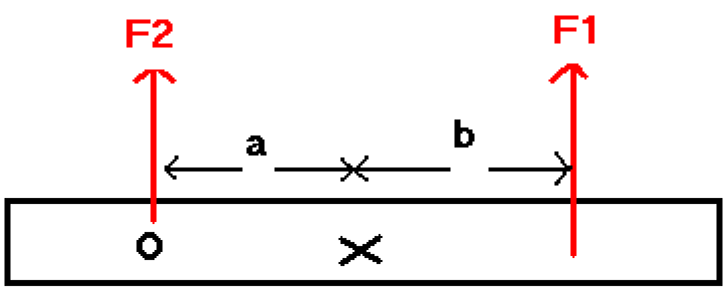
These simple models do, I hope, put across some of the basic concepts about bow rotation and stabilisation. A real bow of course rotates in three dimensions, the bow hand - grip interface isn't fixed and the values of **F**, **x**, **w** etc. all vary during the shooting process so the first law of archery comes into effect. Suck it and see!

THE BASICS OF RISER ROTATION DURING THE POWER STROKE

An idea that seems to float around in archery is that the force the bow hand exerts on the riser when at full draw still exists after the draw hand has released the string. So on release the bow hand generates a forwards force on the riser. In this case to minimise any riser rotation the bow centre of gravity should coincide with the grip (pivot point) or at least be level with it. This view is incorrect. The force on the bow hand at full draw results from the combination of the string draw force and the gravity force (weight) of the bow. When the string is released the draw force component disappears and what's left is the gravity force acting on the bow hand. An additional force on the bow hand is generated by the recoil of the bow.

The following discussion describes the initial (instantaneous) behaviour of the riser (ignoring gravity) after release of the bow string. We have a **stationary** unconstrained riser on which a (recoil) force acts above the grip position.

The starting point will be Mass x Acceleration = Force which I hope most people will be happy with.



We have some object of overall mass **M** to which a force **F1** is applied at some distance **b** from the object's Centre of Gravity at X. The obect is fitted with a spindle (at right angles to the applied force) at a distance **a** from the object's Centre of Gravity. When the force **F1** is applied the object will try to rotate about some axis. The object at the spindle will in general try to move and so a force **F2** will need to be applied to the object by the spindle to prevent any movement. The force is assumed to act for a short enough time **dt** that the force **F1** doesn't change in magnitude, position or direction. (e.g. with an arrow, as it rotates both the drag force and the effective position of where the drag force acts both change).

If you integrate Mass x Acceleration = Force with respect to time you get:-

Mass x Velocity = integral over time of the Force

Mass x Velocity is called the (linear) Momentum. The linear momentum that the object gets comes from the integral over time **dt** of the force **F1** (call it **J1**) and the integral over time **dt** of the force **F2** (call it **J2**). The linear momentum the object ends up with (mass x velocity) has to equal **J1**+ **J2**, the linear momentum you put in. The velocity were talking about is the velocity of the object's centre of mass (COG). The object has to rotate around the spindle so the COG travels tangentially to an arc of a circle of radius **a**. The velocity of the COG is therefore **aA** where **A** is the angular velocity of the object around the spindle. So what we end up with as far as the linear 'conservation of momentum' goes is:

$\mathbf{MaA} = \mathbf{J1} + \mathbf{J2}$ (equation 1)

The rotational equivalent of Mass x Acceleration = Force is Moment of Inertia x Angular Acceleration = applied Torque

If you integrate the above with respect to time (same way as the first case) you get:

Moment of Inertia x Angular Velocity = integral over time of the Torque

The torque is the force x distance to the point of rotation i.e the torque = (**a**+**b**) x **F1**

The integral over time **dt** of the Torque is therefore equal to (**a** + **b**) **J1**

The moment of inertia of a mass around a rotation axis is the mass multiplied by the square of the distance to the rotation axis. Suppose the overall moment of inertia for rotation of the object around the spindle is $\mathbf{I_s}$. We define a value $\mathbf{K_s}$ as:-

$\mathbf{K_s^2} = \mathbf{I_s} / \mathbf{M}$

$\mathbf{K_s}$ is called the Radius of Gyration. If all the object's mass were located at a distance $\mathbf{K_s}$ from the spindle then the Moment of Inertia (the rotational properties) would be the same as the object.

The Moment of Inertia x Angular Velocity = integral of time of the Torque can, for the object, be therefore written as:-

$\mathbf{MK_s^2A} = (\mathbf{a} + \mathbf{b})\mathbf{J1}$ (equation 2)

rearranging equation 2 you get: $\mathbf{A} = (\mathbf{a} + \mathbf{b})\mathbf{J1}/\mathbf{MK_s^2}$ (equation 3)

Substituting the expression for **A** in equation 1 you get:- $\mathbf{Ma}(\mathbf{a} + \mathbf{b})\mathbf{J1}/\mathbf{MK_s^2} = \mathbf{J1} + \mathbf{J2}$ (equation 4)

Rearranging equation 4 you get:- $\mathbf{a}(\mathbf{a} + \mathbf{b}) = \mathbf{K_s^2}(1 + \mathbf{J2}/\mathbf{J1})$ (equation 5)

Equation 5 is what you could call a 'weathervane' equation. It tells you what force you get between the object and the spindle for a given applied force/geometry. (In this case it describes the force exerted on the bow hand as a result of the bow recoil). As you move the spindle about the value of **J2** (i.e.**F2)** will vary. For some position of the spindle **J2** (and hence **F2**) will be zero i.e. the object rotates about the spindle with no force between the spindle and the object. In this case removing the spindle will make no difference to how the object rotates. The condition **J2** = 0 in equation 5 therefore defines the axis of rotation for a free object (no spindle). Putting **J2** = 0 into equation 5 gives you:-

$\mathbf{a}(\mathbf{a} + \mathbf{b}) = \mathbf{K_s}^2$ (equation 6)

As $\mathbf{K_s}$ for any realistic object cannot be zero it follows from equation 6 that **a** can never be zero i.e. under a single applied force for a free body the COG can never be the natural axis of rotation. You will often hear that "the object" rotates at the centre of mass but this is always qualified by something like "and the centre of mass travels in a curve". i.e. if you define a rotation axis to be at the centre of mass then to make the numbers add up there has to be a second rotation axis about which the centre of mass rotates. The centre of mass can never be the true rotation axis.

You can tidy equation 6 up a bit (with a bit of sleight of hand) by applying a theorem related to Moment of Inertia called the Parallel Axis Theorem. This gives you that :-

$\mathbf{K_s}^2 = \mathbf{K_g}^2 + \mathbf{a}^2$ where $\mathbf{K_g}$ is the (constant) object radius of gyration calculated with respect to rotation around the COG.

Substituting for $\mathbf{K_s}$ in equation 6 gives a simple definition of where the rotation axis of free object under a single applied force is located i.e.

$\mathbf{a} = \mathbf{K_g}^2/\mathbf{b}$

In summary the recoil force (with no pivot/bow hand) acts to initially rotate the riser about some axis not at the centre of centre of gravity. The bow grip is normally located between the centre of gravity and the point at which the recoil force acts. The sense of rotation acts to drive the riser into the bow hand so the rotation axis of the bow shifts (nominally instantaneously) to being the grip pressure point. The force exerted by the riser on the bow hand (F2 in the above discussion) is that required to shift the bow rotation axis to the grip.

Post Shot Bow Rotation

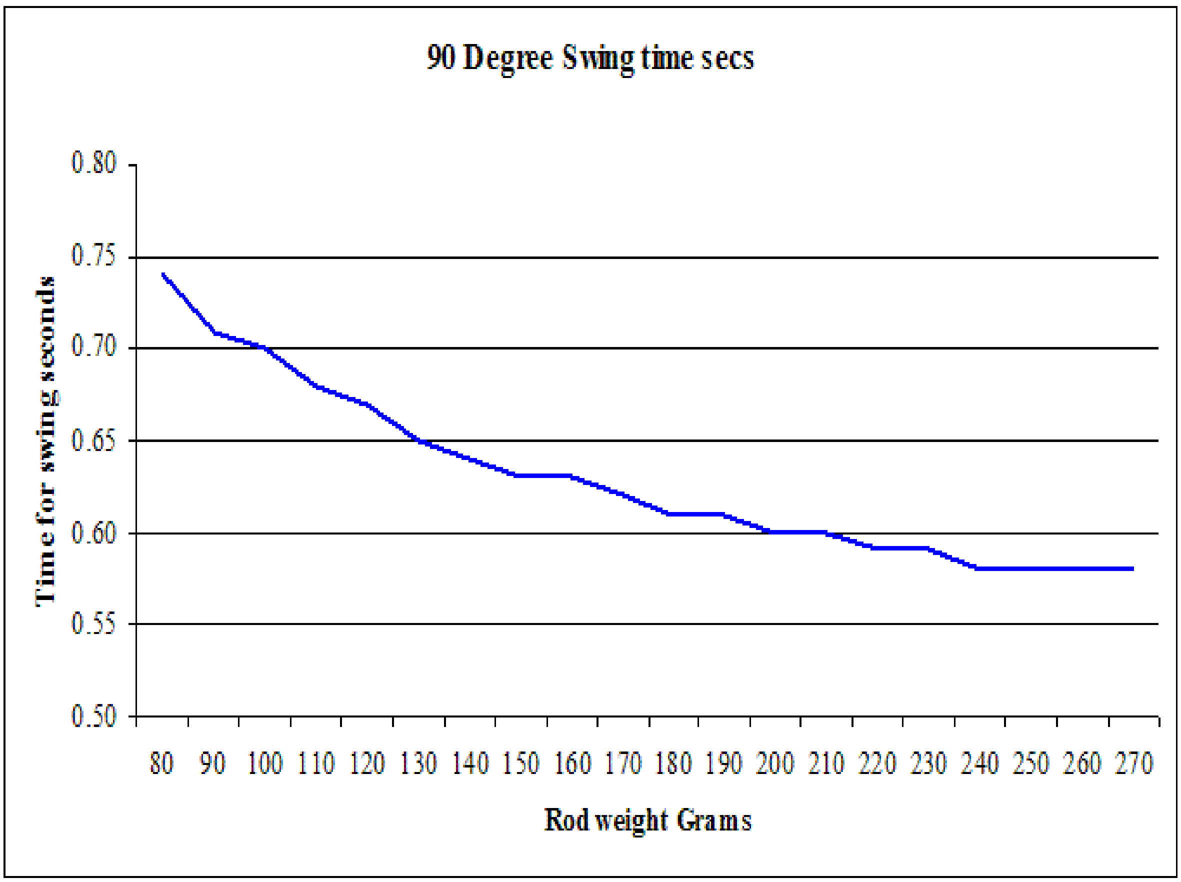
How fast a bow rotates after the arrow has gone is a common discussion topic; surprising as it's completely irrelevant. The general view is that adding weight to the end of a long rod results in the bow rotating faster.

What actually happens is not obvious as both effects are possible depending on the bow configuration you start with and what change you make.

If for a given bow you increase the weight on the rod end then you increase the gravity torque on the bow - the "it rotates faster" argument. However adding weight to the rod end also increasing the bow moment of inertia which acts to reduce rotation rate - the "it rotates slower" argument. The overal rotation rate is complicated by a number of factors:

- The gravity torque on the bow changes as the bow rotates: maximum with the COG level with the grip and decreasing to zero as the COG swings vertically beneath the grip.
- The initial vertical position of the bow COG with respect to the grip (assumed pivot point) affects the gravity torque variation over time.
- Changing the end weight shifts the position of the bow COG which affects its rotaional characteristics

In an attempt to shed light on this issue a simple calculation is made of the time it takes for a bow to rotate from stationary with rod horizontal to the rod swinging down to the vertical with various end weights. A typical 25" riser with all up weight of 1200 grams is used.A weightless rod of length 70 centimetres is used. It's assumed that with the rod horizontal the COG is level with the pivot point. The time for the long rod to swing downwards from horizontal to vertical (i.e. through 90 degrees) is calculated.



As can be seen in this case adding weight to the rod end makes the bow rotate faster, in agreement with the general view. However the swing time difference between the 80gm and 270gm weight is only 16 hundreths of a second - not worth writing home about.

Incidentally increasing the gravity torque by increasing the length of the rod has the reverse effect i.e. it slows down the bow rotation rate (again by a trivial amount).If you push the bow centre of gravity forward with a longer extender or long rod, you can get the illusion that after the shot the bow drop away rotation speed is faster. This is because what archers look at is the movement of the end of the long rod. For a fixed riser rotation speed the longer the rod the faster the end of the rod moves - the speed is directly proportional to the distance the end of the rod is from the grip. So if you double the rod length, with the same riser rotation rate, the end of the rod moves twice as fast giving the illusion of a faster rotation rate.

SOME COMMENTS ON ARROW SPINE

'Spine' is a term that frequently comes up in archery. What confuses the issue that the term spine is used to mean different things in different contexts. I attempt here to clarify the different meanings.

Try bending a sheet of paper - it's easy. Roll the paper into a tube and try bending it again - it's a lot harder. How easy it is to bend a sheet of paper or an arrow shaft depends on its stiffness. The accepted (Easton derived) standard for the stiffness of an arrow shaft is its **static spine**. The shaft is supported at two points a specified distance apart and a specified weight hung at the mid point. The amount the mid point of the shaft drops from the horizontal determines the shaft spine. The lower the stiffness of the shaft the more it sags and the larger the measured deflection. Given the support spacing and the weight hung the static spine depends on the elasticity of the shaft material(s) and the materials' geometries. In the case of multi-layer arrow shafts (carbon/aluminium) the stiffness also depends on the bonding between the different layers. The geometrical factor is the inside diameter and thickness of each material layer. You can find in any engineering handbook a 'beam' formula which in theory would allow you to calculate the static spine for an arrow shaft from the material and geometrical properties. With arrows having a non uniform cross section (barreled shape) you can still have a measured static spine, though in this case you have to define where the arrow supports are with respect to the varying shaft geometry. The spine of an arrow shaft (excluding external factors like temperature) never changes unless the arrow material properties change (e.g. aluminium arrows stiffen over time with use as the crystalline structure alters) or the shaft construction changes (cracks, debonding).

When an arrow is being shot then the term **dynamic spine** is often used. Spine in this context has nothing to do with static spine i.e. stiffness. What is being talked about is how much the arrow bends. How much the arrow bends depends on many factors (shaft stiffness and length; pile, fletching and nock weights, string force and bracing height etc.etc.etc.). So if say you see the expression "increasing pile weight reduces spine" what is meant is that increasing the pile weight will result in the arrow bending more (the actual 'spine' of the arrow shaft of course remains exactly the same). The tems 'Weak' (bends more) and 'Stiff' (bends less) are often used as an alternative to dynamic spine. So the expression 'Adding fletchings increases arrow stiffness' has nothing to do with arrow stiffness, it means that adding fletchings will reduce the amount the arrow bends when shooting it. Confusing innit! Unlike the static spine case there is no simple equation to describe the bending of an arrow while being shot. One of the assumptions in deriving the 'beam' equation mentioned above is that there are no compressive or tensile (stretch) loads on the arrow. When an arrow is being shot you have the string force acting up the arrow's backside creating a compressive load in the shaft so the simple beam formula goes out the window. There are a number of number crunching approaches to modelling this sort of situation. The usual approach is to break the arrow shaft down into lots of small lengths (finite elements) and work out what happens with each small section in relation to the sections either side and build up a composite picture from the bits. Finite element analysis as it is termed is as much an art form as a science.

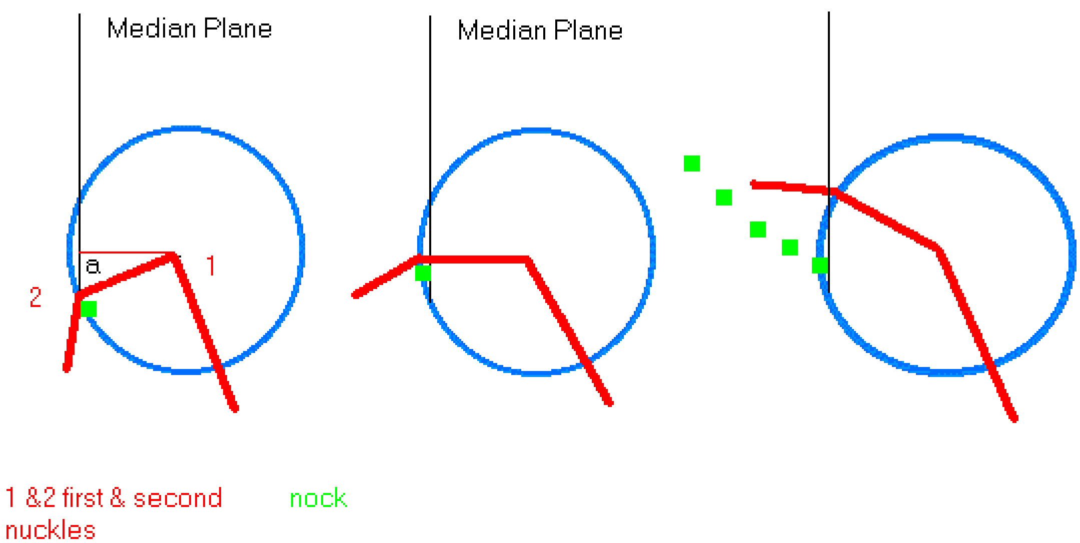
The third usage of spine you occasionally come across is meaning 'direction of flight' of the arrow. Suppose with a set of arrows you shoot a particular group on the target. If you replace the arrow set with one where the arrows bend more when being shot than the arrow group will shift to the right (RH archer). Sometimes you come across an expression like 'So and so makes the arrow weaker/decreases spine' when what is meant that so and so tends to make the arrows fly to the right.

THE LOOSE

It's known that with the finger release of the recurve archer the nock end of the arrow is accelerated sideways, away from the bow, and this sideways acceleration initiates the Archer's Paradox effect. As far as I know no research has been done on how this sideways acceleration is generated. The following are two suggested mechanisms for generating this sideways acceleration that I'll call the slingshot effect and the tab slide effect.

Slingshot Effect

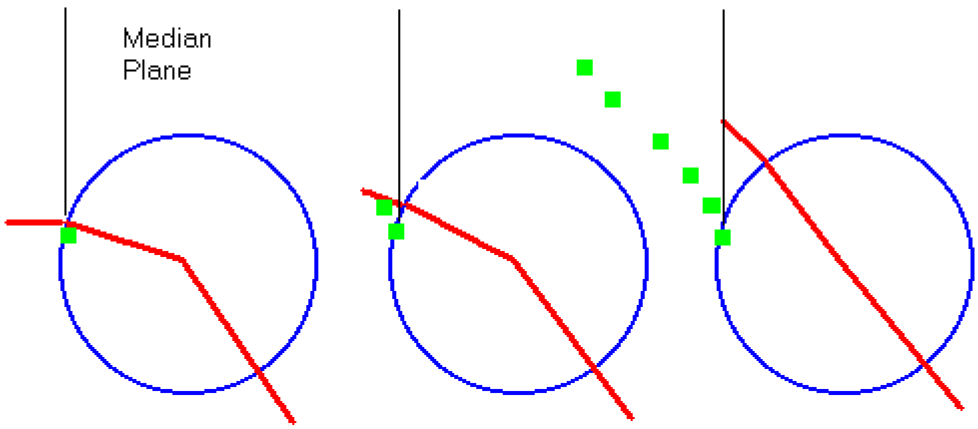
With the slingshot effect the string is located in the second nuckle joint and a 'deep hook' finger configuration is used when holding the arrow at full draw.



The key point is that the string, with respect to the direction of the shot, is located to the rear of the first knuckle joint. At the loose the string stays in the same place on the tab (in the second knuckle joint) and the fingers are rotated by the string, the axis of rotation being more or less the first knuckle joint. The string therefore travels in the arc of a circle forwards and sideways. These resulting forward and sideways displacements appear to be reasonably compatible with those required to obtain the typical Archer's Paradox behaviour. The diagram illustrates the process.

Tab Slide Effect

In this case the fingers have much less of a hook and the string is located in front of the first nuckle joint.



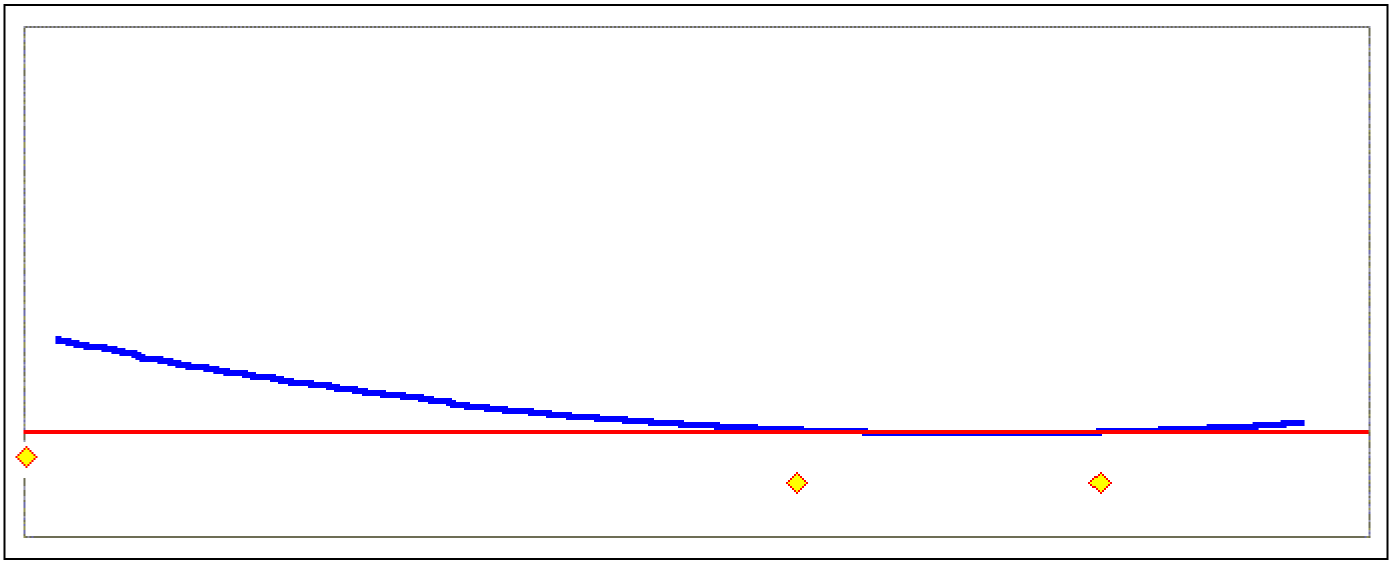
The string is mainly restrained against the pads of the flesh of the fingertips. At the release the fingers are again rotated more or less around the first nuckle joint and the string slides over the surface of the tab. It is the force interaction between the tab and the string that provides the sideways nock acceleration. The following diagram illustrates the process.

Kooi's arrow model suggests that the displacement of the nock by the fingers is around 2mm sideways movement over 3mm forwards travel. Both release mechanisms appear to be compatible with this required nock movement. Depending on how much hook there is in the fingers (angle a) it is feasible that the loose is a combination of the two processes. It should be noted that in both cases the string has left the tab long before it gets anywhere near the fingertips.

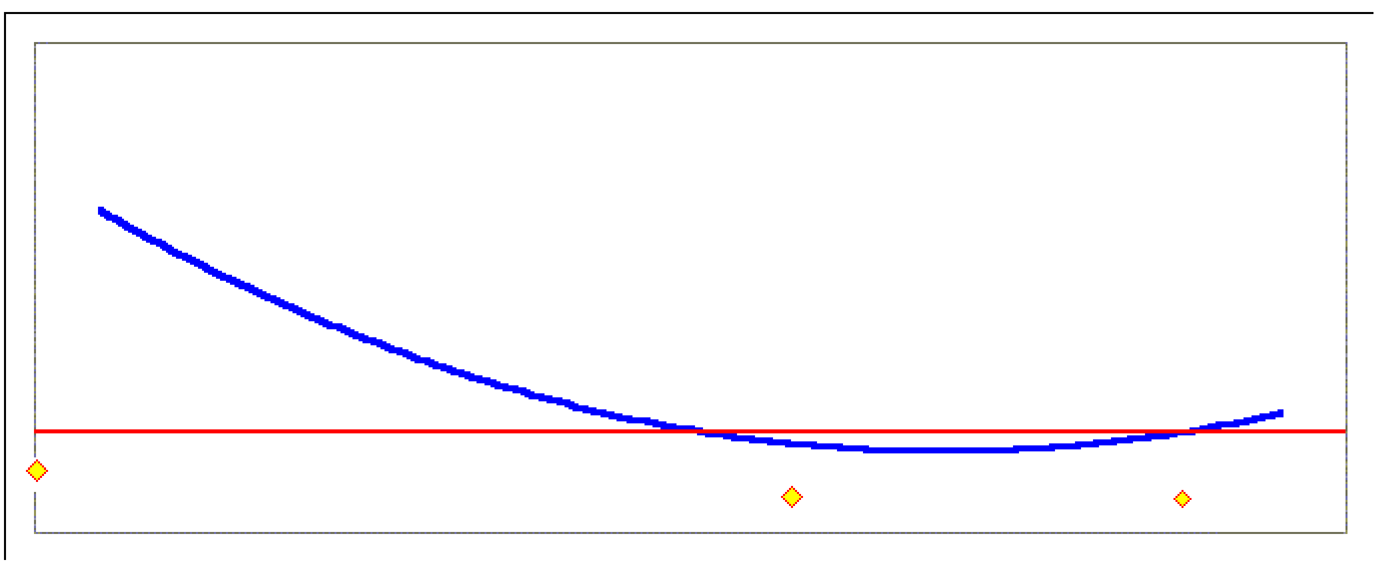
Most tabs will develop some permanent curl in them so although the fingers may be out of the way the string can be dragging across or hitting the outer edge of the tab material on the way past.

SCHEMATIC VIEW OF ARROW BEHAVIOUR ON THE BOW

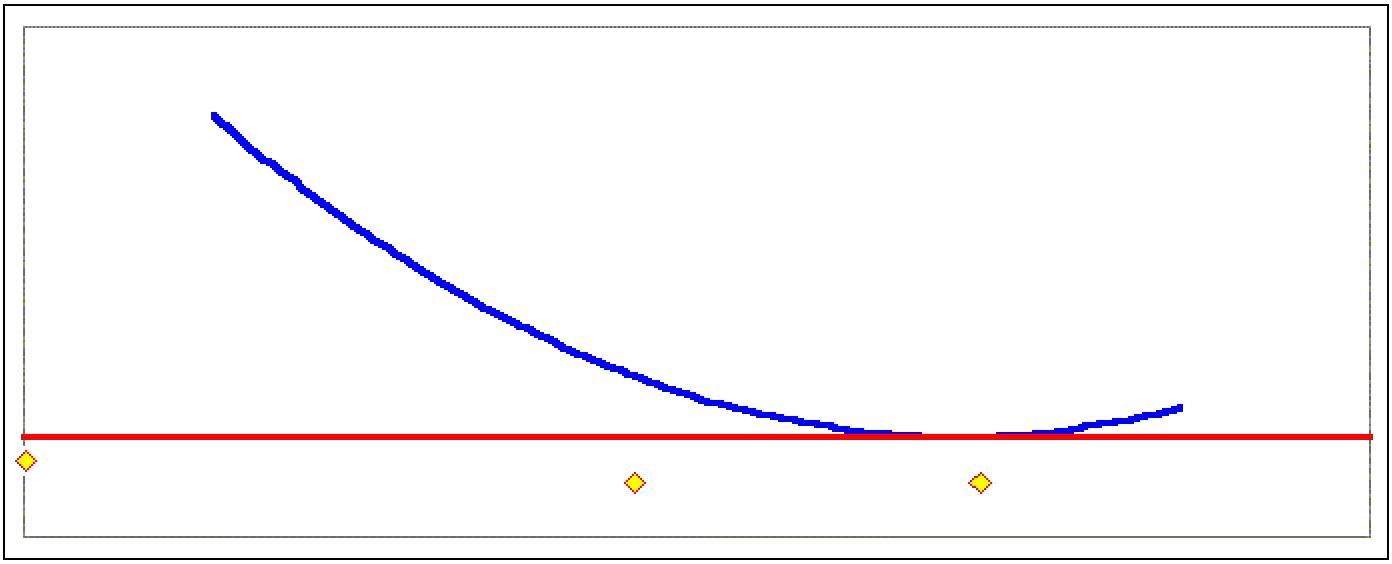
The following diagrams illustrate schematically the behaviour of an arrow (blue line) when being accelerated by the bow. The red line represents the plane of the bow. The diamond markers represent from left to right the full draw position, bracing height and pressure button.



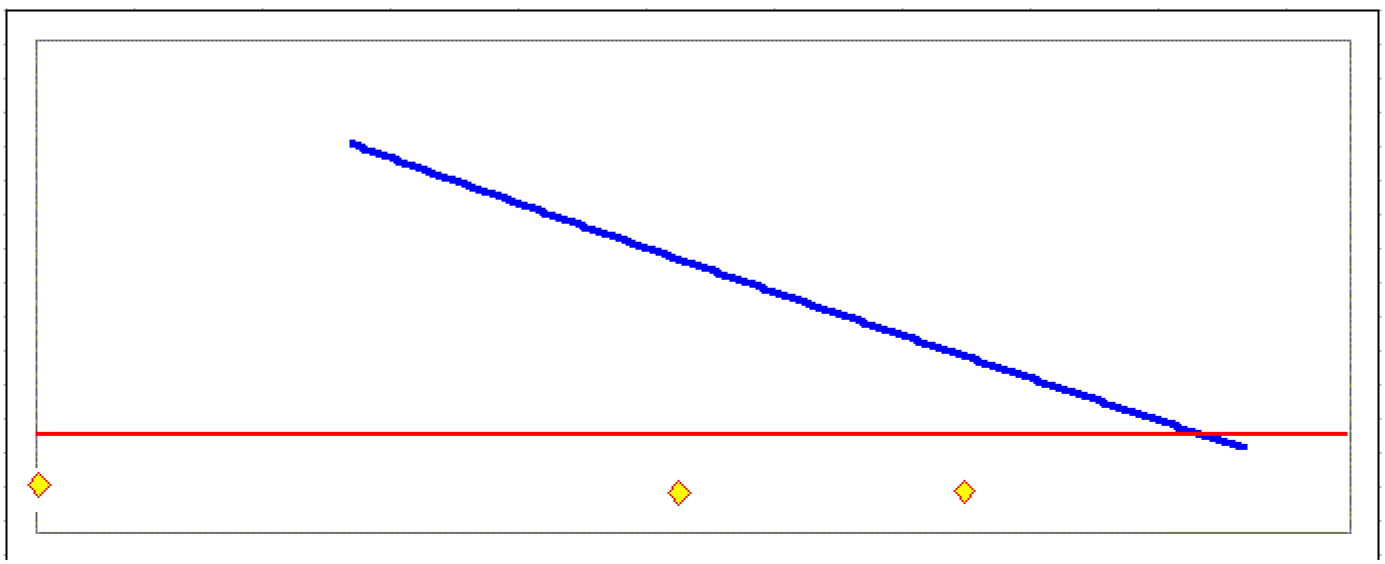
The sideways acceleration of the nock away from the bow by the fingers and the load on the arrow from the bow string start to buckle the arrow. At this point there is no interaction with the pressure button. Note that the rear part of the shaft bends **away** from the bow not as sometimes described the shaft bending towards the bow.



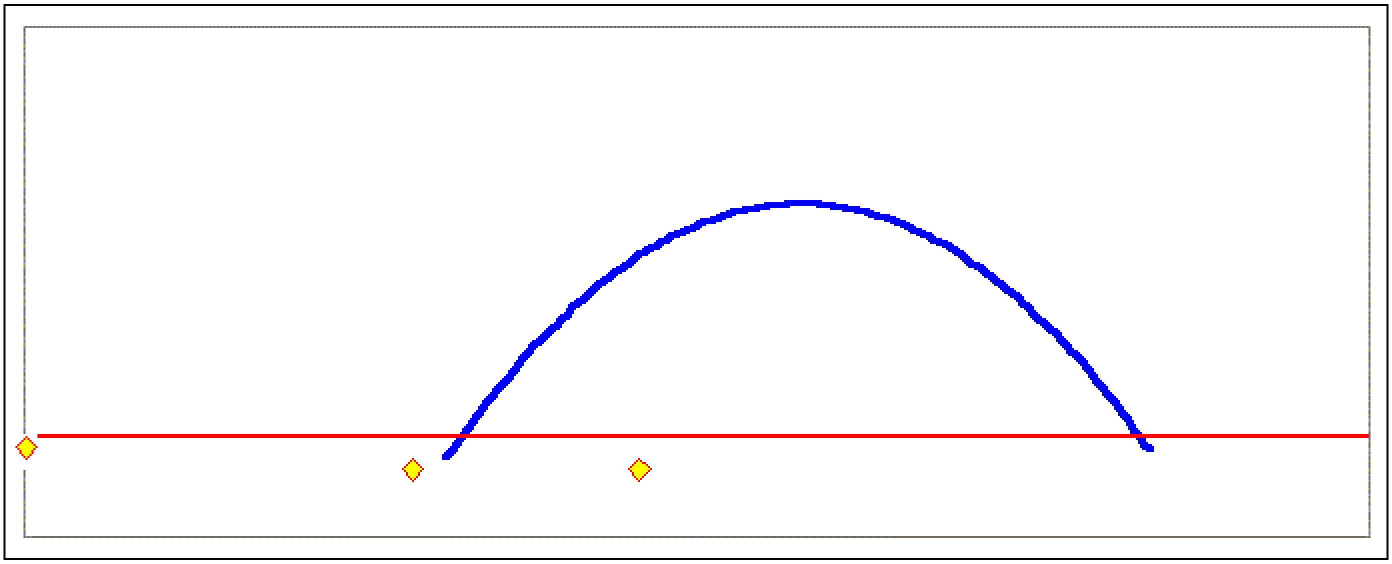
The arrow continues to buckle and the shaft is rotated into the pressure button. The resulting force between the arrow and button result in the shaft section in front of the button bending away from the bow and consequently the shaft section to the rear of the button swivelling into the bow. At this point the arrow shaft sections in front of, and to the rear of the button have different mechanical behavior. This is plausibly the origin of the problem of "arrow forgiveness" if the length of shaft in front of the button is too great.



The nock of the arrow has now reached it's maximum displacement out of the plane of the bow. There is now no force between the arrow shaft and button. The shaft has 'stabilised' into a smooth curve and the entire shaft (ignoring effects of the pile insert) now behaves as a single mechanical unit.



Because the nock of the arrow was displaced sideways out of the plane of the bow there is a torsion spring effect (the twisting of the limbs) pulling the nock rapidly towards the bow. At the same time the bent shaft starts to spring back and of course the string force applies a bending moment buckling the arrow. The result is the shaft quickly forms a bent shape opposite to the original one and the arrow nock is bent/rotated towards the plane of the bow.



When the nock of the arrow reaches the plane of the bow, because of momentum, it keeps going and travels a short distance past this point before reversing the directon of motion. The curvature of the arrow is still away from the bow. As the nock travels back towards the plane of the bow the string exists the nock groove. The combination of the string deceleration direction with the orientation and rotation of the arrow nock are aimed at minimising any lateral tweak on the nock from the string at exit. One condition for this to occur is that the arrow shaft is near maximum bend i.e. when the nock transverse velocity is near minimum.

After the arrow leaves the string it starts to vibrate as a free-free beam so the nock end of the arrow starts to move away from the bow. The aim is to have the end of the arrow having sufficient clearance with respect to the bow riser (shaft selection) and the arrow to have overall near zero rotation (tuning).

The following graph shows the displacement of the arrow nock from the plane of the bow (the horizontal dotted line flagged '0') as function of time as calculated by the Kooi/Sparenberg Archers Paradox model (see reference on Contents page). Nock paths for stiff/weak arrows are included for comparison with a well matched arrow.

The red dots approximately correspond in sequence to the schematic drawings above.

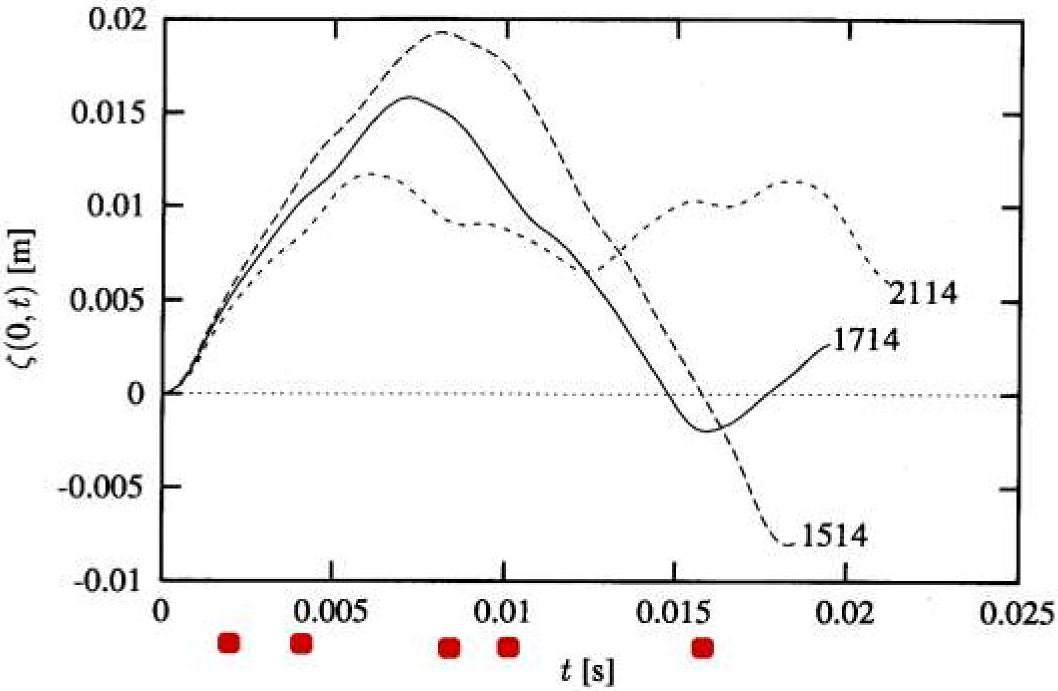


Figure 12. Paths of nock of three different arrows until nock passes pressure point. (——) standard arrow 1714X7, (– –) stiffer (and heavier) arrow 2114X7 and (- - -) more flexible (and lighter) arrow 1514X7. Latter arrow slaps against pressure point.

The following graph shows the physical behaviour of the arrow based on measurement and on mechanical modelling (Pekalski and the Kooi/Sparenberg Archers Paradox model (see reference on Contents page).

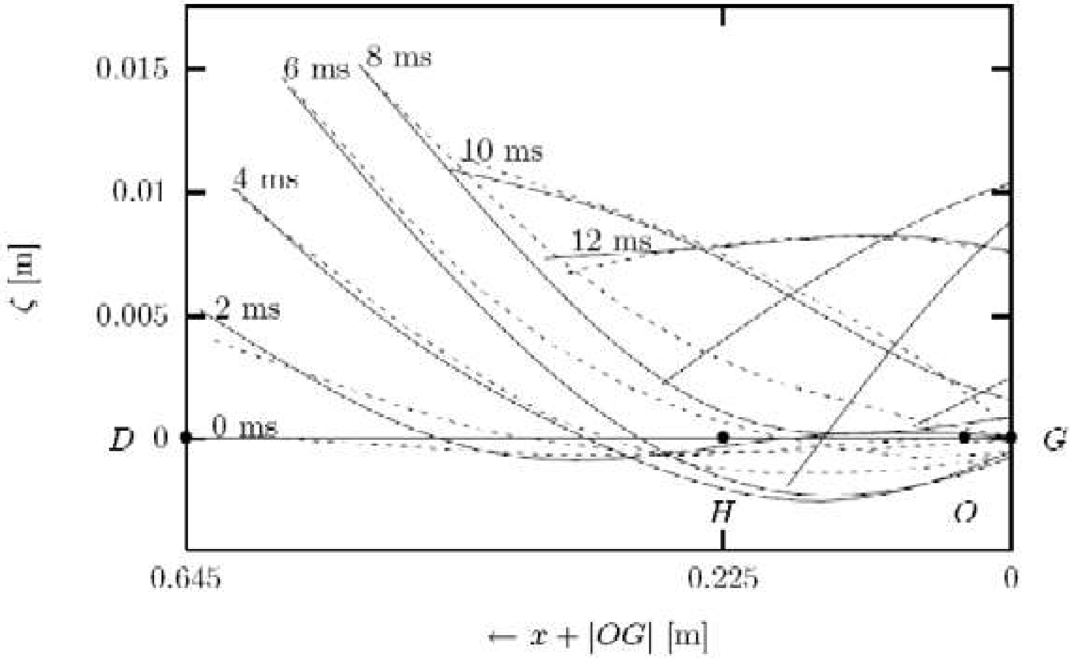
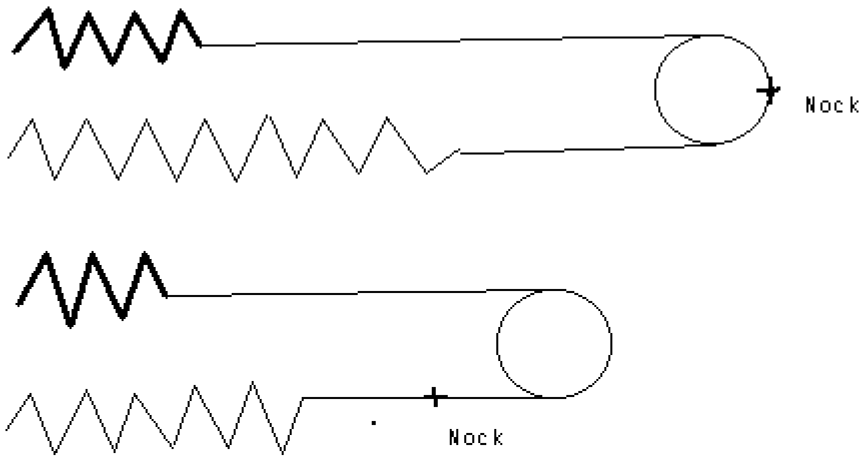


Figure 8: Deformation of arrow: experimental data (- - -) after Pękalski [11], on basis of model derived in this paper (——), every 2 ms after release, until arrow nock passes pressure point at $t = t_g$. Only parts of the arrow for $\xi \in [0, \xi_\gamma(t)]$ are shown.

The following are video based graphics from high speed films illustrating arrow behaviour from Bertil Olssen's web site. Use the back button at the bottom to see the other goodies available on the site.

STATIC V DYNAMIC TILLER



At any given position of the pulley, when stationary, the position of the nocking point depends on the relative strength of the springs only. This is usually called **static tiller**. If the pulley is pulled back and than released to accelerate forwards then the position of the nocking point point depends in addition on the mass of the springs, the moment of inertia of the pulley and the elastic properties of the string. The tension in the string will no longer be the same on each side of the pulley. This behaviour is called **dynamic tiller**.

For a bow shooting an arrow the important tiller is the dynamic tiller. The mass and rotational properies of the arrow and the moving parts of the bow limbs will effect how the nocking point moves. (e.g. the mass of the bow limbs will affect the acceleration of the limb tips).

CENTRE SHOT POSITION

Centre Shot Rules OK

As it doesn't refer to the 'centre' I am always confused by what is meant by the term centreshot. The definition I'm using here is that centreshot is the amount the front of the arrow shaft is moved away (anti-clockwise looking down for a RH archer) from the vertical plane of the bow. A zero centreshot means that the arrow lies in the plane of the bow, increasing centreshot means moving the front of the shaft away from the bow and decreasing centre shot the reverse.

I have only a vague idea about how changing centreshot affects arrow behaviour - so bear that in mind.

I doubt there is some 'optimimum' centreshot for a specific bow/arrow/archer combination, I think its more a matter of getting a good centreshot/button spring combination. The standard rules for setting centre shot run something like:-

"For an aluminium arrow set the front of the shaft one arrow diameter outside the plane of the bow. For a carbon arrow set the front of the shaft around half to one third a diameter outside the plane of the bow."

Is there a logical basis for these ad hoc rules.

Let's split the arrow into two sections, the front section and the back section. The front section includes the pile and a length of shaft roughly corresponding to the bracing height distance. The back section is the length of shaft from around the bracing height position to the nock. When an arrow is released the string buckling of the shaft takes place over the arrow back section. The buckling effectively acts against the mass of the arrow front section (which we can vaguely assume is located at the front of the back section). The heavier the mass of the front section the more the arrow will buckle. The centreshot position determines the strength of the string buckling force. As we increase the centreshot the string buckling force is reduced.

Suppose we have an aluminium arrow. An arrow with a larger diameter will probably have more mass in the front section leading to more buckling but by setting the centreshot at one arrow diameter a larger diameter arrow will have an increased centreshot reducing the string buckling force. These two effects largely cancel each other out so by using the one diameter centreshot rule we end up with a similar amount of arrow buckling whatever the particular arrow diameter/shaft weight is.

Carbon arrows have much lighter shaft and pile weights then aluminium arrows so the mass of the arrow front section is lower leading to less arrow buckling. To compensate the centreshot has to be reduced to less than an arrow diameter to increase the string buckling force to get back again to the 'right amount of buckling' whatever that is.

A Suggested Approach to Setting Centreshot

As there is no identifiable 'best centreshot' the suggested approach is to end up with a good button spring setting.

Set an intitial centreshot as per the rules above (ali 1d, carbon 1/2d).

Install the weakest button spring and set it to around 50%-60% spring compression. (If you don't have a calibrated button you'll have to count the turns from uncompressed to locked up).

Do a bare shaft test adjusting the centreshot until you get a reasonable result.

Fine tune as normal by varying the spring tension. (if the spring goes outside the 50%-60% compression range then you didn't go fine enough with the centreshot adjustment - try again).

The Idea That Pressure Button is Used For Arrow Alignment

In terms of what effect it has on the arrow the pressure button is one of the more complex pieces of equipment on the bow. The section on the plunger button tries to give give some indication of the mechanics of the button - arrow interaction. One of the stories from the past you still come across is the idea that the sole purpose of the pressure button is to 'align' the arrow on the bow.

This (hopefully long discarded) idea was based on the suggestion that when an arrow is being shot it vibrates with two vibrational nodes and a 'tuned' bow was one where these nodes travelled along the plane of the bow. For a 'tuned' bow the arrow leaves the bow with the arrow nodes aligned with the direction of travel and this results in the arrow travelling in a vertical plane in a straight line to the target. The function of the pressure button centreshot position/spring setting was regarded only as a means to align these arrow nodes during the shot and other than this the button had no effect on the arrow.

While the above ideas in terms of Newtonian mechanics are nonsense they became very widespread among coaches and archers. The idea that the arrow on the bow vibrated with nodes travelling in the bow plane fell apart as soon as high speed arrow films became generally available. The idea that tuning was getting the arrow nodes aligned with the arrow flight direction, while understandable, has hopefully been shown to be mechanically a non starter on other pages of this web site.

The notion that the sole purpose of the button was to align these fictitious arrow nodes with respect to the bow gave rise to a number of what can only be described as crackpot theories. One of these was to try to minimise any interaction between the arrow and button hence using the button for initial arrow alignment only. It was suggested that the arrow front 'node' should be positioned so that the arrow flexed around the button i.e. the arrow leapfrogged over the button. The button was used for initial arrow alignment but there was no 'unwanted' interaction between the button and arrow. Strangely no-one suggested that the obvious way to get this effect perfectly was to shoot a left handed bow right handed. The button would be used for arrow alignment but as the arrow would bend away from the button there was no possibility of arrow-button interaction. A similar notion was the idea of replacing the button spring with a matchstick and setting the buttton at zero centreshot. As any arrow-button interaction would be magnified with no spring the bow draw weight could be adjusted to vary arrow behaviour to obtain a 'natural' alignment of the nodes. This for some unexplained reason was regarded as a good idea. As the locking up the button idea became incorporated into a number of how to tune guides there are still archers wasting their time with it. (It's harmless though as inevitably the locking up the button is always followed by a bow tuning process from scratch. The only consequence is some arbitary shift in draw weight).

While an attempt has been made to illustrate some aspects of the effect of the button on the arrow in the plunger button section (I don't understand it either so the description is inevitably a bit woolly) applying a bit of common sense can indicate that the button does effect the arrow behaviour on the bow.

The Easton measurement of shaft spine is based on how much an arrow bends under a force. You hang an approx. 2lb weight in the middle of 28" of shaft and how much the arrow bends is the spine. Stretching things a bit you could say that this is equivalent to hanging a 2lb weight from two shaft lengths of 14"(or a 1lb weight on the end of 14" of shaft). When you shoot an arrow it depresses the button and a typical force required to depress a button is around 5 Newtons (roughly a mass equivalent of a bit more than 1lb.) So the button force is equivalent to hanging a 1lb weight on the end of say 24" of arrow shaft. While I'm playing fast and loose with the mechanics it should be fairly obvious comparing the Easton spine measurement with the button action on the arrow that one effect at least of the button on the arrow is that it's going to bend the arrow a significant amount. So the idea that the button is used for alignment only and has no effect on arrow behaviour on the bow contradicts common sense.

ARROW PENETRATION

Introduction

The introduction of carbon arrows resulted in a number of problems for target archers relating to what happens when the arrow hits the target. (In general here I'm assuming the bound straw type boss). Targets quickly became 'soft' and archers started to get lots of pass throughs - no score and damaged fletchings. In response straw targets were made a lot thicker and with tighter binding to stop the arrows. As a consequence targets became a lot heavier (hernia generators). Targets became a lot harder which resulted in an increased chance of arrow damage on impact. (Arrow breakage was further exacerbated by the growing popularity of barreled shafts which are structurally weaker where it matters). It became also much harder to remove arrows from the target - a possible cause of injury to archers and not to healthy for the arrows either.

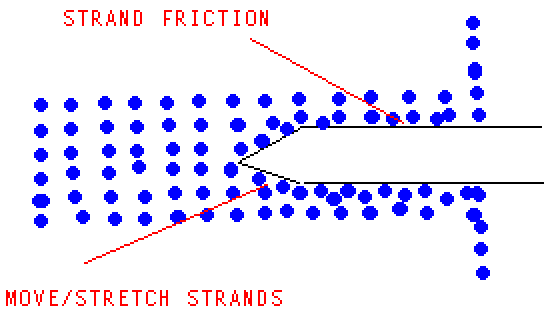
What we want is a light, cheap, easily stored target that lasts a long time and does not damage your arrows. (dream on!). This section is about the behaviour of arrows when hitting a target.

Fundamentals

There are four basic properties of the arrow which relate to how an arrow behaves in terms of penetrating into a target:-

- Arrow Kinetic Energy (half the mass times the velocity squared)
- Arrow Momentum (mass times velocity)
- Point Shape
- Arrow Diameter

In order to look at the different effects of the above factors let's see at what happens as an arrow penetrates a straw target. The target can be looked at as being a bunch of elastic strands all aligned the same way that the arrow has to push its way through.



The pile of the arrow has to push the the strands to the side i.e. move them and in the process stretch them. This of course takes energy and as a consequence the arrow slows down. Along the shaft of the arrow the 'stretched' strands exert a frictional force on the arrow which act to slow the arrow down. The total frictional force will depend upon several factors including how much and how many strands are stretched (i.e. the arrow diameter) and the surface area of the shaft on which the frictional force acts (i.e. the arrow diameter and how far the shaft has penetrated into the target). Once the point of the arrow is through the target then its only the frictional force on the shaft that acts to slow the arrow down. The other thing that will happen as the arrow penerates the target is that some of the strands will snap instead of stretching. A snapped strand will reduce the energy lost via the action of the pile and exert a low frictional force on the arrow shaft. When subsequent arrows are shot into the target any already broken strands encountered will require much less energy for the pile to move aside and will generate a lower frictional force on the shaft.

In reality strands of straw are not very elastic and it is the compression/displacement of the straw by the arrow which generates the various forces on the arrow but from the point of view of looking at what is going on the elastic band metaphor seems a reasonable approach.

Kinetic Energy

The arrow arrives at the target with a given amount of kinetic energy. This energy is lost when the arrow hits the target and the arrow comes to a stop. Most of the energy ends up as heat in the target and some is lost via the flexing of the arrow stuck in the target. If 'x' is the amount the arrow has penetrated into the target at any given moment then there will be a retarding force on the arrow from the pile/shaft behaviour described above at that moment F(x). The definition of Kinetic Energy is that it is the integral over **distance** of the force F(x). In other words it is the arrow Kinetic Energy that defines how far an arrow will penetrate into the (elastic string) target.

Momentum

The arrow arrives at the target with a given amount of momentum which the arrow loses as it comes to a halt. The definition of momentum is the integral over **time** of the force F(x). In other words it is the momentum that defines how long it takes for the arrow to come to a stop. Because the momentum change relates to force x time it is also a measure of the strength of the 'impact' the arrow has on the elastic strings in the target. The arrow momentum is one of the factors which will determine whether the elastic strings will stretch or snap. As how many of the elastic strings are broken affects the value of the frictional force on the arrow F(x) the arrow momentum indirectly affects how far the arrow penetrates into the target. (An extreme example would be shooting at a suit of armour - not enough momentum and the arrow would bounce off i.e. zero penetration irrespective of how much kinetic energy the arrow had).

Point Shape

The shape of the arrow point will determine how fast the strings are pushed aside and also how much stress locally there will be in the elastic strings. With a 'blunt' point the stresses generated in the elastic strings will be spread over a larger volume then with a 'sharp' point. The sharper the point therefore the higher the proportion of the elastic strings that will be snapped rather than stretched. As snapped strings retard the arrow less than stretched strings an arrow with a sharp point will penetrate more than an arrow with a blunt point. Too blunt a point (trying to stretch too many strings too fast) and the arrow might not penetrate at all and bounce off.

Arrow Diameter

The larger the arrow diameter then the higher the number of elastic strings that need to be moved out of the way and the more each string will need to be stretched increasing the pile retardation effect. As the arrow diameter increases the more the strings are streched and so the retarding frictional force/unit area on the shaft increases. The fact that the elastic strings are being stretched more is likely to increase the chance of them snapping. With a larger diameter the shaft area on which frictional force acts is larger. The larger the arrow diameter then the more stopping power the target will provide on the arrow leading to lower arrow penetration. As the 'sharpeness' of the point will effectively increase as the arrow diameter decreases then a smaller arrow diameter will indirectly increase the probability of breaking strands i.e. more target damage.

Comparison of Carbon V Aluminium Arrows

Lets compare how target penetration varies between an aluminium and a carbon arrow, both being a good arrow match for the archer's draw weight/length.

Our aluminium arrow has an all up weight of 443 grains and an outside diameter 0f 0.89 cms. Our carbon arrow has an all up weight of 265 grains and and outside diameter of 0.61 cms.

Target arrow points vary from chisel to hemispherical in shape. The design aim is to provide the maximum stopping power while having a very low probability of a 'bouncer'. The 'parabolic' shape seems to be the most popular shape for aluminium arrows. Carbon arrows vary from parabolic to semi-chisel. This is pure speculation on my part but it seems that barrelled arrows tend to have parabolic pile shape (lower stopping power) while parallel shaft arrows tend to have semi-chisel points (higher stopping power). It may be that you have to keep the point stopping ability low on a barelled shaft to avoid too many arrows breaking on impact.

If we ignore the pile effect and assume that the frictional force/unit area is proportional to arrow diameter (the number off and the amount the elastic strings are stretched) and that the total friction force 'F(x)' is the product of the force/unit area times the area of the shaft in the target then:-

F(x) = a constant times the diameter squared times the arrow penetration

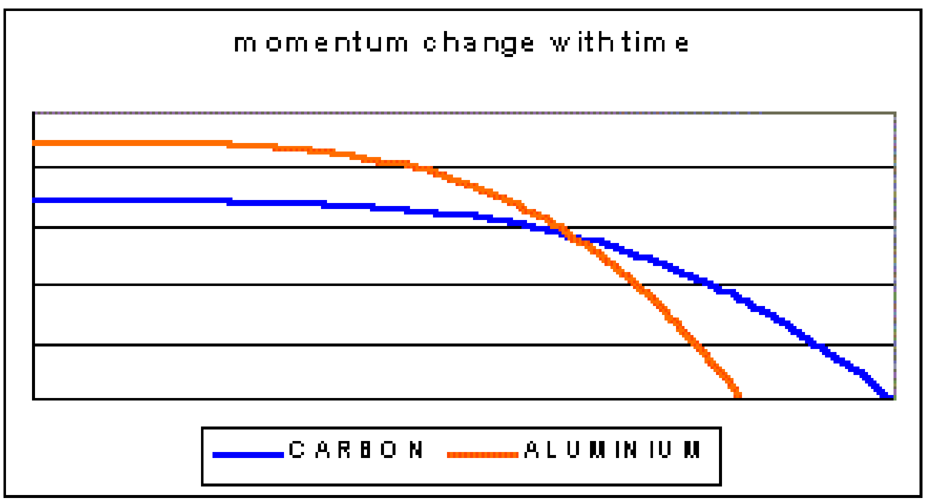
Integrating F(x) dx over the penetration distance 'X' gives you the total arrow Kinetic Energy 'E' i.e.

E = a constant times the diameter squared times the square of 'X'.

If you assume that both arrows leave the bow and arrive at an infinitely thick target with the same kinetic energy then the arrow penetration becomes inversely proportional to the diameter. I.e. the carbon arrow will have 0.89/0.61 = 1.5 times the penetration of the aluminium arrow. The fact that the target has limited thickness will in practice result in the ratio being even higher.

As far as arrows damaging the target (snapping the elastic strings) is concerned the two relevant arrrow factors are the diameter and its momentum as described above (the points assumed being the same shape). The other significant factor is the design of the target itself.

As far as the arrow diameter is concerned its a bit of swings and roundabouts in the rate of target damage. It will very much depend on the nature of the target. In my opinion probably not much in it with maybe the smaller diameter carbon arrows doing more damage.



Again assuming the two arrows have the same Kinetic Energy when they hit the target then the ratio of the carbon arrow momentum to the aluminium arrow momentum will be the square root of the ratio of the carbon arrow mass to the aluminium arrow mass i.e. square root of 265/443 = 0.77. The carbon arrow will have about three quarters of the momentum of the aluminium arrow at target impact. The following graph illustrates how the momentum of the two arrows changes relatively with time as the arrows penetrate the target . The carbon arrow, unsurprisingly, takes longer to stop.

Initially the aluminium arrow has the higher momentum but because the frictional retarding force is lower for the carbon arrow it doesn't loose momentum as fast.

The real problem with target damage relates to the increased penetration of carbon arrows. When carbon arrows were introduced the existing straw bosses could not effectively stop them. One solution would be to keep the same level of binding and increase the target thickness: Pros - limited arrow breakage, Cons - very hard to pull the arrows and very heavy targets. An alternative solution would be to increase the binding tension (less stretchy elastic strings): Pros - better arrow stopping power with an acceptable increase in weight, Cons - high incidence of arrow breakage. The actual change was a compromise of a higher binding tension and increased thickness -which you could regard as a 'best of both worlds' or a 'worst of both worlds' largely depending on what bow/arrow setup you have. If you shoot parallel shaft carbon arrows with a medium poundage bow then you are OK. If you shoot high speed barelled shafts you are in trouble, there is a higher incidence of arrow breakage and because of the tighter binding each arrow causes more target damage so they quickly go soft and you get pass throughs.

Perhaps the optimum solution with current straw targets is to use two, a soft target in front of a hard target; low risk of arrow damage, stopping power and you don't need a fork lift to move the targets. If you equate the cost of a target to three broken arrows then the cost is not to bad either.

Arrow Breakage

When you shoot an arrow there are two points where the arrow shaft is highly stressed and failure is possible, when you shoot it and when it hits the target. When shoot an arrow it's going from say 0 to 250 fps over around 28 inches. High acceleration and therefore high forces. The maximum stress point in the shaft is towards the rear somewhat in front of the fletchings resulting from the Archers Paradox bending and this is the most likely failure point. Arrows (as selected from the charts) have a big safety factor so unless to go for a seriously underspined shaft or overweight pile the chance of an arrow breaking when shooting it is extremely small. When the arrow hits the target it's going say from 250 to 0 fps over around 8 inches much higher acceleration and hence forces than when its being shot. As the pile enters the target the high deceleration results in the arrow 'whiplashing' causing a high stress zone say around 5 inches from the pile. The 'harder' the target than the higher the peak stress in the shaft and the nearer the pile it is. With barelled shafts the diameter decreases towards the pile from the middle so the arrow is structurally weaker than an equivalent parallel shaft arrow.

Varying Targets and Optimising Arrow Weight

With 'target' arrows your trying to stop arrows quickly and safely. With different targets the requirements for the arrow will be different.

For hunting purposes you want your arrow to maximise damage to vital organs so you use a 'broadhead' pile which will cut through tissue over a wide area supported by high arrow momentum to assist target damage.

Arrows in war varied in design with their purpose. In order to cause damage to someone in a suit of armour you first of all needed to penetrate the armour so you had a heavy arrow with a bodkin (needle like) point.

Penetration Example

There is often discussion with bow hunters about getting the right balance between arrow mass and arrow speed. The following is a (tongue in cheek) example of the sort of analysis involved.

Suppose our archers are going to be in a battle against foot soldiers who protect themselves with shields. Our spies have managed to acquire a couple of shields and tests on them indicate that for an arrow, of the type we use, to penetrate the shield it needs a momentum of 100 (remember that penetration of a solid depends on the arrow momentum not its kinetic energy).

With the bows we use, an arrow of mass 4 has a measured speed of 20. The kinetic energy of the arrow (half the mass times the velocity squared) is therefore 800. The momentum of the arrow (mass times velocity) is 80. The arrow of mass 4 doesn't have enough momentum (need 100) so if the arrow hits a shield it will just bounce off. The arrow kinetic energy is more or less independant of the arrow mass (the bow efficiency stays much the same).

If we use instead an arrow of mass 8 then with a kinetic energy of 800 the arrow velocity will be about 14 and the arrow momentum will therefore be 8 times 14 i.e. 112. The mass 8 arrow will penetrate the shield and injure the enemy soldier.

The downside of using the heavier arrow is the loss of speed from 20 down to 14. This means that our range will be reduced and because of the less flat trajectory our archers will probably lose some accuracy as well. The ideal arrow is one that has a momentum of 100 exactly as this gives us the fastest arrow that will penetrate the shield. The ideal arrow mass is given by half the square of the required momentum divided by the arrow kinetic energy i.e. (100 x 100)/(2 x 800) which gives an arrow mass of 6.25. The associated (fastest shield penetrating) arrow velocity is 16.

VIBRATION AND ARROW FLIGHT

An arrow leaves the bowstring bent like a banana around the bow riser. As it flies it vibrates flexing at around 50-60 vibrations per second in a plane more or less at 90 degrees to the vertical. The amplitude of vibration decreases over time because of aerodynamic damping. Clearly this vibration will effect the drag on the arrow. What effect do these arrow vibrational effects on drag have on the arrow flight?

As the arrow vibrates the displacement,orientation and velocity properties are continuously changing along the shaft. As a consequence the aerodynamic drag etc. effects are also continuously changing at any specific point on the arrow over time and also varying along the arrow at any specific point in time. The arrow vibration characteristics (shaft displacement, shaft angle and shaft transverse velocity) keep repeating at a short time interval in a symmetrical way.

On the assumption that the arrow vibration fequency is high enough compared with the time duration of a wind gust, or the rotation (yaw) speed of the arrow, I would guess that the drag effects in the plane of vibration pretty much cancel out. I don't think that arrow vibration will have any significant effect on group sizes

The only significant effect of vibration on arrow drag will be an increase in the drag along the arrow axis, this mainly resulting from the change in angle between the shaft surface and the direction of the airflow. I would expect a vibrating arrow to hit lower on the target than a non-vibrating arrow, the larger the vibration amplitude the bigger the drop.

The other effects that arrow vibration has on drag is that overall the drag on the pile will be marginally reduced and that the drag on the fletching surface will make some contribution to accelerating the arrow. In practice I think both these effects are negligible compared with the overall arrow drag.

It's speculatively possible that vibration generates slight yaw forces on an arrow in flight - just guessing. So different sized fletchings, or bareshaft versus fletched arrows may result in some horizontal displacement on the target.

Don't know of any work having been done on the effect of vibration on arrow flight so the above comments need to be regarded as armchair opinion

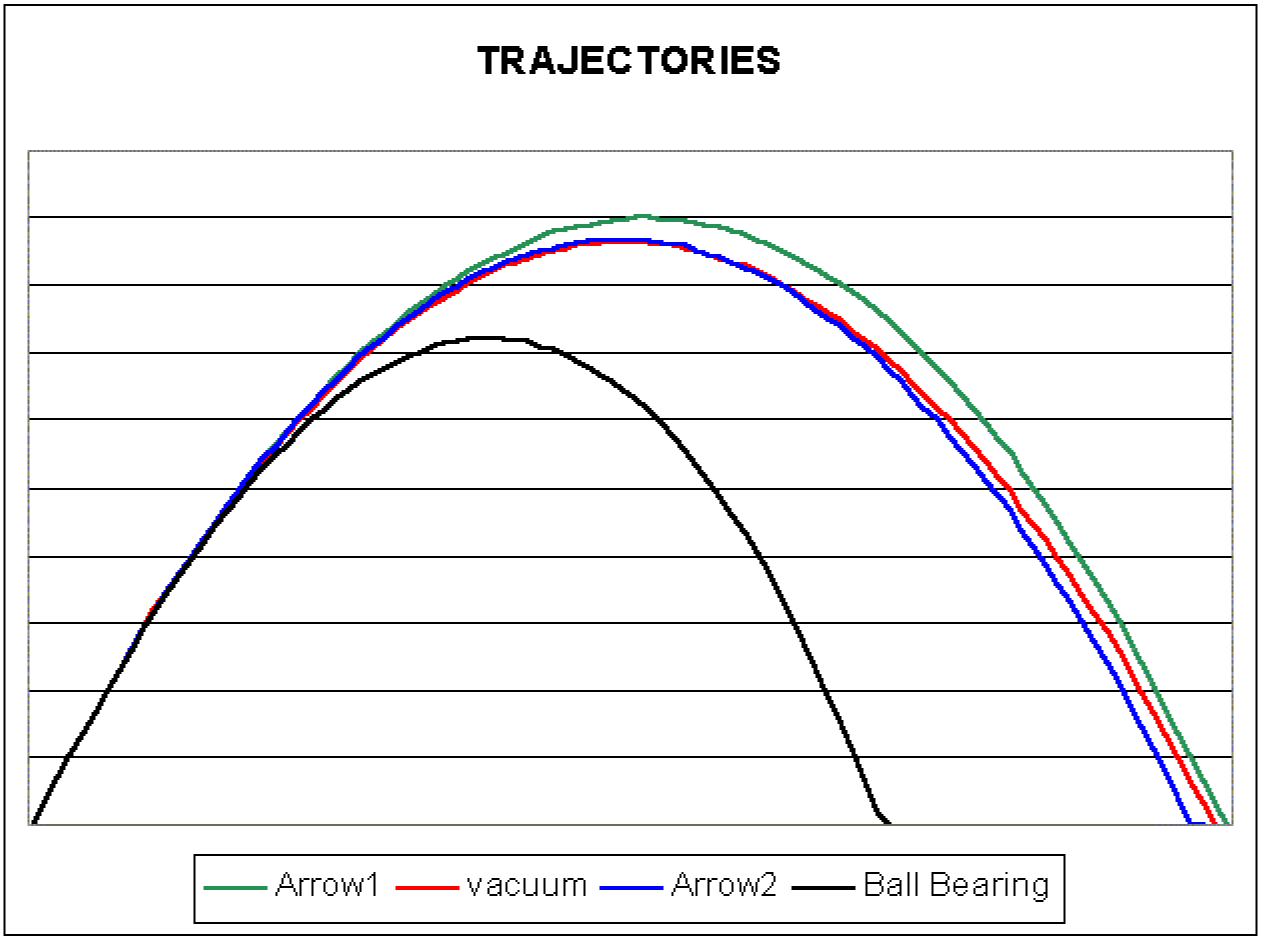
GRAVITY

Throw something up in the air and it goes up , stops and falls down again. Throw it up harder and it goes higher up and also takes longer to come down again. When you shoot an arrow at an angle you give the arrow some velocity in the (up) vertical direction and some velocity in the horizontal direction towards the target. The higher you raise the bow the higher the vertical velocity and the lower the horizontal velocity. The vertical velocity determines how long the arrow stays in the air, the horizontal velocity determines how far the arrow travels towards the target while it is in the air. To hit a specific vertical point you need the right combination of vertical and horizontal velocities i.e. the correct bow angle. You can hit any specific vertical point in two ways, you can have a high horizontal speed and short time in the air or a low horizontal speed with a long time in the air, i. e. you can hit a specific vertical point with two bow angles, usually called the "low" and "high" positions.

Gravity acts on the arrow as a whole always accelerating it downwards. What gravity does in the vertical plane is vary the direction in which the arrow is travelling overall. (ref) The total arrow velocity is the sum of the vertical and horizontal velocities. The arrow's speed in the horizontal plane continuously drops as it loses energy to the horizontal drag. The arrows vertical speed starts high, drops to zero and then increases as the arrow falls back to the ground. The overall arrow speed can therefore either be increasing or decreasing as the arrow approaches the target. Basically the higher the arrow trajectory the more likely it is the arrow will be speeding up as it nears the target.

As will be discussed later a fletched arrow is always trying to point into the net direction of the air flow over it. In the vertical plane the direction the arrow points is essentially defined by its "gravitational" trajectory. The arrow starts off pile upwards at some angle, rolls over to the horizontal and then ends up pile downwards at some angle. Because of this any initial arrow offset to the direction it is travelling or rotation in the vertical plane has a relatively minor effect on where the arrow ultimately hits the target. This is why "nocking point" tuning principally concerns itself with the arrow coming of the rest cleanly. The vertical arrow offset angle is only a secondary consideration.

The following graph illustrates some trajectories.



Illustrated are trajectories of two different arrows and ball bearing all shot at the same angle and the same initial speed. In a vacuum both arrows and the ball bearing have the same trajectory (a parabola) and hit the ground at the same spot. With air you have aerodynamic effects (drag and the Munk effect) which affect the flight. All objects start off with the parabolic flight path but increasingly deviate from it. The ball bearing 'falls short' of the vacuum distance. With a typical target arrow the aerodynamic effects 'cancel out' to a large extent (both 'lift' and 'drag' forces are generated on the arrow) and the arrow hits at a much greater distance then the ball bearing. At short distances the trajectory is very close to the parabolic (vacuum) case. It's feasible to design an arrow which has a greatly reduced range with respect to a target arrow (e.g. flu-flu arrows) and equally possible to design an arrow which goes farther than the target arrow case (e.g. flight shooting arrows). Its possible to design an arrow where the effect of 'lift' outweighs the effect of 'drag' so the arrow range is actually greater than the vacuum case. Flight shooting arrows can be designed to 'use drag' so they can fly further if the air is denser and so the drag forces on the arrow are higher.

The arrow design requirements for long range conflict with the design requirements for accuracy.e.g. for arrow accuracy you want a high arrow FOC, for distance you want a low arrow FOC.

DRAG

Drag forces on an arrow pile, shaft and fletchings are dominated by inertial forces. The basic inertial drag equation used to calculate drag force on an arrow travelling through the air is as presented where 'F' is the drag force, 'D' is the air density, 'C' is a drag coefficient, 'A' is the object area and 'V' is the air velocity

$$F = \frac{CDAV^2}{2}$$

normal to the surface.

The drag coefficient is a fudge factor which takes into account the complicated bits like shape and surface characteristics. For a cylinder, like an arrow shaft, the theoretical value is around 1.2. The velocity is the total net velocity which comprises the effects of the arrow's travel through the air, arrow rotation, arrow vibration and any wind. You need to calculate the drag force based on this total velocity and then as required resolve the drag forces in different directions. You cannot calculate the drag forces in different directions and add the components together to give a total drag force (the air can't be flowing over the arrow shaft in several different directions at the same time!).

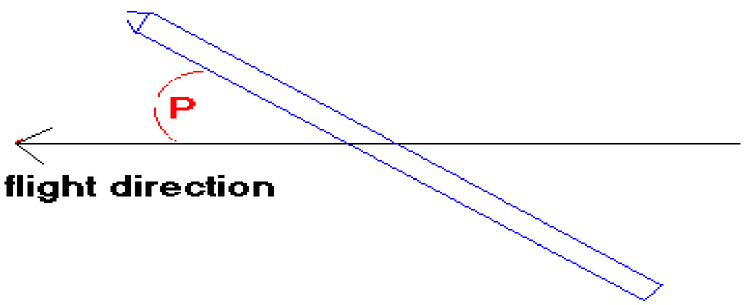
To see where the inertial drag equation comes from suppose you have a fluid flow of speed S and density D impinging on a body surface of area A at an angle a.We need to take for granted that momentum is mass times velocity and that force is equal to the momentum change per second. (Force, Velocity and Momentum are all vector quantities).

The mass of air hitting the surface A per second "M" is equal to:-
D*A*S*Sin(a)
The velocity of the air flow at 90 degrees to the surface A "V" is equal to:-
S*Sin(a)
The impinging momentum/second of the air flow on the surface A is equal to M*V. Part of this momentum will be transferred to the body. Say a fraction X s transferred. then the drag force F on the surface area A is equal to X*M*V. If we define X as 0.5*C then the drag equation becomes 0.5*C*M*V i.e.
F = 0.5*C*A*D*(S*Sin(a))^2

Example Calculation of Drag on an Arrow

There are two drag effects on an arrow, drag that moves the arrow and drag that rotates an arrow. This example only considers the drag that moves the arrow. To simply things (a lot) were going to assume that the arrow has a parallel shaft, the arrow is not vibrating and that the arrow is not fishtailing/porpoising. Drag effects on the fletchings are also ignored. Drag effects are only going to be considered in two dimensions instead of the actual 3.

The arrow is assumed to have the following properties:
Length (L) 0.75 metres
Diameter (d) 0.006 metres
FOC (F) 16%
Speed (S) 50 metres/second
Pitch angle (P) 2 degrees
Total mass (M) 0.018 kilograms
Drag Coefficients Pile = 0.4 Shaft = 1.2
Air density (D) = 1.2 kilograms/cubic meter



Pile Drag

In the drag equation above the velocity 'V' is not (as it sometimes seems to be taken to be) the arrow speed but the speed of the airflow at a right angle to the arrow surface. So for the Pile V = S Cos(P) = 49.97 metres/sec.

[Query 1: how can you talk about the airflow being at a right angle to a pointed shape?
Well the actual effect of the pile shape is include in the value of the drag coefficient and the drag coefficient is based on the shape being symmetrical to to the air flow i.e. along the arrow shaft axis.]

In the drag equation the area 'A' is the frontal exposed area of the body (the area the airflow hits) i.e. the cross sectional area of the shaft so
A = Pi * diameter squared/4 = 0.0000283 square metres

Note that this is only true if the pitch angle is small. With a large angle the area of pile that the airflow will hit will change making life complicated.

The drag force on the pile (Fp) is therefore equal to:-
Fp = 0.5 * 1.2 * 0.4 * .0000283 * 49.97 * 49.97 = 0.017 Newtons

Force is vector, it has direction as well as 'amount of'. The direction of Fp is assumed to be along the axis of the arrow.

[Query 2: Broadhead planing is a big issue so for sure the pile drag direction isn't along the arrow shaft axis? True it isn't, but for a 'target arrow' pile the direction is fairly close to the shaft axis as long as the pitch angle is small. It's an approximation were making]

Shaft Drag

The drag area of the shaft is its length multiplied by its diameter. The fact that the shaft is curved is handled by the drag coefficient.
A = Ld = 0.75 * 0.006 = .0045 square meters

The air velocity at a right angle to the shaft is given by:-
V = S Sin(P) = 1.745 metres/second

The drag force on the shaft (Fs) is therefore equal to:-
Fs = 0.5 * 1.2 * 1.2 * .0045 * 1.745 * 1.745 = 0.01 Newtons

The direction of the drag force is at a right angle to the shaft. The reason for this is that the air can't flow through the shaft. It is only the air flow momentum at 90 degrees to the shaft surface that is transferred between air and arrow (bearing in mind that frictional effects are being ignored as they are negligible in comparison).

Total Arrow Drag

The total drag on the arrow that moves it is the sum of the pile drag and the shaft drag. Because these drag forces are vectors they have to be added vectorially. In this case as the two drag forces are at 90 degrees to each other the total drag force Ft is given by:-
Ft = SQRT(Fp*Fp + Fs*Fs) = SQRT(0.017*0.017+.01 *.01)= 0 .0197 Newtons

The direction of the total drag force in terms of the angle to the shaft axis (Fa) is given by
Tan(Fa) = Fs/Fp = 0.01/0.017 which gives Fa as 30 degrees.

The arrow is therefore accelerated at .0197/0.018 = 1.09 metre/second squared in a direction at 30 degrees to the shaft axis (towards the nock end).

Drag acceleration of the arrow is sometimes quoted in terms of the 'g force'. To get this you divide the arrow acceleration by the gravitational acceleration (9.81 metres/sec squared). i.e the 'g force' equals 1.09/9.81 = 0.11g.

Drag Coefficients and Reynold Number

The drag coefficient relates to the fraction of the incident normal momentum in the air flow that is transferred to the arrow. (e.g a thin smooth cylinder has a (laminar flow) drag coefficient of 1.2 because about 60% (100*1.2/2) of the normal air momentum goes into the drag force on the shaft. With a flat surface 100% of the normal air momentum is transferred so the drag coefficient is (2*100/100) = 2). The drag coefficient also includes the effects of the dynamics of the flow over the arrow (e.g. laminar/turbulent flow). The value of the drag coefficient varies with the Reynolds number of the flow. The Reynolds number is the ratio of inertial forces to viscous forces in the fluid flow system. It is calculated as length x velocity/kinematic viscosity.

Once your out of the region where viscosity has a signicant direct effect on the drag (which is the case for an arrow) then the drag coefficient remains more or less constant with increasing Reynolds number until the nature of the air flow changes from being laminar to turbulent. At this point there is a significant drop in the drag force which is reflected by a drop in the drag coefficient. The drop occurs because with turbulence the boundary layer separates later from the body and the turbulent lower pressure wake is much narrower and hence the drag reduces. Reducing shaft drag by triggering turbulent flow over an arrow shaft by having a roughened surface has been (jokingly) suggested by the odd archer/aerodynamicist. The dimples on a golf ball are there to trigger turbulent flow and reduce the drag. A few years ago a someone (nemecek?) introduced a javelin with a roughened surface to reduce drag by this means. It was quickly banned as there was some risk that spectators in the third row might get skewered. With an arrow shaft it's too thin to sensibly put dimples in it and the net overall effect is arguably fairly marginal. If you get turbulent flow over an arrow, while it reduces the drag it also reduces the lift and the turning moment from the fletching action so swings and roundabouts prevail. For flight shooting it might make a measureable difference but for target shooting my opinion is that it's the usual swings and roundabouts and you would get very little difference in sight mark.

This raises the issue of whether the airflow over an arrow is laminar, turbulent or rather like a swing bowled cricket ball both in varying forms over its flight. The answer I think is rather similar to the cricket ball. What determines the flow Reynolds number (and hence the basic laminar/turbulent flow condition) of a free flying arrow shaft are the air speed, the arrow diameter and the airflow angle of attack (the "nodal alignment" in archery jargon). We're here assuming the arrow has a smooth surface (no turbulence triggers) and ignoring the arrrow vibration amplitude. If the arrow shaft was at 90 degrees to the air flow the flow would be over a circular cylinder and would be laminar. If the air flow was at zero degrees to the shaft then the flow would be essentially over the "flat" arrow surface and would be turbulent. Between these two extremes the air flow is over an ellipse where both the chord length and the ellipse eccentricity vary with the air flow attack angle. Both of these factors determine whether a laminar or turbulent flow condition occurs. As with an arrow the eccentricity is always less than 1 it's basically the air flow angle of attack which determines whether the boundary layer undergoes a transition to turbulent flow before separation. With "typical" values of arrow speed and shaft diameter the critical angle will be somewhere around 2 degrees. If the attack angle is greater than 2 degrees then we probably have a laminar flow condition, If less than 2 degrees we probably have a turbulent flow condition.

In practice the angle of attack of the air flow on an arrow during its flight varies all over the place. Generally the initial flow state will be turbulent (unless the initial launch "nodal alignment" exceeds 2 degrees) then as the angle goes through the 2 degree angle (going up or down) you will get laminar/turbulent flow transitions. As the arrow speed changes this will effect the critical angle. A drop in arrow speed will decrease the value of angle below which you get a turbulent condition. As a rough guide as the bow setup gets poorer, the archer's shot gets poorer or the wind speed increases then you will get a higher proportion of laminar flow occurence during the flight.

The above assumes the arrow shaft is a rigid rod where in reality, at least during the initial part of the flight, the arrow will have a significant vibration amplitude. This will result in rapid variations in the attack angle and air flow velocity at any point on the shaft over time on top of that from the nodal alignment. Anybodies guess on the effect of this but I tend to think that overall like most things to do with arrow vibration it cancels out and has no significant effect. While it's possible to determine the turbulent/laminar status of the boundary layer doing it for real over the flight of an arrow is a bit of poser. Down to wind tunnel tests and guesswork probably.

Air flow over the fletchings will generally be laminar. A crumpled front end or raised tape will act as a turbulence trigger hence the endless advice to keep fletchings in good condition. Occasionaly the turbulent air flow from the shaft will hit one or more fletchings either a because of low attack angle or the fletching is lying close close to the same plane as the airflow. In either case the fletchings are not doing much anyway so the effect is minimal.

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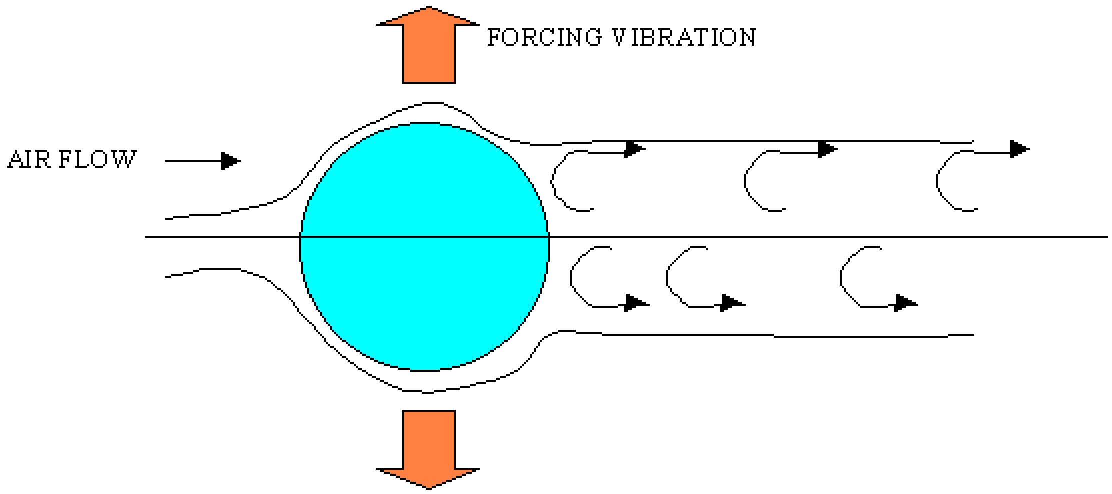
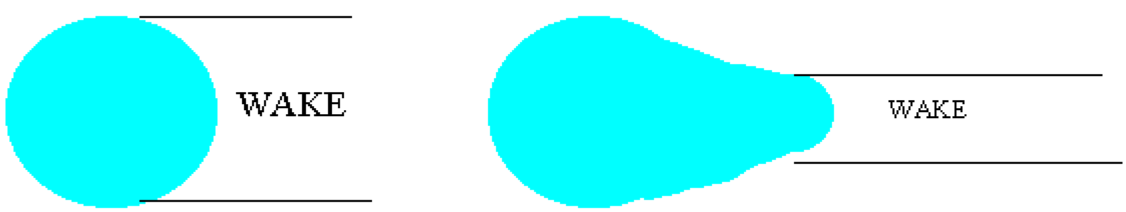
VORTEX SHEDDING AND TORQUE GENERATION

Take for example an arrow stuck in a target with a wind blowing across the shaft as illustrated in the following diagram. As the air flows around the top of the shaft the pressure of the flow decreases to zero. At this point the air flow separates from the shaft. Further round the shaft the pressure gradient is in the opposite direction and so the air flow is in the opposite direction creating an eddy or air vortex behind the shaft. The same thing happens with the air flow round the bottom of the shaft. These air vortices drop off the back of the shaft creating the wake behind the shaft, the main source of drag. This is the effect known as vortex shedding. Frequently these vortices drop off the shaft alternatively from top and bottom.(For a nice photo of this effect click here). When a vortex is shed it creates a 'push' across the shaft at right-angles to the overall wind direction. The shedding of vortices alternatively from each side of the arrow therefore generates a vibrational effect on the arrow shaft. If the frequency of this vortex shedding is close to the natural vibration frequency of the arrow shaft then the shaft can begin vibrating in sympathy. You often see arrows in a target nodding up and down on a windy day. This the effect of vortex shedding induced vibration.

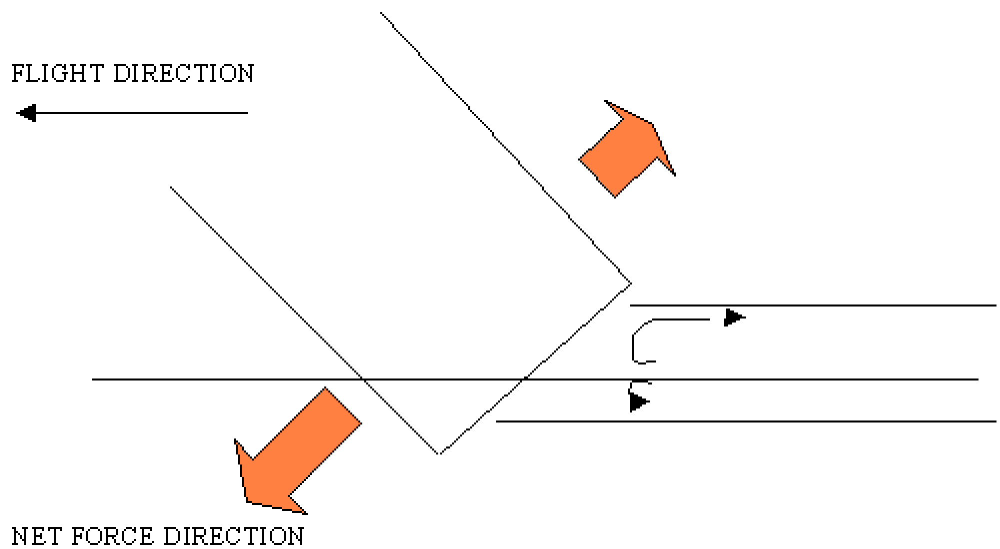


When an arrow is in flight you get this vortex shedding effect from the air flow across the shaft but it has no effect on the overall arrow flight behaviour.

You can change the point at which the air flow separates from the surface either by changing the roughness of the surface, by changing the shape of the surface or by rotating the surface. The attached diagram shows the effect of changing the shape of a cyclist's helmet. By reducing the rate of curvature at the back of the helmet the air flow separates from the helmet much later reducing the size of the wake and hence the drag force.



A special case of the above effect is where the separation of the air flow is not symmetrical around the back of the object. In this case the alternating 'pushes' generated when the vortices are shed do not cancel out and you get a net sideways force. The most familiar examples of this effect are spinning a ball (e.g. tennis) or roughing one side of a ball (cricket) to make it swerve as it flies through the air. With a long thin object the net effect is the generation of a torque on the object in the direction to rotate the front away from the direction of the airflow. The effect is popularly known as the 'leaf-fall' effect as it is this vortex shedding induced torque that makes falling leaves oscillate back and forth as they fall. The attached diagram shows how this effect is generated at the nock of an arrow. In this case it is because if the arrow is at an angle to its direction of flight the effective rate of curvature on one side is steeper than the other. As the force is being generated at the back of the arrow it generates a significant torque as the 'lever arm' is long, say around half a metre.

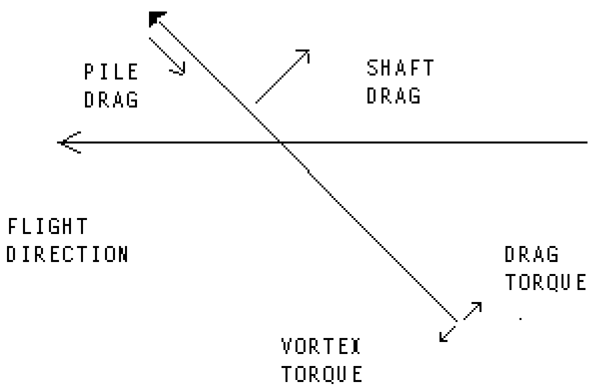


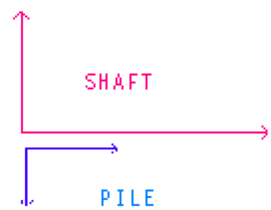
Vortex shedding induced torque varies with arrow velocity and offset angle in exactly the same way as the torque produced from drag on the shaft. The higher the arrow velocity or the higher the offset angle then the higher the torque.

The lateral force from vortex shedding will also effect an arrow if the arrow is spun in flight using the fletchings. In this case a sideways force is generated along the arrow shaft at a right angle to the plane of the air flow. In practice over the arrow's flight this sideways force will tend to cancel out and have little effect.

BARESHAFT ARROWS

An arrow, unless it is shot vertically upwards, can never fly straight. Because the arrow vertical velocity is always changing under the effect of gravity the direction of the air flow (and hence the direction of the total drag force) is virtually always at an angle to the arrow shaft. We need to look at the behaviour of a bareshaft arrow at an offset angle to its flight direction. In the following discussion the drag forces are described in relation to the arrow and to the direction of flight of the arrow as appropriate. From the archer's viewpoint you may be looking at an offset angle in the vertical or horizontal planes. To keep it simple the effect of gravity changing the speed and direction of flight of the arrow is ignored.

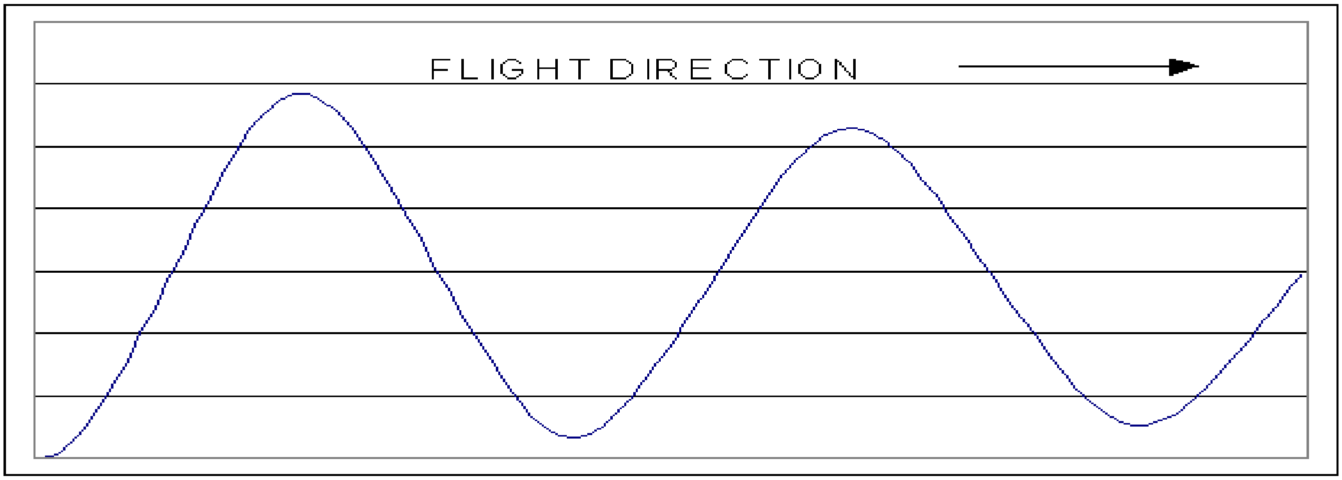




The total drag force on the shaft, acting at a right angle to it, acts to decelerate the arrow in the direction of flight and to accelerate the arrow sideways (upwards in the diagram). The total drag force on the pile, acting along the axis of the arrow, acts to decelerate the arrow in the direction of flight and accelerate the arrow sideways (downwards in the diagram). Ignoring for the moment any arrow rotation then the net effect is a deceleration of the arrow in its direction of flight and a sideways (upwards) acceleration. If the arrow stays with a fixed orientation then it would end up flying in a curve.

In practice the arrow will rotate under the net effect of the drag and vortex shedding torques. As these rotate the arrow in opposite directions, depending on which is the stronger effect the pile of the arrow will rotate towards the direction of flight (drag the winner) or away from the direction of flight (vortex shedding the winner). The resulting flight of the arrow is very different with different directions of rotation.

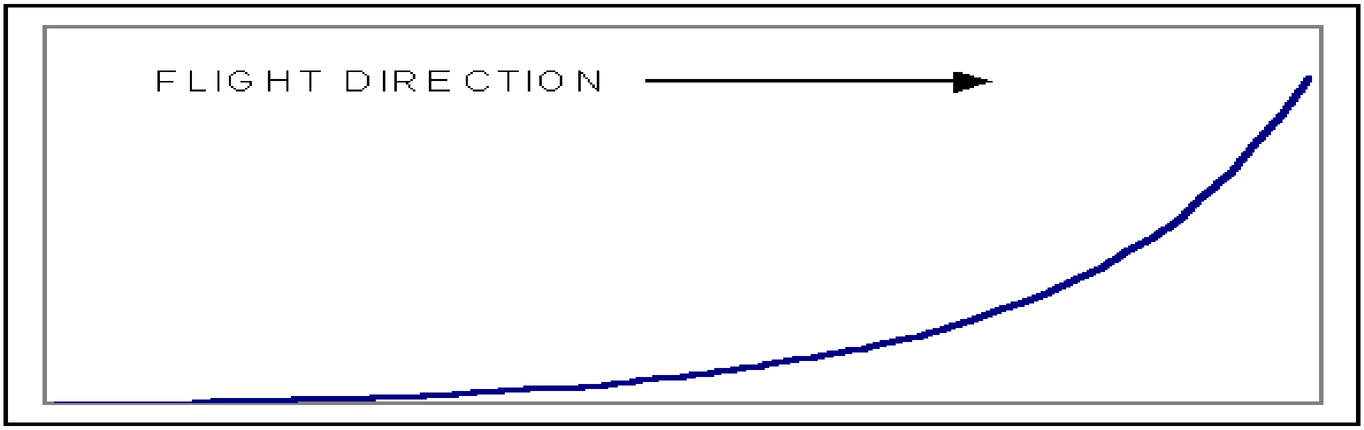
If the arrow pile rotates towards the direction of flight then as the arrow flies along in a curved path the offset angle steadily reduces to zero and hence the 'sideways' component of the total drag reduces to zero. Because the arrow has acquired rotation (angular momentum) then it keeps rotating until the overall drag torque brings it to a halt. The arrow ends up with an offfset angle opposite to the one it started with and so the process repeats with the 'sideways' drag force now in the opposite direction. The arrow therefore flies in an "S" shaped pattern about a mean flight path.



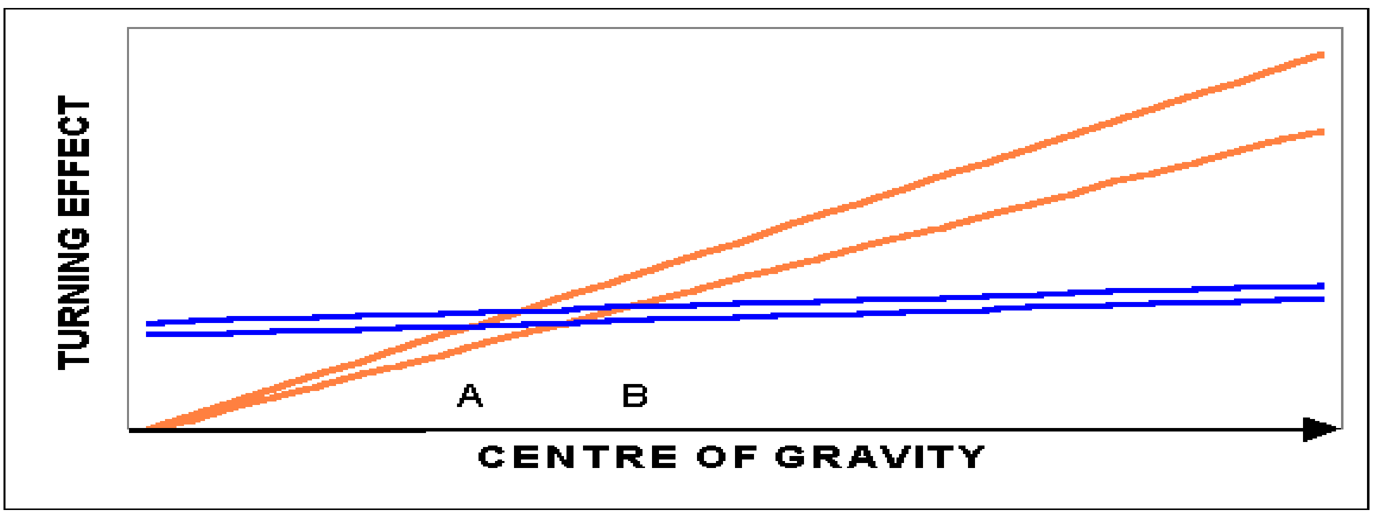
The mean flight path of the arrow is not a straight line but a very gradual curve. This curvature results from the arrow gradually losing velocity to the total drag and hence the 'sideways' drag forces on the arrow also decrease. Each time the arrow zigs and then zags the sideways movement on the zig is greater than that on the zag because the arrow is travelling faster when zigging than zagging. With each zig-zag combination the arrow ends up fractionally moved sideways. This effect cumulates over the arrow flight to produce an overall displacement. This displacement even at 90 metres is only very small and most archers' essentially regard the flight as straight.

A second point is that the fishtailing/porpoising of the arrow represents an energy oscillation between rotational energy and pressure potential energy (think of a swinging pendulum). This 'fishtailing energy' is lost via the drag on the fletching surface and the appropriate section of arrow shaft so the fishtailing/porpoising is steadily reduced by this drag damping mechanism.

If the arrow pile rotates away from the direction of flight then as the arrow flies along the offset angle steadily increases and hence the overall drag force keeps increasing. The arrow is decelerated more and more in the original direction of flight and accelerated more and more sideways. In effect the direction of flight itself rotates. The arrow continues to rotate away from the current flight direction. The overall effect, assuming the arrow does not hit the ground, would be for the arrow to end up flying in an ever increasing spiral as its speed and hence drag forces keep decreasing.



What determines which way an arrow rotates is the position of the centre of gravity. As previously discussed as the centre of gravity moves towards the pile end of the arrow the shaft drag contribution to arrow rotation rapidly increases. The torque from vortex shedding, which acts at one point, slowly increases as the centre of gravity moves forward as its 'lever arm' gets longer. The relative strengths of the two rotational effects as it relates to the centre of gravity is shown in the following diagram.



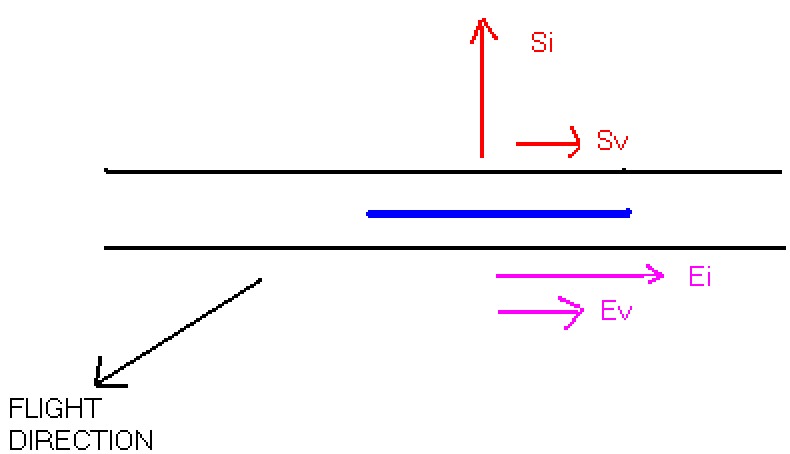
The diagram illustrates how the turning effect from drag (red lines) and vortex shedding (blue lines) vary as the centre of gravity is moved forwards from the arrow centre. If the centre of gravity is behind point "A" then the vortex shedding effect is the stronger and the arrow will fly in a curved path. If the centre of gravity is in front of point "B" then the arrow will fly straight in the "S" pattern as the drag torque effect is stronger. If the centre of gravity lies between "A" and "B" then the arrow can fly either way at any specific instant depending on the arrow's current rotational characteristics. Each torque is shown as two lines because the arrows' rotation has an effect on the air velocity and hence drag and vortex shedding torques.

The cross over point for actual arrows between flying straight or in a curve corresponds roughly to around an 8% FOC. It depends a fair bit on the geometry of the nock as this will effect the magnitude of the Munk moment. So with aluminium arrows if a 7% FOC pile is fitted the odds are that the arrow will fly in a curve, with a 9% FOC pile the odds are that it will fly straight. One would expect most if not all carbon arrows to fly straight as their centre of gravity is further forward. A side effect of this behaviour is that it's much easier to bare shaft tune a low FOC arrow as it curves away a lot more than a high FOC arrow.

In the mists of time when hunters used pointed sticks as arrows it was difficult to hit distant targets because their arrows flew in a curve. The along came some early Einstein who discovered that if you stuck a bunch of feathers on the back of the arrow it would fly in straight line over any distance. Adding fletchings significantly increases the drag torque rotating the pile towards the direction of flight. The arrow will always fly straight irrespective of where the centre of gravity is.

FLETCHED ARROWS

The following diagram is a simpified illustration of the drag forces on a (straight) fletching.

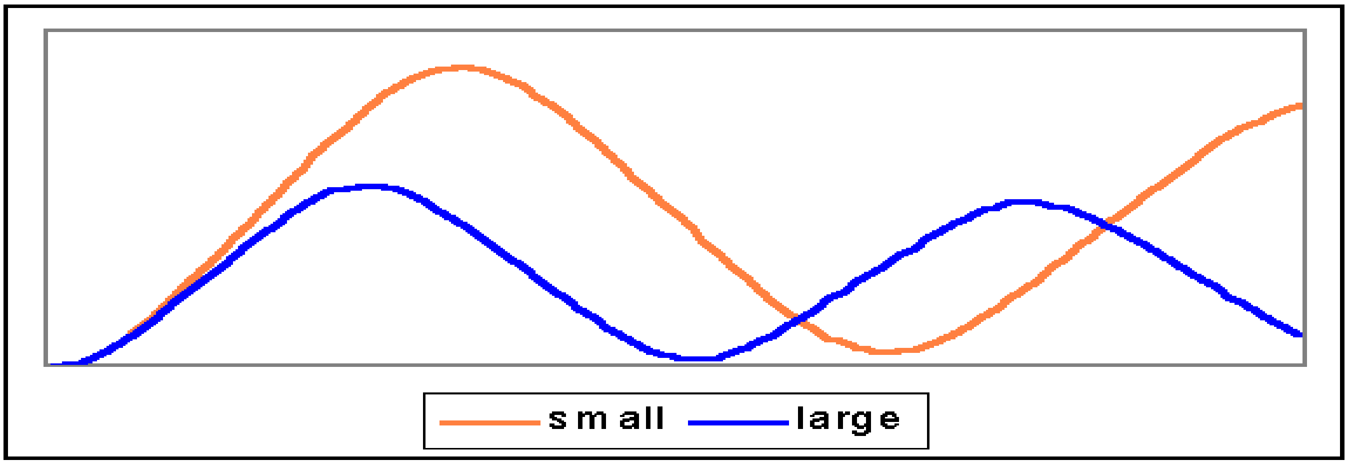


Drag on the fletching surface comprises an inertial drag force (Si) at a right angle to the fletching surface and a viscous drag force (Sv) parallel to the fletching surface. Drag on the edge of the fletching comprises inertial (Ei) and viscous (Ev) forces both effectively parallel to the fletching surface. Under the flow conditions for an arrow the inertial forces are many thousands of times greater than the viscous forces and the latter can in practice be ignored. A drag force at a right angle to the arrow shaft generates a torque which acts to rotate the arrow. A drag force parallel to the arrow shaft acts only to accelerate or decelerate the arrow. In summary then the drag force on the surface of the fletching acts to rotate the arrow (straighten it up) and the drag force on the edge of the fletching acts to change the arrow velocity. (For the case where the fletching is not straight or fitted at an angle to the shaft axis see the section on spinning arrows).

If you put larger fletchings on an arrow then it hits the target lower down. An (incorrect) explanation often given for this behaviour is that it results from the increase in the actual drag on the fletching surface area increasing the overall arrow drag. (Simple arrow trajectory models assigned the effects of fletching area on the pile and shaft drag into an 'imaginary' fletching drag). The correct explanation is given in the section on bareshaft tuning.

The main effect of fletching size is that the larger the surface area of the fletching then the faster an arrow will 'straighten up'.

The diagram below illustrates the different flight behaviour between two identical arrows shot with identical initial flight parameters. The only difference between them is the size (area) of the fletchings, one being small and the other being larger but a sensible size.



The arrow with the larger fletching oscillates much faster than the smaller fletched arrow. As a consequence the distance the arrow gets pushed sideways is reduced with the larger fletching. The other benefit you get from the larger fletching is that because the range of arrow offset angles is smaller there is less "flying sideways" and you get lower contribution to the overall drag from the arrow shaft. The curve of the mean arrow path is therefore reduced. As the fletching gets larger, and hence heavier, it moves the centre of gravity of the arrow back towards the nock. This reduces the proportion of shaft drag that is acting as a fletching and overall reduces the arrow turning efficiency of both fletching and shaft drag as the torque lever arm is shortened. The fletching, from the point of view of good arrow flight can therefore be too big or too small with the right size somewhere in the middle. The lighter the material the fletching is made of the better because of the weight effect.

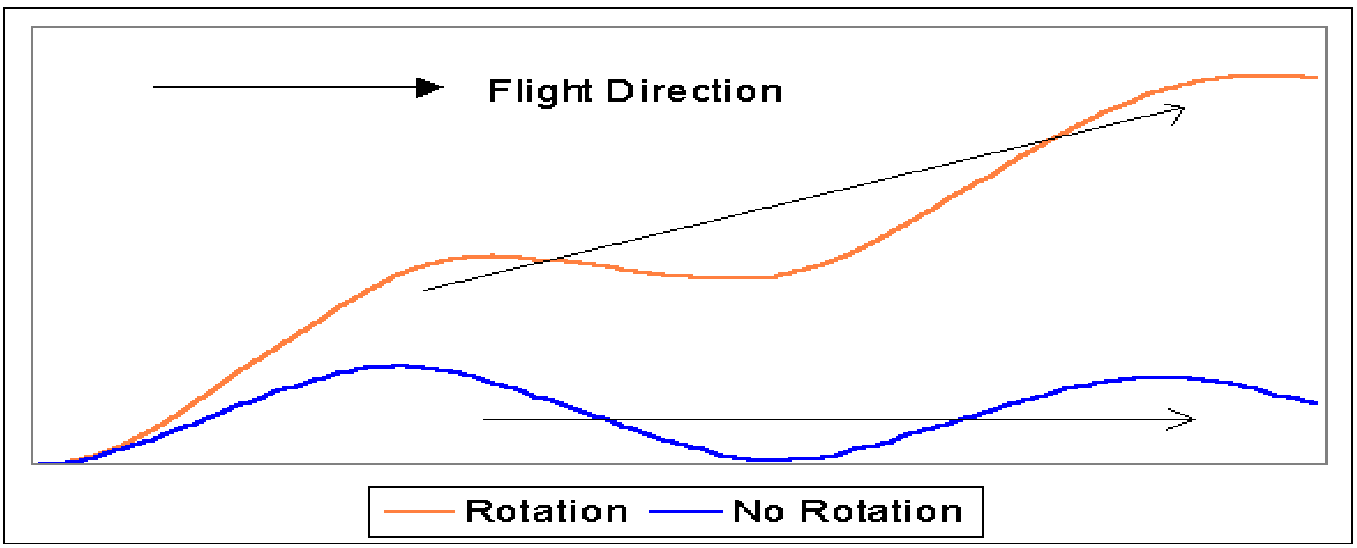
When the arrow leaves the bow it is vibrating as a result of the Archers Paradox effect. A large part of this vibrational energy is dissipated by drag on the fletching surface and the section of shaft that acts as fletching. As the drag depends on the area,the larger the fletching the faster this energy is removed. i.e. the faster the arrow vibration is damped.

The sensitivity of the arrow to wind gusts is also dependant on fletching size. When a gust of wind hits an arrow as well as blowing it downwind it also rotates the arrow. The amount of rotation and the recovery of the arrow from the rotation depends on the fletching area. When the arrow is rotated by a gust the arrow angle results in the sideways drag force on the arrow acting to move the arrow in the upwind direction i.e. to some extent arrows are self compensating for gusts. With respect to tolerance of wind gusts fletchings can be too big or too small, it is a balance between the amount the arrow is rotated and moved sideways and the recovery time. You can have the odd situation that a wind gust from the left ends up with the arrows hitting the target on the left if the recovery time is too long.

Feather fletchings are lighter then plastic fletchings for the same area but have significantly lower drag acting to rotate the arrow as the surface is not solid. If two identical arrows are shot with similar sized fletchings, one having feather and one having plastic fletchings then at short distances the the feather fletched arrow will hit higher. (It leave the bow at a higher speed as the arrow is lighter). In the long run however the plastic fletched arrow will end up hitting the target higher up. The rotational drag from the plastic fletching surface is higher. (And the feather fletch is probably thicker/less straight than the plastic one).

When an arrow leaves it can be rotating (poor tuning or poor shot). If during the shot the push on the arrow from the string does not run through the arrow's centre of gravity then a torque is generated on the arrow creating rotation.

The following diagram illustrates the difference in behaviour between an arrow with rotation coming off the bow and one with no rotation, all other things being equal.



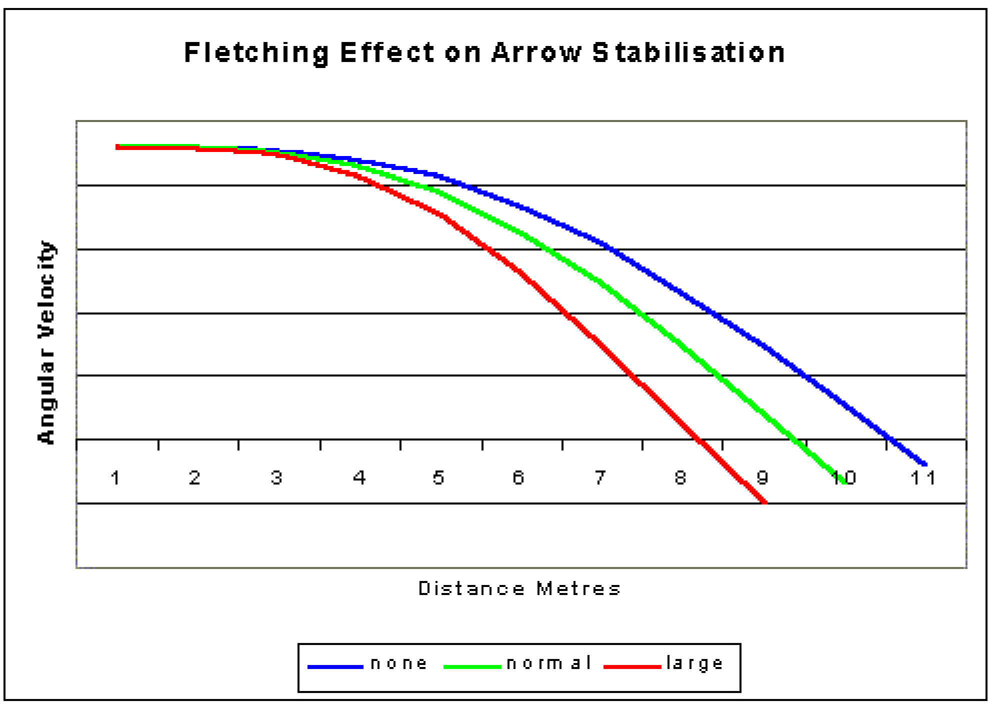
The arrow with rotation ends up with a much larger sideways displacement on the target than the one with none. This is an important aspect in understanding arrow flight. How far the arrow hits from the middle of the target principally results from the initial arrow rotation. The direct effect of the arrow fishtailing/porposing is by comparison relatively small.

You can look at the flight of an arrow as being in two phases. The first phase occurs just after the arrow leaves the bow with rotation from the shot. Because the arrow is at an angle to its direction of flight there is a component of the total drag force acting sideways to the direction of flight. Because the arrow is rotating and hence the offset angle keeps increasing this sideways drag force keeps increasing. The arrow is therefore accelerated sideways until the action of the fletchings removes this initial rotation from the arrow i.e. brakes rotation of the arrow to a halt. The arrow at this point has a velocity in the direction in which it was initially shot plus a sideways velocity. These two velocities add together and as a result the overall direction in which the arrow is travelling is changed. At this point the arrow then enters the second phase of flight which is the oscillation about a mean path discussed earlier. The effect of the first phase is to rotate the initial direction of flight the arrow has in the second phase. This is illustrated by the black arrows in the above diagram.

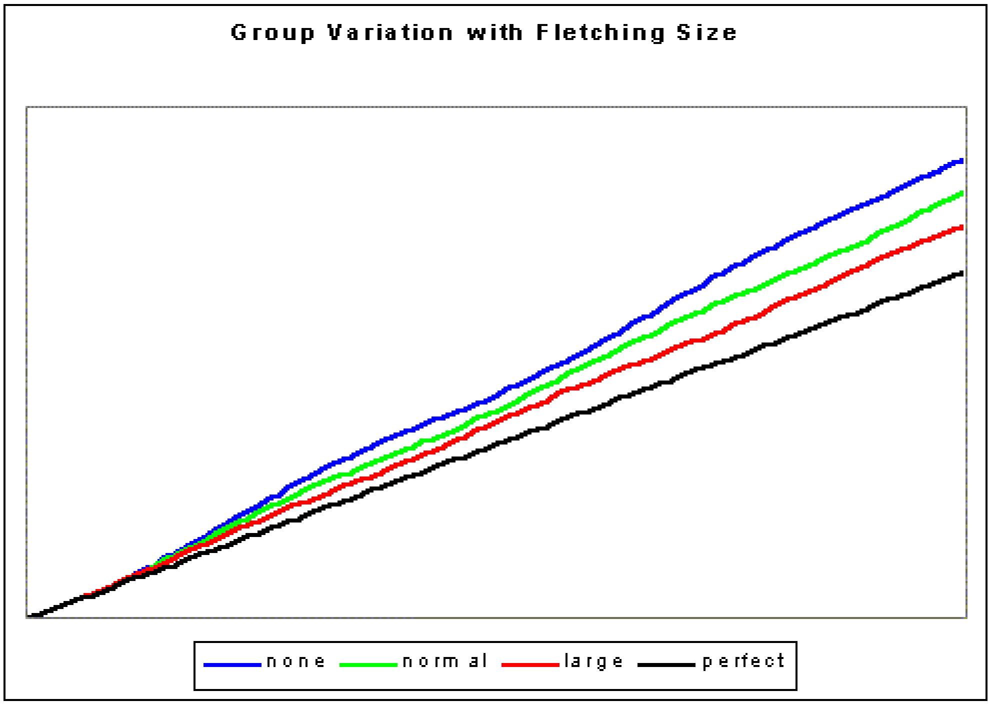
The two phases of flight are easily seen if you stand behind an archer while an arrow is shot. The arrow seems almost to leap sideways out of the bow in the first phase, what archers often call "the kick". After the kick the arrow seems to fly straight to the target (second phase). Frequently the oscillations of the arrow in the second phase of flight are too small to see.

Modern carbon arrows with their FOC's of around 14-17% will fly with perfect stability without any fletchings fitted, so why bother with fletchings at all. You get less wind gusting problems with no fletchings. The answer is that to minimise groups you need to stabilise the arrow flight as fast as possible - this is the primary function of fletchings.

If an arrow is shot from a bow with a poor setup/poor shot it leaves the bow rotating with some angular velocity. Until this angular velocity is removed (the arrow flight is 'stabilised') the arrow flies in a curved path. The longer it takes for the arrow to stabilise the bigger the resulting angle between the direction the arrow was shot and the direction the arrow ends up travelling.

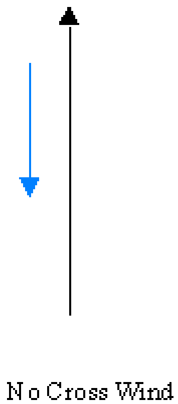


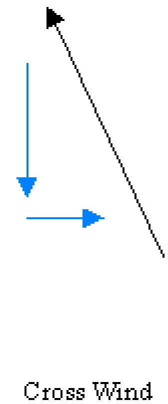
The graph illustrates how the 'stabilisation distance' varies with the fletching size. It shows the variation of arrow angular velocity with distance for three identical/identically shot arrows. The only difference between the arrows is the fletching size (bareshaft, typical fletching,large fletching). The arrow is stabilised when the angular velocity drops to zero (crosses the 'x' axis). The larger the size of the fletching the faster the arrow stabilises.



This graph illustrates the consequences on group size of how fast the arrow stabilises. Although the difference in angle between the required direction (the black line) and the 'after stabilisation' direction is small, small angles at large distances can result in quite large lateral displacements, certainly enoough to cause you points. (note at this scale the effect of the arrow fishtailing is not very obvious).

The arrow fletchings will always try to rotate an arrow to the position where there is no fletching torque i.e. the position in which the net air flow direction is along the arrow shaft. The net air flow velocity is the sum of the arrow velocity and any wind velocity. The "natural" orientation of the arrow depends on any cross wind. The following diagram illustrates the natural arrow positions in the presence of a cross wind and with no crosswind.

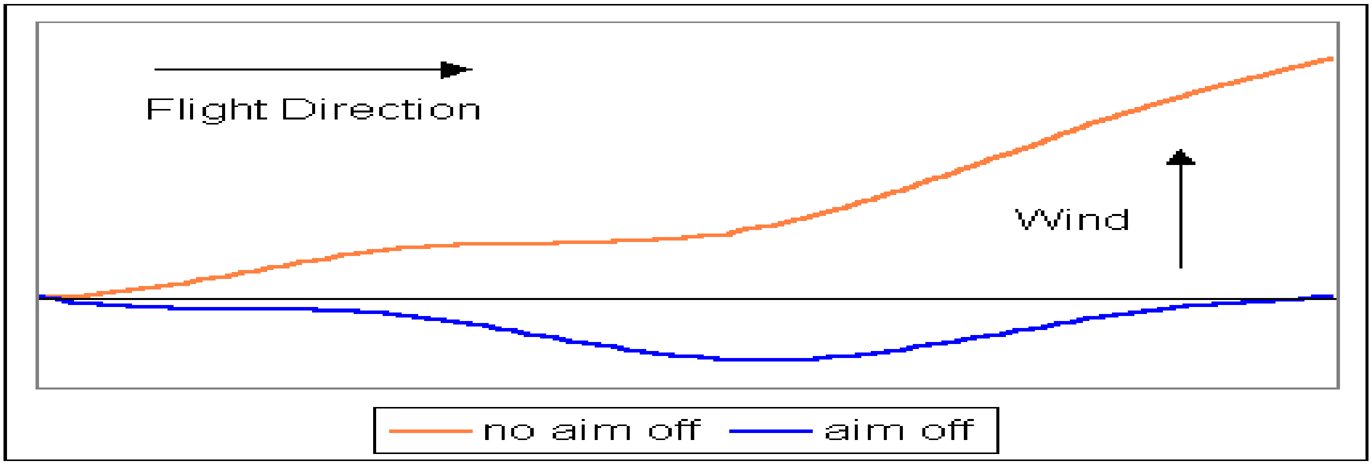




If there is no cross wind then the net wind direction runs directly from the archer to the target i.e. the arrow will always be trying to fly straight. If there is a cross wind then the natural arrow angle will be at an angle to the arrow direction of flight. The arrow's tail will "hang out". At its natural angle there is no net torque on the arrow and there is no net sideways component of the drag from the shaft. Because the arrow flies at an angle in a cross wind the drag in the direction of arrow flight increases and the arrow will hit lower down on the target. Even at its natural angle there is a sideways drag force component on the arrow from the pile and the edges of the fletchings accelerating it in the downwind direction.

As the arrow loses horizontal speed to drag in the course of its flight the strength of the cross wind increases relative to the air flow from the arrow speed. As the arrow flies in a crosswind therefore the natural angle steadily increases, the arrow's tail swings out.

To compensate for the downwind drift of the arrow archers either aim-off or adjust the windage on the sight. The purpose of aiming off is to give the arrow a horizontal velocity in the upwind direction to balance the downwind drift. Aiming off also changes the arrow's flight characteristics as the arrow is now leaving the bow in a different direction. The first phase of flight as defined above becomes much more complicated as in addition to the arrow offset angle and arrow rotation from the shot the effect of the cross wind, the arrow's aim off velocity and the arrow aim off angle all interact to define the arrow behaviour. There may be more than the two phases of flight identified above with a cross wind as, when oscillating, there is the possibility that the arrow could rotate enough for the sideways drag from the arrow's forward velocity to reinforce the cross wind drag. The following diagram illustrates the effect on arrow flight of aiming off.



Where on the arrow shaft should the fletchings be placed to get the most out of them? What you want the fletchings to do is rotate the arrow as fast as possible. You want the drag torque on the fletchings to produce the maximum rotational (i.e. angular) acceleration. The angular acceleration depends not only on the torque on the arrow but also on how easy it is to turn it. How easy it is to turn depends on the point about which it rotates. Hold a long rod at the weight end and its easy to twist about. Hold it where it screws into the bow and its much more difficult to twist. The "rotatability" of an object is called its moment of inertia. The angular acceleration you will get is the applied torque divided by the moment of inertia. Both items depend on the point of rotation of the arrow. It turns out that to maximise the angular acceleration the fletching should be located as near the nock end of the arrow as possible.

Comments on Spin Wings Vanes by Rick McKinney

Edited version of discussion on Archery Talk Forum
For full version see Archery Talk

Introduction (by Rick McKinney)

I have been thinking about some of the comments on this thread and how if you try something and it does not work, then we (me included) comment on how bad it is or it doesn't work well for most, etc. Many people do not quite understand what another person is saying with absolute certainty unless you spend time to figure out exactly what is said, just as we have discussed here. I will use an example from my past if you all will indulge me for a moment of reminiscing.

Years ago, Darrell Pace was one of the first to shoot Spin Wing vanes and claimed they were the best. I figured I would try them and found them to be lacking without a doubt. My groups opened up and so I figured the only reason Darrell was using them was because he was being sponsored by Range-O-Matic, the makers of the Spin Wing vane. I voiced this opinion to those who asked why I did not use the Spin Wings. Anyway, I received a call from the son-in-law of the owner of Range-O-Matic. He was a USAT team member and asked me why I did not like the vanes. I told him that they did not group well and I got better results with my Myro-vanes made by Shig Honda. He asked me if I wouldn't mind trying them again at the next training camp and he would set them up. As my ego was fuming from this "insult", after all who does he think he is telling me I don't know what I am doing? Well, needless to say, I told him that sure, if he was willing to spend the time and effort I would try them but I had my doubts and told him so. It was more to confirm to him that they did not work for me. Well, when we were at the next camp I gave him 9 arrows and said have fun and walked away. He had to clean off the fletchings and then he fletched me up with some Spin Wings. I looked at them once he was finished and told him I doubt that they would work and sure enough they grouped horribly! I looked at him and smiled. He said, "Don't worry, I have a few things to try before we find what will work for you." So he took the arrows and stripped them down and re-fletched them again with a different placement and angle. An hour or so later, he gave me the arrows again. I shot them and my heart skipped a beat! They grouped REALLY good at 50 meters. Well, then I thought, I have three other distances to try before I got too excited. Needless to say, they grouped exceptionally well! As I swallowed my pride and looked a bit sheepish at him, I asked him what he did to make them work. He told me how to test the fletchings and figure out what will work and what will not work. I was so thankful that I let him talk me into trying them again. A few months later at the World Target Championships I set a new 70 meter world record on the third day and going on to win the Individual title. It is a wonderful feeling shooting the best score ever at a very stressful event. I feel that the Spin Wings gave me just a bit more edge on my shooting and never would have had that opportunity if it wasn't for giving it another try. What was even more humbling was that all the Soviet men were in line to shake my hand right after I set the world record. The US archers came up to me after words and asked what that was all about. I had to grin.

I guess I should tell you a few things about Spin Wing vanes. There are several types including pliability, drag, height and length.

First are the colors. White is the softest which allows for more forgiveness if the vane hits the rest or plunger. Yellow is next, then red, blue and finally black is the stiffest. Obviously the black will hold it's integrity downrange better than the rest. However, you have to determine if one performs better than the other by testing. Yes, it can become expensive. I have always stayed with the white because I have always had to deal with clearance issues.

Next is the length of the vane. It depends on the speed of the arrow to determine which vane length you should use. The faster the shaft the smaller the vane needed. If you get too much drag on the shaft (longer fletch) you may end up with a parachuting effect downrange causing your groups to open up. That's why you see more archers using the 2"+ vanes with their x10's. Most use the 1¾" vanes with their ACE's and I have recommended using the 1 9/16" vane for McKinney II.

Now you also have to keep in mind of the clearance issue. This can be due to the height of the vane (the 1 9/16" and 2" vane are lower profiles, while the 1 3/4" and 2 3/16" vanes are higher profiles). If you are touching anything you may need to go to a smaller height vane if you cannot get better clearance. Using lipstick on the edge of your vane will show you if you have clearance issues. The lipstick will leave a mark where it hits. You can adjust your nock as well to get better clearance which I talk about a little later.

Now location of the vane becomes a bit critical. The length down from the nock is important. You do not want the vanes near your fingers. I know this sounds a bit weird but this part does affect the performance of the vane if your fingers touch the vane while releasing. Don't put the vane down the shaft too far either (further from the nock). The farther down the shaft the more unstable the flight becomes. So get it back near the nock as close as you can without your fingers touching the vanes upon release.

Next is vane angle. You need to put the vanes on close to 0 degrees. The more angle you put on this vane, the more drag created and the less you will group (again, parachuting effect). Once you figure that out, then you need to decide best nock location compared to the vane. If you turn your nock a little it may make all the difference in the world for better grouping. This can be found easily by shooting and plotting your arrows. Shoot a few ends and move the nock a bit, shoot and plot. Once you find which gives you the best grouping then write everything down. The more information you have the easier it is to do this again and again. For instance, I had one fletch going exactly 12 o'clock high when the nock was on the string which gave me the clearance I needed.

Now, once you have done all of this you will need to verify the vane performs well in all conditions. Testing the vane in different winds and wind angles helps to learn how the vane performs and of course testing in the rain will help you understand which vane works best. You are looking for the over all performance of a vane, not one that does well in one particular condition.

Don't forget there are two vane drags available. The light drag and standard. Usually, those with heavy poundage need to use the light drag vane. Those with lighter poundage should try the standard vane.

The Elite vane needs to be compared with the regular vane to find if it works better. I did not find the Elite to work for me. However, I have seen Vic Wunderle use them and was successful with them. So again you must try them to find out if they work.

All of this takes money to find out which vane works. What I suggest is to get a group of archers together. Each of you can buy one or two different packets of vanes and share. This will keep your costs down and allows more testing.

Here is another little story to show you how important it is to find out how the vane works. I was doing some testing for Richard Carella who was the inventor of the vane. He recommended I try the 2" vane. It was a little lower profile than the 1 ¾" and it just might give me an edge. So I put them on and they worked extremely well. My scores jumped up about 3-5 points at 50 and 70 meters (this was where I ran most of my tests). I was getting ready to go to a major event and decided to re-fletch my vanes so I stripped the 2"ers off grabbed some tape out of the 1 ¾" vane packet thinking it did not matter. Well obviously it did matter. The tape in the 2" packet was a lot slimmer than the ones in the 1 ¾". Thus I changed the drag of the vane and the performance was lousy to say the least. This just shows you that even a top archer will do silly things not thinking them through until it is too late. A good lesson learned though and it made me be more methodical. Oh and use the force!

Discussion

Question:

Rick - Can you provide a little more color as it regards this sentence?

So he took the arrows and stripped them down and re-fletched them again with a different placement and angle. An hour or so later, he gave me the arrows again. I shot them and my heart skipped a beat! They grouped REALLY good at 50 meters.

In your last post I got the impression that 0 degrees was what you were trying to achieve. I guess I'm curious about the placement and angle that he was trying to get.

RM Answer:

He had the vanes a little too close to my fingers. They were fine at full draw but I knew that when I let go, my fingers would touch the vanes. Also, the vanes were about 2-3 degrees on the shaft. He made them 0 degrees. Then he tweaked the nock alignment until they started grouping. I think that these three things helped me shoot some great scores. Actually two of these items were fairly simple, distance of the vane from the fingers and angle. However, tweaking the nock around until I got absolute clearance was paramount. As I said, I had one fletch that lined up right with the string, thus the "cock" fletch was really lower than the normal positioning. Now, this does not mean it will work for everyone, but it really worked for me. My upper "hen" fletch would sometimes hit my plunger causing erratic flight and poor grouping. Just turning the nock a little eliminated that problem.

Comment:

Spin wings are interesting and not as straight forward to set up as a straight fletch. They take up a wider path than a straight vane that must be accommodated (nock alignment) to get the best clearance. Some strike the lower vane and most strike the upper or hen fletch. I have seen an upper vane strike a clicker and a sight bar! The first time I tried them I shot poorly with them as well and went back to straight hard vanes. I now use them on my indoor arrows instead of feathers. (You know, you grow)

RM Answer:

If the vane is being hit by the clicker it could be due to the clicker being too soft (most of us keep it soft so if you shoot though it, the arrow doesn't go too far off course). If the clicker is too soft, it really will fly back out when you release the string and come out and hit the fletching. I have seen this in high speed films. You want it soft but not too soft. I have found that if I draw the arrow back with all three of my fingers ¼" below the arrow (no finger pressure against the nock) and watch the clicker click to see if it moves the plunger (the clicker will be too stiff then) or the clicker bounces upon the click (clicker is too soft) and adjust accordingly. If it is hitting the sight bar, then you can either move the sight bar in closer for now, especially if you cannot get weaker arrows.

Question:

- on vane fragility

RM Answer:

Using rubber vanes is easy maintenance, but if you watch the top archers (medal winners) there is a 99% chance they are using the Spin Wing type vane. Once you figure it out you will see what I mean by getting better groups compared to rubber vanes.

Question:

- on vanes/tape detaching from shaft

RM Answer:

First you might want to use like a woman's curling iron and lightly touch the edge of the vane when it is on the shaft so that the vane will curl around the shaft. Ludmila Ahrzanikova (sp?) of the former Soviet Union and now a Dutch citizen taught me that little trick. The art of using the tape is a challenge. First you do not stretch it too much when you apply it and like John said you could use a little touch of glue to hold it. Normally the only reason that it does not stick is due to the surface area is not clean enough. Just the oily surface of your fingers could contaminate the surface area to keep it from sticking properly.

Question:

- on arrows sticking together in the quiver

RM Answer:

Actually to keep the vanes from sticking to each other, once you fletch them just lightly powder them. The powder will eliminate all the unnecessary sticky areas and eliminate them from attaching themselves together so much. A real nuisance for sure.

Question:

According to Spin-wing instructions the drag colors variations from the least to the most are: 1.black and white 2.yellow 3.blue and 4.red. This means that the drag is not related to the "softness" of the vane?

How can I know if my vanes are standard or light drag? because in the paper which comes with the vanes doesn't says anything about that. Sometimes he sheet instructions is yellow and sometimes purple. I don't know if the drag properties is determined by the colour of the sheet instructions.

And the last question is that the instruction sheet says "available sizes: 1-9/16", 1-3/4", 1-3/4"VLD, 2", 2-3/16" and 2-13/16". What does "VLD" mean?

RM Answer:

VLD- very light drag.

It would appear that the drag relationship to color is slightly different than the stiffness relationship. Not exactly sure why that is. However, if the instructions say it believe it. Black was a weird one for me. It seemed to be more fragile than the rest and I had all kinds of difficulties with it (just didn't group!). Now, having said that, don't forget that you are mainly looking for grouping and should keep ALL options open to find what gives you the best group, not what someone says or the instruction sheet tells you. I never really cared what an expert said only to gather information. All of my belief is in the arrows going into the center. If they did not go into the center it was not a good setup.

Question:

- using spin wings for indoor shooting

RM Answer:

You are right on increasing the spin and drag by making the angle greater and this is great for indoor shooting. Several years ago, I used the 2312 (I think) using the 5" spin wings to win Vegas. They shot great. The difference between my shooting and yours is the compound/release vs recurve/fingers. The speed I had was probably 30-50% slower than your setup thus the 5" spin wings. Yes, when you go outdoors, you will have to make a lot of adjustments but you are on track from what I am reading here. If you have a drop away rest, the spin wings will be fantastic (no clearance issues). Just recognize the spin and drag will need to be minimal for your speed capabilities (probably the 1 9/16", 0 degrees).

Right now I am playing with my "skinny McKinney's" using a 1 3/4" Spin Wing. I have them at 5 degrees plus which is relatively sharp but I figured that it just might work since I am only shooting 18 meters. This would never work long distance, but it does work at close distance. For my Hippos I have used 4" feathers with a sharp helical. The drag keeps them stable.

Question:

- on vane length to use

RM Answer:

As for determining what drag or what length of vane to use, as I mentioned above the heavier arrows (therefore a bit slower) will need a longer vane. When I used the old A/C 1508 arrow which weighed about the same as the 2114, I used the 2 13/16" vane. Did it work? You bet! I tied my 345 at 50 meters with them and averaged near 1325 that year with them. So they did work well. Since the arrow was just about traveling near 205 to 210 (similar to the current x10) that length of vane was a good stable one. When the ace was brought out in 1988 Richard Carella was asked by Jim Easton to help him develop a vane that would work better for the faster arrow, hence the VLD 1 ¾" and 1 9/16" vane. Just think of a jet. The bigger the plane, the slower and the larger the wing span. The faster the jet, the smaller the wing span needed. Now...unfortunately I have not taken the time to determine at what speed do you need to switch.

Question:

- on vane color/stiffness and drag

RM Answer:

Drag is based on the flexibility of the vane. Thus, if it is softer or stiffer, it definitely will have a drag difference. Maybe the angles are identical but you can be sure this changes aerodynamically in flight. For those who feel that there is no drag difference that is fine. However, when you change the color pigmentation of this material it does change the flexural dynamics. Especially down range. If you disagree, please feel free to do so as I disagree with you. My personal experience and Richard Carella's opinion was that there was a difference due to color. If the vane is a bit softer then it just might open up a little more than the slightly stiffer color, thus causing a difference in drag.

Yes, some very interesting comments made here about various items. First is the black material. I had always presumed it was stiffer than the rest and I do recall Dick telling me that it was stiffer, but it may have been changed to a softer material. I do believe that this material is a bit more fragile than the others. It always broke down faster than most of the other colors. However, Vic Wunderle used them for years and had a lot success with them.

As for the metallic green ones. I did play with them but do not recall the flex level of them. They were a bit on the fragile side too if I remember correctly. I mainly used the white because they were so consistent over the course of using them. Even when they were scraggly looking, they performed exceptionally well. Next, I used the yellow because they were fairly decent as well. I played with the blue, red and black and did not like them due to either their unforgiving performance or their fragile side.

Question:

- Spin Wings v offset flat vanes

RM Answer:

As far as putting straight vanes at a sharp angle to get them to act similar to the Spin Wing. I am sure it is fine. However, if it was as good as the Spin Wing, then why doesn't the top archer do it? It doesn't take a brain surgeon or a rocket scientist to figure out if one performs better than the other and I am sure they have tried it! The simple techniques as I have discussed should give a big percentage of archers a better grouping pattern than they have with straight type vanes.

Question:

One thing I always worried about with spin wings was the affect of "bent" or "creased" vanes on arrow flight. What I mean by that is you can have 6 perfectly fletched arrows with spinnies, and after three ends 3 of those have at least one vane with a bend or crease from arrow impacts. A lot of the time, this goes unnoticed in an archer's quiver. Likewise, you can easily curl a fletched arrow more or less than normal...

So to me, all that seems to lead to inconsistent drag and performance once the arrows get banged around in normal use...

With vanes such as the Flex-fletch or the AAE plastifletch Max that I now use, once they are fletched, they pretty well maintain the same angle and shape for the duration...

I often worried about that fragile nature of the spin wings - not because of re-fletching often, which is simple enough, but because of the potential affect on drag it may have.

RM Answer:

A great question.. I know that many people worry about the performance of the vane when it gets creased, but my experience has shown no difference in performance. I shot one national championships that even had two and a half vanes on my arrows and they still were going in the middle. One archer saw my arrows and said, "Are you using your practice arrows here?" (I was on the practice field at the time warming up before the round began). I mean these spin wings were so mangled that if I didn't have the confidence in them I would never have thought to use them. However, they were working so good and I really didn't want to take the time to refletch them. I told the guy they were the arrows I would use at the competition. He did not believe me. I told him to come to target one and see for himself. He did and just walked away shaking his head. I won by the way.

There are some things that I do to make sure the vanes are working as best as they can. First, when I pull my arrows from the target, I always inspect the nock ears, spin the shaft and then run my thumb down the taped edge on all three vanes. This insures that there is no loose part that might fly up when I shoot it and then it will fly like crap and end up in the grass…. I only did that once! Next I take the vanes and wrap them around the shaft opposite as the lay. This gets them close to being where they originally should be. These little steps insure that the vanes, nock and shaft is in working order. These simple little items takes so little time and you can train yourself to do it every time you pull your arrows that it becomes a good habit and eliminates that one freaky shot that costs you a tournament.

I remember when I first used mylar vanes (MyroVanes by Shig Honda). Dick Tone told Jay Barrs that he should not use the vanes because they were inconsistent. He showed Jay that the vanes when flexed made a different sound, thus each was different in flex and consistency. Jay's simple little question was quite cute. He asked Dick, "Well if they are so inconsistent then why does Rick shoot so well with them?" Dick told him, "I haven't figured that out yet!" Mind you, I had just shot a 345 at 50 meters setting a new world record at the time! The reason I bring this up is that no matter what it looks like on paper, no matter what the reasoning you use to question the consistency or quality of the potential of the product, you will only know if it works by testing it! Put it through all kinds of tests so that you know how it works. If it goes in the center, it works! No matter if it is logical or not!

Question:

- Why use high maintenance Spin Wings rather than rubber vanes

RM Answer:

I can fully appreciate your comments about using a rubber fletch versus a Spin Wing vane. I would guess that most people will not notice a big difference or any at all if they are not in the "elite" level of competition. Most of the comments I made here was just a statement of fact. The Spin Wing vane has won so many medals since the late 1980’s that it is just a fact that they are the preferred choice of the champions (world and Olympic).

The most fragile and sensitive fletch and the elite archers are willing to take the time to keep that high maintenance on them so they can get a point or two extra. I agree with you that the rubber fletch will do the job for 90+% of the archers out there. I was just stating the facts of what you see in the elite world. If the rubber fletch was just as good, I would say that most “elite” archers would go with the rubber fletch because of what you stated, easy to fletch and easy to maintain.

I won my first world title with the PSE 260 rubber fletch (2115 x7), my second title with AAE rigid plastifletch (A/C 1508) and my third title with the Spin Wing (A/C 1508). You can see that I used three entirely different vanes and did well with them, but the Spin Wing came into play in the mid-1980’s. Check the records and you will see that they literally dominate for over 20 years. Again, it baffles me that one product can be so dominant with no financial reward other than winning.

SPIN WINGS COMPARED WITH FLAT VANES

At the Beijing Olympics the majority of archers were using spin wing vanes. A few were using K vanes but as far as I am aware **all** were using curved vanes.

A lot of club archers use, and swear by, offset flat vanes but clearly elite archers prefer curved vanes. The obvious question is why curved vanes are the choice for the elite archer.

There are a few obvious advantages that curved vanes have.

- They look cool (let's face this is the basis for a lot of archery equipment selection)
- Because of the way they are made there is a high uniformity in weight and shape
- Their lighter weight means a lighter shaft and consequent higher arrow speed and FOC

The original Carella patent highlighted the "wind dependant" variable geometry of the Spin Wing. There's probably some truth in this idea but extremely difficult to quantify it. I doubt that this concept is the top of the list in the preference for curved vane fletchings.

The other advantage that curved vanes have over offset flat vanes is in the aerodynamics of how the spin is generated which is the main point of this note,

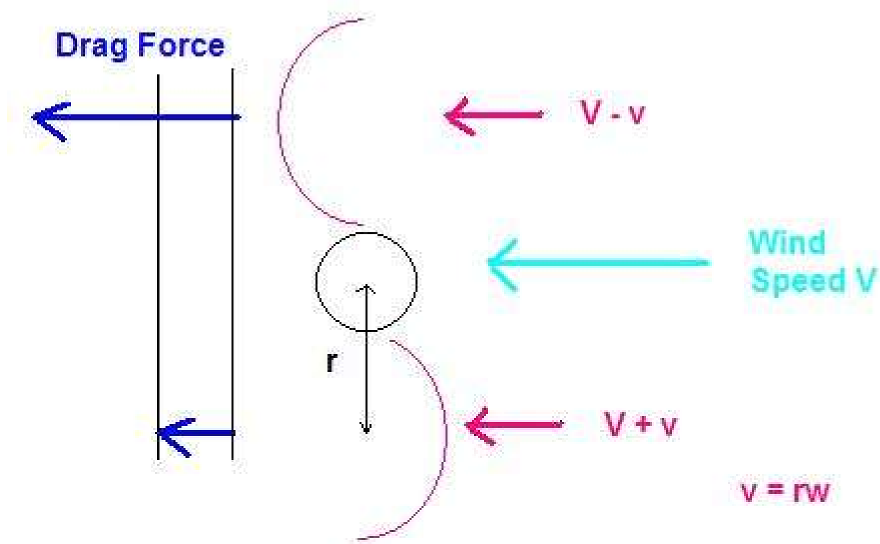
The aerodynamics of offset flat vanes has been briefly discussed before in the main article. This article highlighted two major drawbacks to the offset flat vane approach:

1. Because the vane has to be at an angle to the shaft you incur a lot of drag along the the shaft axis slowing the arrow down. The more spin you want the bigger the offset angle and the more of this axial drag you get.
2. Arrow vibration and any arrow fishtailing will reduce (even reverse) the spin acceleration of the arrow.

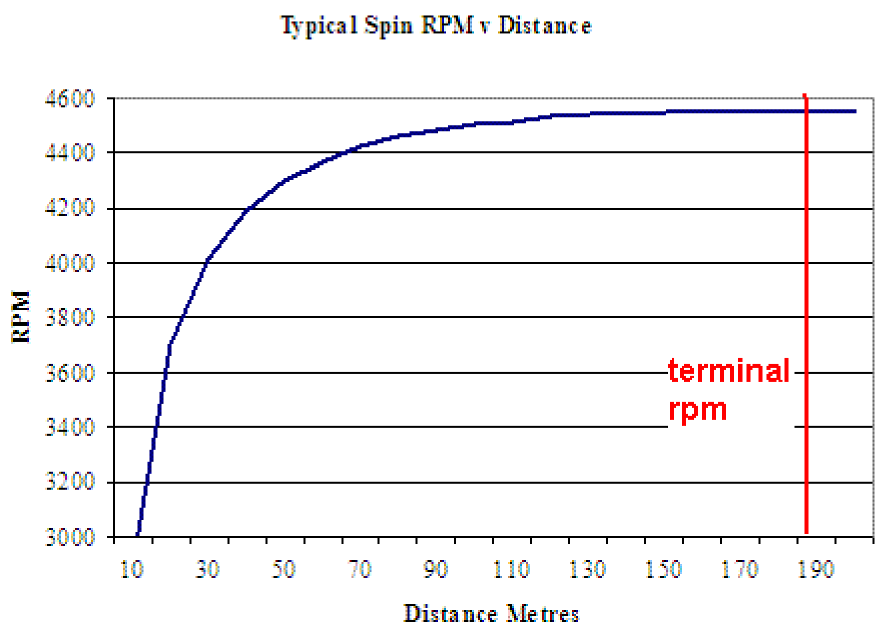
Curved vanes have neither of these drawbacks.

A purely curved vane (ignoring the "twist" you have with Spin Wings) spins on the same basis as an anemometer or those revolving vertical "S" shaped signs you often see outside garages. Spin is generated, not by having a different air flow angle of attack on opposing vanes (the offset flat vane method) but by opposing vanes having different drag efficiencies (different drag coefficients) because of the vane shape.

The following diagram illustrates the basic spin operation for a curved vane.



The top vane, because the "cup" faces into the air flow has a higher drag coefficient then the lower vane facing in the opposite direction. The drag force on the top vane is therefore higher than the lower vane resulting in a net torque which spin accelerates the arrow. It spins in an anti-clockwise direction as per the drawing. As the arrow spins faster and faster the top vane is moving away from the air flow V at a speed v (**w** is the angular velocity and **r** the distance from the vane centre of pressure plane to the arrow axis). The net air flow speed onto the top vane is therefore V-v. As the spin rate increases the net drag on the top fletching decreases. The reverse is true for the lower vane. As the spin rate increases the net air speed on the lower fletching (and hence the drag force on it) increases. At some spin RPM the drag forces on the top and bottom fletchings will become equal and the arrow will have reached a nominal terminal velocity. This nominal terminal spin RPM can be described by a simple quadratic equation but as in practice (Recurve FITA) an arrow never reaches the terminal spin RPM and the nominal terminal spin RPM varies over the arrow flight, not really relevant.



Some crude wind tunnel type calculations suggest that for a typical (flat offset vane) target arrow the flight distance/time required to reach spin terminal velocity is around 100 - 200 metres/ 2 - 5 seconds. Problems with Spin Wing type vanes are their complex shape and vane flexibilty so no sensible estimates feasible - by me anyway. Bertil Olssen has made some wind tunnel terminal RPM measurements for spin wing fletched arrows giving a value of around 5000 RPM.

The important aspects are that because the curved vane surfaces are parallel to the arrow shaft the only axial drag incurred on the fletching surfaces is the insignificant frictional drag. (Not actually true for Spin Wings because of the twist in the vane). For a given required spin rate curved vanes have lower axial drag then an equivalent offset flat vane.

Also the direction of the spin acceleration with the curved vane, unlike the offset flat vane, doesn't depend on the angle between the air flow and the arrow shaft. With a flat vane if the air flow reverses onto the fletching surface, spin braking occurs and the spin acceleration can go negative. With a curved vane if the air flow reverses onto the fletchings, the two fletchings just "switch roles" and the spin acceleration direction is unchanged (Imagine what would happen if the main airflow was going left to right instead of right to left). With the curved vane you get spin acceleration in a constant direction.

THE GYROSCOPE MYTH

The behaviour of spinning objects is complicated. Spinning objects behave in a way that seem at odds with 'normal common sense'. When you put one end of your toy gyroscope on top of your Eiffel tower instead of falling down it goes round and round. Weird! All sorts of anti-gravity and perpetual motion machines have been invented based on using gyroscopes. (unfortunately they don't work).

The common gyroscope myth is that if you spin something (arrows included) then you get 'gyroscopic stabilisation' i.e. the object stays steadily pointing in the same direction. There are things around called 'gyroscopic compasses' and bullets are spun with rifled barrels to confuse the issue.

In reality when you spin a free flying object it 'destabilises' it and makes it wobble about.

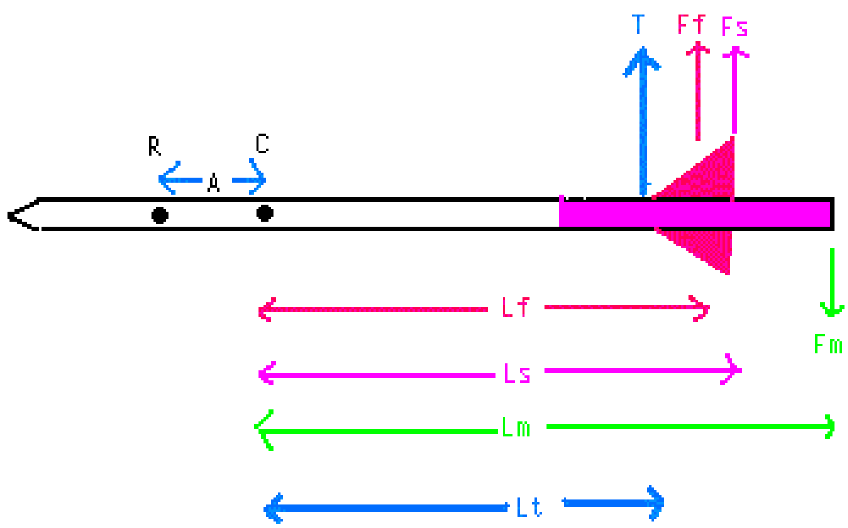
Toss a pencil from one hand to the other, trying not to impart revolution to it with your hand. The pencil stays more or less pointing in a constant direction. Now do the same only this time spin the pencil between your fingers as you release it. The pencil ends up corkscrewing around all over the place. - gyroscopic **de-**stabilisation!

Gyroscopic 'de-stabilisation' occurs significantly where you have a torque applied to the spinning object (this is how the gyro/Eiffel tower toy works, gravity supplies the torque and so the object goes round and round in circles). With arrows you fit fletchings to provide a torque to straighten the arrow up (stabilise it if you like). The most important effect the fletchings have as regards arrow groups is removing any rotation (angular momentum normal to the shaft axis) the arrow has when it leaves the bow. The faster this is done the smaller the change in arrow flight direction and hence the smaller the arrow groups. Because of the fletching torque the gyroscopic effect in principle tries to make the arrow revolve like the gyro toy. Any spin acts against the fletching action in stabilising the arrow and so any spin will have detrimental effect on arrow group sizes.

The problem of spin destabilisation of an arrow has been reported many times in books, articles etc. It is often incorrectly described as the arrow flight becoming "unstable" from losing too much speed at longer distances - "the excessive drag story". The result is that the increase in the size of arrow groups at longer distances being larger than the general trend. A better explanation, which does not require re-writing Newtons laws of motion, is in terms of the arrow spin to speed ratio. As the arrow travels its speed drops and the spin rate increases so the spin/speed ratio increases. If this ratio becomes too large then the arrow will start to weave around as the gyroscopic effect on the arrow (higher with higher spin rate) is no longer dominated by the fletching torque on the arrow (which drops as the speed drops). This effect usually has a catastrophic effect because as the arrow starts weaving it loses speed at an even higher rate so it weaves even more and so on - a runaway effect. Visually the arrow appears to fly quite nicely for 70 metes or so and then goes haywire. A related phenomenon is the arrow that appears to fly straight most of the way and then appears to start fishtailing. Again this not due to the arrow becoming unstable at lower speed. How much an arrow fishtails (it's amplitude) depends on the arrow speed. As the arrow speed drops the fishtailing amplitude increases.

CALCULATION OF THE POSITION OF THE (ROTATIONAL)CENTRE OF PRESSURE

The following example of how to calculate an arrow centre of pressure makes two basic simplifications. Firstly the arrow is assumed to be initially stationary i.e.no linear motion, not rotating (fishtailing) and not vibrating. Secondly the shape of the fletchings is assumed to be a right angled triangle, the nearest simple shape that approximates to a fletching. The centre of pressure calculated is that relating to arrow rotation only. The drag force component acting through the centre of gravity which acts only to move the arrow (from part of the shaft) is ignored. Note that we get both linear and angular acceleration so the arrow centre of mass has to move.



The approach is first to calculate the total pressure and centre of pressure locations for the shaft drag, fletching drag and Munk moment individually and then calculate the arrow total pressure and centre of pressure location from the three components.

In the diagram the total drag force (T) acts at the arrow centre of pressure at distance (Lt) behind the centre of gravity (C). The total drag is the sum of the fletching drag (Ff), the shaft drag (Fs) and the Munk moment (Fm). The distances from the centre of gravity to the fletching drag, shaft drag and Munk moment centres of pressure are Lf, Ls and Lm respectively. The resulting instantaneous axis of rotatation of the arrow (R) is at a distance 'A' in front of the arrow centre of gravity.

If you equate the moments for the arrow total pressure/centre of pressure to the indivual shaft/fletchings/Munk moment total pressures/centres of pressure you end up with the distance Lt being given by:-

Lt = (Fs Ls + Ff Lf - Fm Lm)/(Fs+Ff-Fm)

Example

Suppose the arrow is 80 cm long and 0.5 cm diameter. The arrow FOC is 13%. The fletchings are assumed to be 2.5 cm long with each fletching having a total area of 3.5 square cm. The front of the fletchings are fitted 73 cm from the front of the shaft. There are 3 fletchings fitted at 120 degrees to the shaft and they are assumed to be triangular in shape.

To make life simple it is assumed that the drag properties of the shaft and fletchings are identical so instead of drag forces we can use drag areas. (main difference is in the shaft and fletching drag coefficients).

With an FOC of 13% the centre of gravity is 10.4 cm in front of the centre of the shaft.

Munk Moment

The value of Fm is assumed at 1.5 square cms. (based on some rough measurements made some years ago).The centre of pressure is assumed to act at the back of the arrow so Lm = 80/2 + 10.4 = 54 cms.

Shaft Drag

The shaft area contributing to rotational drag Fs = 2 x 10.4 x 0.5 = 10.4 square cms. (see section on FOC). Because of symmetry the distance Ls is half the shaft length i.e. 40 cms

Flechings

For a triangular fletching the centre of pressure horizontal position is 2/3 distance along the base from the front. (The vertical position doesn't matter as the fletchings are assumed not to be spinning the arrow)

i.e. Lf = 73 + 2.5 x 2 / 3 - (40-10.4) = 45.07 cms

The effective area Ff of the fletchings = 1.5 x 3.5 = 5.25 square cms.

(the multiplier 1.5 allows for the fletching angle = 2 x sin squared (alpha/2) where alpha is the angle between fletchings).

Lt is therefore (10.4 x 40 + 5.25 x 45.07 - 1.5 x 54)/(10.4 + 5.25 - 1.5) = 40.4 cms

i.e. the centre of pressure is 40.4 centimetres behind the arrow centre of gravity.

Any arrow rotation will have the effect of moving the centre of pressure further back so the 40.4 cms represents the minimum distance between the centre of gravity and the centre of pressure. (With e.g.

fishtailing the influence of the shaft drag decreases and the influence of the fletching drag and Munk moment increases)

If 'Ig' is the arrow moment of inertia at the centre of gravity and 'M' is the total arrow mass then the distance of the instantaneous arrow axis of rotation in front of the centre of gravity 'A' is given by:-

A = Ig / (Lt x M)

e.g. if Ig was 5400 gm cm squ. and M was 18 gms then A = 5400/(40.4 x 18) = 7.4 cms

In reality over time the arrow spin angular momentum varies (as it fishtails/porpoises) and its linear speed (ignored above) varies. As such an arrow does not have an "axis of rotation" (for example it's travelling at around 200fps :)). Engineers will define the (spin) axis of rotation as being at the centre of mass but this is really a practical convenience as it decouples the linear and angular momentum. One could just as well define the axis of rotation in this sense as being at the tip of the archer's nose (not so useful though!).

Archers from what I've heard/read assign a different meaning to "arrow axis of rotation" which is based on how they see the arrow behaving. So they describe the arrow as "rotating at the point", "rotating in front" or "rotating behind" the point. What they are describing is the combined effect of the arrow rotation and the arrow linear movement (sideways/up-down). In this case the centre of pressure position, as regards arrow response, is best regarded as being based on the total drag on the arrow combined with (the relatively small) existing spin angular momentum. If you balance an arrow on one finger and give an upward push at various points on the shaft behind the cog then this well illustrates the overall arrow behaviour in response to varying position of the overall centre of pressure.

FORWARD OF CENTRE (F.O.C.)

The FOC value for an arrow indicates how far forward of the centre of the shaft the centre of gravity (COG) is located, expressed as a percentage.

If 'L' is the length of the shaft and 'D' is the distance from the centre of the shaft to the COG then the FOC = 100 x D/L.

e.g if the arrow is 80 cm long and the FOC = 12% then the COG is 12*80/100 = 9.6 cm in front of the shaft centre.

The FOC relates to two different aspects of shooting arrows, how the arrow behaves on the bow when being shot and how the shot arrow flies through the air.

In order to hit what you are aiming at the arrow needs to come off the bow straight and with no rotation. One of the principal factors which affects how the arrow comes off the bow is how it bends when being shot ("weak/stiff arrow"). For a given draw weight, shaft weight, shaft stiffness and length of arrow shaft the main way the amount of bending is affected is by varying the pile and nock weights. The heavier the pile weight or the lighter the nock weight then the more the arrow will bend. The shaft stiffness and associated weight depend on the shaft construction e.g. carbon arrow shafts are stiffer for the same weight then aluminium shafts. For the way the arrow behaves on the bow then the FOC is a guide to what the pile weight should be for the arrow to 'match' the bow in terms of coming off straight i.e. have the right amount of arrow bending.

Manufacturers publish recommended values for the FOC e.g an FOC of 7-9% for aluminium shafts, 11-16% for ACE carbon shafts. These values are largely based on the standard pile weights available for the shaft. In practice recurve archers often use higher FOCs by e.g. using specially made heavier tungsten points.

The reason the recommended FOC values are higher for ACE then for aluminium shafts is because the carbon shaft is much lighter then the aluminium for the same shaft stiffness. As the shaft is lighter the COG is further forward & the FOC is larger.

While the FOC value is limited by how the arrow behaves on the bow it also affects how the arrow flies through the air. This is related to the arrow total drag and the fletching action. As covered in the section on drag, the drag force on an arrow is split between two separate forces; one which acts through the arrow centre of gravity which acts to move the arrow and one which acts somewhere else, roughly around where the fletchings are which acts to rotate the arrow.

If you don't want to plod through the section on drag then A Rough Guide to FOC tries to give an idea of why FOC is so important to the drag properties of an arrow. The ideal FOC value for arrow flight performance is 50% i.e. the arrow balance point is at the front of the arrow. In reality for OR archery the maximum practicable FOC is in the low 20's. The limiting factor is arrow speed. For a given arrow shaft/nock/fletching all up weight the only way to increase FOC is to increase the point weight. Problem is increasing point weight increases overall arrow weight and hence reduces arrrow speed. For best arrow performance you need the best combination of FOC and arrow speed. For example the reason for the low recommended FOC of 7-9% for aluminium arrows is not that this is a good FOC value in itself just that if you try to increase the FOC value to a higher value the arrow speed drops to an unacceptable level.Overall arrow performance is lower.

The principle drag effect on the arrow which makes you 'miss' with a bad shot or a gust of wind is the drag on the shaft. You can break the total drag force on the arrow shaft into two components, a component that acts through the arrow centre of gravity which acts only to move the arrow (no rotation) and a second component located to the rear of the COG cog which acts like a fletching to rotate the arrow. The relative size of these two forces depends on the arrow FOC. If 'L' is the length of the arrow shaft and 'A' its diameter then the total shaft drag area is LA. The shaft area Fa which relates to the shaft drag force acting through the cog is approximately given by:-

$$Fa = LA(1-FOC/50)$$

This is only an approximation because any rotation (fishtailing) of the arrow will affect arrow lateral movement and also the value of the shaft drag area.

e.g if the arrow is 80 cm long and has a 0.5 cm diameter then:-

with an FOC of 8% this shaft drag area is around 80 x 0.5(1-8/50) = 33.6 square cm with an FOC of 16% this shaft drag area is around 80 x 0.5(1-16/50) = 27.2 square cm

or to put it another way each 1% increase in FOC reduces this shaft drag area by about 2%.

The overall fletching area with respect to how the arrow flies comprises three elements:

- the effective area of the fletchings
- the shaft fletching area
- vortex shedding torque (expressed as an area)

The shaft fletching area is determined by the position of the COG i.e. the value of the FOC for the arrow. The shaft fletching area = 2 x D x A = 2 x FOC x L x A / 100. (A, D and L as defined above). In other words the higher the FOC value the higher the shaft fletching area.

For example suppose you have a 80 cm long arrow with 0.5 cm diameter.

with a 7% FOC the shaft fletching area = 5.6 square cms
with a 11% FOC the shaft fletching area = 8.8 square cms

As what is important physically is the turning moment generated on the shaft from the fletching areas let's look at this from this viewpoint taking moments with respect the shaft centre of mass

The shaft fletching effect drag F_s = FOC x KLA/50 (where K is the area to drag force constant).

The turning moment on the arrow from the shaft drag is FOC x $KL^2A/100$

Assume we have fletchings with the centre of pressure at distance P behind the shaft centre with a fletching effect drag of F_f. Then the turning moment on the arrow from the fletchings is F_f (P + FOC x L/100).

The total turning moment on the arrow T = FOC x $KL^2A/100$ + F_f (P + FOC x L/100).The equation for T illustrates how the arrow length, area, FOC and fletching position affect the turning moment on the arrow. This combined with the arrow rotational moment of intertia determine the stability of the arrow.

In practice the higher the arrow FOC the smaller the diameter is likely to be and also the size of the fletchings will probably be smaller (compare the typical fletching size/diameter of aluminium arrows to carbon arrows).

The overall speed of response of the arrow to fletching torque (its angular acceleration), i.e. how fast it straightens up, depends not only on the area of the fletchings but on the fletching torque and the 'rotatability' of the arrow, its moment of inertia. The FOC value effects the torque on the arrow from the fletching area and defines the area of the shaft that acts like a fletching. As the FOC increases the effective fletching area increases and the 'lever arm' increases. At the same time the 'rotatibility' of the shaft decreases (higher moment of inertia). Overall the arrow fletching response increases with FOC.

Having a high FOC for an arrow provides two principal benefits - better arrow groups and reduced wind sensitivity. When you aim at the gold but the arrow ends up in the black something must have changed the direction of the arrow. An arrow mechanically has to leave a bow going in the direction it was pointed and with its axis very closely aligned with the direction it's going. The arrow changes direction after it leaves the bow and the cause is arrow rotational energy (cartwheeling). The arrow flies in a curved path until this kinetic energy is removed by fletching drag (the stabilisation distance). Having a higher FOC results in faster energy dissipation (more fletching action) and because the overall drag force (net momentum) moving the arrow sideways is smaller the amount the arrow direction is changed is reduced. The result is more forgiving arrow to bad tuning or a poor shot leading to reduced group sizes. In a wind the faster arrow rotation rate results in reduced wind drift.

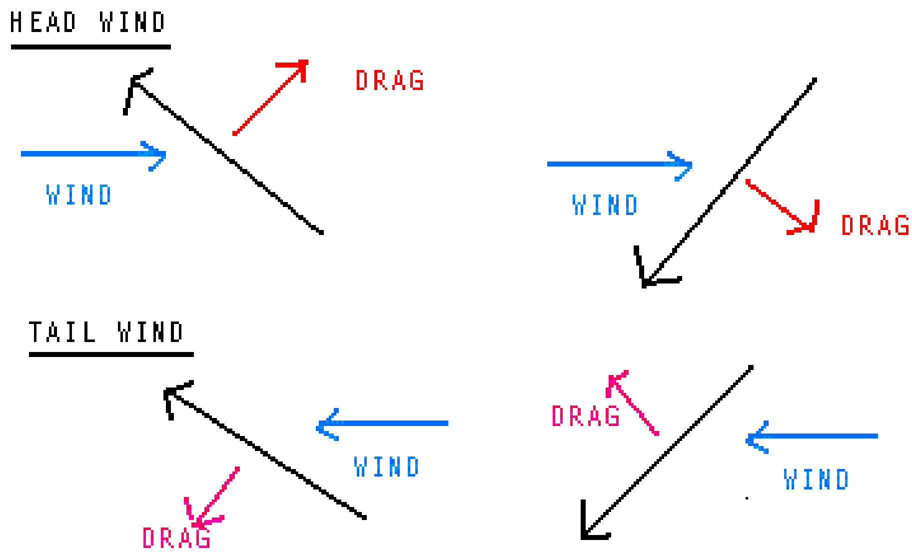
The downside to a higher FOC is because the offset angle between the arrow axis and the direction it's going will in general be smaller, the drag on the pile will increase; lift from shaft drag will be reduced and probably the arrow will be heavier and hence going at a lower speed. All these factors result in 'loss of sight mark'.

A recent example of how FOC affects flight comes from throwing the javelin. Javelins don't have any fletchings and because of the tapered end don't have any vortex shedding torque. Javelin rotation relies solely on shaft drag. The problem was that there was insufficient 'fletching' and javelins were often landing flat and skidding. Also because of the low FOC a lot of drag lift was being generated. Competitors were throwing javelins over 100m which was too for far safety at most stadiums. A couple of years ago the regulations were changed increasing the required FOC value. Now javelins rotate and stick in the ground nicely. The increased rotation rate has reduced the vertical drag component and the distances being thrown have been reduced to within safety acceptable distances.

An FOC calculator is available if required.

ARROW ROLL-OVER AND WIND

With no wind present then the impact height or total distance travelled for an arrow is closely connected to the arrow 'roll-over' rate. The wind effect (headwind/tailwind) on arrow height or distance is similarly related to the arrow rotational characteristics.



If the arrow is flying 'nose up' then the wind drag force acts to lift the arrow with a head wind and drive the arrow down with a tail wind. The reverse applies if the arrow is flying 'nose down'. When you shoot an arrow its starts off flying nose up and ends up flying nose down. How much of its flight the arrow spends nose up as opposed to nose down depends on how fast the arrow rotates. The overall wind drag effect, i.e. does the arrow hit lower in a headwind and higher in a tailwind or the reverse, depends on the relative proportion of time the arrow is flying nose up to nose down.

Suppose you start with an arrow with a high roll-over rate and then by some means gradually reduce it. Initially the arrow will hit higher in a tailwind and lower in a headwind. As you reduce the roll-over rate evenually you will reach a point where the arrow starts to impact higher in a headwind and lower in a tail wind.

The factors which affect arrow roll over rate (in order of importance) are:

1. Amount of fletching torque

Increasing the fletching area or arrow FOC will increase the arrow roll-over rate.

2. Arrow Moment of Inertia

As the arrow gets heavier it will rotate more slowly under a given fletching torque.

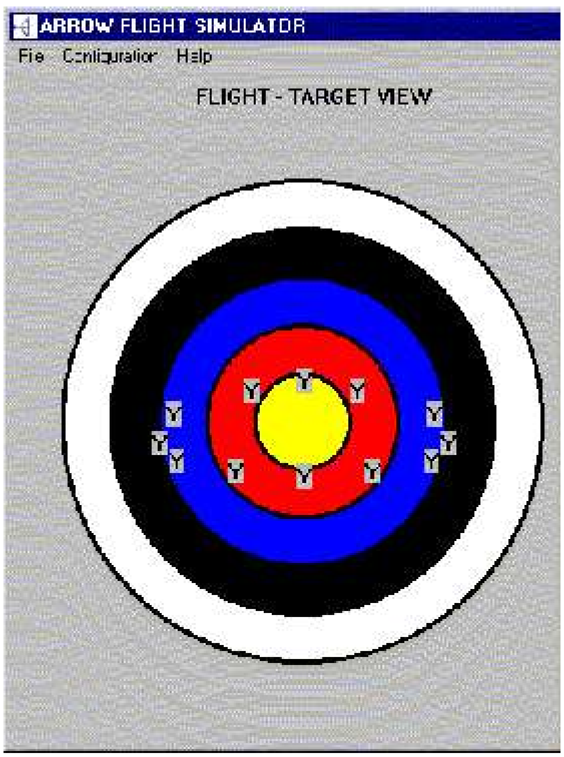
3. Arrow Speed

The faster the arrow and the flatter the trajectory then the less time the arrow will have to roll over.

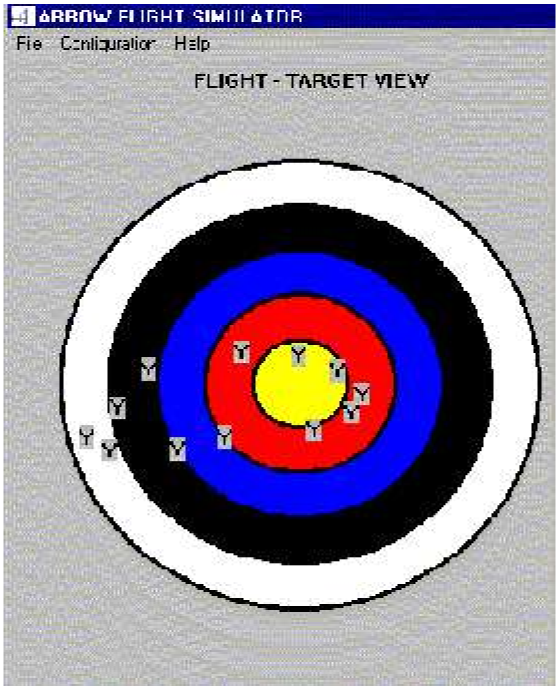
Target arrows invariably carry enough fletching to tighten the arrow groups (high arrow rotation rate) so they will hit lower in a headwind and higher in a tail wind.

The effect of a headwind or tailwind on the height variation of where the arrow hits are not the same. If the wind drag is pushing the arrow up then the overall downwards acceleration is gravity minus the wind drag. If the wind drag is pushing the arrow down then the overall downwards acceleration is gravity plus the wind drag. The amount the arrow hits high for a given tailwind is less then the amount the arrow hits low with the same wind as a headwind.

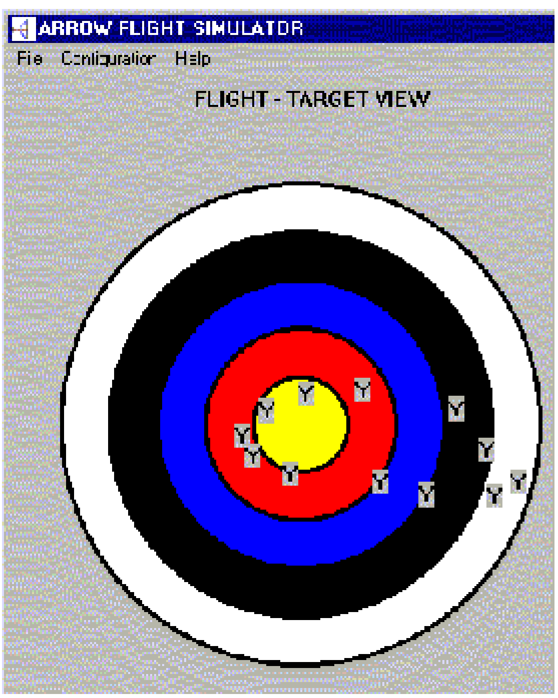
The diagrams simulate how where the arrow hits varies as a constant wind speed is rotated (at 30 degree intervals) through 360 degrees. Diagrams are presented for a 'perfect' arrow a stiff arrow and a weak arrow. In each case it can be seen that the drop in height for a headwind is greater than the increase in height for a tailwind. For an explanation of the variation in horizontal displacements for the weak/stiff arrows see the section on variable tuning.



Perfect Arrow



Stiff Arrow



Whippy arrow

WIND DRIFT BEHAVIOUR WITH VARIABLE WIND STRENGTH

Introduction

What makes any assessment of arrow "wind drift" difficult is that apart from the relative behaviour between two arrows depending on the specific two arrows being compared it also depends on the distance shot and the wind conditions under which the comparison is made.

It needs to be emphasised that with any discussion about arrows the requirements for an Olympic recurve bow and a compound bow are very different. Many arrow "wind drift" discussions happily mix comments from recurve and compound archers about experience with different specific arrows. This is comparing apples with pears and the result is very confusing. Everything on this page (in fact this site) relates to the olympic recurve bow only.

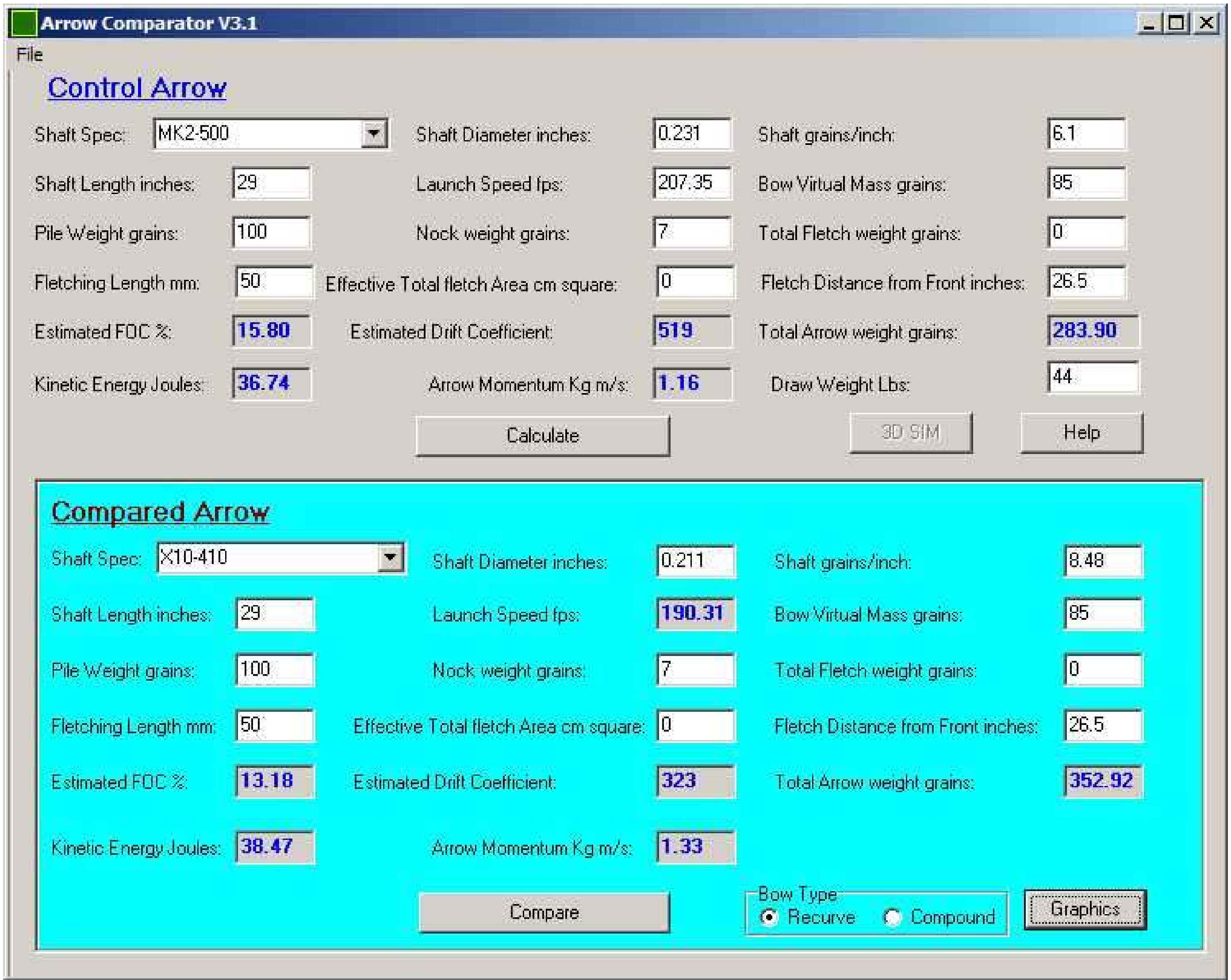
Comparing arrow performance, in terms of grouping, with no wind or with a constant wind is relatively straightforward. The more difficult area is comparing arrow performance under tournament conditions where the wind strength is variable. The usual comparison in this situation is often between a forgiving (i.e. good grouping) arrow with high speed/high FOC etc. and a heavier arrow shaft with lower speed/lower FOC which is (usually) less forgiving but "expected" to be less affected by wind and changes in wind strength. It is this comparison, done using a simple flight simulator, about which this page attempts to say something useful.

As ever the "results" of a comparative simulation to some degree depend on which two arrow shafts you choose to compare. The wind drift comparison for the constant wind case compared ACE and X10 shafts. In this case the forgiving arrow (ACE) had greater wind drift in absolute terms then the heavy shaft (X10). Have to keep up with the times so in this evaluation the comparison is between a new generation all carbon arrow as the forgiving arrow and the X10 as the heavy shaft arrow. The difference is the new generation of Nano/McKinney all carbon shafts although they represent the "forgiving" arrow class, on paper and from what testing has been done, they appear to equal or better the X10 in absolute wind drift performance.

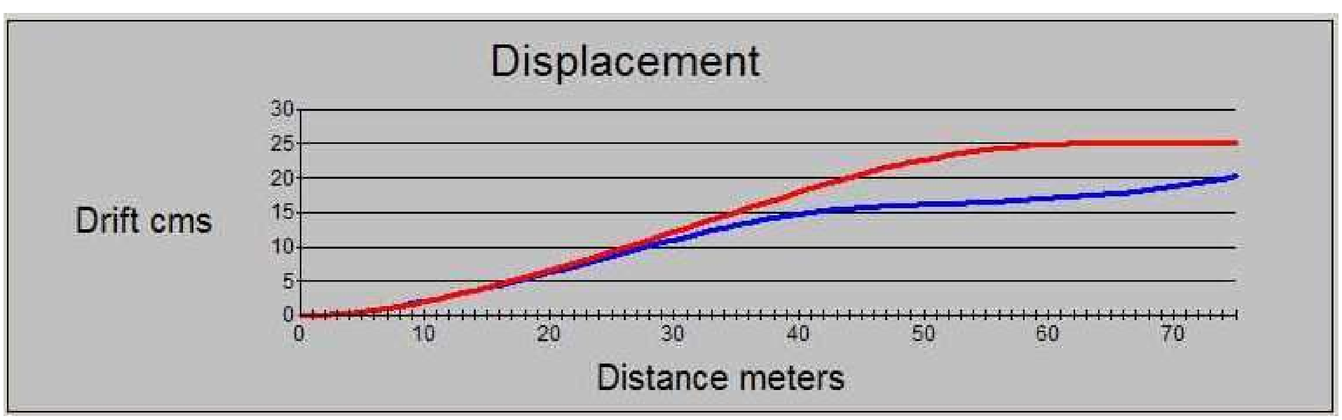
The following is no attempt to say arrow X is better or worse than arrow Y. The simulator results in qualitative terms, as normal, should be taken with a pinch of salt. The only way to evaluate arrows is objective testing by shooting them for real.

The Compared Arrows

The following screen dump gives the characteristics of the two arrows being compared. The Mckinney 500 represents the "forgiving" arrow class and the X10 410 represents the heavier shaft arrow class. Bareshaft arrows are used in the simulations. The nominal wind condition for all simulations is a 4 metres/second cross wind (at 90 degrees). In all the flight simulations the McKinney is presented as the Blue line (forgiving arrow) and the X10 is presented by the Red line (the heavy shaft arrow).

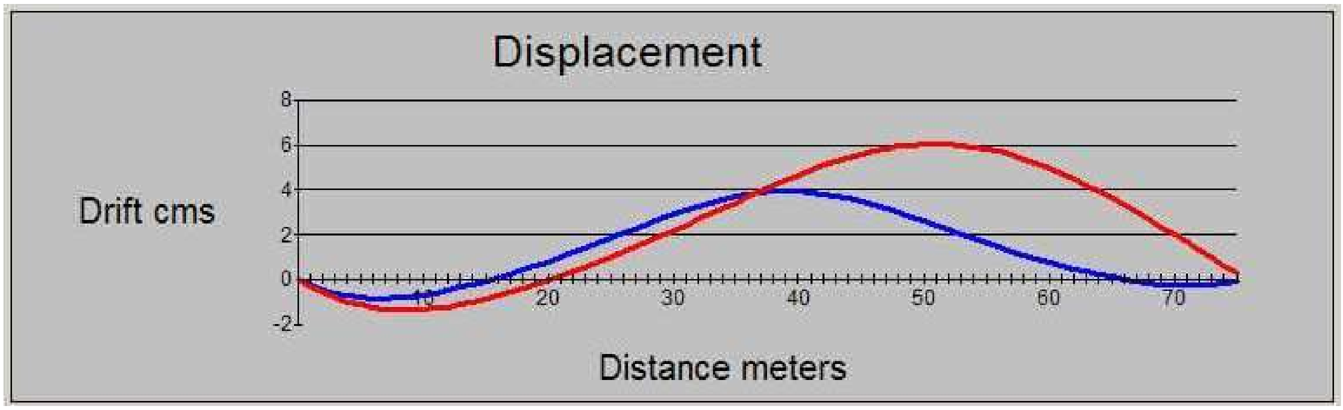


Absolute Wind Drift at 75m - 4 m/s wind



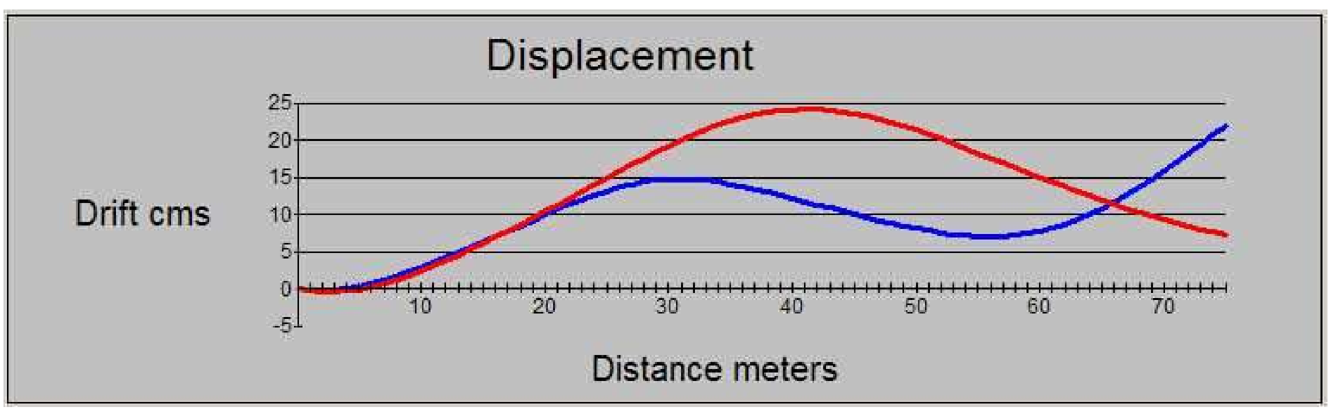
The wind drift with zero windage adjustment on the sight is represented. In this case the "forgiving" arrow has less wind drift then the heavier shaft arrow. With different shafts and properties the reverse might be the case. Remember we are only trying to look at behaviour, not comparing specific arrows.

Windage Adjusted at 75m - 4 m/s wind



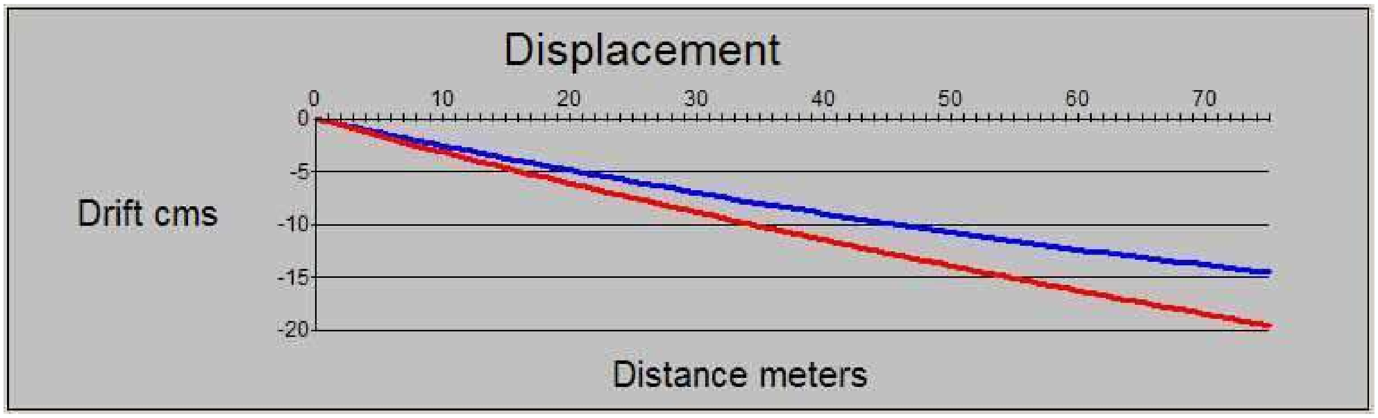
The sight windage for both arrows is now adjusted so that with a perfect shot both arrows hit the target centre. The archer from now on keeps this windage setting - no aim off or windage adjustment is made.

Perfect Shot at 75m - But wind speed has increased to 7 m/s



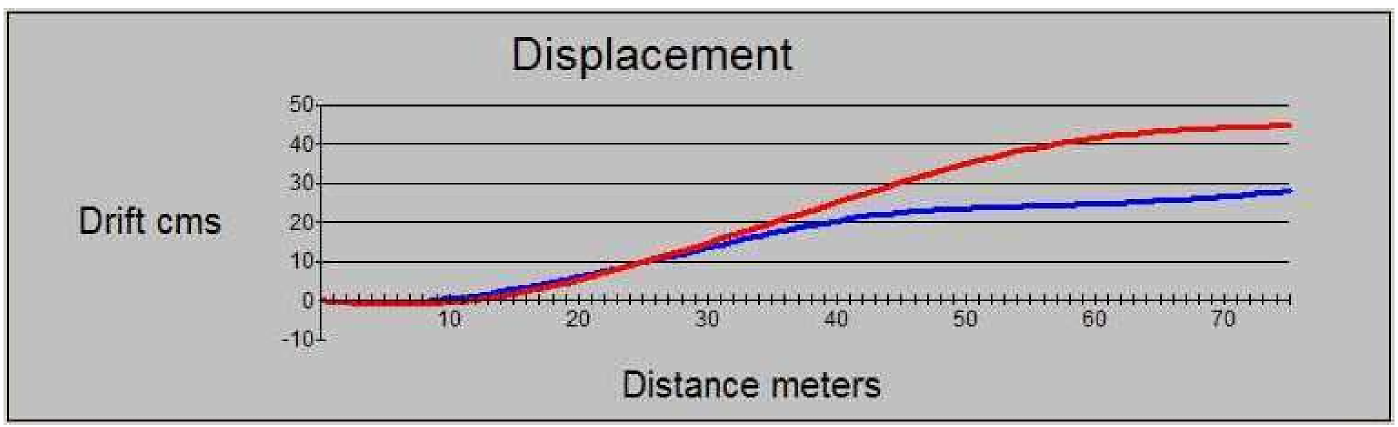
With the archer making a perfect shot the wind, without any aim off or sight adjustment, has increased to 7 metres/second. The result is the heavier shaft hits nearer the centre then the forgiving arrow. The reason I think is that the forgiving arrow is fishtailing faster than the heavy shaft arrow. At 75m concidentally the heavy arrow is drifting towards the target centre (near minimum) while the forgiving arrow is drifting away from the target centre (near maximum). If you repeat the simulation with fletchings on the arrows the fishtailing frequency is higher and the result is the forgiving arrow hits nearer the middle. The inevitable conclusion is that with variable winds the fletching selection is critical for any specific instance.

Perfect Shot at 75m - 1 m/s wind



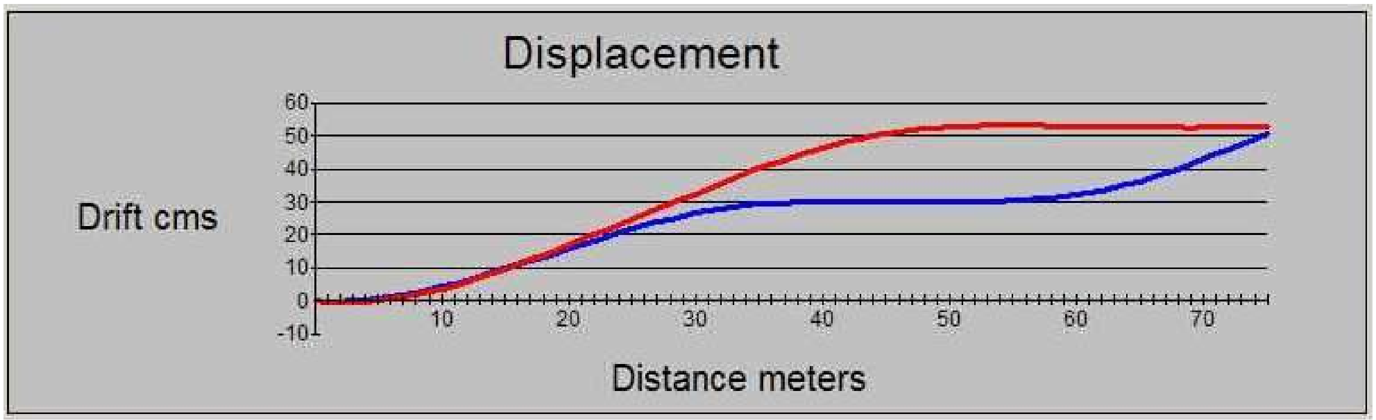
With the archer making a perfect shot the wind, without any aim off or sight adjustment, has decreased to 1 metres/second. In this case I believe the absolute wind drift is the driving arrow characteristic determining the relevant shaft positions. As the forgiving arrow has the lower absolute wind drift it hits nearer the middle than the heavy shaft arrow.

Poor Shot hitting downwind at 75m - 4 m/s wind



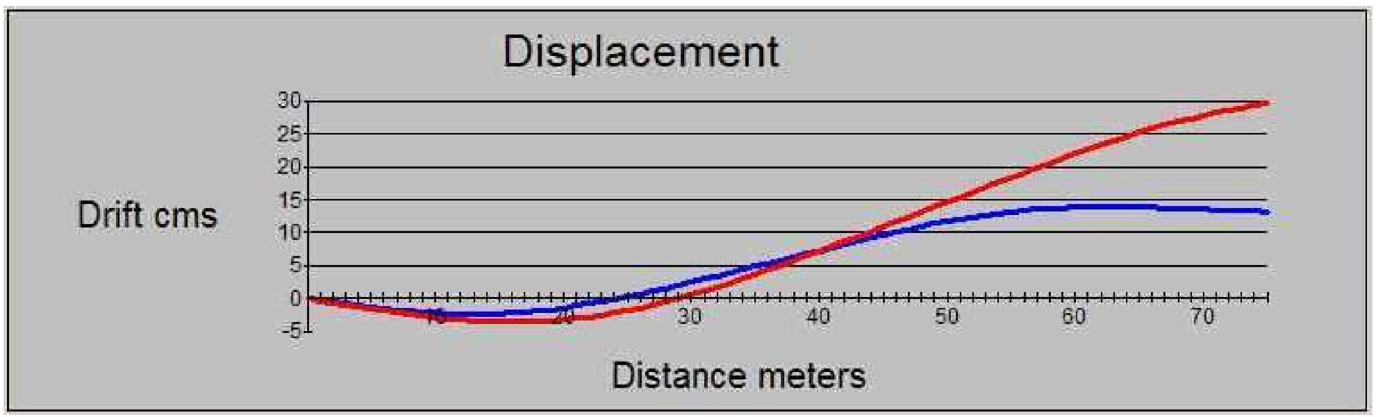
The archer makes a poor shot (same for both arrows) which results in both arrows heading and hitting down wind of the target centre. The forgiving arrow hits nearer the target centre than the heavy shaft. (by definition it is more forgiving to archer error).

Same Poor Shot Hitting Downwind at 75m - But wind speed has increased to 7 m/s



The unnoticed increase in wind speed pushes both arrows further downwind - but not by the same amount. The heavier shaft arrow is relatively less affected then the lighter arrow.With different arrows/different change in wind strength then the forgiving arrow could end up further from the centre than the heavy shaft arrow.

Same Poor Shot Hitting Downwind at 75m - But wind speed has decreased to 1 m/s

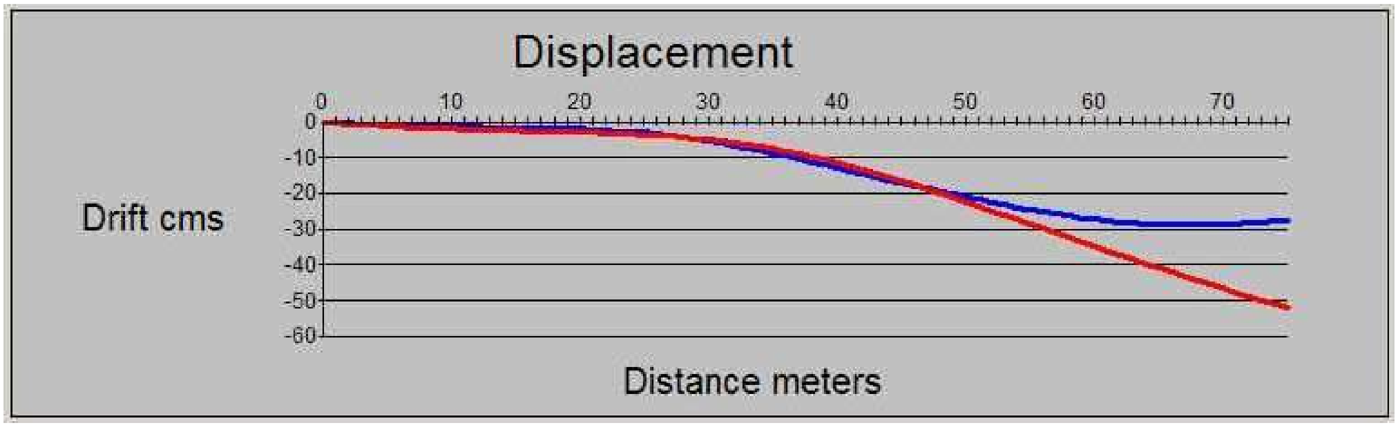


The unnoticed decrease in wind speed acts in the archers favour as it offsets some of the damage done by the poor shot. The reverse of the previous case occurs. Now the forgiving arrow benefits more from the wind change then the heavy shaft arrow. The forgiving arrow moves more towards the target centre than the heavy shaft arrow. It is this effect that for me largely nullifies the heavy shaft argument. Assuming changes in wind strength are random (increasing/decreasing), then sometimes you win sometimes you lose as regards the heavy shaft and over a lot of arrows wind variation gains and losses will more or less cancel out so you're overall better off going for the more forgiving arrow.

Wind Drift Assymmetry

Once we have a wind, which is assumed to come from a specific direction then there is no longer a symmetry between those arrows that go upwind and downwind so the above simulations need to be repeated for the arrow going upwind situation.

Poor Shot hitting upwind at 75m - 4 m/s wind

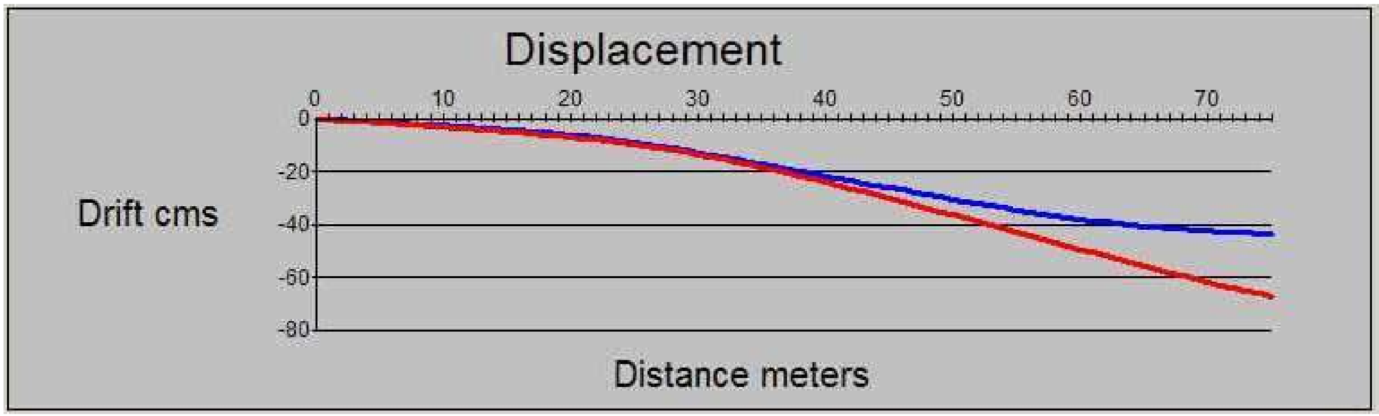


The "poor shot" has the same (shot) value as the downwind case, it is just the reverse in terms of the arrow direction.

Poor Shot hitting upwind at 75m - But wind speed has increased to 7 m/s

The increase in wind strenght blows both arrows back towards the target centre acting to offset the consequences of the poor shot. The forgiving arrow benefits most from this, but again this probably results mainly from higher fishtailing rate of the forgiving arrow with only a marginal direct benefit from the arrow's lower mass (though the higher fishtailing frequency is a consequency of the lower shaft mass/higher FOC).

Poor Shot hitting upwind at 75m - But wind speed has decreased to 1 m/s

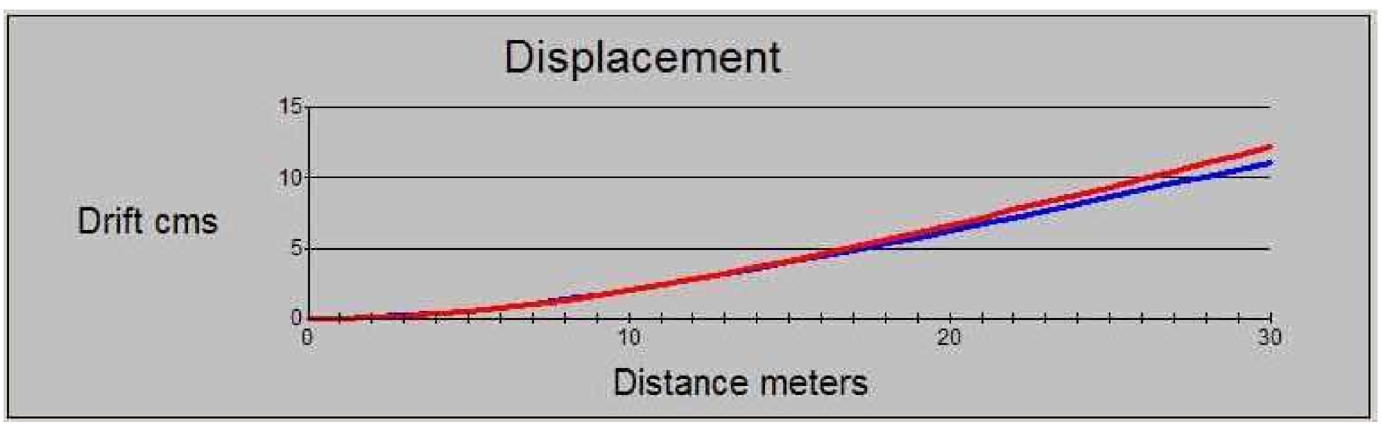


The drop in wind speed combines with the direction of the poor shot to increase the displacement of both arrows from the target centre. The arrow with lowest wind drift in absolute terms is least affected by this combination.

Wind Drift behaviour with Distance

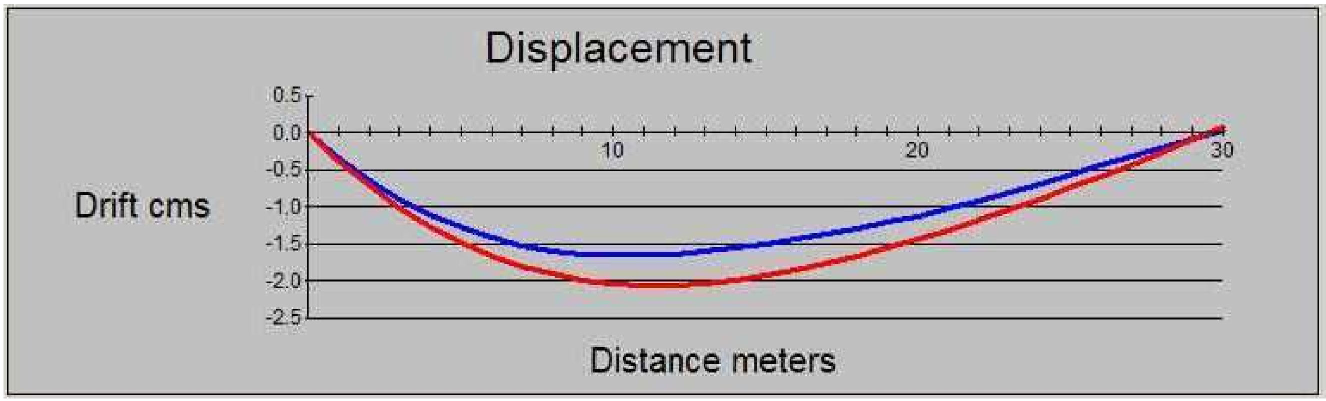
Relative wind drift behaviour will vary with target distance as how the arrow fishtails and the consequent side to side motion of the arrow will affect where it hits. The relative hit positions of the two arrows will to some degree depend on the relative phases of the two arrow's fishtailing at the point of target impact. The above simulations are therefore repeated at a 30 metre target distance where this effect is reduced.

Absolute Wind Drift at 30m - 4 m/s wind



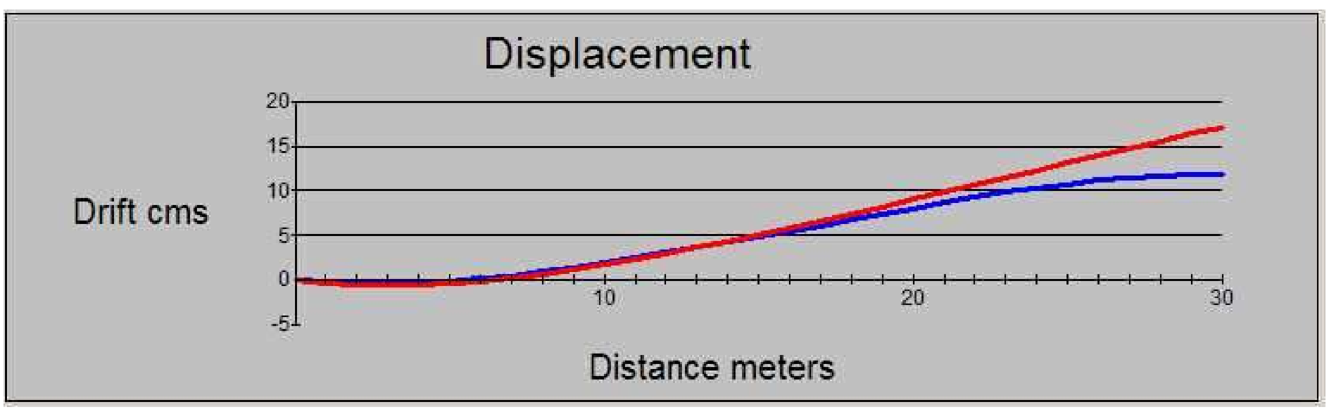
The forgiving arrow has the lower lateral displacement at 30 metres. I don't think this has anything to do with wind drift per say but is the result of the better stabilisation characteristics of the forgiving arrow. Simulation of the this situation where the heavy shaft arrow has the least absolute wind drift still results in the more forgiving arrow having the lower lateral displacement.

Windage Adjusted at 30m - 4 m/s wind



The sight windage for both arrows is now adjusted so that with a perfect shot both arrows hit the target centre. The archer from now on keeps this windage setting - no aim off or windage adjustment is made.

Perfect Shot at 30m - But wind speed has increased to 7 m/s

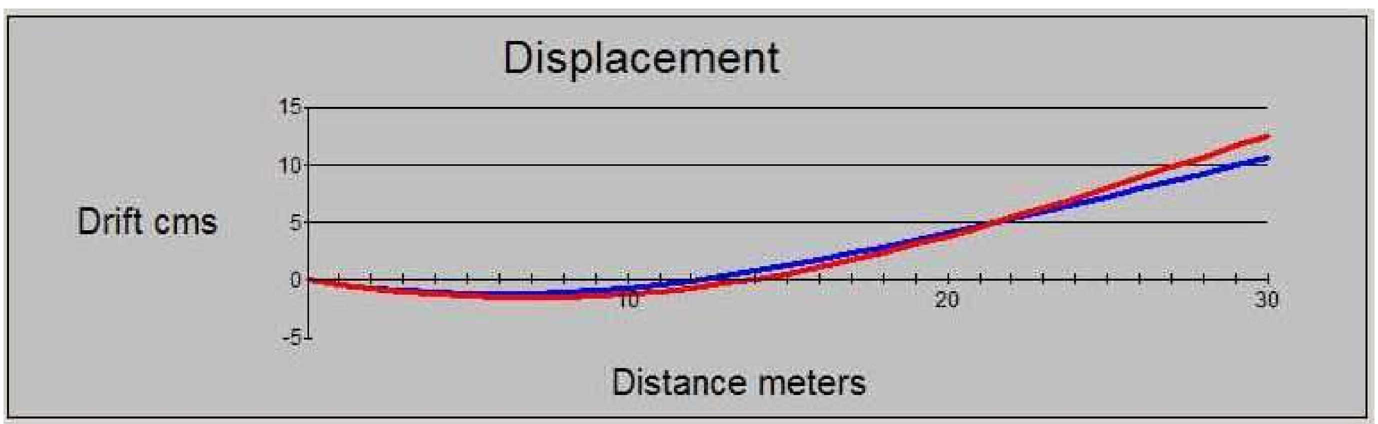


The heavy arrow is offsest more than the forgiving arrow by the increased wind speed. Again I believe this effect occurs mainly with the better stabilisation and faster fishtailing of the forgiving arrow rather than anything to do with arrow mass or absolute wind drift properties.

Perfect Shot at 30m - But wind speed has decreased to 1 m/s

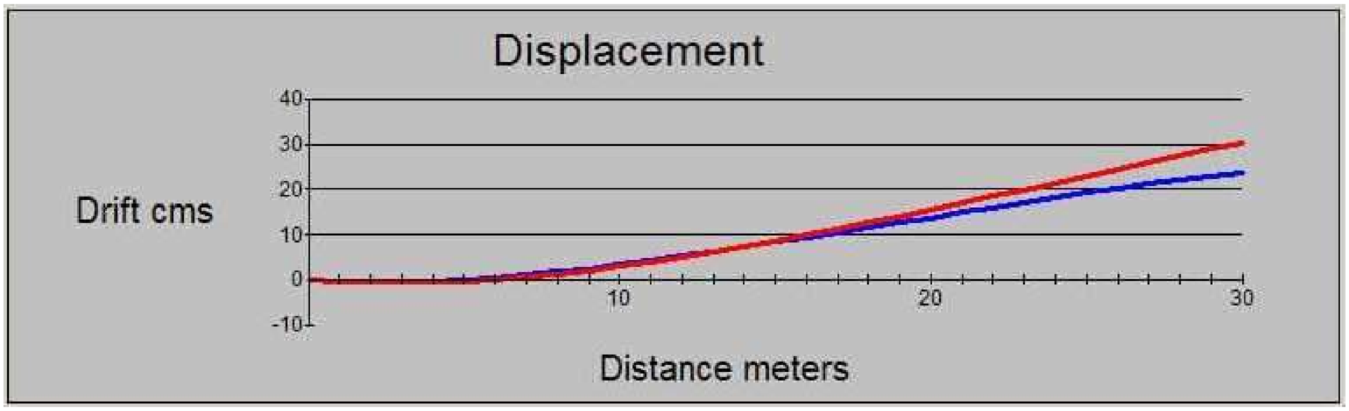
The forgiving arrow is less affected by the wind speed drop. Again I don't think absolute wind drift has much to do with this.

Poor Shot hitting downwind at 30m - 4 m/s wind



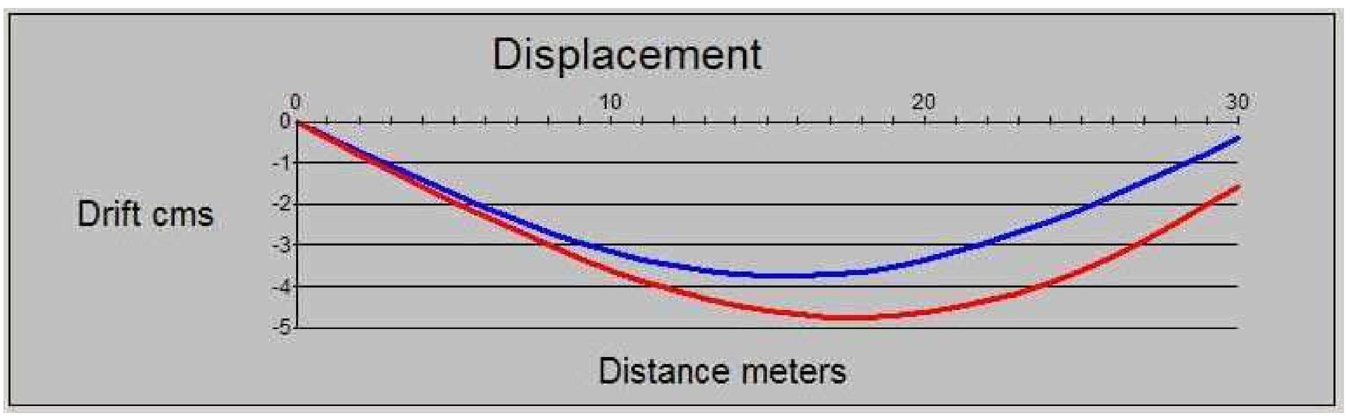
Again wind drift properties of the two arrows are considered to be irrelevant. Arrow stabilisation (forgiving characteristics) are are regarded as the main player.

Same Poor Shot Hitting Downwind at 30m - But wind speed has increased to 7 m/s



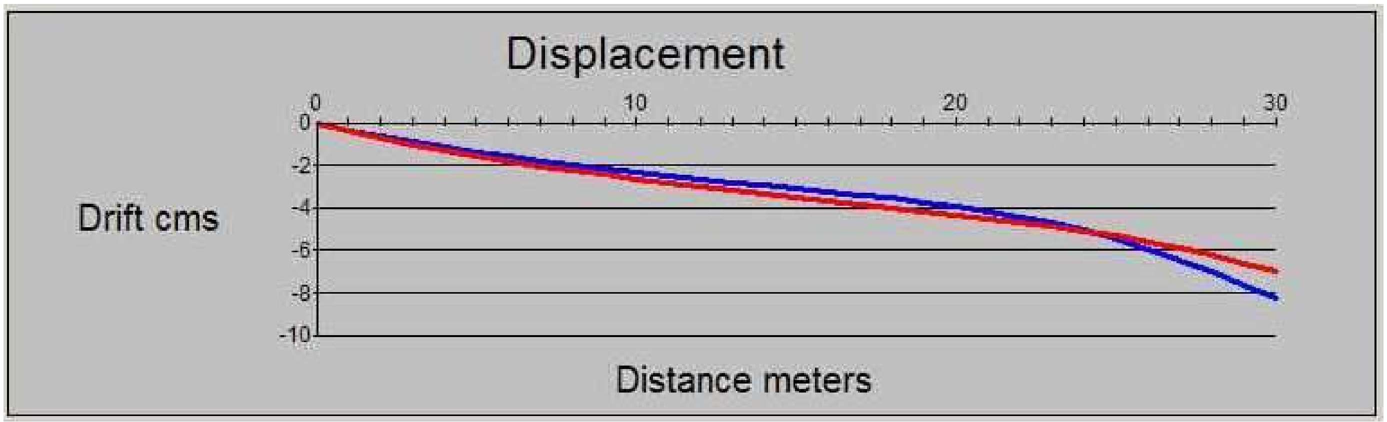
Again wind drift properties of the two arrows are considered to be irrelevant. Arrow stabilisation (forgiving characteristics) are are regarded as the main player.

Same Poor Shot Hitting Downwind at 30m - But wind speed has decreased to 1 m/s



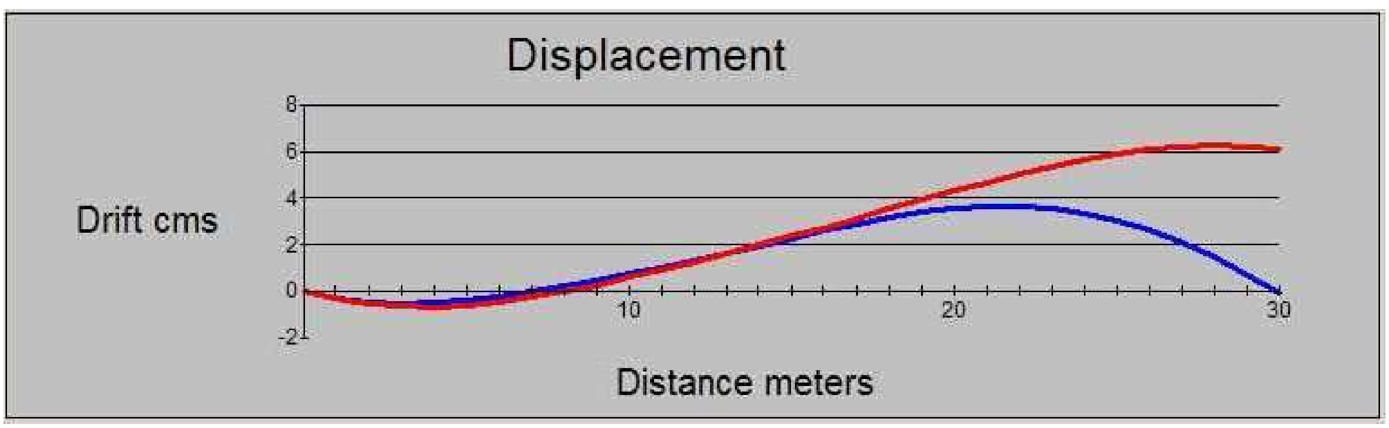
Again wind drift properties of the two arrows are considered to be irrelevant. Arrow stabilisation (forgiving characteristics) are regarded as the main player.

Poor Shot Hitting Upwind at 30m - 4 m/s wind



In this case the higher mass arrow (heavy shaft) is the better performer. This may be the effect of the heavy shaft arrow, having a lower speed, requiring a larger windage aim off angle.

Same Poor Shot Hitting Upwind at 75m - But wind speed has increased to 7 m/s



Better performance of the forgiving arrow put down to it's faster, lower amplitude fishtailing.

Same Poor Shot Hitting Upwind at 75m - But wind speed has decreased to 1 m/s

Increased deviation of the two arrows similar.

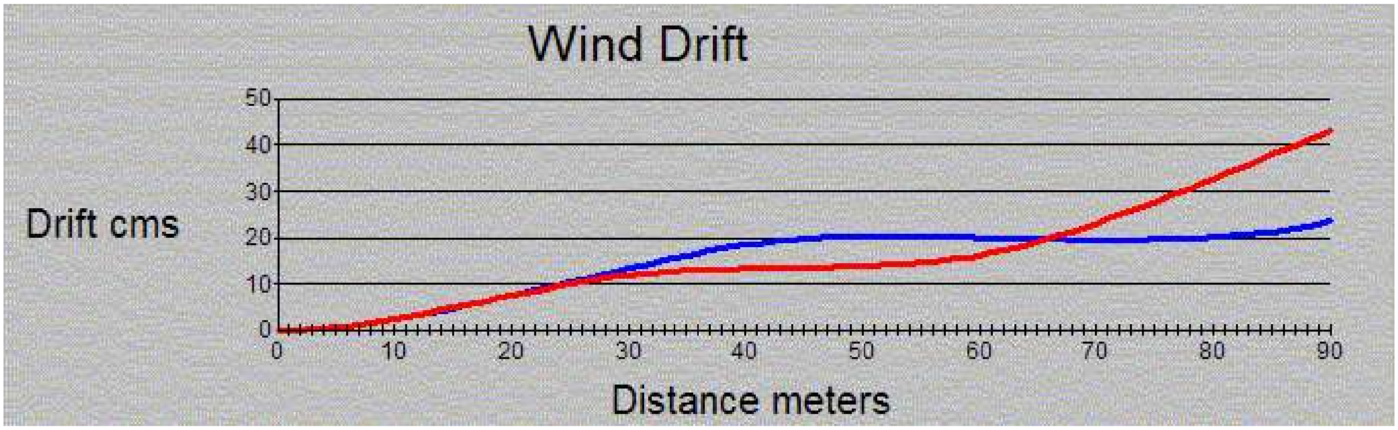
THE HEAVIER ARROW HAS LESS WIND DRIFT MYTH

One of the pieces of nonsense you frequently come across in archery is "a heavier arrow has less wind drift". Factually it may often be true but it's a very misleading comment so I'll try to put a more realistic spin on it.

The approach is to compare the performance of two arrows using a (fairly simple) arrow flight simulator. Don't believe the results quantitively but it will hopefully put across the idea. The two arrows (picked out as equivalent from the Easton Shaft Selector) are an X10-550 and an ACE-570. Both arrows are 29" long with identical piles (120 grain) and nocks (6 grain). Bareshaft arrows are used in the simulation as were trying to compare shaft performance only.

Estimated values for the arrows are total weight X10 = 343 grain, ACE = 309 grain; FOC for X10 = 16.6%, ACE = 18.5%. The asumed relative arrow launch speeds are X10 = 200fps and ACE = 208fps, the ACE being faster because it's lighter.

If we shoot both arrows perfectly with zero windage adjustment in a 5m/s crosswind then the following picture illustrates the simulated arrow flight paths. The blue line is the X10 flight path and the red line the flight path of the ACE.



Clearly in the 70 - 90 metres distance range the X10 has less wind drift than the ACE. There are two factors at work here. The X10 is 34 grains heavier than the ACE so for the same drag force accelerating the two arrows sideways the X10 would have a lower sideways acceleration. However the heavier X10 shaft (lower FOC) is aerodynamically a poorer performer then the higher FOC ACE so the X10 will incur more drag force accelerating it sideways. In this case the effect of the increased mass of the X10 outways the effect of the higher sideways drag force on it so the result is less wind drift than for the ACE. This may not always be the case. (The obvious example is the McKinney 2 arrow - a lighter shaft which will have lower wind drift than the X10 with a similar flight simulation). You can also see that the above simulation predicts that the ACE will have less wind drift then the X10 in the 30-50 metre distance range.

Where the basic misunderstanding generally seems to exist is by oversimplification of the mechanics. Remembering your school physics distance = half the acceleration mutiplied by the square of the time and the time of travel equals the distance divided by the speed.
Applying this to wind drift with;

- s = the lateral wind drift distance
- f = the lateral drag force on the arrow
- t = the flight time of the arrow
- d = the target distance
- v = the arrow horizontal speed
- m = the mass of the arrow

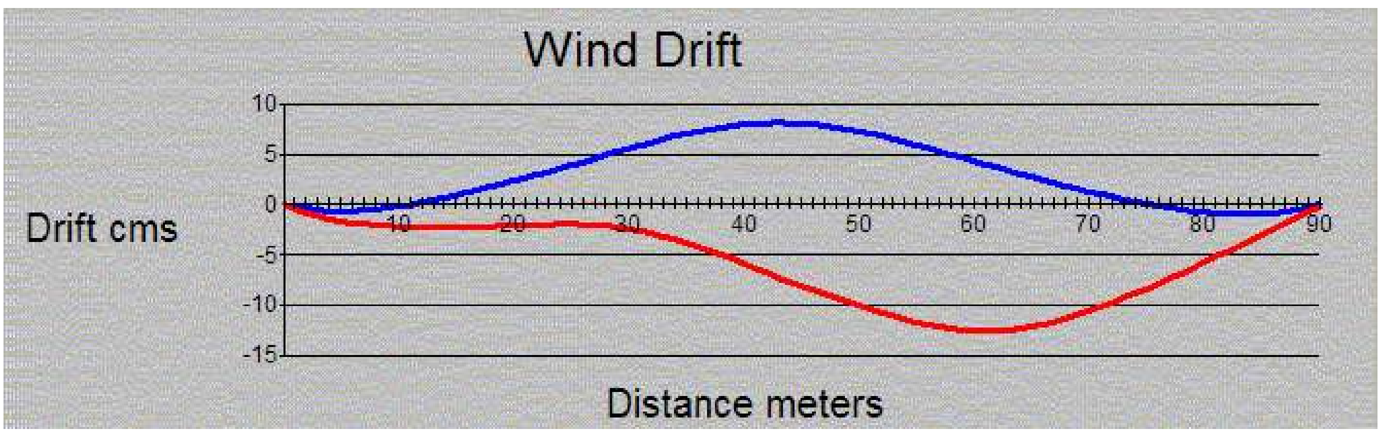
Then the down wind acceleration = force/mass = f/m
the windrift distance $s = 0.5 * (f/m) * t^2$ and arrow flight time $t = d/v$
Putting the value for t in the expression for wind drift gives you:
$s = [\ 0.5 * f / v^2\ ] * d^2/m$

Very often (e.g. in pin tape programs) the actual arrow flight aerodynamics are ignored and the simple assumption is made that $f = k * v^2$ where k is a constant i.e. $k = f/v^2$. The end result for the wind drift equation is that
$s = [\ 0.5 * k\ ] * d^2/m$

So our schoolboy physics gives you that the larger the mass the less the wind drift and that the wind drift is proportional to the square of the target distance. Both conclusions are incorrect. The problem is that the expression in the [ ] brackets is not a constant as both f and v are fairly complex functions for both of which arrow mass (or rather the arrow mass properties) is one of the parameters. The above flight simulation clearly demonstrates that the assumptions about wind drift variation with mass and distance are both incorrect.

It's at this point the argument often stops - the heavier arrrow has less wind drift! Note that this argument conveniently forgets that an equivalent aluminium arrow, although its considerably heavier than the X10 would have considerably more wind drift than the X10, so in this case the lighter arrow would have less wind drift. Clearly saying that a heavier arrow has less wind drift is being oversimplistic

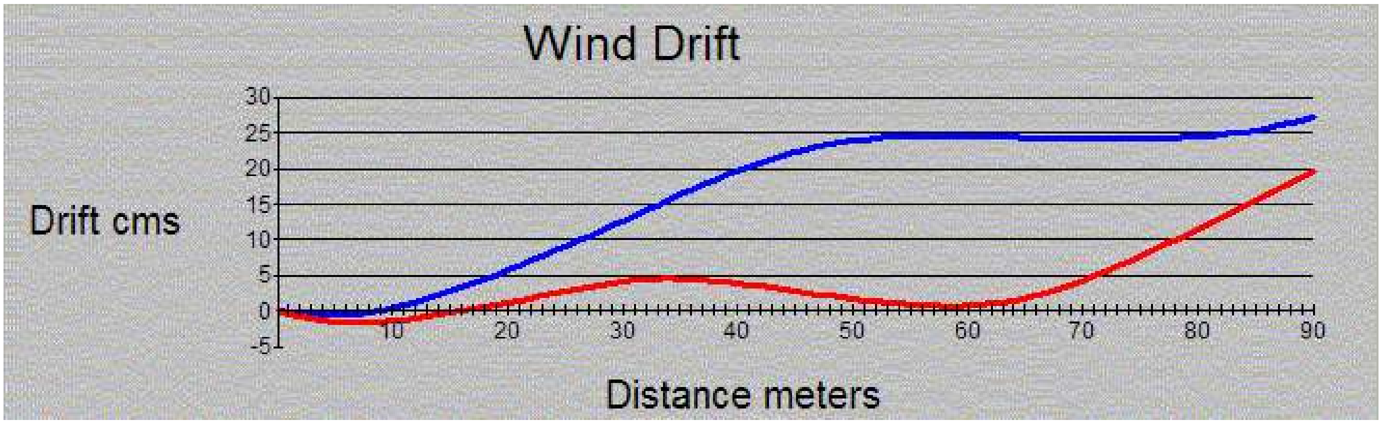
Let's move into the real world. If an archer shoots a perfect arrow in a wind and the arrow hits left in the blue the archer doesn't spend the rest of tournament peppering the blue, he adjusts the windage (or aims off) so the perfectly shot arrow hits the X. The following picture illustrates the arrow flight paths with the windage correctly adjusted.



As you can see, the actual wind drift has now become irrelevent as a perfect shot with either arrow will hit the X. *(The same is true with the effect of gravity. You "aim off" to allow for gravity just as you "aim off" to allow for wind. With Lunar Archery and a different gravity force you would have a different aim off just the same as you have a different aim off with a different wind strength. Absolute values of "wind drift" or "gravity drift" are not very important.)*

What does matter is not the 'wind drift' but what group sizes the archer is going to get with the two arrows. Which of the two arrows shooting in the wind is going to more 'forgiving' to the archers' variability which at the end of the tournament is going to give him the highest score.

The following picture illustrates the flight paths of two arrows where the windage has been perfectly adjusted and the archer has shot a less than perfect arrow.



For this particular shot the ACE gives a better result than the X10, it hits nearer the middle. With further simulation it becomes clear that **in this case** the lighter ACE arrow gives you smaller groups than the X10 and the lighter arrow is the best performer. Note the emphasis on 'in this case'. Even with the same two shafts if anything changes, launch speed, wind conditions, arrow length pile weight etc. then you are back to square one as regards wind performance. It is impossible to predict in a simplistic way which of two arrow shafts is going to be better. Flight simulation may give some indications but actually shooting arrows and measuring their relative performance is the only realistic method.

In the above example two different shafts were compared so more than one variable was being changed. Suppose instead we compare the X10 above and same X10 with an additional say 20 grains of mass. The result as regards wind drift and arrow performance depends very much on how the extra mass is added (one of the oversimplifications in the expression 'The heavier arrow'). If we add the 20 grains extra to the shaft then the absolute wind drift of the arrow remains much the same - the extra mass is cancelled out by the increase in the drag force drifting the arrow. The grouping performance of the heavier shaft is worse than the lighter shaft. If we make one arrow 20 grains heavier than the other by adding 20 grains to the pile then the heavier arrow has less wind drift than the lighter arrow and the heavier arrow groups better than the lighter arrow. So how you make the heavier arrow heavier makes a big difference

So the next time you hear (as you invariably will) that 'a heavier arrow has less wind drift' hopefully you will be aware that this an oversimplistic approach which does not take into account the aerodynamics of the arrow and may be true or false depending on what two arrows you are referring to and how one arrow is made heavier than the other.

All the above assumes that the strength and direction of the wind is constant. What happens if they are not?

To a large extent depends on the type of bow. With a recurve bow how "forgiving" an arrow is to archer form variation is a major factor in the overall arrow performance as regards tournament scores. Wind drift for recurve archers with variable wind strength is considered on another page.. For compound bows arrow aerodynamic performance, i.e. how "forgiving" it is, appears to be of very little interest. As long as the arrow is stiff enough so the bow remains a point and shoot device, overall weight and diameter, i.e. absolute wind drift, seems to be the only consideration, at least with the average club archer.

FLIGHT INSTABILITY

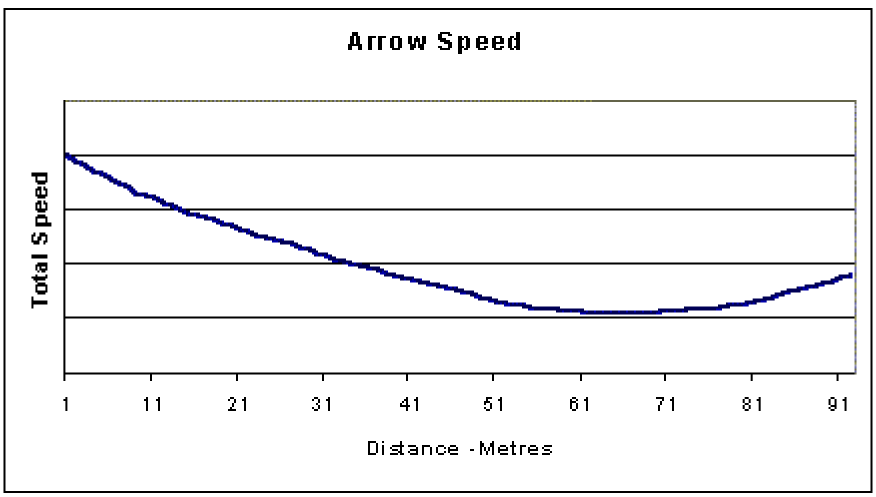
Archers have often reported the observation that at longer distances the arrow group sizes seem to increase more than would be expected solely from the increased distance. Andrew Middleton on his web page on arrow flight ballistics refers to this effect as longer distance 'flight instability' and it's such an appropriate term that I have 'borrowed' it.

This long distance flight instability effect is I think complicated and I don't claim to understand it. What I think I can do is put forward some of the factors that contribute to generating it.

Arrow Distance

We tend to think of the target distance as being the horizontal distance but the flight path of the arrow through the air, because it travels in an arc is much longer. The proportional increase in arrow travel distance through the air in going from 70 to 90 metres is larger then the proportional increase between the horizontal 70 and 90 metres distances. The difference depends a lot on the initial arrow speed.

Arrow Speed



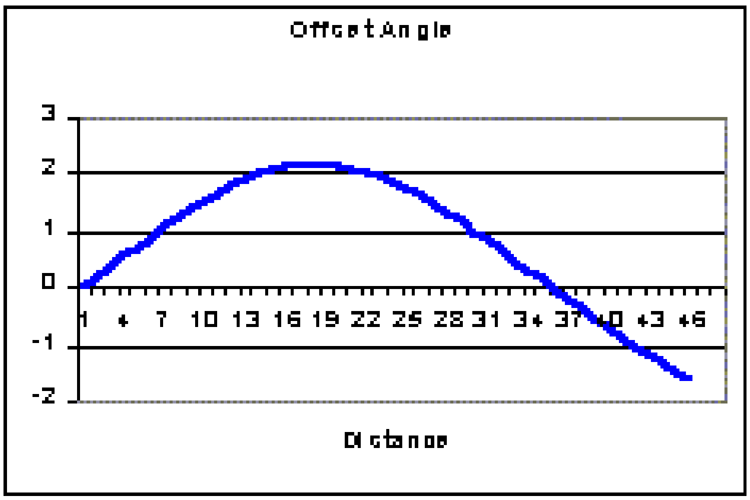
At longer distances, with higher arrow trajectory, the arrow is more likely to be speeding up in the latter part of its flight. On the way down the arrow is losing speed to drag but gaining speed from gravitational acceleration. At longer distances (the arrow 'falls' further) the speed gain from gravity outweighs the speed loss from drag. This increased speed results in increased drag forces moving the arrow about and increased fletching action.

The graph illustrates how the total speed of an arrow varies with distance. With a typical target arrow at 90 metres target distance the arrow speed is increasing over around the last 20 metres of flight. The drag forces on the arrow are proportional to the square of the velocity.

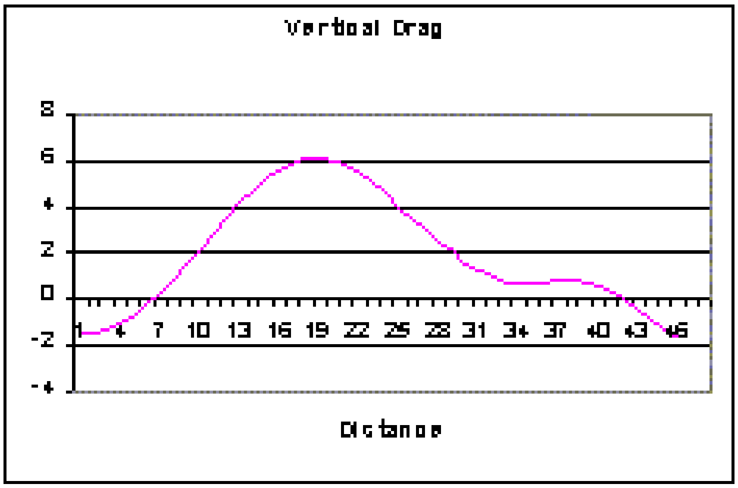
Arrow Drag

This is the complicated bit. To keep it simple I am only going to consider the vertical component of the drag force on the arrow and assume that the arrow does not fishtail (horizontally) at all.

When you shoot an arrow at the instant of release the arrow is more or less pointing in the direction its travelling. Because gravity is accelerating the arrow downwards the (offset) angle between the direction the arrow is pointing and the direction the arrow is travelling steadily increases. The fletching action works to rotate the arrow to reduce the offset angle and as the rotation builds up the gap starts to close and eventually the offset angle reduces back to zero.

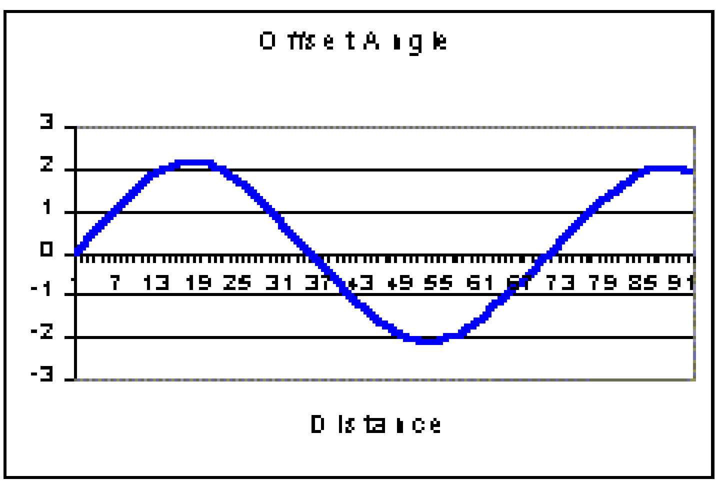


The graphs illustrate this behaviour at a 45 metre target distance. The offset angle increases to about 20 metres distance and then reduces to zero at around 37 metres. For most of the flight the air flow acts on the lower surface of the arrow.

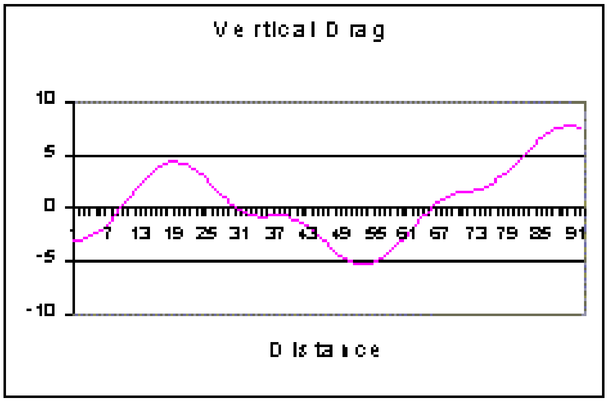


The associated vertical drag over 45 metres is illustrated in the second graph. For virtually all of the flight the drag provides a 'lift' force pushing the arrow upwards.

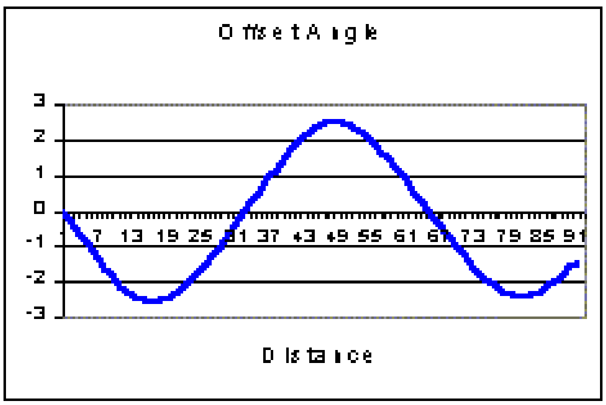
The following graphs illustrate what happens at 90 metres distance.



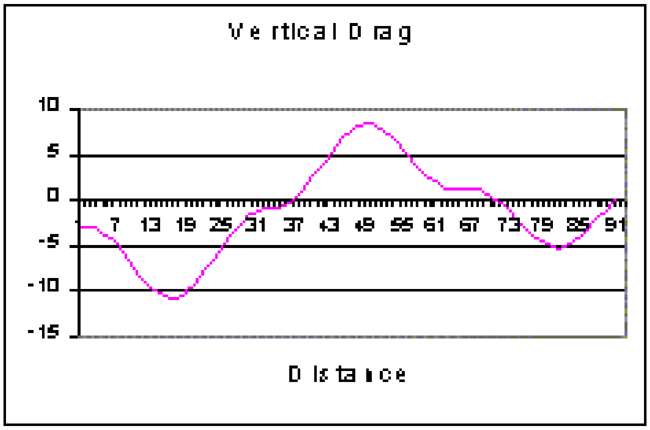
The arrow now has enough flight time for its direction to oscillate around its direction of travel. The air flow over the arrow oscillates between acting on the lower and upper surfaces of the arrow.



As a consequence the vertical drag force oscillates between pushing the arrow upwards and driving the arrow downwards. In addition the lift force on the arrow increases towards the latter part of the arrow flight because of the increased arrow speed.



The preceding graphs relate to a perfectly shot arrow leaving the bow with zero rotation. If the arrow leaves the bow already rotating in some direction (a poor shot) then this can make a significant difference to how the offset angle varies during the flight as illustrated for a poor shot at 90 metres.



The poor shot can result in a marked change in how the lift force varies on the shaft over the flight and hence where the arrow ends up on the target. The way the offset angle oscillates and the consequent way the vertical component of the total drag force varies is very sensitive to the direction and the amount of rotation the arrow has when it leaves the bow. At short distances (less than 45 metres say) the flight time is short enough so that only a small amount (or even zero) offset angle oscillation occurs. The longer the distance the more oscillations you get and so the vertical drag effects on the arrow become increasingly sensitive to how the arrow is shot.

A one line explanation of arrow flight instability would run something like the following. "At longer distances the development of a natural arrow 'wobble' combined with the increased arrow speed towards the latter part of its flight amplify any variations in how the arrow leaves the bow resulting in a larger spread of arrow impacts on the target".

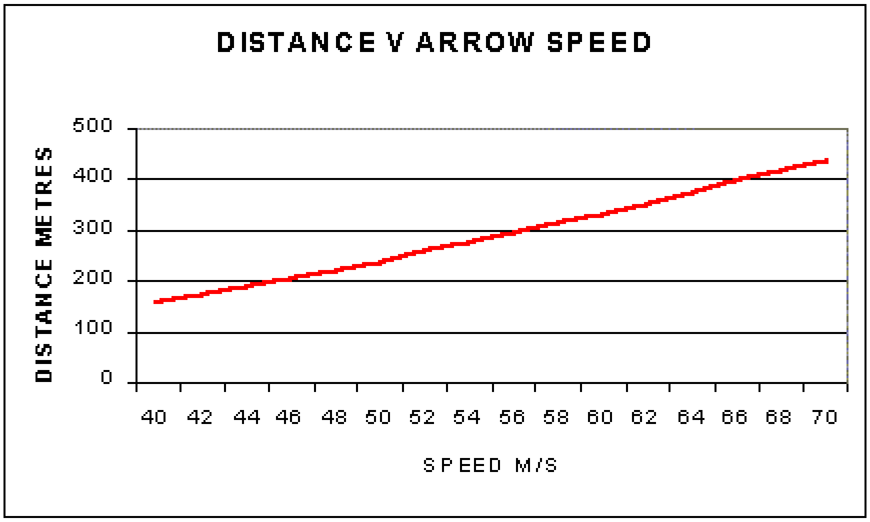
FLIGHT SHOOTING

The aim of flight shooting is to shoot an arrow (into the ground) as far as possible. I have no practical experience of flight shooting, always a good place to start, but it's possible on a purely mechanical basis to look at what a likely to be the characteristics that make a good bow/arrow system for distance when accuracy is not an issue.

An example of a 'custom designed' flight bow used By Don Brown to set a world record of over 1336 yards in 1987. is given the at following link:

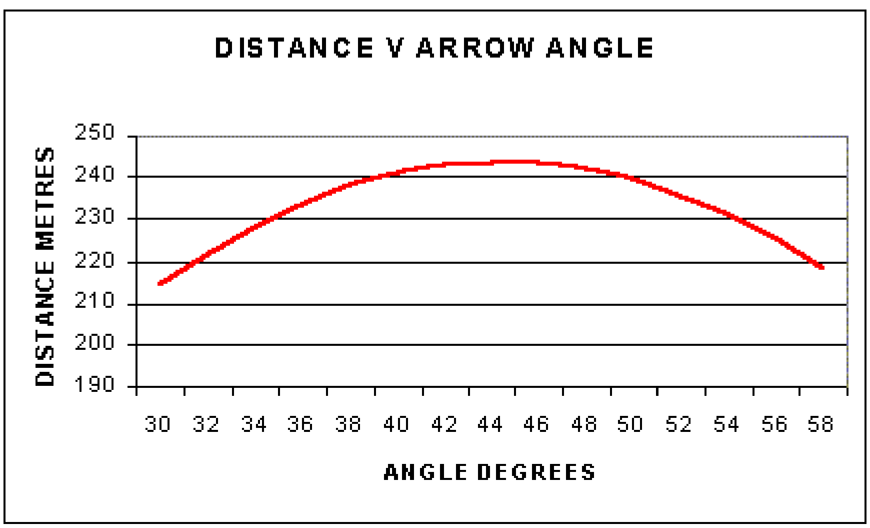
The approach to looking at flight shooting is to take a 'typical' target arrow and vary is properties one at a time to see how this affects how far the arrow can be shot.

Velocity



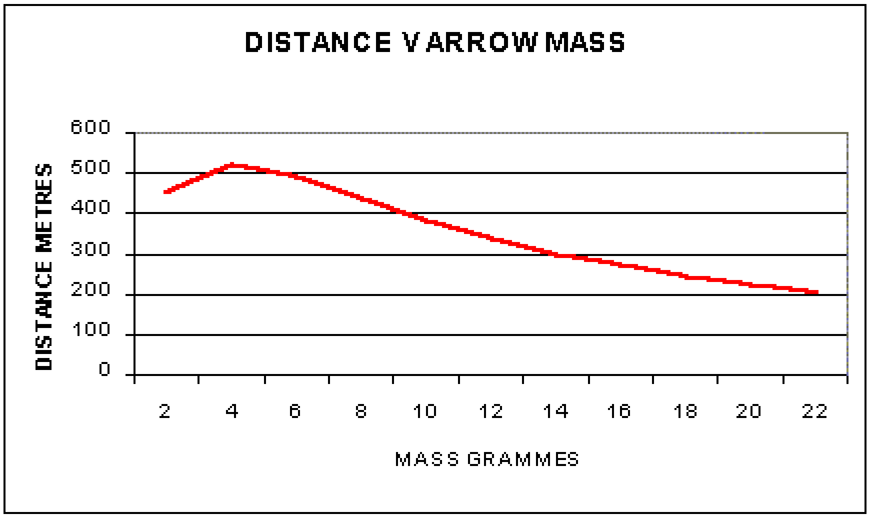
The higher the speed at which the arrow leaves the bow then the farther it goes. No surprises there. We need a bow with a high potential energy storage in the limbs and an efficient use of this stored energy in creating a high speed arrow.

Arrow Angle



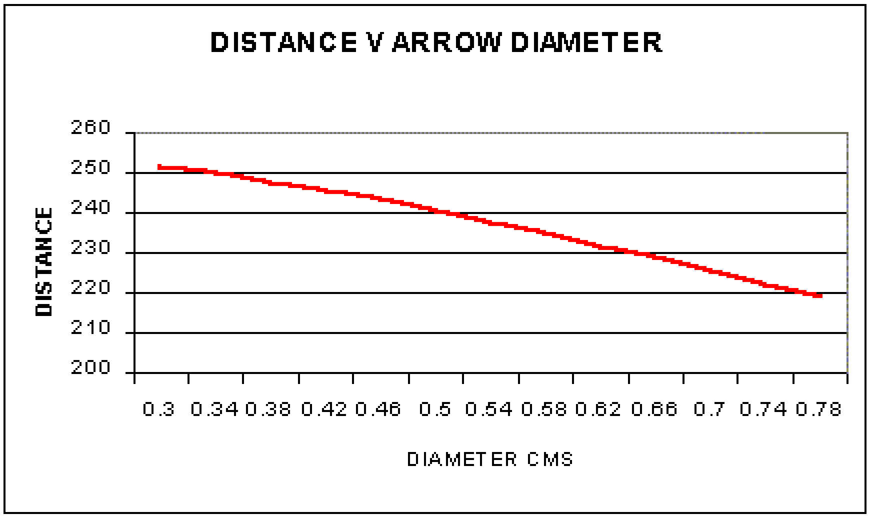
If there were no aerodynamic forces then the angle for maximum distance would be 45 degrees to the horizontal for any object. With aerodynamic effects then the angle for maximum range becomes a function of the object properties. For anything that could be called an arrow the angle for maximum range is slightly under 45 degrees, between 44-45 degrees say. Shoot angles for target archery in general only go up to around 10-15 degrees.

Arrow Mass



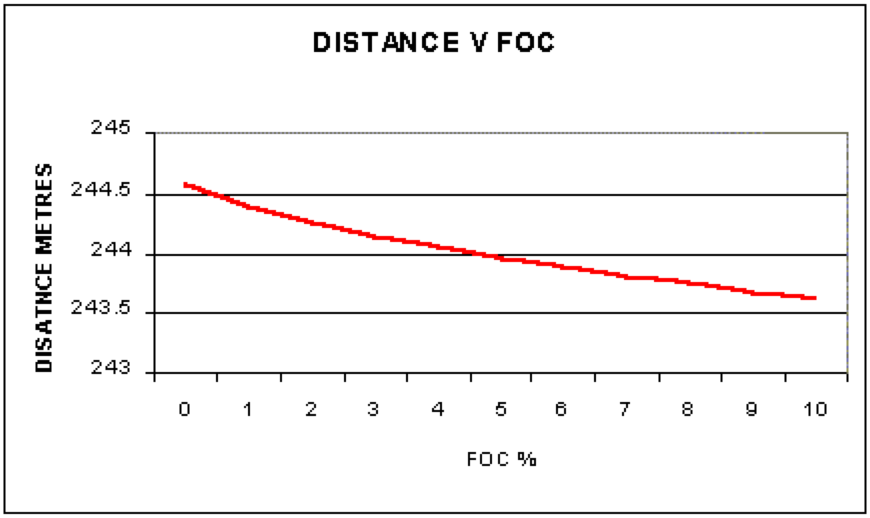
Changing the arrow mass will change the speed of the arrow from the bow. The approach in the above graph is to assume the kinetic energy of the arrow leaving the bow is constant so changing the arrow mass also changes its speed. (No allowance for changes in bow efficiency). As the arrow decreases in mass and the bow exit speed increases then the arrow up to a point goes farther. At some point the effect of drag deceleration of the arrow will outweigh the increased initial speed so there is an 'optimum' arrow mass for maximum range. This optimum mass will be much lighter than any feasible arrow that can be made with current materials so in effect the lighter the arrow the further it goes.

Arrow Diameter



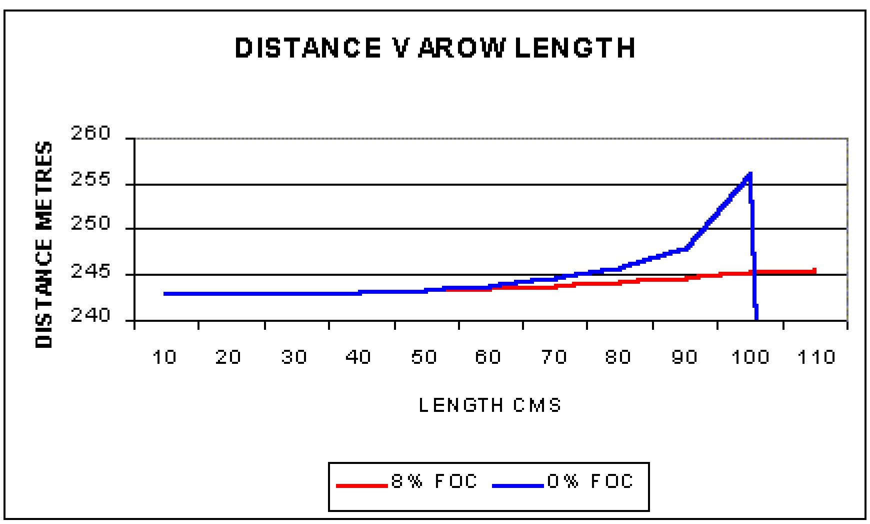
Increasing the arrow diameter will increase the drag on the pile of the arrow and on the shaft. (the arrow mass is assumed independent of the diameter). Drag on the pile is all bad news as it slows the arrow and reduces the distance. Drag on the shaft is overall a benefit as it increases the vertical component of the total drag on the arrow (which a flight arrow is designed to maximize). The net effect is detrimental to range. To maximize range we want a thin an arrow as possible. A way to have a thin arrow with the high arrow acceleration we need for that high speed is to reduce the distance from the nock at full draw to where the arrow contacts the bow. This effectively 'stiffens' the arrow. In the Don Brown bow the grip is in front of the riser reducing the nock-bow distance while allowing for efficient use of the muscles in the draw. A consequence of this approach is that the draw length is reduced. In order to get a high arrow speed with a smaller draw length you need a high draw weight and a bow design which stores a lot of energy at the start of the draw. The highly recurved limbs provide the latter bow characteristic.

Arrow FOC



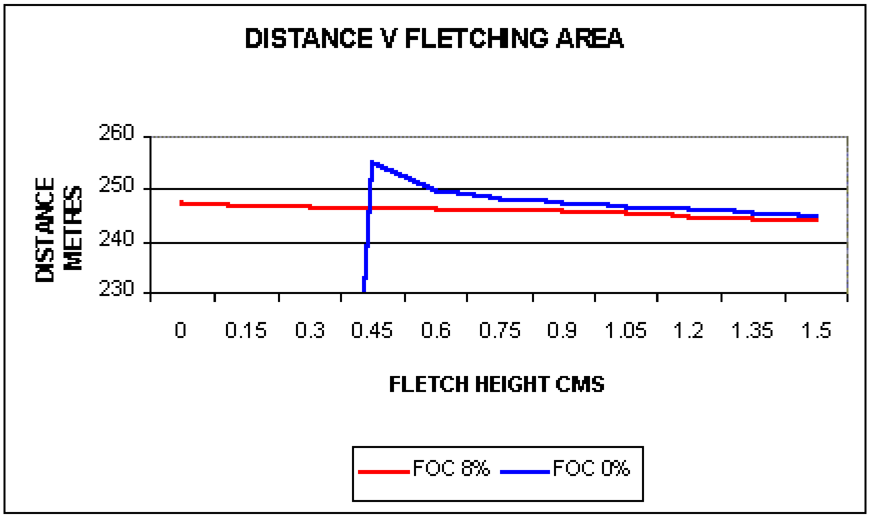
The graph indicates that the lower the arrow FOC than the the further it goes. This relates to two aspects of arrow flight, shaft drag and arrow rotation rate. Flight arrows use the drag on the shaft to maximise the vertical component of the total arrow drag (net upwards) and so they go further.The nearer the FOC is to zero the higher the shaft drag area and so the further the arrow flies. A lower FOC also reduces the rate at which the drag on the shaft and fletchings rotate the arrow again overall increasing the vertical component of the total arrow drag.

Arrow Length



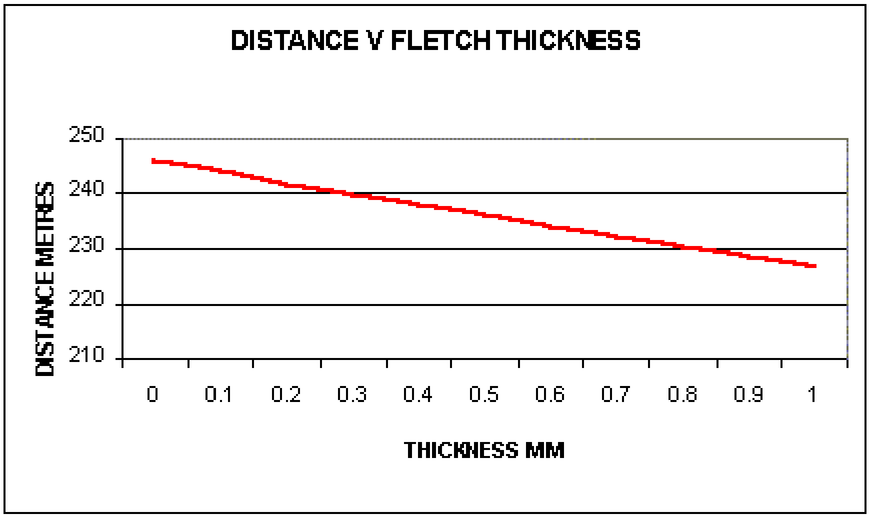
For the target arrow (assumed 8% FOC) as the arrow gets longer there is a marginal increase in arrow range. This results from the increasing shaft area and the larger arrow moment of inertia increasing the drag on the shaft. This shaft drag acts to slow the arrow down in the horizontal direction but also generates an upward force and net there is a benefit in increased distance. With the zero FOC arrow you get the same effect but because there is no fletching action from the shaft eventually the increased shaft drag results in the arrow loosing all horizontal speed and parachuting down. As the arrow length increases so does its mass which means a lower initial speed so there is a balance to be struck on arrow length and mass. The mass effect on length will predominate so a short arrow with overdraw is likely to be the preferred approach.

Fletching Area



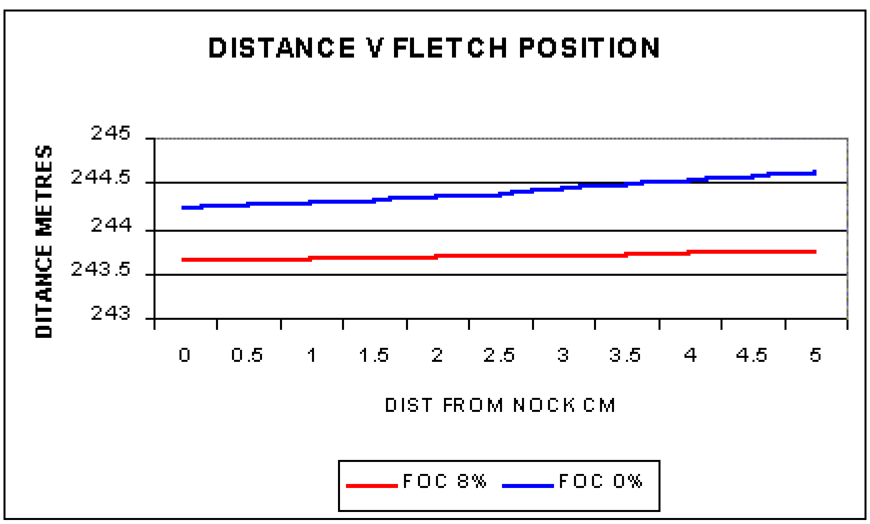
The length of the fletching is assumed constant and the fletching shape is taken to be a right angled triangle. The height of the rear end of the fletching is therefore directly proportional to its area. For the target (8% FOC) arrow increasing the fletching area has a small effect, decreasing the maximum range. A bigger fletching area increases the arrow rotation rate and therefore reduces the vertical component of the total drag as mentioned re FOC above. Target arrows have a lot of fletching action much of it coming from drag on the shaft. A flight arrow as mentioned above will have a low FOC and therefore small or zero shaft fletching action. The blue curve in the graph represents how the fletching area affects the range of a zero FOC arrow. Because of the Munk moment to get any distance requires having enough fletching area to obtain 'stable' arrow flight, otherwise the arrow just bombs. In theory the closer the fletching area lies to the minimum the higher the arrow range. In practice you have to allow for the effect of any rotation the arrow has leaving the bow.

Fletch Thickness

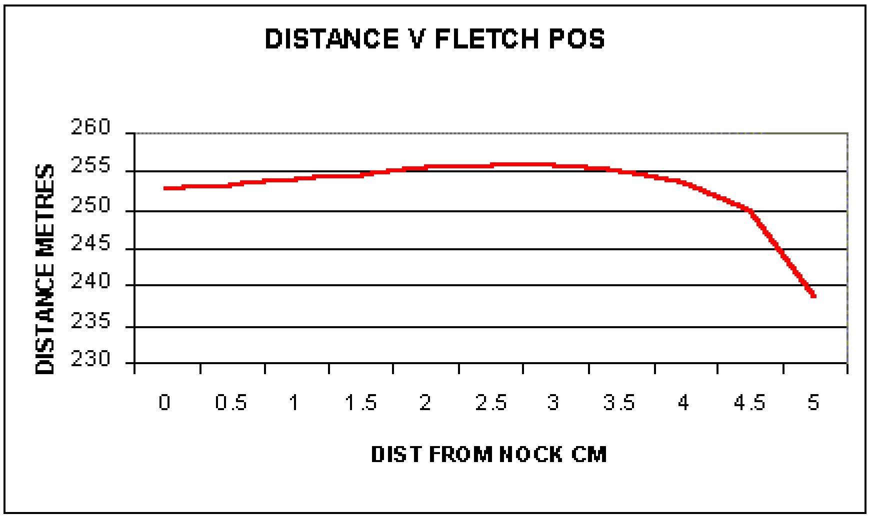


The thicker the thickness of the fletching the more drag there is slowing the arrow down. What is required is a very thin, rigid and straight fletching.

Fletch Position



The graph illustrates how the arrow range is effected by how far the back of the (3.5 cm long by 1.5cm tall) fletching is from the rear of the arrow. The fletching position affects the rate of rotation of the arrow. For the both the target arrow and the 'flight' zero FOC arrow the fletching position has only a marginal effect on arrow range. As the fletching position moves forward the range marginally increases. For flight shooting the standard arrow (fletching + shaft) has way too much fletching action and even with the flight arrow (fletching area only) the standard arrow fletching is too large. The following graph illustrates the effect of fletching position with a smaller more sensibly sized fletching.

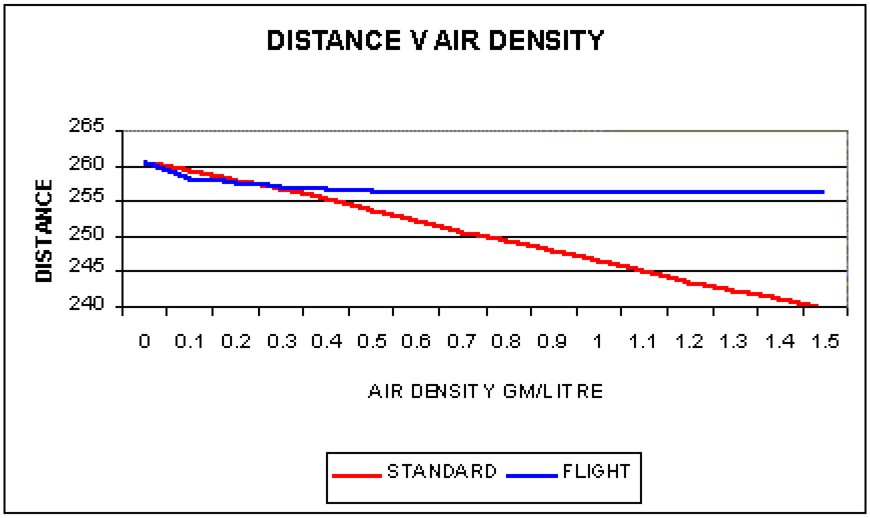


With a correctly sized fletching the fletching position becomes a 'tuneable' parameter with the maximum range obtained, in the example above, with the rear of the fletching around 3 cms from the end of the arrow.

Nock Weight

The weight of the nock can have a number of influences on the performance of a flight arrow. Increasing the nock weight will make the arrow act stiffer possibly allowing for a lower spined (less diameter and less mass) arrow to be used. The nock weight can be used as an alternative way of varying the arrow FOC. Having weights on both ends of the arrow will affect the arrow moment of inertia and consequently the rotation rate of the arrow affecting its drag characteristics.

Air Density



The aerodynamic forces on an arrow are directly proportional to the air density. With zero density, a vacuum, there are no aerodynamic forces. For the standard target arrow which is shot with generally flat trajectories drag, as far as distance is concerned, is not an issue. The arrow is not designed to use drag efficiently as far as distance goes. The above graph illustrates this, the higher the air density the lower the range of the target arrow. The flight arrow, in contrast, is designed to use drag on the arrow to increase it's range, so the effect of increasing air density has only a marginal effect. In fact around the normal air density of 1.2 gms/litre the arrow range increases as the air density increases, so a drop in air density, e.g. high humidity, can reduce the distances being shot.

ARROW SELECTION

One of the areas for recurve archers which seems to result in sleepless nights and hair loss is arrow selection. i.e which arrow shaft should I get and what pile weight should I put in it. The following is a suggested method for selecting arrows using a systematic approach. As usual there is no better method than trying different arrows for real and seeing how they group, but in general this is not a feasible option. I'm assuming up front that you know your arrow length and draw weight

Step One

Use an arrow selection chart/program to get a set of alternative arrow/pile combinations which are recommended as likely to work well with your bow.

The arrow selection charts are 2D, from your arrow length and weight you get a recommended set of alternative shafts. If you use Bloggs Corp. chart they are obviously only going to recommend Bloggs' arrows so using a multi-manufacturer chart is better. If you only have Bloggs' chart then you can use the suggested

Bloggs spine range of the recommended arrows to include other manufacturers arrows in the initial pool of arrow shafts.

Arrow selection programs are 3D, from the information you put in you get a recommended set of shafts and associated pile weights deemed to work well with the bow. If the program vendor is commercially neutral than you get recommended arrows from different vendors and the arrow database is hopefully regularly updated.

Note that arrow selection charts/programs only try to give you a set of alternative arrows that will work well with the bow, they do not tell you the 'best arrow' for you to shoot.

If an arrow shaft is too weak then the arrow will hit the bow on the way past, you will have a clearance problem. If the arrow is too stiff then you won't be able to tune the setup. With an arrow selection chart/program you are identifying arrow shafts that fit into the 'window' between these two limits i.e. arrows that will have good clearance and be tuneable. Different shafts in the window will vary in how forgiving they are to archer variability in terms of sensitivity to the angular momentum the arrow has leaving the bow but this effect is far outweighed by the requirement to have an arrow with good (flight) grouping properties. Because of this arrow selection programs do not have to be particularly accurate - just identify shafts that are somewhere around the middle of the window.

The fact that arrow selection programs do not have to be very precise is lucky because there is currently no available method for an archer to accurately match an arrow to a specific bow. (People who create mathematical models of arrow behaviour on the bow have I think some optimism that this might at some time be feasible, but I would put this into the 'blue sky' category). A major factor in selecting a good arrow match are the properties of the bow (limb geometry, mass properties, elastic properties etc. etc. etc.). With the arrow selection charts for a recurve the matching arrows are defined against the arrow length and draw weight. The basic assumption is that at any given time all the current recurve bow properties are much the same, so all bows with the same draw weight will have more or less the same properties. On the whole this works pretty well though in some cases, if say the limb design is radically different, the standard selection charts fall over to some extent. If on the other hand you tried an arrow match with a 25" bow 40# draw then the tables wouldn't work. The same applies to some extent to the arrow properties (material density, elasticity etc.), all arrows are assumed to have similar characteristics. It is because the selection tables are based on the typical properties of archery kit at a given time that the selection tables have to be periodically revised (or in the case of an arrow selection program a recalibration has to be carried out). Bow/arrow design does change, if slowly, over time. As long as there have been bows there has probably been an empirical approach to arrow selection which in principle hasn't changed much, even though these days it gets wrapped up in fancy looking computer programs. For an overview of the methodologies suggested for arrow selection procedures see The Archers Paradox & Modelling A Review

Step Two

Whittle down our initial pool of arrows on the basis of the specific archer's requirements. These are to some extent unpredictable but I'll mention a few of the obvious ones.

How much you're prepared to spend is the first one. If you only want to spend X on a dozen arrows then any arrow set costing move then X can be removed from the pool.

If you want arrows for indoor shooting only and you are a 'fat arrow line cutter' enthusiast then only the maximum diameter aluminium arrows are of interest. The selection will probably be influenced by having enough shaft wall thickness so you're not replacing damaged arrows every week.

If you have a low poundage bow and want to shoot 90 metres then the overall arrow weight (i.e. arrow speed) becomes important. There are a number of tools around for calculating arrow speed and relating this to arrow range. (e.g. pin tape programs). You may end up with a requirement that the all up weight of the arrow has to be less than X and so all heavier arrows can be removed from the pool.

Sep Three

Try to determine which of the arrows remaining in the pool will give the best result in terms of having the smallest arrow groups i.e overall the most forgiving arrow.

Most of the work in having a good flying arrow has already been done by the arrow designer. There would not be much point in selling an arrow which works fantastically well on the bow and flies like a pig.

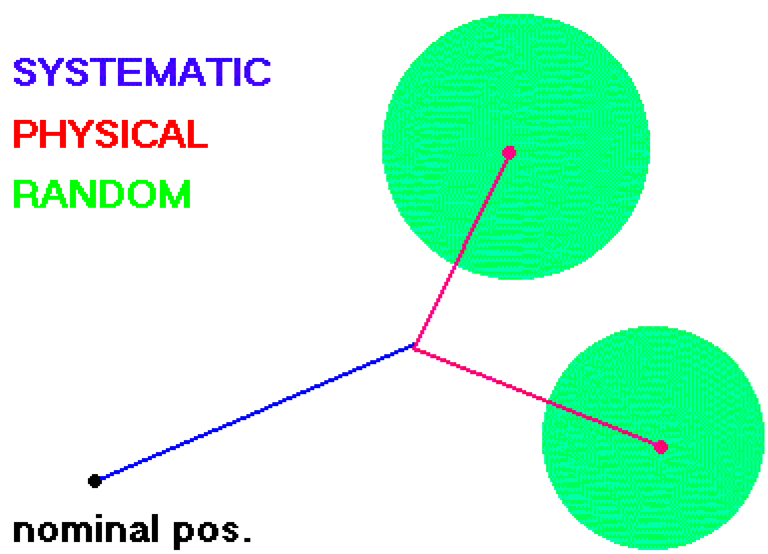
Modern bows are very tunable so the differences between the arrows left in the pool with respect to how they behave on the bow are far outweighed by how they fly. What moves the arrow off the target centre is drag so we need to choose the arrow from the pool with the best drag characteristics. Basically were looking for the arrow with the best combination of minimum diameter, maximum fletching effect and rotation speed.

Unfortunately there is no quick fix method of assessing how well an arrow will group. Arrows will vary in how they group at different distances and in different wind conditions. FOC is a reasonable guide, the higher the FOC probably the better the arrow flight performance. However overall flight performance depends on more than just the FOC so the highest FOC arrow may not be the best. For a downloadable program aimed at trying to identify, "which of the possible arrows may be the best" see the Program downloads page

Having purchased a new set of arrows the final part of the selection process is selecting from the set the subset of arrows to be the 'competition set'. There will be physical differences between arrows in a nominally identically set which will result in the arrows hitting at different points contibuting to increased group sizes. Is it possible to select the best subset of arrows i.e. identify arrows which are physically the closest match in terms of how they behave in flight?

There are three factors which contribute to where the arrow hits, the arrow's physical properties, systematic errors and random errors. Systematic errors result from the equipment setup (including tuning) and from how the archer shoots (i.e. an archer may have a tendancy towards a repetitive error e.g. arrows tend to go high right or whatever). Random errors result from each shot the archer makes being slightly different with no systematic structure to the variations.

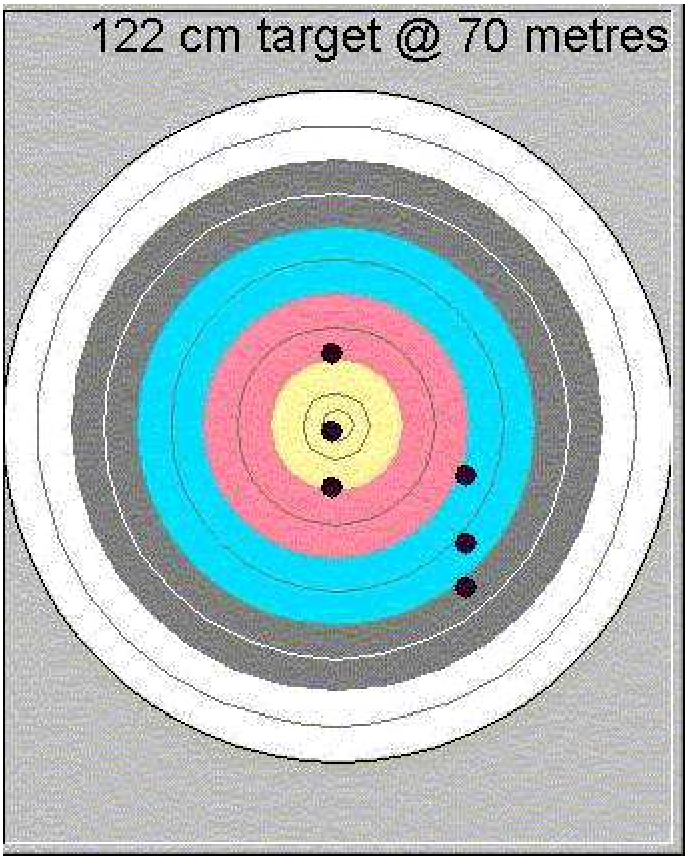
Although these three factors to some degree interact with each other in terms of where the arrow hits the up front hypothesis is that the effects of systematic errors are relatively consistent between physically different arrows and that random errors are treatable using a statistical approach. The following diagram illustrates this assumption.



The 'nominal position' is where a 'physically standard' arrow would hit with no systematic or random errors. The relative positions between the centres of the groups for the individual arrows is determined principally by the physical differences between the arrows,

As a quick test of the above hypothesis the behaviour of three physically different arrows is looked at using the arrow flight simulator for where the arrows hit and the Arowmaster program (Ref 1) to analyse the hit patterns. The physical difference used is the shaft weight; there is a 'standard' arrow, one with a shaft 3 grains heavier and one with a shaft 5 grains lighter. The systematic error used is a slightly mistuned bow.

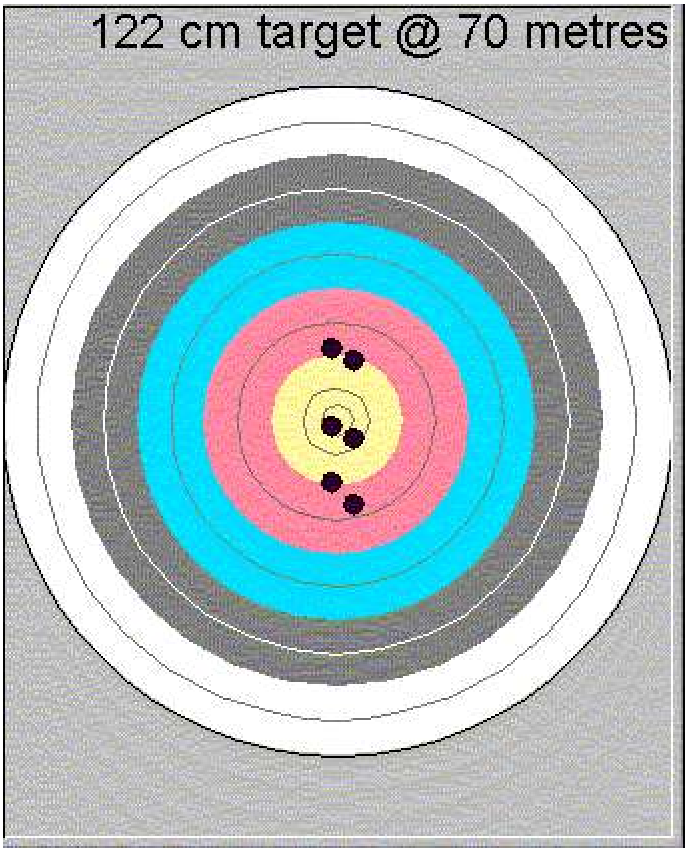
The following diagrams illustrate the effect of the systematic error. The arrows are assumed to be perfectly shot with no random error.



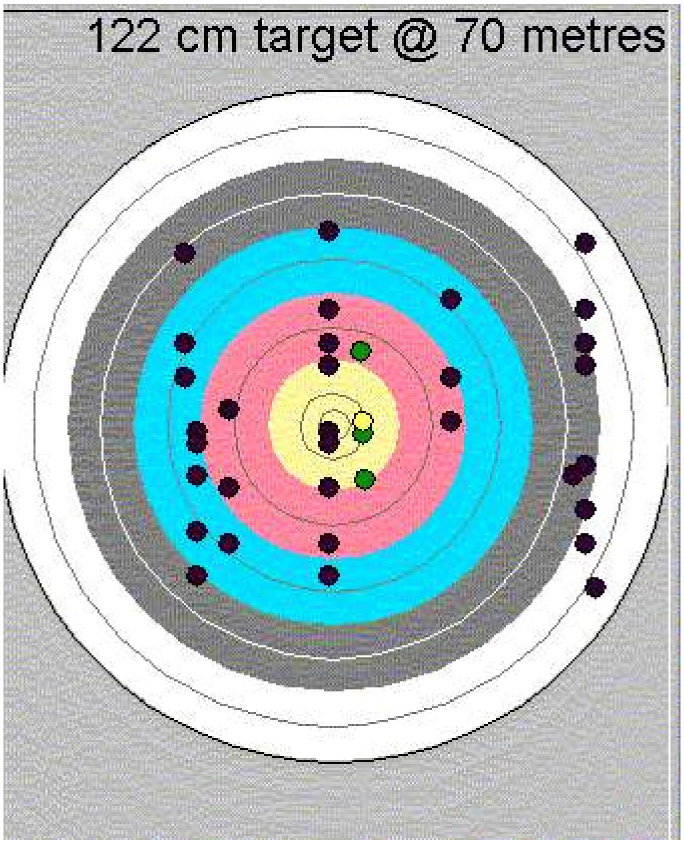
The arrows in this case are bareshaft. The vertical arrow hits (black dots) down the target centre are for the case with no random or systematic error. The hit near the middle is the standard arrow, the hit above it the light shaft and the one below it the heavier shaft. The three hits to right and down are the same three arrows with the added effect of the systematic error.

With no systematic error the distance between the standard shaft and the plus 3 grain shaft is less than the diference between the standard and minus 5 grain shaft. The differences between the arrow hits is proportional to the physical differences between them.

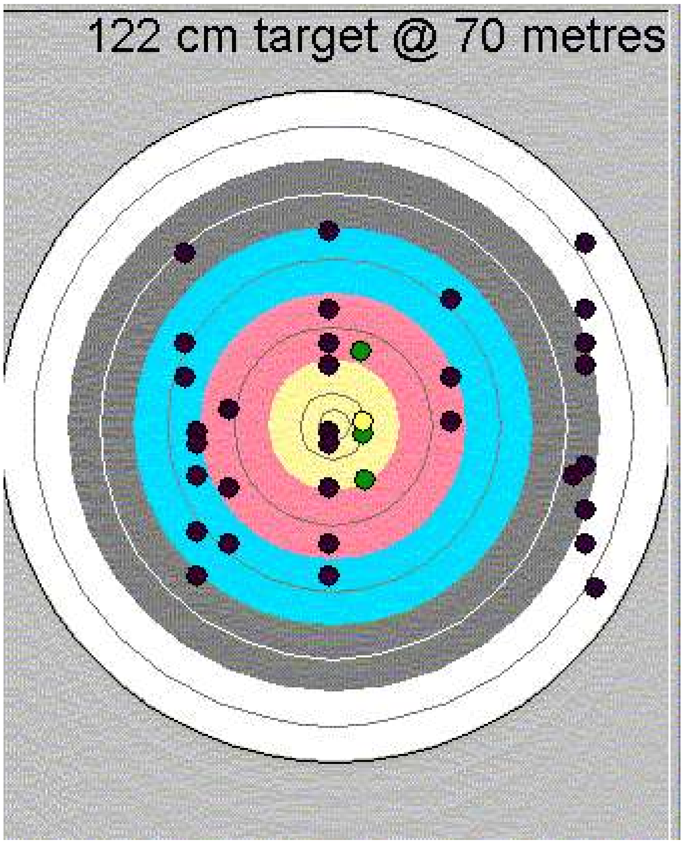
With a systematic error introduced the relative positions between the arrow hits remains proportional to the physical differences between the arrows. In fact the effect of the arrow physical differences appear to be somewhat exaggerated presumably due to the interaction between the physical difference and the systematic error.



This diagram represents exactly the same case as the previous one except that the arrows are now fletched. The fletchings unsurprisingly greatly reduce the effect of the systematic error. A consequence of this is that the differences between where the arrows hit with respect to their physical differences are also reduced. This suggests that using bareshaft arrows for arrow selection is likely to be a more sensitive approach than using fletched arrows.

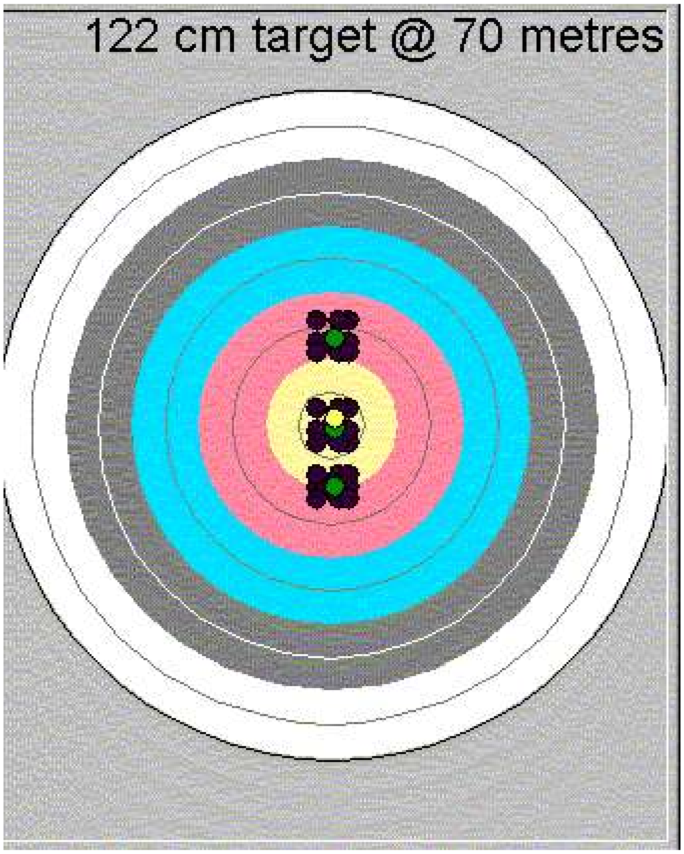


To the situation described above is now added the random error resulting from the archers variablility. The basis for selecting the archer's skill level is that the archer will put all the bareshaft arrows shot on the target. Note that the arrow flight simulator assigns 'random' variations in a systematic way so three arrow hit distributions do follow a pattern. The centres of the individual arrow hit distributions are calculated with Arrowmaster.



In this figure the black dots represent the arrow hits for the three arrows. resulting from physical difference, systematic error and random error. The 'sight pin' has been adjusted to get all the arrow hits on the target. The green dots are the calculated centres of the individual arrow groups for the three arrows. Again the relative positions of the individual arrow group centres proportionally relate to the physical differences between the arrows.

This result seems to support the original hypothesis that it is possible to select a best set of arrows from an overall set by analysing the arrow hit patterns.



This figure represents the same case as the one above except that the arrows are fletched. The actual individual arrow hit positions are illustrative only as the resulting groups were so compact. Again the relative positions of the individual arrow group centres are proportional to the physical differences between the arrows.

On a practical note if an archer's skill is such that that the groups when shooting the test set of fletched arrows is such that arrows are hitting each other then this is a fairly pointless exercise as you may end up damaging the arrows in the process of selecting them.

Another consideration that needs to made during the arrow selection process is the group size of the individual arrows. The physical arrow difference plus any systematic and random errors may result in significant differences between the group sizes of individual arrows. At the end of the day what you are looking for is a minimum overall group size for the set. The best set selection would be made on selecting arrows where the arrow group centres best 'group' but possibly excluding arrows which show a proportionally large individual group size.

A detailed description of a process for arrow selection has been given by Vittorio Frangilli (Ref 2). The procedure described here differs from the above approach in that selecting the best set is based on overall group sizes of the set rather than biased towards arrow group centres. When selecting arrows on a 'manual'. basis I think using group sizes is the only realistic approach. To work with group centres sensibly requires a number cruncher like Arrowmaster. Intuitively I feel that using group centres rather than overall group size is a preferable approach for a couple of reasons. The group centre positions relate more directly to the relative physical characteristics of the arrow than the group sizes as the effect of archer's variability is largely eliminated. Arrow selection is done under a particular set of environmental conditions. Tournaments will be shot is different conditions (e.g. wind). The relative behaviour of arrows will more closely match to the group centres than to the arrow hit distributions. Frangilli also points out correctly that arrow selection based on group sizes is only for the better archer (he suggests around 1200 Fita minimum for a recurve archer). This limitation results from the archer's variability being an integral part of the selection process. Using a group centre approach the average archer can use and benefit to some degree from an arrow selection procedure.

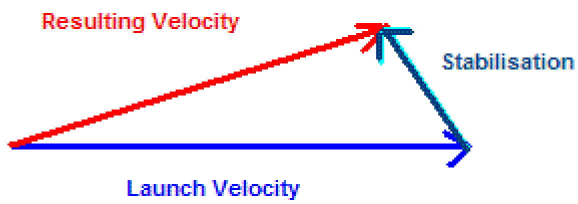
Ref 1: Arrowmaster
Ref 2: Vittorio Frangilli, Arrow Selection, Archery Focus, Jan/Feb 2002

ARROW FLIGHT STABILISATION

Introduction

The various mechanisms involved in arrow stabilisation after it has left the bow have already been covered on other pages (notably the sections on fletched arrows and drag). It is however such a fundamental topic with respect to understanding arrow design, arrow flight and bow tuning that it's probably worth pulling all the relevant bits together into a single unit. I will not rehash material like arrow rotation axis, centre of pressure etc. in detail as already covered on other pages. I'm assuming these have been read. I am also going to ignore the effects of gravity and the Munk moment as these just complicate things without adding anything to the general idea.

The words 'arrow stabilisation' are often come across but my definition is that arrow stabilisation has occured when all the rotational kinetic energy that the arrow has at launch is reduced to zero, or to put it another way all the arrow angular momentum at launch is reduced to zero.



The base issue is that if an arrow has some angular momentum at launch then during the stabilisation period the arrow acquires via drag a changed velocity, both speed and direction being altered. If the arrow was launched with the correct speed and direction to hit the target center then after stabilisation the arrow speed and direction are no longer those to hit the target center. (For the purposes of this description I'm assuming that what's wanted is a zero launch angular momentum, so I am not considering tuning optimisation of the arrow launch angular momentum with respect to distance or wind. These topics are covered separately under variable tuning wind/distance).

There are two aspects to arrow stabilisation, fletching action and drag effects. The two will be considered separately and then various aspects combined.

Fletching Action

Suppose you have a weight sitting on a table. There is a downward constant force **F** on the weight, the effect of gravity. To lift the weight you have to do work against this force so if you lift the weight a distance **h** to have to expend an energy **Fh**. All this hard work you've done doesn't disappear. This energy can be regarded as being stored in the weight as (gravitational) *Potential Energy*. If you let the weight go it falls down and the potential energy is converted to Kinetic Energy. Just as the weight reaches the table all the potential energy you put in by lifting it has been converted to Kinetic Energy.

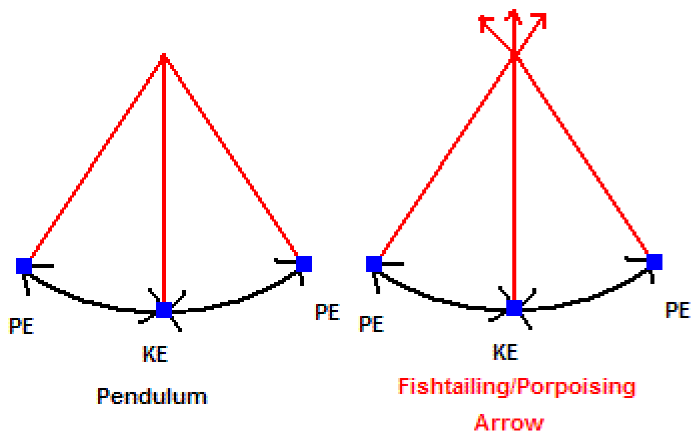
Suppose you have weight on string, a pendulum. If you displace the pendulum some amount you are lifting the weight and storing potential energy in it. If you let the pendulum go it swings back. Same as the weight above the potential energy is converted to kinetic energy. When the pendulum reaches the lowest point all the potential energy (ignoring frictional etc. losses) has been converted to kinetic energy. From its lowest point the pendulum keeps swinging (raising the weight) until all the kinetic energy is converted back into potential energy. So a swinging pendulum is just an energy oscillation between kinetic and potential energy and with no energy losses would go on indefinitely. The angle through which the pendulum swings depends on how much total energy it has and time it takes to swing depends on the gravity force on the mass. The length of the pendulum effects both the angle and the time of swing.

What's all the above to do with fletchings?. Suppose you have an arrow with an overall fletching surface area **A** with the arrow pointed directly into an overall air flow of speed **S**. The drag force on the fletching surface area is only frictional so it's negligible. If we push the arrow (at its centre of pressure) then the arrow rotates about some axis (determined by the centre of pressure distance from the arrow centre of gravity). If the arrow has been rotated by an angle **a** then the inertial drag force on the fletching surface is proportional to $\mathbf{ASin^2(a)S^2}$. If the distance from the center of pressure to the arrow rotation axis is **L** and the arrow is pushed through a small angle **t** then the distance through which the arrow has been pushed against the drag force is **Lt**.

So the energy required (force times distance) to rotate an arrow from an angle **a** to an angle **a+t** is proportional to $[\mathbf{ASin^2(a)S^2}][\mathbf{Lt}]$. If an arrow is at an angle **a** to the airflow then it has (similar to the lifted weight) a (drag) potential energy. The stored potential energy depends on the angle to the airflow, the overall fletching area, the arrow speed and the distance **L** (which depends on the arrow length, diameter, FOC, centre of pressure and moment of inertia). This potential energy at arrow stabilisation equals the rotational kinetic energy the arrow was launched with as a result of the torque input to the arrow by the bow.

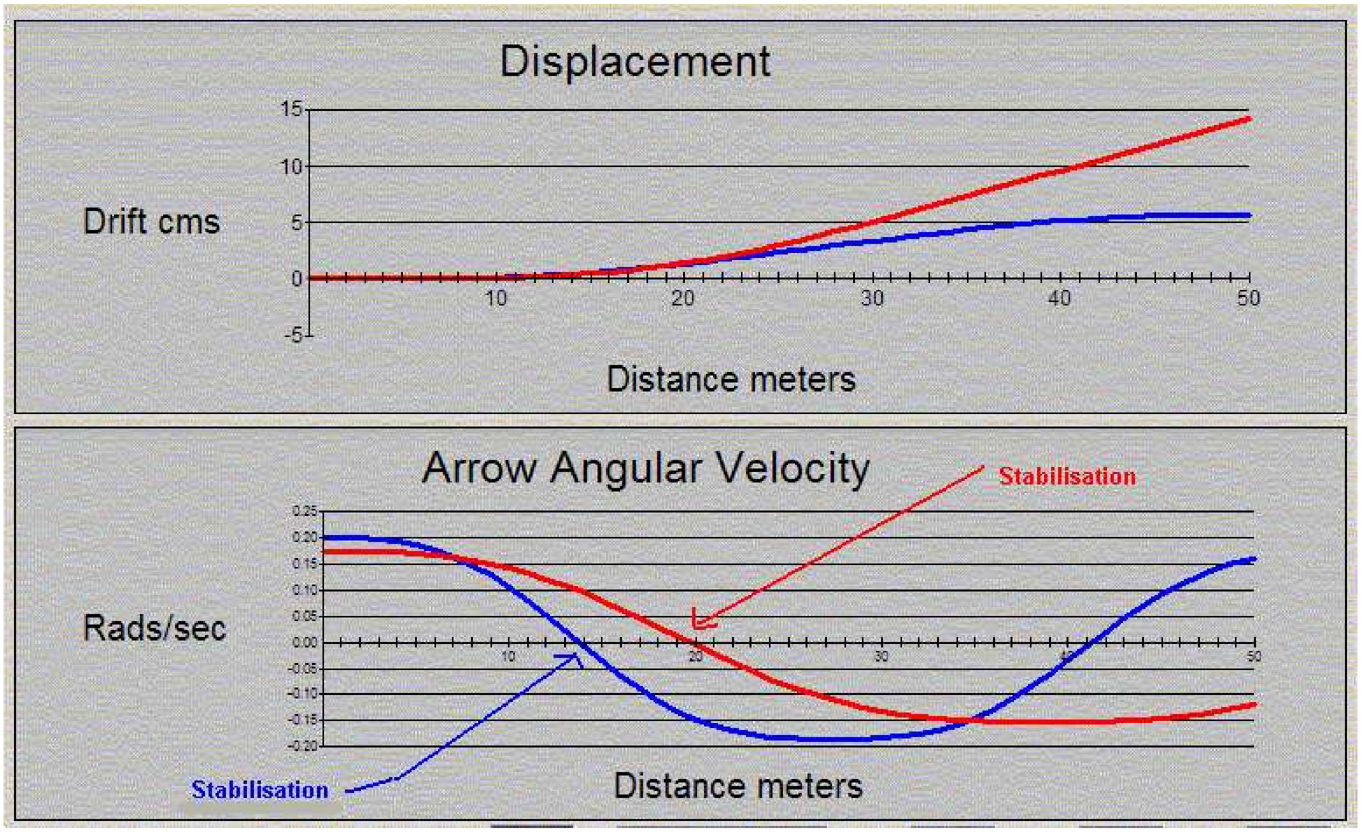
As the force against which the arrow is rotated is not constant but depends on the airflow angle and the overall air flow speed (arrow linear speed and angular rotation speed) it's a more complicated case then lifting the weight. The more the arrow has rotated the higher the force against which the arrow is moved.

The aim is to minimise the time it takes and minimise the angle through which the arrow rotates for arrow stabilisation as this minimises the change in overall velocity of the arrow resulting from drag (as we'll see in a minute).

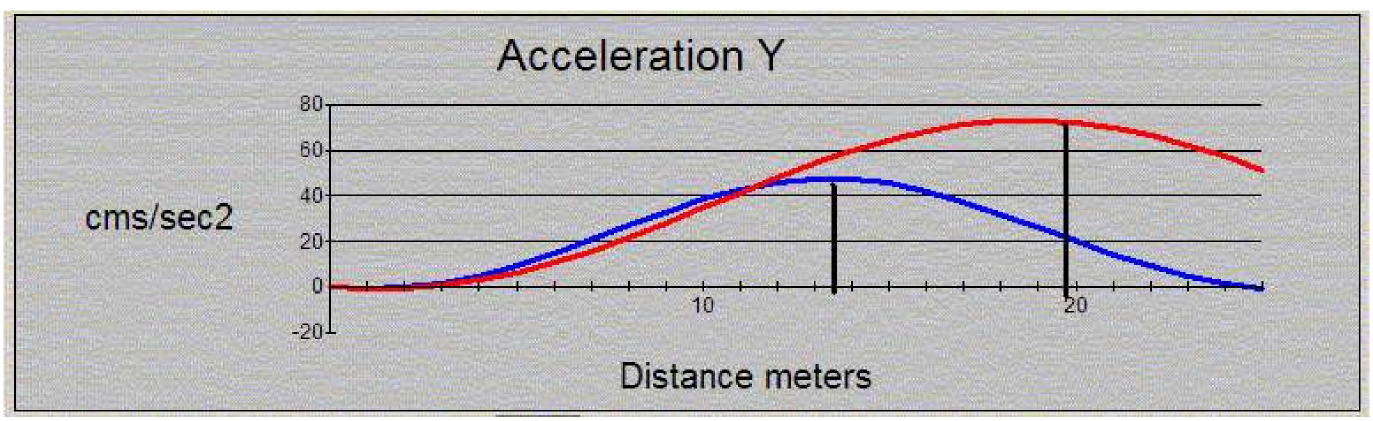


Once the arrow has stabilised then you have an arrow with a changed velocity and with the arrow shaft at some angle to the air flow. The behaviour of the arrow is then similar to the displaced pendulum above. The arrow fishtails/porpoises back and forth with an energy oscillation between fletching potential energy and and the arrow rotational kinetic energy. As discussed elsewhere fishtailing/porposing has a minimal effect on the arrow overall flight direction as the drag effects are more or less symmetrical and cancel out. The launch alignment of the arrow itself has no significant effect in itself in changing the overall arrow flight path.

The effect of arrow stabilisation on flight direction is illustrated in the following figure. In this case the comparison is made between a fletched arrow (blue) and a bare shaft arrow (red). The fletched arrow stabilises faster and attains a lower offset angle than the bare shaft because the increased fletching area means more potential energy per degree offset. The result is the change in direction of travel is higher for the bare shaft than for the fletched shaft. This of course is the basic principle behind the bare shaft tuning method.



The following graph illustrates the lateral drag acceleration on the same two arrows. The vertical black lines indicate the respective stabilisation distances. The bare shaft experiences a higher lateral drag acceleration and over a longer distance/time then the fletched shaft hence the bigger shift in travel direction.



Drag Effects

The drag effect were interested in is the change in acceleration of the arrow as a consequence of its rotating to what the 'normal' arrow acceleration would have been with no rotation. To simplify this am going to ignore the effect of gravity on the drag acceleration of the arrow and also ignore the drag effects on the arrow pile.

If the arrow shaft is at an angle **a** to an overall airflow of speed **S** then there is a drag force acting at 90 degrees to the shaft accelerating the arrow in some direction depending on the arrow's orientation in space and its current velocity. If the arrow leaves the bow with some rotational kinetic energy the angle **a** is dependent on the consequent angular velocity and will increase from about zero to some maximum angle determined by the fletching action (as above). If the surface area of the shaft contributing to this drag acceleration is **W** then the drag force on the shaft is proportional to $\mathbf{WSin^2(a)S^2}$ (with **W** being determined by the shaft length, diameter and the arrow FOC). If **dV** is the change in arrow linear velocity as a result of the arrow rotational kinetic energy over the stabilisation time **t** and the effective average acceleration of the arrow resulting from the rotation is **f** then **dV = ft**. To minimise the change in velocity from the launch kinetic energy what's wanted is to minimise the stabilisation time, the angle of rotation and the drag area contributing to the arrow acceleration. The higher the arrow speed then the higher the average acceleration also.

Combination of Fletching Effect and Drag

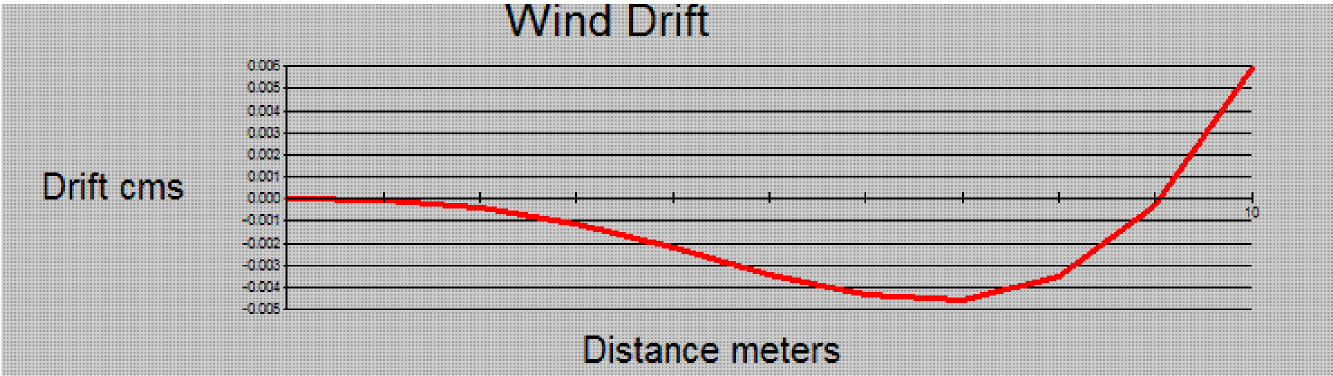
What constitues a 'good' arrow is one where its properties minimise the time and angle of rotation (fletching effect) while at the same time minimising the consequent drag acceleration resulting from the launch angular momentum (drag effect). We can look at the effects of some arrow properties to see how this works.

Arrow Diameter

Part of the shaft area contributes to the fletching area (FOC effect) so for the fletching action the larger the arrow diameter the better. As regards the drag acceleration the larger the diameter the larger the drag area so in this case the smaller the diameter the better. So whether a smaller or larger diameter is better as regards the change in velocity there is no definite answer. It's going to depend on their relative values (FOC being the driving force here). However as we can (in theory) always increase the fletching area by using larger fletchings the smaller arrow diameter is probably going to be the preferred option.

Arrow Launch Speed

As both the fletching action and the drag acceleration both depend on the square of the arrow speed at first sight it would appear that speed is fairly irrelevant.



However up till now we have ignored the pile drag. The ratio of shaft drag to pile drag acting to drag accelerate the arrow is proportional to the square of the tangent of the airflow angle **a**. So at launch (**a** =0) the pile drag is much greater than the shaft drag. As the arrow rotates the drag ratio rapidly changes so when the angle gets to around a few degrees the shaft drag exceeds the pile drag. The lateral drag acceleration from the pile is in the opposite direction to the lateral acceleration from the shaft so it offsets it. The above picture illustrates how the lateral arrow drift changes direction as the shaft drag becomes more important than the pile drag. The overall lateral arrow movement is still zero after about 9 metres. The result is that the higher the arrow launch speed the lower the change in the arrow velocity at stabilisation. There is a clear benefit in having a higher launch speed. (Note this means we should really revisit the Arrow Diameter issue as there is here a benefit from a larger arrow diameter). The simple way to increase launch speed is to have a lower mass arrow,

FOC

FOC initially appears to be a no brainer. The higher the FOC the larger the fletching area and fletching drag torque and so there's a clear benefit to the fletching aspect. The larger the FOC the shorter is the stabilisation time (higher potential energy storage per degree) and the maximimum value of the angle **a** is reduced so overall the lateral drag acceleration is reduced. However in practice to get a higher FOC you need a lighter shaft and/or a heavier pile so there are knock on effects to arrow mass, launch speed, moment of intertia, diameter and Uncle Tom Cobbley.

Arrow Mass

Don't go there! Changing arrow mass has knock on effects to just about everything

What the above illustrates is that you can't isolate any individual arrow property and say that changing X in some way is going 'to be better' in some way. Every arrow property is spaghetti entangled with every other property. It is only the behaviour of the composite arrow that really means anything. Having said that an arrow with a heavy pile, light shaft, small diameter, short arrow length and large fletchings is likely to acquire the minimum change in velocity through having launch rotational kinetic energy.

Tuning

If an arrow has angular momentum at launch then during the arrow stabilisation period the initial launch velocity is changed to a greater or lesser extent depending on the arrow properties. The obvious solution to this problem is to minimise the launch angular momentum in the first place by the the setup of the bow/arrow/archer system. The less angular momentum the arrow has at launch, for a given arrow, the less change in velocity we end up with at the end of the stabilisation process. Minimising launch angular velocity is what we mean by 'basic bow tuning'. Optimising the launch angular velocity to minimise groups i.e. 'group tuning' takes into account external sources of angular momentum into the arrow.

PRINCIPLES OF BOW/ARROW TUNING

Rick McKinney's book "The Simple Art of Winning" published in 1996 is the earliest reference I know of which made the correct connection between the alignment and rotation the arrow has when leaving the bow and the consequent effect on it's subsequent flight direction (called in the book "nodal planing"). The following pages attempt to put some technical substance to this topic hopefully leading on to a basic understanding of how the various tuning methods work and why the optimum "tuning" setup for a given archer/arrow/bow combination is dependant on target distance and wind conditions.

There is no "how to tune" guide contained here. There are lots of these around - some good, some not so good and some just plain silly. For what it's worth, in my view, the two best bow setup and tuning guides around currently are contained in "The Simple Art of Winning" - Rick McKinney and "The Heretic Archer" - Vittorio Frangilli.

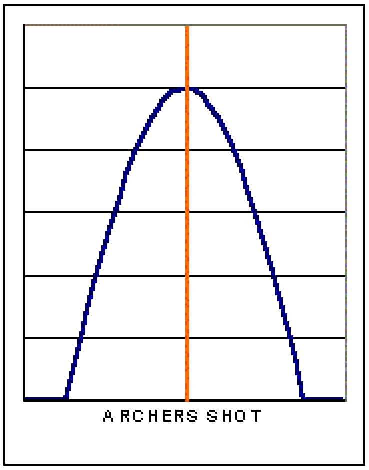
All archers indulge in some form of bow tuning (or setup). The bow and arrows we buy have some degree of tuning built into the design and the archer usually carries out additional modifications to the setup to improve the tuning. This discussion presents an overview of what tuning is, why it makes a difference and looks in particular at what archers generally mean by 'bow tuning', the control of the rotation the arrow has when leaving the bow.

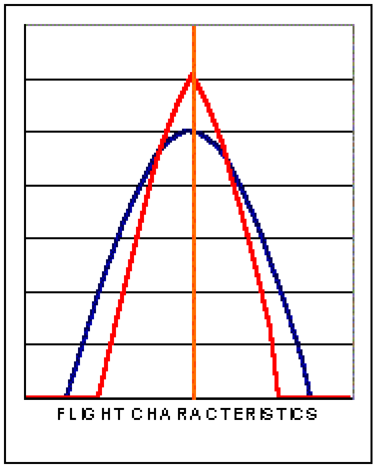
The following diagram is a schematic representing the elements resulting in an arrow hit on the target.

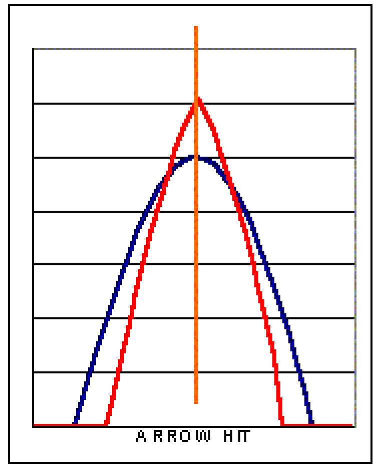
ARCHER ---> BOW/ARROW---> INITIAL FLIGHT PROPERTIES----->ARROW HIT

What determines where the arrow hits the target are the initial arrow flight properties (direction of travel, speed etc.) and the physical properties of the arrow (mass, length etc). If we replace the archer with a shooting machine which operates the bow/arrow system exactly the same way on each shot and the bow/arrow system responds exactly the same way on each shot then the initial arrow flight properties would be exactly the same on each shot. If all the arrows had exactly the same physical properties then every arrow would hit in exacly the same spot. In this case there would be no benefit to be gained from bow tuning.You adjust the shooting machine so the bow is pointing in the right direction to hit the target centre and then you get a perfect score.

Archers are not shooting machines (though some seem to get pretty close to it). The way the archer operates the bow each time will in some way be slightly different. As a consequence the operation of the bow/arrow system will be slightly different. The resulting initial arrow flight characteristics will be slightly different and as a result where the arrow hits will be slightly different. The following diagrams summarise what happens. In each graph the vertical axis represents the proportion of arrows shot.







The archer tries to make each shot exactly the same (like the shooting machine represented by the vertical orange line). The archer will vary round this perfect shot represented by the blue line in the 'Archers Shot' graph. Most arrows will be shot at or near the peak of the blue curve. The further away you get from the perfect shot than the lower proportion of shot arrows (you hope) you will get. The variation in the archers shot will feed through to a variation in the initial flight characteristics the arrow has leaving the bow (the middle graph) and a consequent variation in by how much the arrow misses the centre of the target (represented by the third graph). Strictly speaking the shape of the curve in the third graph should be like a letter 'M' rather than the bell shape illustrated. The probability of making a perfect shot and hitting the 'x' is actually very small (otherwise 'Robin Hoods' would be a daily ocurrence).

At the end of the day what we want is to produce the lowest variation in where the arrow hits (minimise group size). There are four mechanisms utilised to do this.

The first mechanism is designing the bow/arrow system to minimise archer's variability in the first place.(It is this area which many of the archery regulations are aimed to cover). Installing a mechanism to check draw length (a clicker or a draw stop) will reduce variation in draw length and hence variation in arrow speed. Using a back (peep) sight or a bubble level will reduce variablity in aiming. Installing a set of pressure sensors in the bow grip so that an LED lights up when you have the correct bowhand pressure would reduce bowhand torque.

The second mechanism is designing the bow/arrow system so that the variations in the archer's shot produce the minimum variation in the initial arrow flight characteristics. (This is why there are two curves in the middle graph above. The archer's shot variation can produce different distributions of the initial flight characteristics). What is usually termed 'arrow matching' is a prime example of this. Selecting the right spine/pile weight for a particular arrow length/draw force will result in less initial arrow rotation with a poor shot then selecting the 'wrong' arrow. Another example is using a long sight sidebar. The longer the sidebar then the less error there is in the arrow direction for a given archer misalignment of anchor point, head position etc.

The third mechanism, which relates to the arrow design only, is minimising the spread of arrow hits on the target for a given distribution in the intial arrow flight characteristics. (This is why there are two curves on the right hand graph. A given distribution of the initial flight characteristics can produce different arrow hit distributions (groups) on the target depending on the arrow physical properties). The obvious example of this was the change over from aluminium to carbon arrows with their smaller diameter, higher FOC etc. Everybodies scores went up (unfortunately not due to everybody suddenly shooting better). Playing about with the physical properties of the arrow to reduce groups is a form of tuning though that is not what is generally understood by the term.

The fourth mechanism is what is generally understood to be 'bow tuning'. The archer's perfect shot will result in a specific set of initial arrow flight characteristics and variations from the perfect shot will result in variations in the values of these flight characteristics. The question is 'are there specific values of the initial flight characteristics associated with the perfect shot that minimise the arrow hit distribution (group size) resulting from the archer's shot variability'. Let's take each of the initial flight characteristics in turn:

Direction

Divorcing direction from arrow speed, there is clearly an optimum direction in which the arrow should be travelling when it leaves the bow to hit the centre of the target. This direction will depend on target distance, an uphill or downhill target and the effect of wind. Direction however is defined by the archer at the time of the shot. Anything one can do to minimise the effects of variation in direction are covered by mechanisms 1 and 2 above.

Vibration

I don't see any mechanism (other then the physical bending of the arrow at short distances) by which the amount of vibration the arrow has will significantly effect the arrow hit variation with archer's variability outside what is covered by the arrow matching process of mechanism 2 above. The optimum is presumed to be the minimum amount of vibration amplitude in flight (hence minimising vibrational drag effects) compatible with good arrow clearance during the arrow launch.
There have been a number of reports that on completion of a fine (group) tuning process at 70m the bare shaft ends up hitting to the left of the fletched shafts (RH archer). Arrow vibration amplitude/associated drag effects possibly coupled with the arrow rotation characteristics is put forward as a totally speculative suggestion as to the cause of this phenomenon and therefore vibration may have some small influence on group sizes.

Speed

Don't know the answer to this one. The problem here is that as you change the arrow speed you have to change the properties of the bow and the arrow and other factors like the archer's physique enter into it. At short distances I don't think speed matters. At longer distances my guess is that a 'higher' arrow speed will reduce group sizes for a given archer's shot variability compared with a 'lower' arrow speed. Whether there is an 'optimum' speed I have no idea.

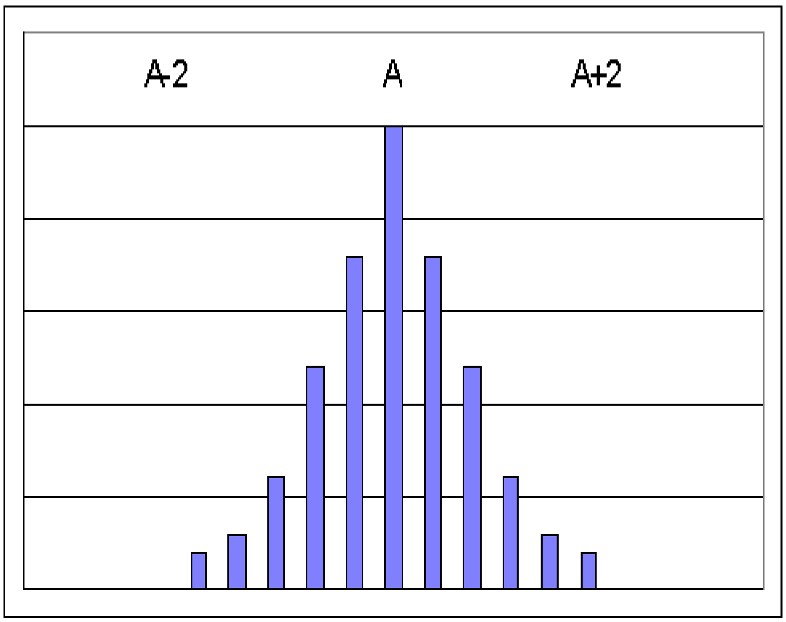
Alignment

By alignment I mean the angle between the direction the arrow is travelling and the direction the arrow is pointing (sometimes called Nodal Alignment). As discussed elswhere the arrow misalignment can only be a small value and it does not have a significant effect on where the arrow hits. Having said that, the arrow leaving the bow straight is preferable.

Rotation

Arrow rotation is usually split between horizontal rotation (pressure button tuning) and vertical rotation (nocking point tuning) so I will do the same. In practice an arrow only has rotation (the combination of the horizontal and vertical components) and as a bow is always shot at angle the horizontal component is not horizontal but lets keep things simple.

Horizontal Rotation (Pressure Button Tuning)

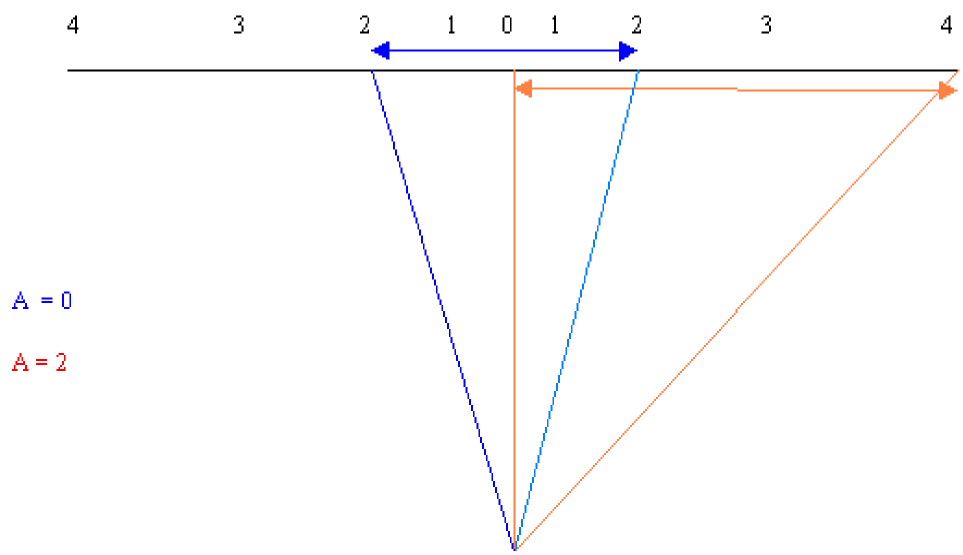


Suppose we have an archer who shoots lots of arrows with a specific bow/arrow combination. We mount a camera above him and record how much horizontal rotation each arrow he shoots has when it leaves the bow. If we then plot a graph of the number of arrows that came out against the amount of rotation the arrow has then we get something like the following.

The arrow rotation with the highest number of arrows (the high point of the graph) represents the archers average (perfect) shot and the spread around it represents how much the archer varies around his average. The shape of the distribution indicates how good, i.e. how consistent on the shot, the archer is. For our imaginary archer the amount of rotation of the average shot (maximum number of arrows counted) is at value 'A' and the archer's variation in the shot goes from values A-2 to A+2.

The variation in arrow rotation is dependant on the archer, the bow and the arrow. For a given archer/bow combination different arrows will result in differing variations in rotation e.g. one arrow might give a variation of A+5, A-5 while another might give a variation of A+2, A-2. A part of the tuning process is the selection of the best arrow match giving the lowest variation in arrow rotation (mechanism 2 above). This is usually done by using an arrow selection chart.

If an arrow leaves the bow with horizontal rotation it ends up hitting the target horizontally displaced by some amount. This displacement mainly results from the initial arrow rotation (angular momentum) and offset angle with a small contribution from the arrow fishtailing about. We do another test, this time measuring the amount the arrow is displaced sideways for a particular amount of initial rotation. The thing we would notice is the amount the arrow is displaced increases faster than the increase in the value of the arrow rotation. In other words the distance between the arrows shot with rotations of 3 and 2 is bigger then the distance between the arrows shot with rotations 2 and 1, and this is bigger than the distance between arrows with rotations 0 and 1 (The vaules 0-3 are just numbers to represent the relative amounts of rotation)



Suppose we give the archer a bow and some arrows and he shoots them. By accident the average rotation value "A" for this setup is 2. The rotations of the archer's arrows will vary between 2 + 2 = 4 and 2 - 2 = 0 (using the variations from the average that were measured in the first test). We then give the archer another bow/arrow combination to shoot with. This time by coincidence the average rotation value 'A' is 0. The arrow rotations for this setup vary from 0 + 2 = 2 to 0 - 2 = -2. The attached diagram illustrates the arrow spreads obtained with the two setups. As can be seen the smallest spread, or group size, is obtained when the average arrow rotation value 'A' is zero.

The minimum arrow spread (group size) is obtained when the average arrow leaves the bow with zero offset angle and no rotation. The purpose of basic bow tuning is to get the setup so that the archers most frequent (i.e. perfect) shot meets this criteria. The fact that it is a statistical process does impact on the merits of the various tuning approaches that have been proposed. You can speculatively take the argument one step further. If the distribution of arrow hits produced by the archer is consistent and has a bias in one direction or another then tuning to match the arrow hit distribution, i.e. tuning to fit the archer's variability, would in theory produce higher scores then the conventional zero rotation approach. (Otherwise known as group tuning).

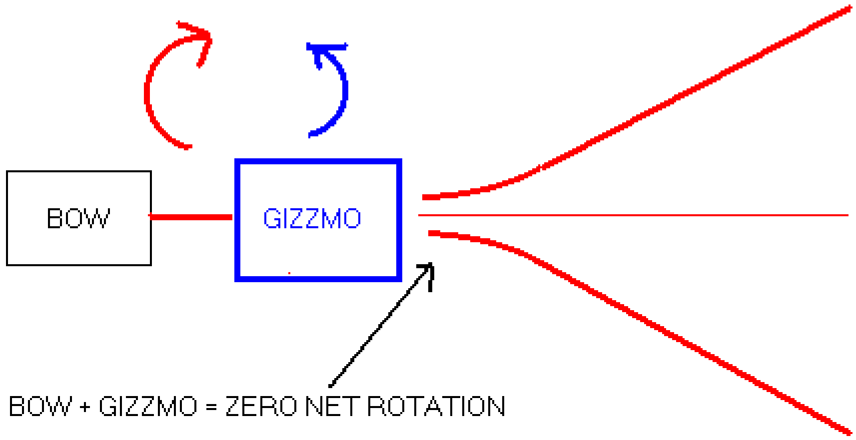
The fact that tuning relates to the archer's average and variation from it in shooting means that a statistical approach has to be applied to any tuning system. If you shoot one arrow though a paper sheet and it happens to be dead straight you can't just go off to celebrate. That arrow might be your 'A-4' arrow. A tuning approach either has to be based on looking at the same time at a lot of shot arrows like the test archer above or if the approach practically can only use a few arrows at a time, e.g. bare shaft tuning, it needs to be repeated lots of times and a composite picture built up.

A second consideration is the properties of the arrow itself. Sideways arrow movement type tuning approaches like bare shaft and walk-back relate to the variation of sideways drag force on the arrow with offset angle. The arrow weight, speed, rotational characteristics and diameter will affect how sensitive the tuning process is to the offset angle. For example compare bare shaft tuning with an ACC carbon arrow and an aluminium arrow. If we shoot the bareshaft carbon and aluminium arrow with the same initial offset angle and rotation, all other things being equal, the gap between the fletched and bare shaft arrows will be much larger for the aluminium then for the carbon arrow. The carbon arrow will probably have a higher FOC then the aluminium arrow resulting in faster arrow rotation. The sideways drag on the aluminium arrow will probably be greater than for carbon arrow because of the larger arrow diameter. It will be much easier to fine tune the aluminium arrow than the carbon.

There are two additional points to be made with respect to pressure button tuning which to some extent invalidate what has just been said.

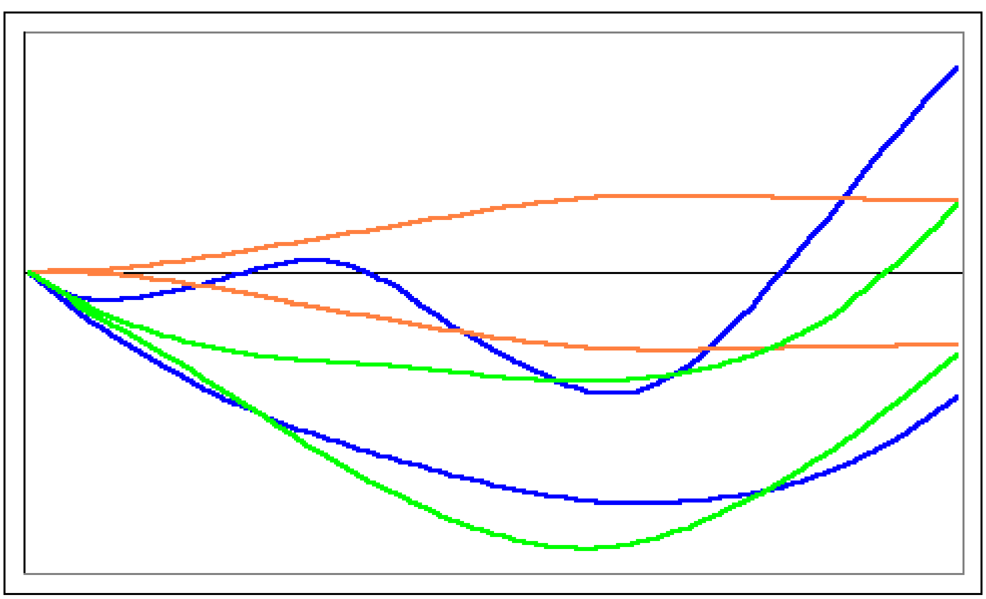
The first point is arrow stabilisation. When an arrow is shot with horizontal rotation it initially 'swerves' until the effects of ths initial rotation are taken out by the fletching action. It obviously 'depends' but for your typical arrow (unless you are one of those archers who fit windmill sails on the back) it takes somwhere around 15-20 metres for the arrow flight to stabilize. At longer distances this doesn't matter but if you are shooting only 18 metres indoor the arrow is basically 'swerving' right up to hitting the target. The optimum tuning set up for short distances may be found to be different from the optimum tuning set up at longer distances.

The second point is that the assertion that the perfect shot should have zero rotation is based on the assumption that there is no external influence which affects arrow rotation between leaving the bow and hitting the target. Suppose as per the following diagram there is some 'magic gizzmo' located in front of the bow which adds angular momentum (rotation) to the arrow.



If the arrow leaves the bow with no rotation then it leaves the gizzmo with rotation and hence the group size increases. If instead we adjust the bow so that the arrow leaves with just the right amount and direction of rotation to balance the gizzmo then it leaves the gizzmo with zero rotation and we get the minimum group size again. The general principle is that if there is something acting to change the arrow rotation between leaving the bow and hitting the target then the optimum tuning setup for the bow will not be zero arrow rotation. The optimum rotation of the arrow from the bow will be that which best counteracts the external influence to provide minimum group size. As any 'gizzmo' will in reality act over the whole arrow flight it is not possible to completely compensate for it, only minimise the increase in the sizes of groups.

Any wind acts like a gizzmo changing the arrow rotation. When shooting in a wind therefore it follows that the optimum initial arrow rotation (the button tuning) in terms of group size becomes dependant on wind strength, wind direction and the distance to the target.



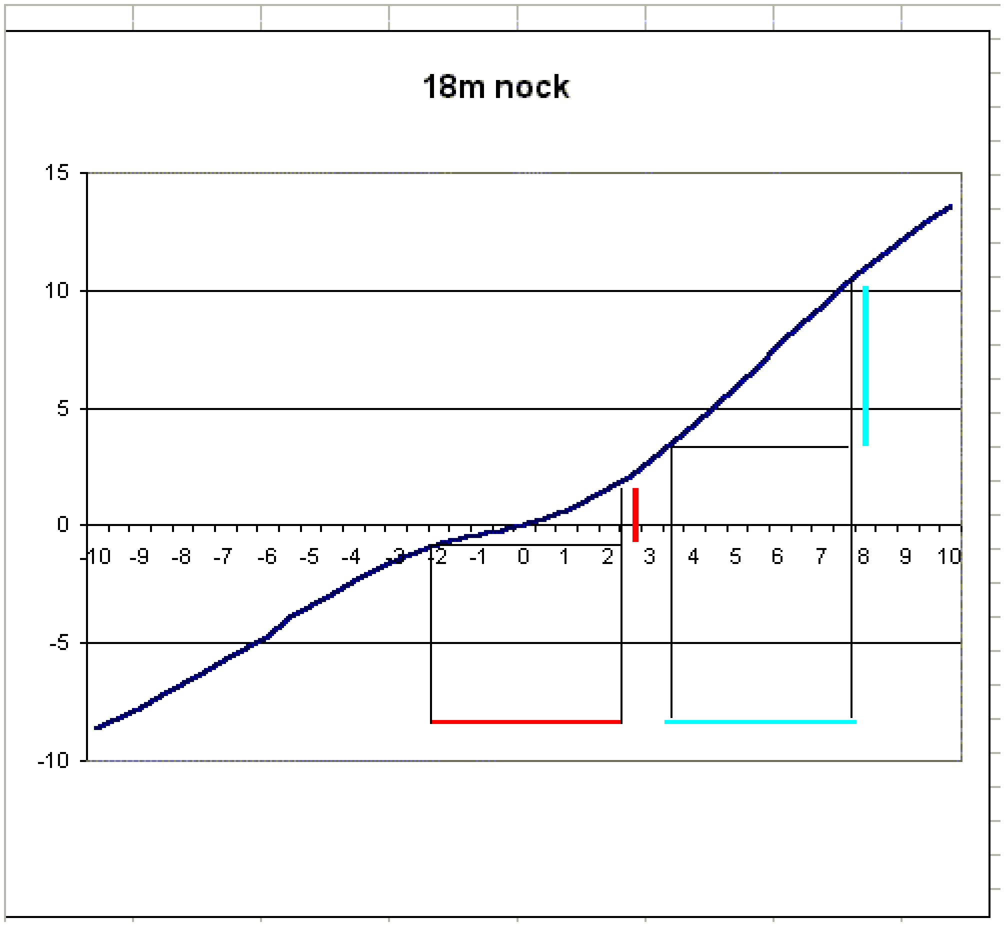
The diagram illustrates the affect of a cross wind on arrow group sizes. The red lines indicate the flight paths and resultant group size for a representative archer with a perfectly tuned bow with no wind present. The blue lines indicates what happens in a cross wind to the same conventionally 'zero rotation tuned' archer/bow setup. The group size increases significantly. Most of the increase comes from the arrow (the zig-zag blue line) that comes off the bow with the nock end rotating into the wind. In this case the sideways drag force from the arrow's forward motion reinforces the sideways drag from the wind at a number of points during the arrow's flight and as a consequence the arrow ends up with a high downwind lateral displacement. The green lines show the flight paths and group size for a bow optimally tuned for the wind conditions and target distance. In practice you cannot optimally tune the bow for the current conditions. As a general guideline a good setup when shooting in a cross wind will require the arrow to leave the bow with the nock end rotating in the downwind direction. The key to having good groups in a crosswind is to avoid the sideways drag on the arrow from its velocity reinforcing the sideways drag on the arrow from wind. This topic is discussed in more detail in the section on Variable Tuning

Vertical Rotation (Nocking Point Tuning)

Much of the discussion relating to horizontal rotation applies equally to vertical rotation. There is one key difference in that in the vertical plane there is always an external force affecting arrow rotation - Gravity. Because the gravitational acceleration results in the rotatation of the arrow there is no optimum value for the initial vertical rotation of the arrow, it becomes a function of distance (time of flight and launch angle) as well as the arrow rotational properties. The basic tuning setting of zero vertical rotation for the arrow leaving the bow, although it works well for short distances will probably become increasingly unstuck as the target distances increase. In the case of wind the bow tuning is adjusted so that the arrow leaves the bow rotating in the same sense as will result from the action of the wind on the arrow.If you regard gravity as acting like a wind that always comes from one direction then gravity always rotates the arrow in the sense of pile down and fletching up so that should be the rotation direction of the arrow at launch resulting from the nocking point position. (Effectively a paper tune should show the fletching going through the paper slightly higher than the point). This makes the relative positions of the bare shaft and the fletched shaft somewhat unclear as far as nocking point tuning using the bare shaft method goes. At longer distances the bare shaft will hit higher than the fletched shaft (higher launch speed and higher initial lift force). At short distances as the arrows are launched rotating pile down the bare shaft will get less lift than the fletched shaft so it's maybe possible for the bare shaft arrow to hit lower than the fletched shaft. It will depend on a combination of factors.

It is not possible, short of having a height adjustable button/arrow rest assembly, to adjust vertical arrow rotation on the fly and any adjustment is limited by the arrow interaction with the arrow rest. So the general nocking point tuning guidlines (assuming you don't group tune) runs something like a) at short distances go for a zero rotation tune (bare shaft impacts same height as fletched shaft) and b) at long distances have the bare shaft impacting slightly above the fletched shaft. This of course assumes that there is no headwind/tailwind component which will also effect arrow rotation in the vertical plane. Short of having a set of strings with different nocking points for different distances and wind conditions then you end up with a some compromise nocking point setting. I'm told (before my time) that it was once fairly common practice for archers to use different strings with different nocking points at different distances. The practice seems to have died out.I suppose this is because arrows these days are faster/more forgiving and competition distances have essentially reduced to 70m and 18m.

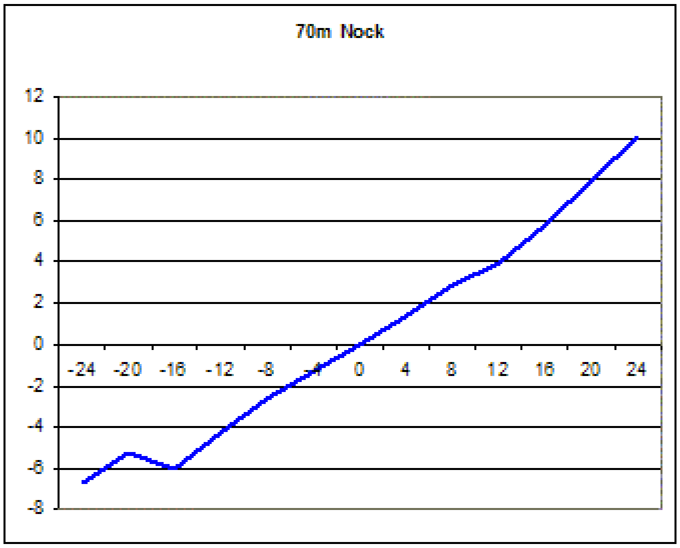
The sections on Variable Tuning - Distance and Flight Instability relate to the nocking point tuning subject.The following graphs illustrate how the effects of gravity affect the basic principle of tuning as described above.



The graph represents the vertical displacement from the target centre (vertical axis) as a function of the amount and direction of rotation in the vertical plane of the arrow leaving the bow (the horizontal axis) at a target distance of 18 metres.. The data is produced using the arrow flight simulator for a specific set of arrow properties. A negative rotation represents a high nocking point (bareshaft impacts below fletched shaft) and a positive rotation a low nocking point. The red and turquoise horizontal bars represent the arrow rotation for the 'perfect' shot (rotation 0 and 6) and the width of the bar represents the variation in rotation from how much the archer varies from the perfect shot. The corresponding vertical coloured bars indicate the vertical spread (group size) of where the arrows hit resulting from the archer's variation. I have ignored the fact that the turquoise archer will adjust his bowsight so that his perfect shot has zero displacement from the target centre which will have some effect on his group size.

The overall shape of the curve through the zero displacement point is 'S' shaped. If the curve was a straight line then whatever the arrow rotation was for the perfect shot the group size would always be the same. In fact the group size for the archer with zero rotation for the the perfect shot is smaller than for the archer with perfect shot rotation of 6.

If there was no influence on arrow rotation after the arrow had left the bow then the curve would be symmetric about the zero displacement point and there would be a clear optimum setting for the nocking point position. The effect of gravity results in the curve being assymetric. At 18 metres the effect of gravity is small but you can see from the simulation that the curve risers faster with a positive rotation (low nocking point) than it does with a high one. The arrow (vertical) groups will for an average archer (wide-ish bar) be smaller if the nocking point is slightly high (bare shaft maybe impacts below fletched shaft).



The 70 metres distance graph is generated in similar way to the 18m graph except it uses the Drift simulator. The curve still shows the arrow displacement rising faster with a positive arrow launch rotation. In this case the bare shaft arrow will invariably hit higher than the fletched arrow.

The model produces an interesting dog leg (in this case at a -1.6 rads/sec launch angular velocity) which occurs at a very clear "magic" point regarding the arrow flight parameters. Any suggestions about this point any whether it might relate to the "optimum" tuning setup would be welcome.

When it comes to setting a nocking point where you are going to be shooting different distances, e.g. a Fita round, then the only option is to look at the group sizes at the different distances and come up with the best overall compromise setting.

Tuning Principles - The Bow Aspects

It has been pretty much an 'open season' in recent years about inventing explanations for bow tuning. We've had arrow alignment, nodes, purple elephants, arrow vibration etc. None of these 'explanations' have agreed with known factual data or complied with Newtonian mechanics.

The above discussion shows that bow tuning is all about controlling the angular momentum (rotation) that the arrow has when it leaves the bow. For 'basic tuning' the bow is adjusted so that for the average shot the arrow leaves the bow with zero angular momentum. For 'group tuning' the bow is adjusted so that the amount and direction of arrow rotation for the average shot is that which results in the tightest groups. Arrow angular momentum on leaving the bow results from the overall torque generated on the arrow during the power stroke. What is termed 'bow tuning' is therefore all about adjusting the torque input into the arrow from the bow.

The archer has two basic arrow torque controls at his disposal the nocking point position (torque in the vertical plane) and the plunger button settings (torque in the horizontal plane).There are alternative methods of torque adjustment e.g changing draw weight but nock and button are the conventionally used controls.

How the nocking point position affects torque input into the arrow is fairly obvious, the higher the nocking point the more torque is generated by the string re rotation in the vertical plane in the point going down direction and vice versa. Torque adjustment is made by moving the nocking point up and down in response to the arrow behaviour in whatever tuning method you are using.

How the button effects arrow torque is more complex (and as yet not undersood in detail). Looking down on the bow and assuming a right handed archer then the following torques act on an arrow during the power stroke;

- The finger release and the string force on the arrow generate a clockwise torque on the arrow in the initial part of the power stroke.(the button centreshot position varies the magnitude of this initial torque).
- The force between the arrow and the plunger button generates an anticlockwise torque on the arrow. (This force also generates a bending moment on the arrow which complicates things)
- The torsion spring effect of the limbs generates an anticlockwise torque on the arrow throughout virtually the whole power stroke
- The string force on the arrow will generate an anticlockwise torque on the arrow in the latter part of the power stroke
- The string separation of the arrow from the nock can generate either a clockwise or anticlockwise torque on the arrow depending the how the arrow behaves. Minimising nock - string torque is part of the tuning process.
- The stress/strain behaviour of the arrow itself can generate torque on the arrow

These torques are interdependant but fortunately the archer doesn't have to be concerned with the detail only the end result of having zero arrow rotation on bow exit. Centreshot position is a coarse adjuster of arrow torque. Increasing centreshot increases the overall anticlockwise torque on the arrow decreasing centreshot decreases overall anticlockwise torque. The required centreshot position is defined as reducing overall torque on the arrow to the point where arrow torque control becomes within the control of the pressure button spring adjustment. Centreshot position has nothing to do with 'arrow alignment' as is often quoted. Alignment of a bent stick doesn't mean anything anyway. The pressure button spring is the fine arrow torque controller. Increasing spring pressure increases anticlockwise torque on the arrow and vice versa. The final test that a correct setup has been attained whatever tuning methodology is used is that the button spring is in control of the arrow torque. e.g. with bareshaft tuning you must be able to move the bareshaft hit position from left to right of the fletched arrow with button spring adustment. If you cannot do this then the centreshot position is incorrect

Summary

The sources of angular momentum into the arrow comprise:

Horizontal rotation

- Movement of arrow nock by action of the fingers on release
- Bow hand position (torque)
- String force on the arrow nock (buckling)
- Force on the shaft from the pressure button
- Torsional spring effect from the bow
- Separation of nock from the string

Vertical rotation

- Pressure distribution of the string fingers
- Bow hand position (torque)
- Reaction between arrow shaft and rest
- Nocking point position
- Vertical string forces on the arrow nock (limb movement variablity)
- Separation of nock from string (maybe?)

The items above for the effects of the bow and string hands really relate to the archer's technique and the bow parameters are adjusted to include the effects of 'form'. The normal controls used to vary the net arrow angular momentum are the nocking point position and the plunger button spring tension. These are adjusted using some systematic process (the tuning method) to obtain zero angular momentum or minimum arrow groups. By selecting the correct arrow specification for the bow in the first place the arrow will leave with near zero angular momentum and only fine adjustment is required.

BUTTON TUNING STRATEGIES

Introduction

For the majority of recurve archers 'how to pressure button tune' becomes a choice between a walk back approach or a bareshaft approach. The following is brief discussion of why I think that a sensible walk back tuning method is the best approach. (opinions of course may vary).

For pressure button tuning to be a painless experience I believe two requirements are needed.

1. The correct arrow must be selected in the first place.
2. The archer should understand what he's doing when tuning.

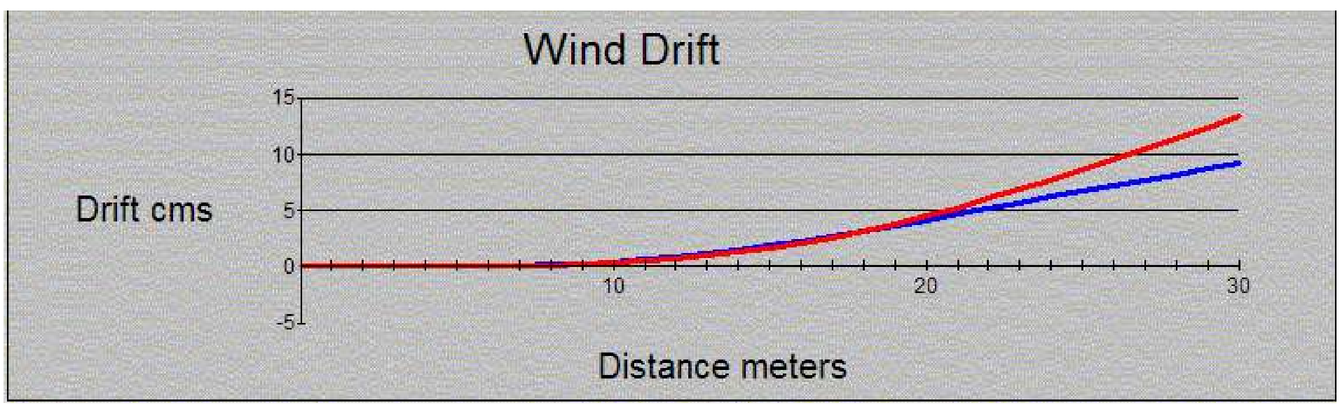
The first point is fairly obvious but in practice I think causes a lot of problems. You often see advice about changing pile weight, brace height nock point weight etc. in order to turn a bad arrow selection into a tuneable arrow, but this is usually suggesting rearranging the deck chairs on the Titanic. Only real way of turning the wrong arrow into a tuneable arrow is to change arrow length or draw weight, only in rare cases a practicable option.

Re point 2, although there are many 'how to tune' guides around you get the impression that many of them were written by people who had little or no understanding of what tuning is actually about. As a result there are lot of 'alchemical recipes' around which are either over complex, ambiguous or just plain nonsense. You get a series of steps which for an individual seems overall to work but no recognition that step 14 which involves locking up a pressure button or standing on one leg with a bag over your head serves no useful purpose and isn't actually necessary.

All tuning methods are used to determine the amount and direction of rotation the arrow has at launch. With the walk back method this is done by directly determining whether the arrow travels in a straight line in the vertical plane from launch to target. With the bareshaft approach you estimate both the amount of arrow rotation (gap between fletched and bare shaft) and direction of arrow rotation (bare shaft left or right of fletched shaft). When choosing between the two methods the criteria has to be which method is the most sensitive i.e. which method will get me closest to a perfect button setup.

The sensitivity of a button tuning method is going to depend on the properties of the arrow (weight, fletching size etc.). In the following example I'm assuming a 'typical' target arrow, a 29" ACE-570. The bow is fairly poorly tuned. In practice whether using a walk back or bareshaft method a number of arrows will be shot and the centre of the group determined. The group centre is assumed to be the point where the perfectly shot arrow would hit so it depends solely on the bow setup not on the archer. Of course how accurately you can determine the centre of the group does depend on the skill of the archer, so there is always some limitation on how accurately you can tune.

The following two graphs compare the sensitivity of the walk back and bareshaft approaches at 30 metres and 70 metres for the same tuning situation. The blue line represents the flight path of the perfectly shot fletched arrow and the red line the flight path of the corresponding perfectly shot bareshaft arrow. The horizontal axis is the distance and the vertical axis the horizontal displacement of the arrow.

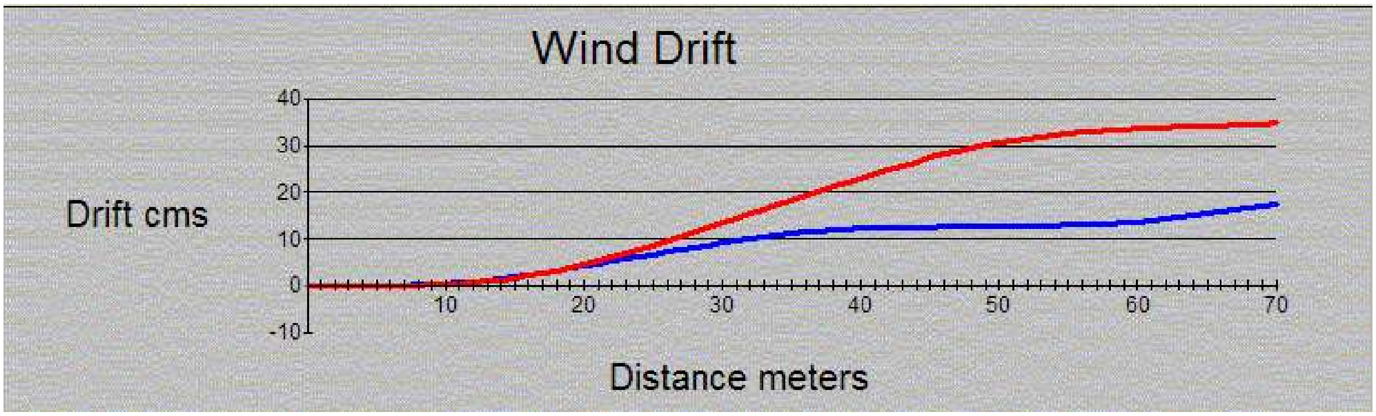


The first obvious point you can see from the 30 metre graph is that trying to bareshaft tune this arrow at around 20 metres would be a complete waste of time as the bareshaft and fletched arrows would be in the same group almost irrespective of the tuning. All that will happen as you change things is that the bare/fletched arrow group will move around the target face.

With a walk back approach the distance the fletched arrow is from centre at 30 metres is around 9cm to the left. This distance is probably identifiable with an average archer's group size.

With a bareshaft approach the bareshaft is hitting about 4cm to the left of the fletched arrow, maybe just about identifiable by the average archer.

Clearly for these arrows at 30 metres the walk back approach is more sensitive and the arrow hits less likely to be misinterpreted than using the bareshaft approach.



At 70 metres distance with a walk back approach the fletched arrow hits about 18 cms to the left of centre. With a bareshaft approach The bareshaft arrow hits around 17 cms left of the fletched arrow. So the two approaches in terms of group centres have about the same sensitivity.

Point to bear in mind is that the group sizes at 70 metres will be larger than the group sizes at 30 metres and that the bareshaft groups will be proportionally larger than the fletched arrow groups. For the average archer grouping fletched arrows at 70 metres is not (much) of a problem. To group bareshaft arrows at 70 metres you have to be pretty good. Overall the advantage still goes to the walk back approach.

It is perfectly feasible for an archer, at shorter distances, to use both walk back and bareshaft methods at the same time, just shoot a bunch of both bareshaft and fletched arrows using the controlled bow alignment you need for a walk back. You get both the fletched and bareshaft group centre positions at the same time so you can use the two apporaches to verify each other. Going to longer distances you just drop the bareshaft at the distance relevant to your skill level.

A third alternative is to use bare shaft arrows for a walk back tuning method. This has a higher sensitivity then the fletched arrow alternative. So for the 70 metre case the bare shaft sensitivity re walk back is about twice that of the fletched arrow. (although in the example presented a lot of the bareshaft arrows would probably miss the target making defining the group centre difficult).

On a practical level although the above suggests a walk back approach to be the more sensitive it is a technically more difficult tuning method. The bare shaft method is technically simple, quick and if you can move the bareshaft across the fletched arrow using spring adjustment only gives an unambiguous result. A lot of things can go wrong with a walk back approach. Because it requires shooting arrows at a distance, say 70/90 metres, any errors resulting from a misaligned sight bar, variable head position or anchor point and the archers own arrow spread at distance make the results uncertain. What I do when basic tuning, the practical bottom line, is do a 30m bareshaft tune and follow this up with a walk back approach at point blank, 30m and 70m distances. Any long distance lateral deviations which can sensibly be assigned to the setup rather than the archer or wind are then corrected with a small adjustment to the button spring. Always bear in mind that a basic tuning approach will only result in a reasonable setup, quite a long way in absolute terms from perfection though for 90% of archers perfectly adequate for their level of skill.

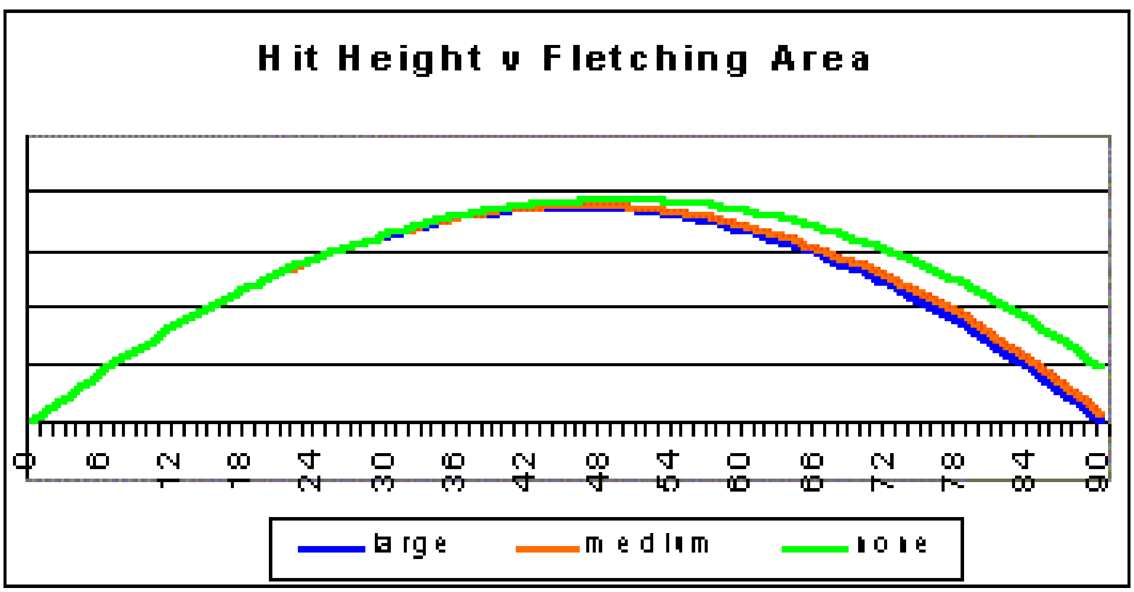
BARE SHAFT TUNING - ARROW ROTATION

Introduction

Bare shaft tuning is a method frequently used to adjust the nocking point and pressure button settings to 'tune' a bow. Enough has been written about bare shaft tuning to fill a large warehouse so I am not going to describe the methodology but rather describe the principle of the approach.

Invention of the bare shaft tuning method is credited to US Archer Max Hamilton in 1963 (Third Edition of the National Archery Association Instructor's Manual published in 1982).

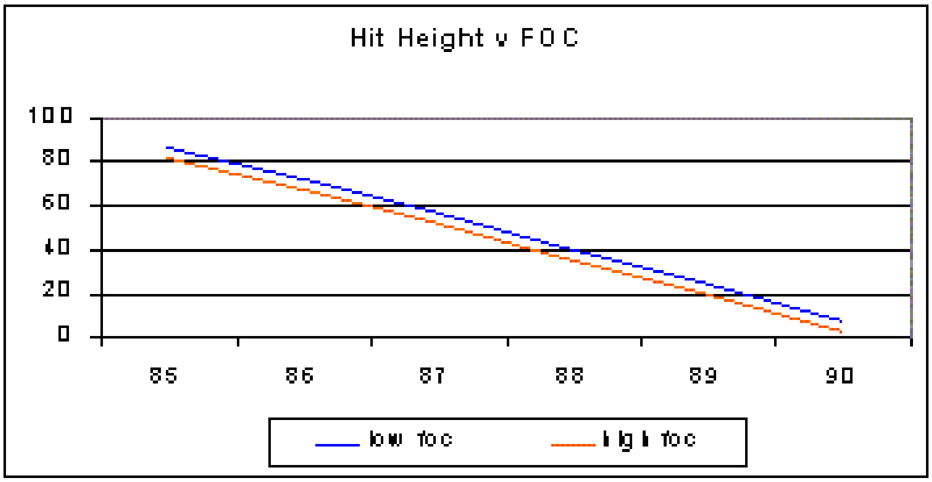
Suppose we shoot three arrows exactly the same at some distance, e.g. 90 metres, with identical arrows apart from the fletching size. One arrow has a 'large' fletching, one arrow has a fletching half the size of the large fletching and one arrow with no fletching. The fletchings are assumed to be of the plastic variety. The trajectories of the three arrows would be something like that below.



The arrow with the largest fletching hits lowest. The medium fletched arrow hits a bit higher and the bareshaft arrow hits quite a lot higher. The separation in height between the arrows happens in second part of the flight, on the way down.

The height difference between the arrows is often explained as being caused by the larger fletching having more drag slowing the arrow down. This is a bit of a myth. If it were true there would be a much larger difference in hit height between the medium fletched arrow and the large (twice the area) fletching. The amount of drag depends on the drag area. The drag area of a fletching which slows the arrow down is the 'edge' profile, say around 0.3 square cms for plastic vanes. Compare this with the area of the shaft at around 40 square cms. The drag on the shaft swamps the fletching drag.

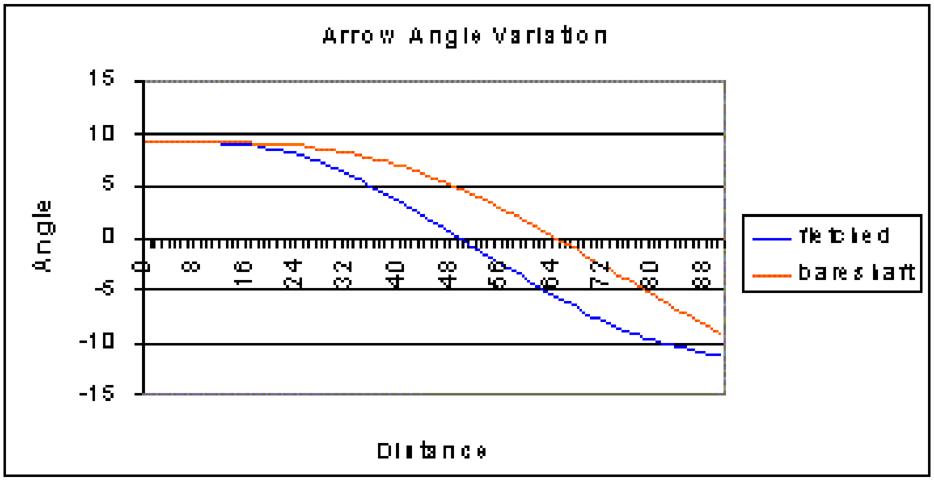
Suppose we shoot two arrows, again identically. The arrows are exactly the same (weight, fletchings etc.) apart from having different FOC values. The (last part) of the trajectory is illustrated below.



What you get is that the higher the FOC of the arrow, everything else being the same, the lower it hits on the target. In this case it is obviously not 'fletching drag' causing the difference in height.

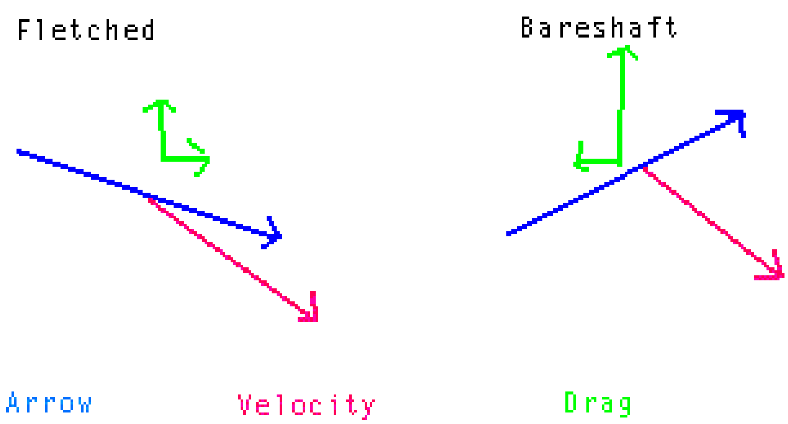
What dominates how an arrow files is the magnitude and direction of the total drag force on the arrow which moves it about of which a significant component is the drag force on the arrow shaft. The magnitude and direction of the shaft drag force depends on the angle between the direction the arrow is pointing and the direction the arrow is travelling.(ref) When you shoot an arrow at say 90 metres the arrow starts off at an angle around 9 degrees (the bow angle). The arrow hits the target at an angle around minus 9 degrees i.e. the arrow rotates in the vertical plane during its flight through an angle of around 18 degrees. What rotates the arrow is the drag force on the fletchings and a section of the shaft so how fast the arrow rotates depends on the area of the fletchings and the FOC as well as the angle between the direction of flight and the direction the arrow is pointing. There is always a lag between the direction the arrow is travelling and the direction the arrow is pointing, the larger the fletching/FOC the smaller this lag is. As the shaft drag depends on this lag it is this lag, which depends on how fast the arrow rotates, which causes the difference in hit heights shown above.

The following graph illustrates how the angle of where the arrow is pointing varies over its flight. (the medium and bareshaft arrows as per the first diagram are used).



Both arrows start off at the same angle, which is also the initial direction of flight. During the first part of the flight the bare shaft 'rolls over' much more slowly then the fletched arrow. The fletched arrow becomes horizontal at around 49 metres, not long after the arrow starts to fall down. The bareshaft arrow does not become horizontal till about the 64 metres distance. During the last part of the flight the bareshaft arrow is rotating a lot faster then the fletched arrow so the two arrows end up hitting the target at fairly similar angles.

The following diagram represents the drag forces on the fletched/bareshaft arrow shafts on the way down at some specific distance to illustrate why the slower rotating arrow ends up hitting higher on the target. (the direction of the drag force from the pile and edges of the fletchings always runs along the shaft axis).



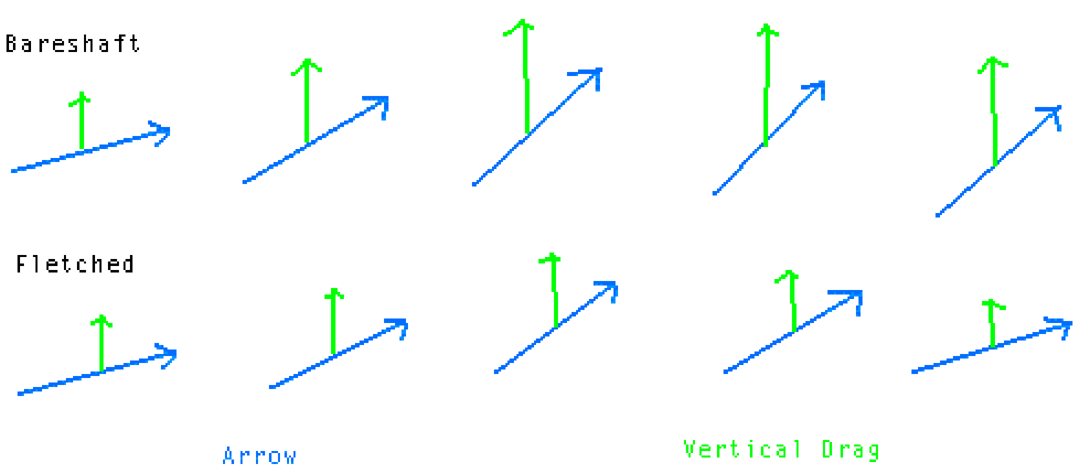
The bareshaft arrow because it has a much larger offset angle then the fletched shaft has a much larger shaft drag. The drag direction is mainly upwards so the rate of fall of the bareshaft arrow is slower than the fletched arrow. This is why the bareshaft arrow ends up higher on the target. The larger the offset angle the more drag there is acting to rotate the arrow which is why the bareshaft arrow ends up rotating faster than the fletched shaft.

Arrow roll-over also relates to how wind affects the hit height of the arrow (ref).

What has all the above to do with bareshaft tuning? With bareshaft tuning you look at the relative hit positions of a fletched and bareshaft arrow vertically (nocking point) and horizontally (button). The reason the two arrows hit at different points is for reason just described, the bareshaft arrow rotates slower than the fletched shaft.

Nocking Point Tuning

Nocking point tuning is aimed at getting the arrow out of the bow with no arrow rotation in the vertical plane. If the arrow comes out with rotation then what the fletching is doing is braking this rotation. The less fletching you have then the less brakes you have so getting rid of the rotation takes longer with the bareshaft arrow than with the fletched arrow. The following diagram illustrates the different braking effect you have between a fletched and a bareshaft arrow and the consequent effect on how shaft drag affects the arrow flight.



In this case the nocking point is low so the arrow rotation is in an anticlockwise direction. Because the fletched arrow rotates faster than the bareshaft arrow it accumulates much less shaft drag in the upwards direction and so ends up hitting lower on the target.

Because, as indicated in the introduction, the bareshaft arrow will end up hitting above the fletched arrow because of the effect of the 'gravitational trajectory' you can only nocking point tune at short distances.

Button Tuning

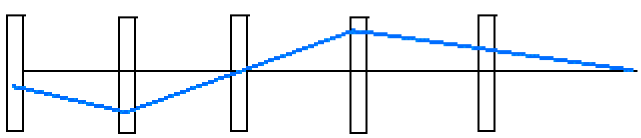
Button tuning is aimed at getting the arrow out of the bow without any rotation in the horizontal plane. The effect is exactly the same as for nocking point tuning described above. (just rotate the diagram through 90 degrees). The only difference is that because there is no horizontal gravity you can button bareshaft tune at any distance. Button tuning with a bareshaft approach at 70/90 metres is likely to be the most sensitive tuning method available to most archers. Unless you want to spend a lot of time looking in the grass for arrows however you need be a reasonable competent archer and have a reasonable bow setup to start with.

Combined Tuning

The recommendation when bareshaft tuning is first get the nocking point sorted and then tune the button. There is a reason for this. The settings for nocking point and pressure button are not independant of each other. If you change the nocking point then the effective button setting will be changed and vice versa. The reason the nocking point is adjusted first is because, for basic tuning, it's the less important. As mentioned in the section on Tuning Principles the optimum nocking point position depends on the target distance so you only ever have a 'thereabouts' setting. Ignoring wind effects, there **is** an optimum button setting and group sizes are more sensitive to the button setting than the nocking point. If you determined the button setting first and then adjusted the nocking point then the result would be the more critical button setting being 'off'.

WALK BACK TUNING

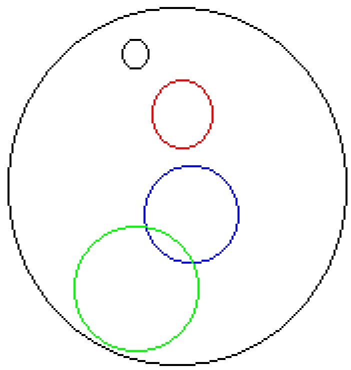
When you shoot an arrow it is not possible to see the details of how the arrow flies as it's going too fast and because of the distance and perspective. The walk back approach is a method of looking at the the flight of



arrow flight path

the arrow through the air.

When you shoot an arrow, where it hits the target is where the arrow is in the air at that particular distance. If you shot an arrow through a set of paper sheets, as illustrated, then the holes in sucessive sheets would give you a record of the arrow flight. Another, practical way, to do much the same thing is to have a fixed target and for the archer to shoot sucessive arrows at increasing distances. What defines the approach as a walk back is that the aimed at point is the same for all distances. The arrow pattern on the target is a record of the arrows' flight through the air. Note that there is in reality no actual point on the target which the archer is trying to hit. The 'target' if any is the centre of the group for the arrows at the longest distance. Because the arrow pattern is derived not from a single arrow's flight but from a number of different shots (and each shot by the archer is invariably going to be slightly different) you cannot look at a single arrow set pattern but have to look at the pattern of arrow groups at each distance.



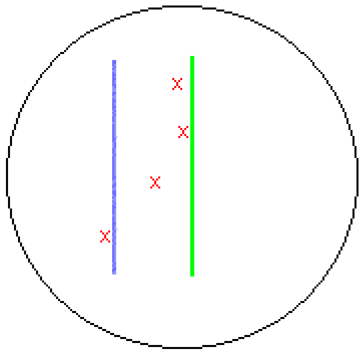
Assuming you aim at the same point on the target at each distance you end up with something like the following;- the arrow groups will tend to get larger and hit lower on the target with increasing distance and the left to right movements of the groups represents, for a non tuned bow, the effect of the arrows' fishtailing/porpoising.

Having got a visual picture of how the arrows fly can anything useful be got from it?

The first description of using a walk back approach for bow tuning I am aware of was in a pamphlet, 'Bow Tuning', by Roy Matthews published in 1984. The 'theory' described is that the shape of the arrow pattern on the target indicates to the archer whether an adjustment to the pressure button position or spring tension is required and in what direction to improve the tuning of the setup. Following Matthews' description of the idea is a comment that boils down to that at least for him the idea doesn't work. Whatever its origin, the idea that you can determine whether a change in button position **or** spring tension to tune the setup can be determined from a walk back arrow pattern is nonsense. As mentioned in the introductory section on arrow flight you can't tell from how the arrow flies whether or not the bow even has a pressure button fitted let alone discriminate between the effects of button position or spring tension. Despite the fact that it doesn't work this tuning method has proved remarkably durable in terms of being put forward as a viable method in archery magazines, catalogues etc.

My guess is that the origin of the walk back pattern-what you do with the pressure button myth originated as a piece of false logic. If you have a perfectly tuned bow then the arrow pattern is a straight line down the target. As you mistune the bow more and more then the arrow pattern you get becomes more and more curved. A 'tweak' of the button position will mistune a bow more than a 'tweak' of the spring tension. So if you start with a perfectly tuned bow you get a more curved pattern if you change the button position then if you change the spring tension. The false logic is reversing this observation - if I change the button position (from tuned) it gives me a curved pattern, therefore if I have a curved pattern changing the button position will give me a tuned bow. This cock up is usually presented as "a cow has four legs, therefore everything with four legs is a cow". Anyone you see trying to milk a table is likely to be an archer who advocates this walk back tuning approach.

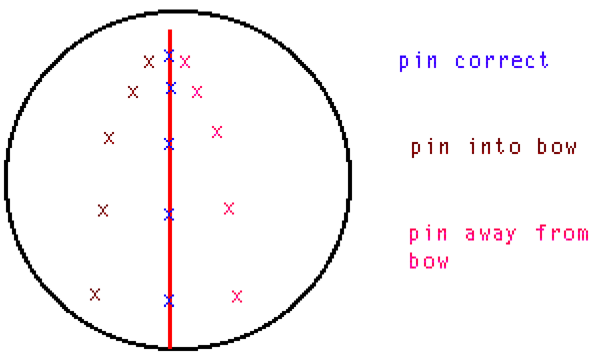
In order to get anything out of a walk back arrow pattern we need to start with a viable pattern in the first place and this requires establishing the pattern baseline and having the correct setup for the bow sight and the mark aimed at.



The baseline is where the vertical plane corresponding to the string running down the centre of the (vertical) bow limbs cuts the target. Unless the arrow pattern is looked at with reference to this line then the pattern can be misinterpreted.

In this and following diagrams the 'x' represents the centre of the arrow groups at different distances. The baseline for this pattern could be anywhere e.g. the blue and green lines. The pattern needs to be looked at with respect to the right baseline. The top of the baseline represents where the arrow would hit at no distance.Looking at the pattern with respect to the first (highest) arrow hit is meaningless.

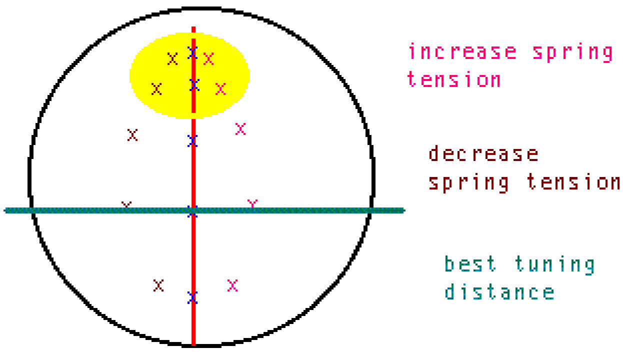
The sideways position of the bowsight should be such that the pin lies in the plane of the baseline i.e. with the string centred on the bow limbs the string should 'cut' through the pin.



This results in the baseline being a line dropped vertically from the mark being aimed at on the target. Any sideways movement of the pin away from this position will have the effect of a rotational distortion of the arrow pattern on the target. e.g. suppose you have a perfectly tuned bow and the pin in the correct position. The arrow pattern will be a straight line down the target. If you screw the the pin in towards the bow (RH archer) and repeat the walk back then the arrows will hit increasingly more to the left as the distance increases. The following diagram illustrates the effect. - lots of different arrow arrow patterns and all with a perfectly tuned bow!

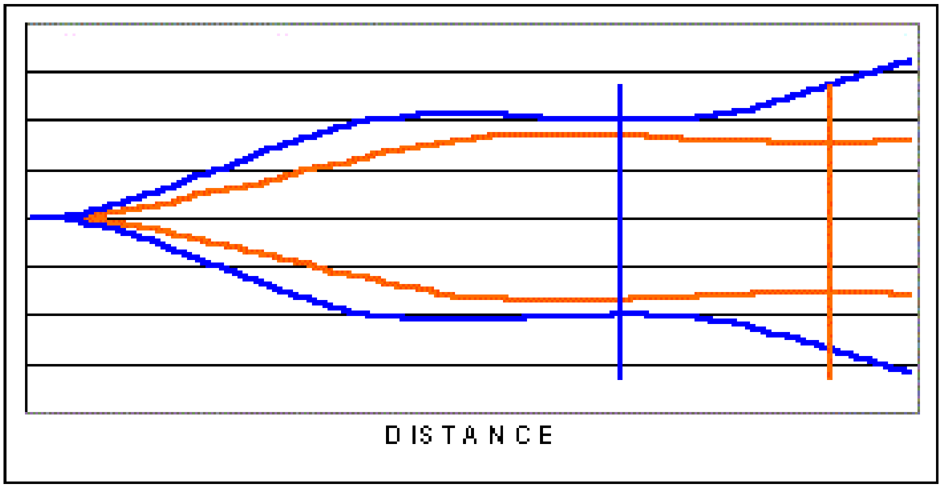
You get, at least in theory, a similar distortion of the arrow pattern with a vertical movement of the pin. In order to get a true arrow pattern then the pin position and the height of the mark on the target should be such that the arrow leaves the bow horizontally at all distances (so don't try a walk back on a hill). If say the bow is canted up and you shoot each arrow the same way then as you walk backwards the arrows fly higher and the arrow pattern is bent upwards. Alternatively if the bow is say canted up and you keep aiming at the same mark then the bow angle has to be continuously reduced as you walk backwards. In practice, over the short distances involved in a walk back, the bow being canted up (or down) will make little difference.

As an aside, unless you are doing a walk back with bareshaft arrows which naturally fly in a curve (see the section on bareshaft arrows), it is physically impossible to get a concave arrow pattern i.e. one that bends in towards the baseline. You sometimes see write ups on walk back tuning illustrating this pattern (the reason being of course that no consideration is given to the baseline, only to the first arrow hit).



Having got the correct set up for a walk back arrow pattern it can now be used for basic bow tuning. The method is pretty much the same as bareshaft tuning of the pressure button. The difference is that instead of using a bareshaft arrow to 'point' towards the position of the baseline, you know where the baseline is. Because a bareshaft arrow behaves differently to a fletched shaft both on the bow and through the air the walk back approach is a more reliable tuning method. If the walk back arrow pattern moves away from the baseline and then curves back towards it, the shooting distance which gives the maximum horizontal displacement of the group from the baseline is the most sensitive distance with respect to tuning. The actual tuning approach is much the same. With a sensible button position if the group pattern starts off going to the right of the baseline then (RH archer) increase the spring tension and vice versa.

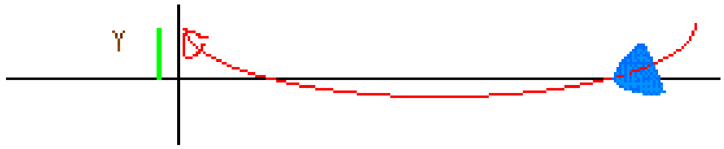
A variant of walk back tuning is to shoot arrows at different distances and look at the sizes of the arrow groups at each distance. Arrow groups result from the variation in how the archer shoots. One way the archer's shot varies is in how much rotation the arrow has leaving the bow which gives rise to fishtailing. The effect of fishtailing is that the group size varies in area with distance in an oscillatory fashion. For an archer of given ability the variation with distance depends on the rotational properties of the arrow e.g. its weight, FOC, fletching area etc.

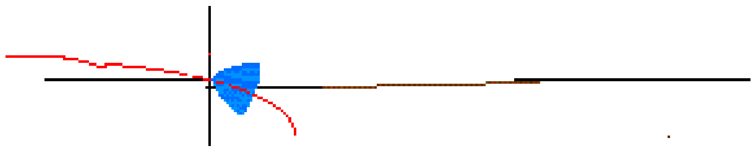


The chart illustrates the variation in the area of the arrow group with distance for a blue arrow and a red arrow. In this example the only difference between the two arrows is the FOC value. For the blue arrow the group size is a minimum for the blue target distance. If the target is nearer or further away then the arrow group size will be larger. The same effect happens with the red arrow with respect to the red target. The point is that because the characteristics of the two arrows are different the optimum target distance with respect to arrow group size is different. This raises the possibility of 'arrow tuning' i.e. selecting/designing an arrow with good characteristics for the specific distance and fine tuning the arrow by e.g. changing the pile weight or fletching size to minimise the groups at that distance. The arrow flight profiles above represent the worst shot arrows. The better shot arrows will have less rotation and the optimimum distance re group size will be further than for the worst case. The better arrows will however always be inside the worst arrow envelope.

PAPER TUNING

Paper Tuning is a method of bow tuning popular with compound archers. The method is to shoot arrows through a sheet of paper placed in front of the bow and adjusting the bow until the tear pattern is a 'bullet hole' i.e. the fletchings pass through the same hole as the arrow pile. The arrow is therefore leaving the bow straight with no vertical or horizontal rotation.





For recurve archers, using the paper tuning approach has limitations because of the Archers Paradox effect. The effect of the finger release results in the arrow leaving the bow with significant vibration in the horizontal plane. The following diagram indicate the problem:-

Because the arrow is flexing, even with a perfectly tuned setup you will probably get a horizontal tear in the paper because of vibration of the arrow as it passes through the paper. (illustrated by the green line).

If the arrow is of length 'L' and speed 'V' then the time for arrow to pass through the paper is L/V.

If the arrow is vibrating at frequency 'F' then the time to go through a complete bending cycle is 1/F.

E.g if L = 80 cm, V = 55 metres/sec and F = 60 cycles/second then the time for the arrow to go through the paper is 80/5500 = 0.015 seconds and the time per vibrational cycle is 1/60 = .017 seconds. The number of bending cycles that the arrow goes through when passing through the paper is 0.015/0.017 = 0.9 cycles. In general we can expect the arrow to go through multiple bends while passing through the paper which will result in a horizontal tear varying from zero (the arrow snakes through a single hole - unlikely but possible) to the amount the arrow flexes sideways (which depends on the arrow - anything up to 2 inches say).

You can use paper tuning in principle for three purposes, arrow dynamic spine assessment, nocking point adjustment and pressure button adjustment.

Spine Assessment

If the arrow comes out of the bow with a large amount of rotation (very weak/stiff arrow) then you will get a very wide horizontal tear in the paper, the combination of the arrow vibration and its rotation. If this tear is too big its unlikely that any amount of bow tinkering or tuning will produce a good flying arrow and the arrow needs to be changed or replaced. Rick Stonebraker's tuning guide puts the maximum allowable horizontal tear at 3 inches. Any larger then this then a weaker/stiffer arrow as appropriate is required.

Nocking Point Adjustment

There is a negligible amount of Archers Paradox effect in the vertical plane so any vertical tears in the paper result from arrow rotation. You can therefore adust the bow (usually the nocking point) towards having zero vertical tear implying the arrow is leaving the bow with no rotation in the vertical plane. As any vertical rotation will result in the arrow porpoising it is important that the 'zero tear' is obtained over a range of distances. At very short distances the amount the the arrow will have rotated will be small - low tuning sensitivity. At longer distances the arrow may have rolled over to the horizontal or even be aligned in the other direction - possibility of false interpretation. The tuning 'distance range' will depend on the arrow (say 2-10 metres)

Pressure Button Adjustment

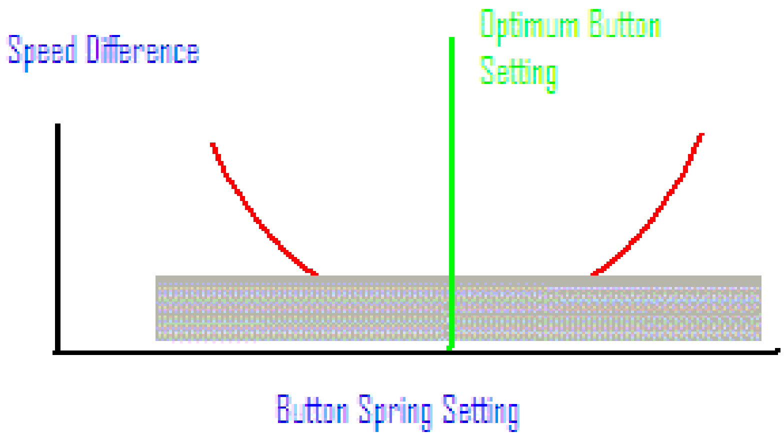
In the horizontal plane the paper tear is essentially going to be a random combination of the arrow vibration and any arrow rotation in the horizontal plane. Even a perfectly tuned bow is going to give an unpredictable horizontal tear depending on how the arrow 'snakes' through the paper. For pressure button adjustment therefore paper tuning is not a method that can be recommended

If an archer tries to get a bullet hole tear by adusting the pressure button what effectively is happening is that the arrow rotation (mis-tune) is being used to offset the arrow vibration effect as far as the paper tear is concerned. As the arrow rotation tear effect depends on the bow to paper distance if at a specific distance you get a bullet hole tear then by moving forward or backwards the tear magically reappears again.

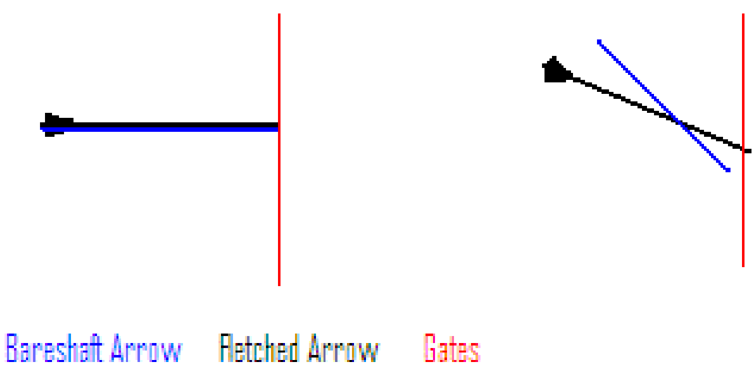
Approaches to tuning inevitably comes down to archers preference (some swear by, some swear at). In my own ranked list of ways of bow tuning paper tuning resides at the bottom.

SPEED VARIATION TUNING

A method for getting the best button spring setting as regards tuning that seems have to appeared in recent times is measuring arrow speed with a chronograph. The basic approach is to measure the speed difference between a fletched and bareshaft arrow using a 'gate' type chronograph. This speed difference is recorded as the button spring tension is varied across a range which includes the optimum spring setting.



If you plot a graph of the bareshaft/fletched arrow speed diffference against spring setting you get a curve similar to the one illustrated. The spring setting where the curve has its lowest value is the optimum spring setting as regards tuning. In practice because of various errors involved in the speed measurement you cannot determine the minimum point from the graph (the grey area) but you can infer its position from the observed curves either side of the optimum spring setting.



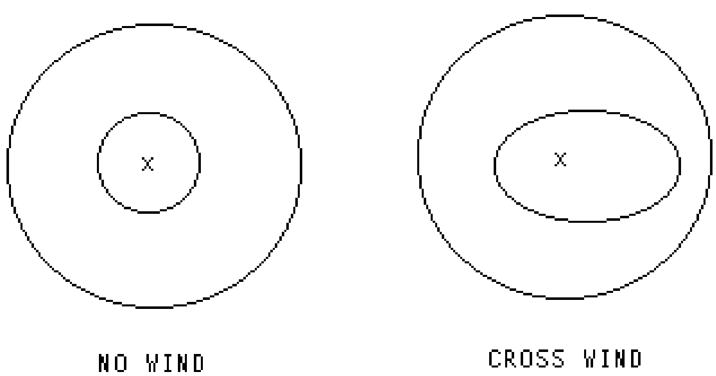
How does this approach work?. Well always remember that with any tuning process what we are varying is how much angular velocity the arrow has at launch and in the case of the pressure button we are trying to get the average launch angular velocity equal to zero. If with a given button setting the bareshaft and fletched arrows are launched with the presumed same initial amount of rotation then over a given distance, because of the 'braking' effect of the fletchings the bareshaft arrow will rotate more than the fletched arrow, What gate type chronometers measure is not the linear velocity of the arrow but how long it takes for the pile of the arrow to pass between the two gates. This is not necessarily the same thing (which is why accurate arrow speed measurement with a chronometer is quite complicated). As can be seen from the diagram because the fletched arrow rotates less than the bareshaft one the measured speed for the fletched shaft is higher than for the bareshaft arrow. The higher the launch angular velocity the higher this measured speed difference will be. With zero launch angular velocity the measured speed difference between the two arrows will be just that due to the arrow (fletching) mass difference.

Measured arrow speed will also be affected by the arrow vibration but as the frequency and phase of vibration of the two arrows will be much the same it does not invalidate this method as a tuning procedure.

VARIABLE TUNING

Introduction

In the section on the principles of bow tuning it was mentioned that the tuning setup with respect to arrow group sizes was dependant on the wind and the compensating aim-off angle (windage adjustment) used when a wind was present. This section will expand on this idea and describe what I call a 'variable tuning' approach aimed at reducing group sizes compared with a conventional tuning approach. In the following discussion I am only going to consider what happens in the horizontal plane to the arrow.

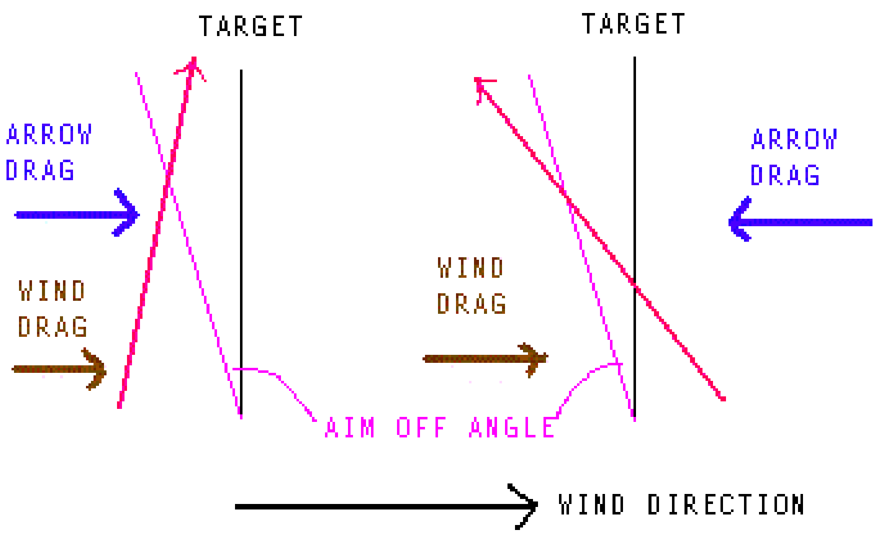


With a conventionally tuned bow, i.e. no arrow rotation with a perfect shot, you get a group pattern fairly symmetrical around the perfect shot (the 'x' that hits the centre of the target). When shooting in a cross wind the archer adjusts the windage so that the perfect arrow again hits the middle but the arrow group is no longer symmetrical. The arrow group extends much further down wind than it does upwind (wind direction is from left to right in the above diagram). If we first understand why the arrow group gets stretched in the down wind direction then we can come up with a strategy, variable tuning, which will reduce this stretching effect hence overall reducing the arrow group size.

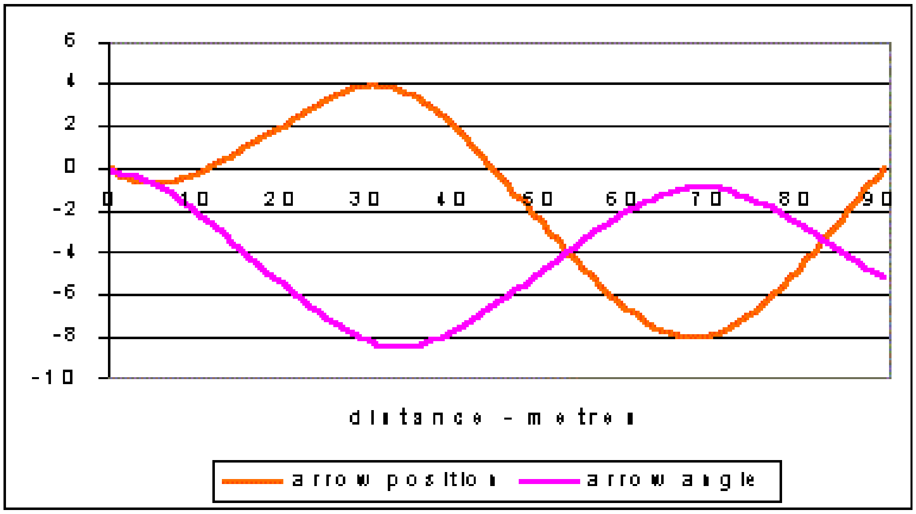
The photo (courtesy of Rick McKinney) illustrates the downwind stretching that occurs with arrow groups even with top archers. For the average archer the resulting groups would be nowhere near as compact.

Conventional Tuning Behaviour

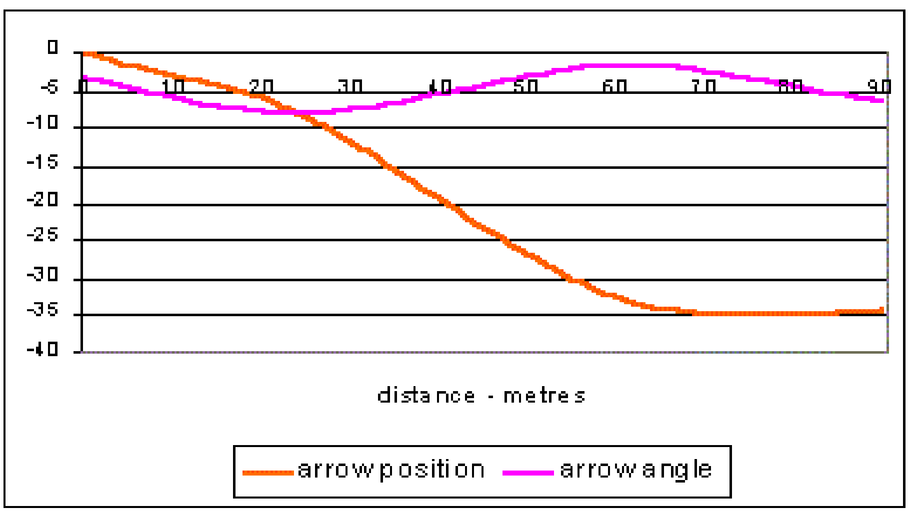
The section on Fletched Arrow Flight describes how arrow groups are created by the horizontal rotation that the arrow has when leaving the bow changing the direction of flight of the arrow. If the variation in rotation the arrow has around the perfect shot is much the same in the clockwise/anticlockwise directions then the arrow group distribution, with no wind, will be more or less symmetrical around the perfectly shot arrow. Once you have a cross wind this symmetrical behaviour disapears. The following diagram illustrates the basic difference.



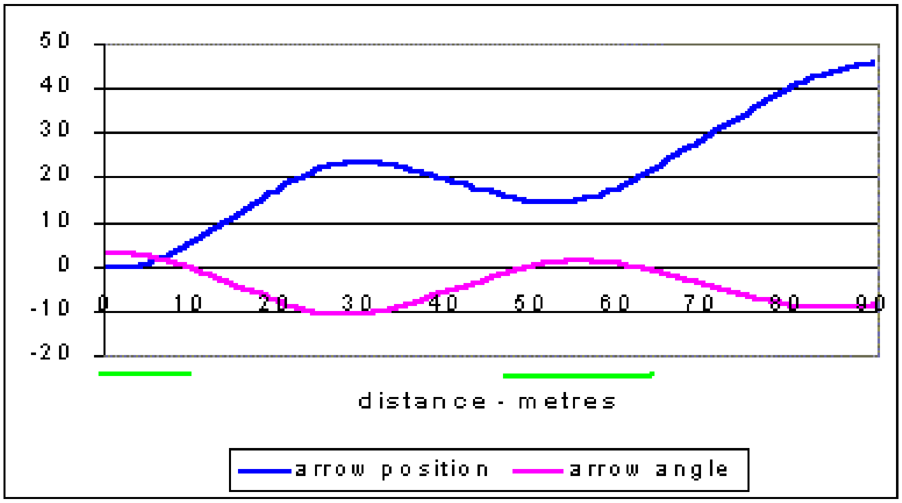
Strictly speaking the assymetry comes from the change in the wind vector and how this interacts with respect to the arrow orientation. Though technically incorrect I will describe the effect by separating the horizontal drag effects from the wind and from the arrow velocity. The drag force on the arrow from the wind always acts in the same direction (left to right in the diagram). The drag force on the arrow is in the same direction as the wind drag if the arrow comes off the bow rotating clockwise and in the opposite direction if the arrow leaves the bow rotating anticlockwise. The total sideways drag force is the 'sum' of the drag from wind and from arrow velocity. i.e. the total sideways drag force, and hence sideways arrow acceleration, will either be the sum or the difference between the wind and arrow velocity drag effects. There is a big difference in the arrow's sideways acceleration between the arrow offset angle being in one direction or the other. The drag force not only moves the arrow sideways it also rotates the arrow. Again as the drag force varies on the fletching area the angular acceleration of the arrow will also vary. This variation in sideways drag not only happens when the arrow leaves the bow but during the the flight of the arrow. As the arrow fishtails about the wind and arrow velocity drag forces will, depending on the orientation of the arrow, reinforce or oppose each other at different points in the arrow's flight. The following three graphs illustrate the behaviour of an arrow when having to aim off in a cross wind. In all three graphs the cross wind direction is upwards i.e. right to left. The example archer normally groups within the blue with no wind at 90 metres and is shooting in moderate wind of around 10 mph.



The graph represents the 'perfect' shot which hits the centre of the 10 at 90 metres. When the arrow leaves the bow ('straight' in the aim off direction) the wind rotates the arrow in a fletching downwind direction (negative angle) and so initiates the fishtailing of the arrow. At no point during the flight of the arrow does the arrow angle go sufficiently positive (fletching upwind) so that the wind drag reinforces the arrow velocity drag in the horizontal direction.



This graph represents one extreme of the archers variability. In this case the arrow leaves the bow with the fletching downwind and the fletching end of the arrow rotating in the downwind direction. Because the fletching is already rotating downwind the arrow gets minimal, zero or even negative rotational net push on the fletchings in the downwind direction. As a consequence the initial arrow rotation is less than for the perfectly shot arrow. At no point during the flight of the arrow does the arrow angle go sufficiently positive (fletching upwind) so that the wind drag reinforces the arrow velocity drag in the horizontal direction. The arrow ends up hitting upwind of the centre of the target much the same as for the no wind condition.



This graph represents the other extreme of the archer's variability. In this case the arrow leaves the bow with the fletchings in the upwind direction and with the fletching end of the arrow rotating into the wind. In the initial part of the flight the horizontal drag forces from wind and from the arrow's velocity reinforce each other so you have a high downwind acceleration (first green bar). This acceleration basically cancels out any benefit from aiming off. The combined wind and arrow drag also give the fletchings a larger initial push so the amount the arrow swings about is higher than the two previous cases. The period between distances around 10 to 40 metres works for the archer because due to the high rotation in the fletching downwind direction and corresponding shaft angle there is a considerable arrow acceleration in the upwind direction which starts to move the arrow back towards the target centre. What does the damage to where the arrow hits is when the arrow swings back (second green bar) so that the horizontal drag forces again combine to accelerate the arrow in the downwind direction. In this case the arrow hits the target at 90 metres before the upwind shaft drag acceleration can recover any of the lost ground.

The relevant points relating to group sizes when shooting in a wind (and appropriate to this discussion) are:-

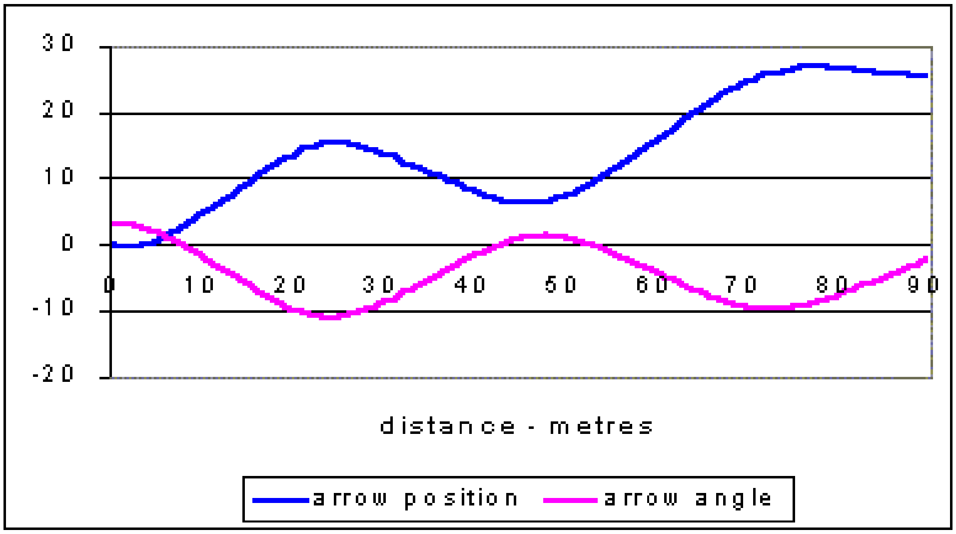
Aim Off Angle:- The more we rotate into the cross wind so that the perfect shot hits the centre of the target then the lower the horizontal drag force from the wind on the arrow will be. The aim off angle will increase if the wind strength increases or if the target distance increases.

Initial Arrow Rotation:- We get an initial high downwind arrow accleration and a lot of arrow rotation if the arrow leaves the bow with the nock end rotating in the up wind direction.

Arrow Rotation Period:- If the arrow rotates through a full cycle during its flight combined with an adverse initial arrow rotation then the result can be a large downwind impact. The degree the arrow hits downwind also depends on the target distance with respect to the arrow rotation period. The deviation of the arrow from the target centre increases/decreases with distance as it is the combination of distance and rotation period that determines how far away from the centre the arrow is at any distance.

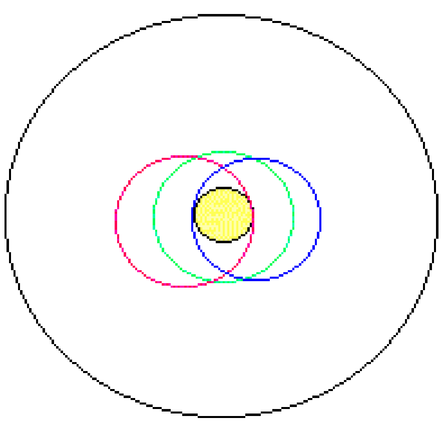
Bear in mind that the above items are not independant of each other.

Variable Tuning Strategy



Aim off and arrow rotation properties can only be changed by modifying the bow or arrow setup with wind strength and distance. Serious convential tuning involves looking at the variation of group size with distance caused by fishtailing and selecting optimum sets of arrows for each distance. The majority of archers will stick with one set of arrows. For example the graph illustrates the effect of increasing the fletching size for the same case as above where the arrow leaves the bow with the fletching rotating upwind. In this case the shorter arrow fishtailing period acts in the archer's favour.

The one thing the archer can easily control by ajustment of the plunger button pre-tension is the variation in angle/rotation of the arrows that the archer shoots. The key is to prevent any arrows coming out of the bow rotating nock upwind. Increasing spring tension will result in the arrow leaving the bow with the nock of the arrow having more rotation towards the bow (RH archer) and decreasing spring tension the oppposite effect.



In the diagram the green circle represents the archer's typical group (no wind). If the button spring tension is increased to move the group to the left until the right hand side of the group is near the middle then all the arrows are leaving the bow with the fletchings rotating towards the bow to some degree. The 'worst' shot has the arrow leaving the bow straight.. The spring adjustment from the green group to the red group represents the maximum spring adjustment required for a variable tuning approach for a left to right wind. The blue group represents doing the same for a right to left wind by decreasing the button spring tension. These variations in spring tension my be limited by requiring good arrow clearance.

When shooting in say a right to left wind by decreasing button spring tension you can avoid most if not all arrows having the horizontal wind plus arrow drag situation which in theory can reduce group sizes. (The headache as with conventional tuning is that group size goes up **and** down as shooting distance increases). It should be pointed out that spring tension adjustment is not a substitute for aiming off, the spring tension should be tweaked and then the required aim off determined.

What all the above boils down to is that the optimum tuning set up as regards button spring tension is not fixed but is dependant on wind conditions. The actual optimum setup is a complex interaction of the arrow and wind properties. Using the flight simulator you can determine for a given situation this optimimum setup which can produce significant group sizes over a conventional tuning approach. (See the graph in the section on bow tuning). In practice of course you can never get this optimum setup but the simulator indicates that a button spring adjustment in the right direction (towards the optimum tuning setup) can reap appreciable benefits over a conventionally tuned bow.

Practical Experience

Theory is fine but its where the arrows go that counts. As far as I know no serious testing of the above concept has been carried out.

(Note: Jan 07 - In The Heretic Archer, Vittorio Frangilli reports having tested this concept of spring adjustment with wind conditions and cautiously concurs with it. Always nice when a theoretical prediction is subsequently supported by experimental testing as it suggests the basic ideas about tuning are along the right lines. Whether it's a strategy with practical application only time will tell).

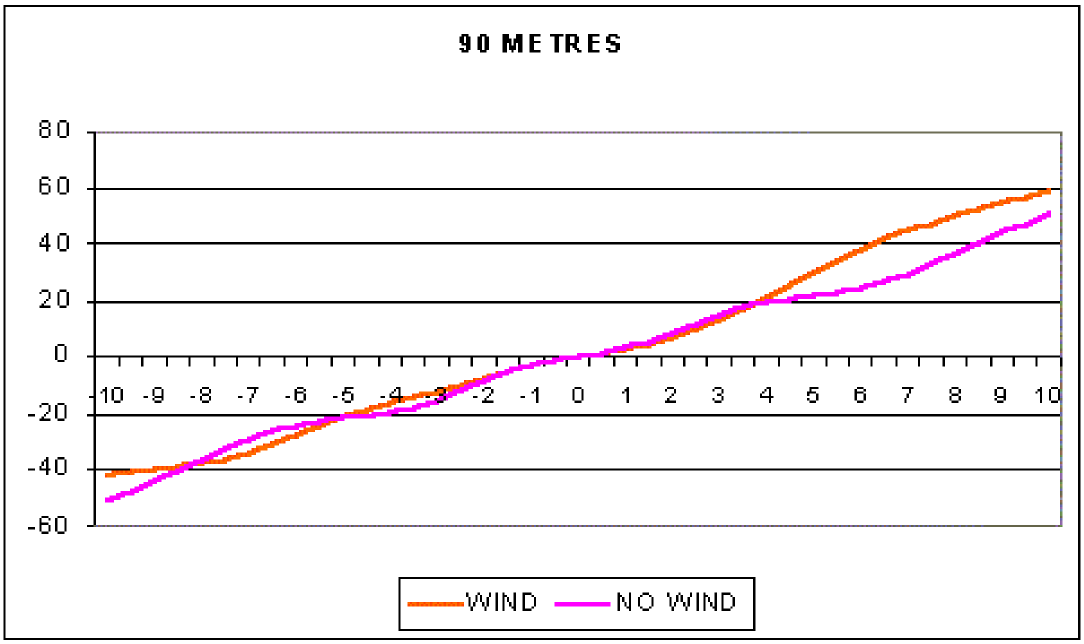
When I first came up with the idea of variable tuning a few years ago I tested it using a standard button modified so that I could easily manually adjust the button spring tension. The problem with this was that I kept losing the zero (the conventially tuned) spring setting. In order to implement a variable tuning strategy you need a plunger button with a calibrated spring pre-tension system so that you always know where you are and can always reset to zero. In practice this means you need a Beiter button. My subjective views based on trying out the idea are as follows:

At distances up to around 40/50 yards tweaking the button spring appear to have no effect on group sizes. (this is what you would expect as the arrows would not have completed a full rotational cycle and the groups are small anyway)

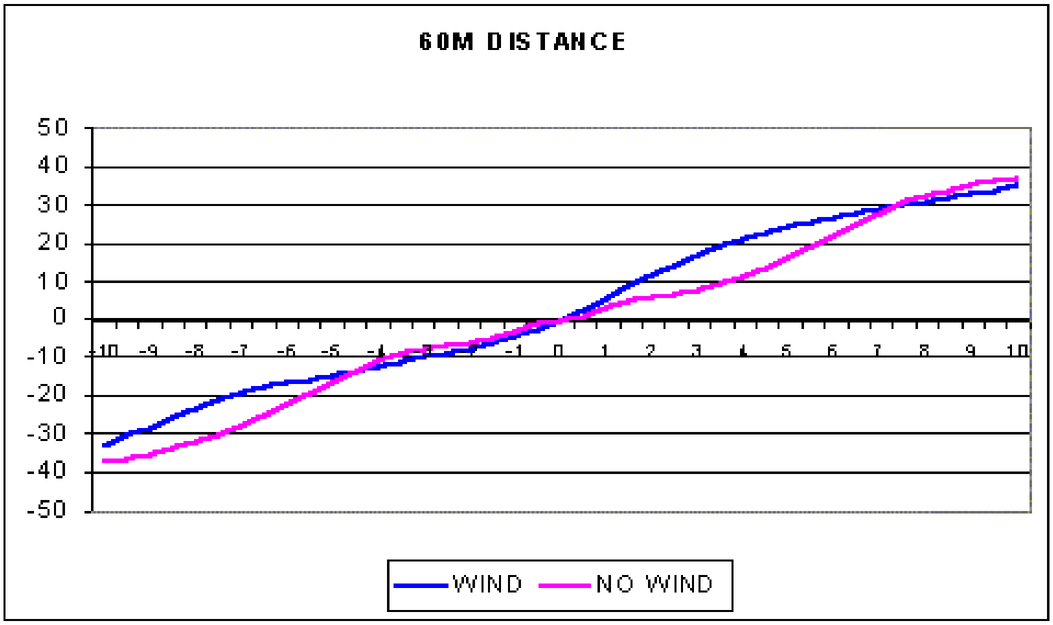
At distances 60 to 80 yards there was a subjective reduction in group sizes. On occasion the group sizes seemed to be significantly reduced. (This may be me just having a good day or possible getting the spring setting right on the button (pun intended)).

At 100 yards adjusting the button spring seemed to make no difference to the group size.

The following two graphs (generated using the arrow flight simulator) shed some light on the subjective results obtained above from using the variable tuning approach. Both graphs plot how far the arrow hits horizontally from the target centre in cms (the vertical axis) as a function of the amount and direction of horizontal arrow rotation off the bow (negative rotation = nock end of arrow rotating downwind). A comparison is made between where the arrow hits with a wind and with no wind. In both wind and no wind cases the perfect arrrow hits the target centre. The comparison is made at target distances of 90 metres and 60 metres.



The main point from the this curve is that you only start to suffer from the downwind stretching of the arrow groups when the arrow rotation goes over the value of around 4.5 (the point where the wind curve starts to lift above the no wind curve). This point corresponds on the target to around the blue 6 ring. So if your arrows go mainly in the gold and red you will see no benefit in general from a variable tuning approach at 90 metres. However using variable tuning will not make any significant change to the group size (the two curves are very similar with negative rotation) and could reduce the consequences of the occasional howler.



At 60 metres distance the wind curve starts to lift above the no wind curve when the arrow rotation goes over the value of around 0.5. This corresponds on the target to around the gold 9 ring. So unless all your arrows go in the 10 ring at 60 metres there will be a significant reduction in group sizes from using a variable tuning approach.

It should be noted that the above curves are based on the physical properties of my arrows and evaluation of the possible benefits are based on my typical arrow groups. While the general shape of the curves will be generally applicable any individual archer needs to run the above simulation based on their specific arrows and evaluated with respect to their specific arrow groups. (Of course there is no real subsitute for actual shooting).

Conclusion

The idea of a variable tuning as a practicable strategy is currently an untested idea but may be worth looking at. One problem is that many archers tend to regard a tuned bow as a fixed thing. Having spent a lot of time and effort tuning the bow for a no wind condition hearing that as soon as a wind blows the bow is not tuned anymore is not going to be popular.

A second problem is that currently there is probably not a plunger button on the market useable by elite archers to implement a variable tuning approach. If one takes a Beiter button as an example, this button has 10 click stops for one rotation of the spring tension adjustment knob. At 70 metres let's say one click stop moves the arrow group sideways by 5 cms. If your horizontal group width at 70 metres is 30 cms. (average archer) then a variable tuning strategy will require a maximum spring adjustment of 3 click stops. If on the other hand your group width at 70 metres is 8 cms (elite archer) then the maximum spring adustment required is less than 1 click - you can't do it, there is insufficiently fine adjustment of the spring tension. (This comment is not of course a criticism of the Beiter button).

VARIABLE TUNING - DISTANCE

Target archery rounds are generally carried out over a variety of distances. The optimum setup for the bow and arrrow with respect to getting the highest score (minimum group size) is a function of distance. Generally unless there is a specific reason to tune the setup for a particular distance (e.g. 18 metres for indoor) a 'one size fits all' approach is used, a single setup is used for all distances.

There are two aspects to distance tuning, the bow setup and the arrow setup. These two aspects are not independant so as with any form of tuning it's a case of going round the loop on an iterative basis until no further improvement can be detected.

The basic concepts behind bow and arrow tuning with distance have already been covered in previous sections so here the various relevant bits are just pulled together as a package without repeating all the details.

Bow Setup

Minimum group size for a specific distance is dependant on the rotation in the vertical plane that the arrow has when it leaves the string. If there was no gravity then the optimum set up would be zero rotation in the vertical plane for all distances. With gravity the optimum bow exit rotation for a specific arrow and arrow speed with respect to minimizing groups is a function of target distance.

You can basically split "tuning" into coarse adjustment (limb angle, centreshot, bracing height) and fine adjustment (nocking point position and plunger button spring). Only fine tuning adjustment is being considered. Unfortunately arrow exit rotation in the vertical plane is affected by both nocking point position and button spring tension (it's assumed the bow setup is such that the arrow rest has no effect on arrow rotation). The assumed process is to set the nocking point and then adjust the button spring for zero arrow rotation in the horizontal plane (the more important of the two rotations) and live with the consequent change in vertical arrow rotation, going round this loop as required. Adjustment is made on an incremental trial and error basis looking for the optimum.

Tuning for distance is a bit of a "black art" with no defined procedure that I know of. There are (at least) two possible processes that seem to be used. One is to measure how the arrow group size varies directly at specific distance as the nocking point is changed, the other is to look at the variation in hit height difference between fletched and bareshaft arrows. Which ever process is used what distance is it done at?

Using an arrow flight simulator an assessment is made of the two processes and they are compared to the basic tuning 'zero vertical rotation' situation. Arrows are assumed always to have zero rotation in the horizontal plane so the groups used are the two dimensional vertical arrow spreads. 'Typical' values for the bow/arrow system are assumed and for the archer's skill level. As the 'best' tuning process will depend on both these factors the following table should be regarded as indicative only. To allow for the change in face size the group sizes at 50m and 30m have been weighted by a factor of 122/80 so that group sizes can be correlated to scored points value.

	Minimum Group Size				Bareshaft/Fletched hit				Basic Tune
distance	90m	70m	50m	30m	90m	70m	50m	30m	N/A
90	0.78	3.48	10.38	10.61	15.10	11.90	7.88	10.61	12.52
70	2.98	1.07	10.89	4.56	2.11	5.31	11.06	4.56	9.99
50	12.56	12.29	3.27	11.32	4.63	4.38	16.86	11.32	8.30
30	7.53	4.72	6.17	0.10	0.82	3.19	5.90	0.10	1.84
Total Size	23.85	21.56	30.7	26.58	22.65	24.77	41.70	26.58	32.64
Normalised	1.11	1.00	1.42	1.23	1.05	1.15	1.93	1.23	1.51

In the above table, each column represents a different bow (nocking point position) setup. e.g for the 90m column under Minimum Group Size the bow is tuned to minimise the group size at 90m (0.78) and the consequent groups at 70m, 50m and 30m presented in the same column. The Bareshaft/Fletched Hit columns work on the same principle except that in this case the nocking point is adjusted so that the fletched and bareshaft arrows hit at the same vertical height for the specific distance, specified at the top of the column . The Basic Tune column gives the group sizes at the different distances assuming zero vertical arrow rotation on bow exit. Total Size is the overall (weighted) group size for all distances combined for that setup. Each Total size is normalised to the Total Size for the Minimum Group Size at 70m.

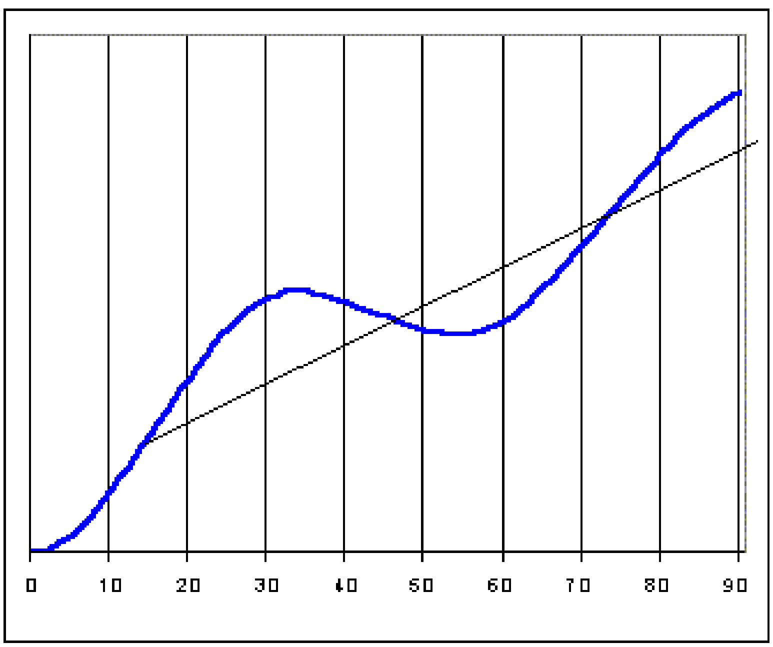
The best setup overall is obtained by minimising groups at 70m. Using the bareshaft method at the longer distances also performs very well (bareshaft at 90m comes second overall). Tuning by whatever means at 30m does better then at 50m - don't ask me why! There was an anomaly at 50m in that it was not possible to bring the bareshaft down to the same height as the fletched shaft, possibly a combination of the bow angle and the rotation properties of the arrow. The 'basic tune' on the whole did not work as well as the group size or bareshaft methods. This is anyway a bit artificial as it more or less corresponds to the 'bullet hole' tear in a paper tune approach. In practice a basic tune is going to be more like the 30m bareshaft column which works well.

When actually tuning for distance it may practically be a case of first determining the best strategy for a particular archer's skill and equipment and then actually doing the tuning. An approach something like the above table is required for real rather than a simulation. Using a bareshaft approach at long distance (again limited by archer's skill) is a fast method of getting into the right area followed up by tuning on a group size basis.

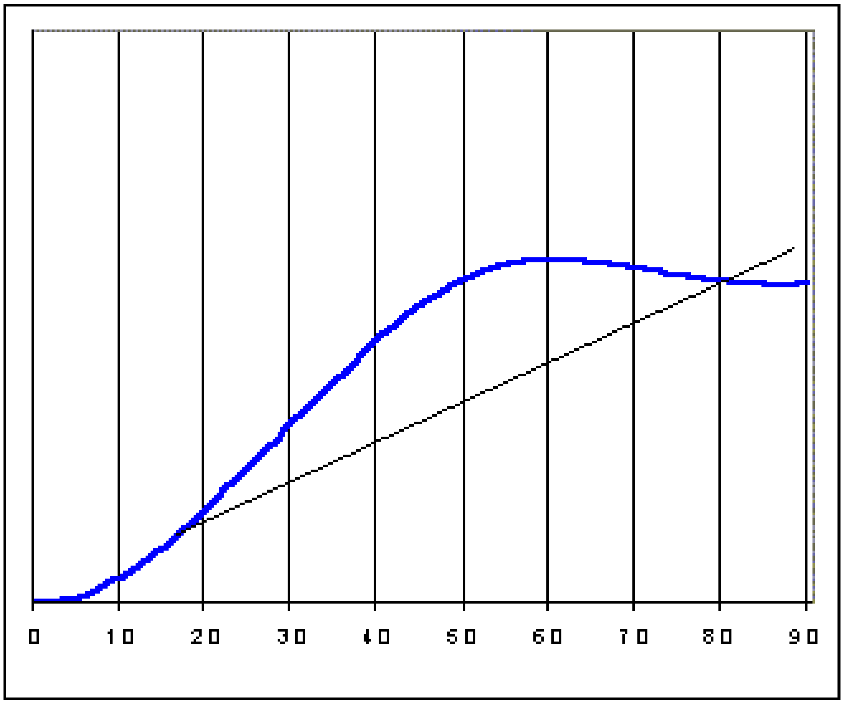
A clever idea that archers report using is that once a tuning setup is established it is referenced by recording the relative hit positions of fletched and bareshaft arrow group centres at a specific distance. If say the bow is disassembled/reassembled instead of repeating the whole group tuning process the setup is adjusted to recreate the reference value. e.g. for the 70m group tune in the table above at 30m the bareshaft would hit around 20cms vertically above the fletched shaft.

Arrow Setup

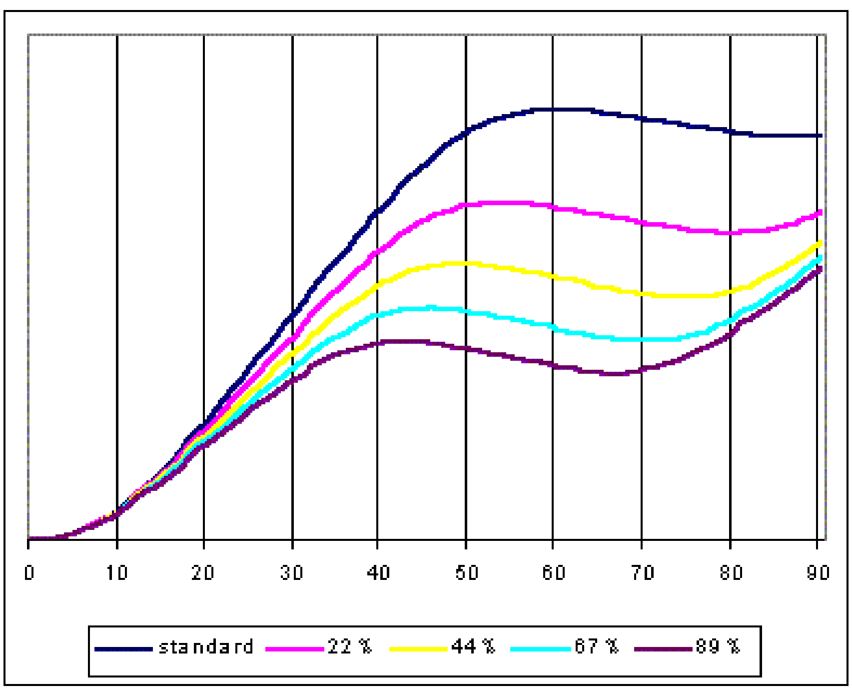
The arrow has essentially already been selected before the distance tuning procedure begins for its tuneability, FOC, speed etc. The factor which has a secondary influence on group size is the arrow fishtailing amplitude and period as it relates to the target distance. A less then perfectly shot arrow ends up travelling in a different direction to that shot, the main source of groups. Superimposed on this is the side to side movement of the arrow resulting from fishtailing (up and down movement from porpoising is difficult to identify and is assumed to be incorporated in the nocking point tuning process). Using very 'ball-park' numbers, with an average/poor skill archer the fishtailing amplitude can be around 25% of the total group size and for a reasonable/good skill archer around 35%. Taking the fishtailing wavelength as the travel distance for the arrow to complete a side to side movement cycle the associated wavelengths are around 60m and 100m.



This graph ilustrates what happens for the poorly shot arrow. The black line is the nominal post stabilisation arrow direction. The actual arrow path (blue line) oscillates around the nominal arrow direction. The archer loses out badly at 30m, gains slightly at 50m, no gain/loss at 70m and loses out to some extent at 90m.



This graph ilustrates what happens for the well shot arrow. The fishtailing wavelength is much longer so the archer loses out at all distances apart from 90m where some benefit is gained.

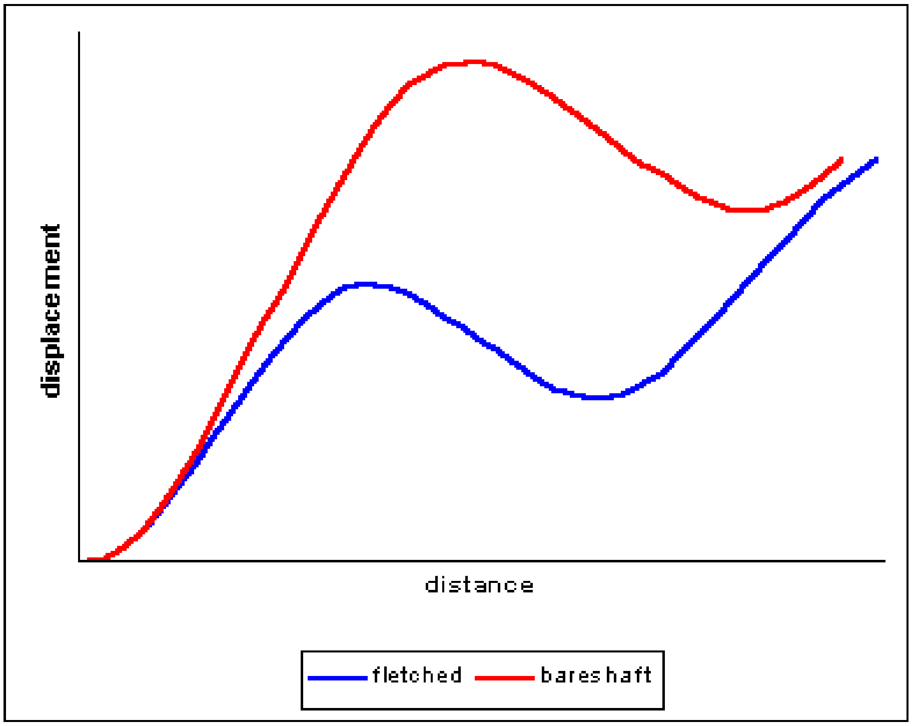


The only practical way the fishtailing effect can be modified (in the archer's favour) is by playing around with the fletching size and position (which is mainly limited by the wind sensitivity of the arrow). This graph illustrates the effect of increasing the fletching size for the good archer by varying amounts. The larger fletchings result in more rapid stabilisation and smaller groups anyway but the effect on the arrow fishtailing is to reduce both the amplitude and wavelength.

For the 44%,67% and 89% increased size over the standard for example the groups at 90m remain much the same while getting an improvement with a reduced 70m group size. Increasing fletching size shows diminishing returns but the main penalty is incurred if the fletching size is too small.

In practice it's difficult (short of an archery equivalent of Hawkeye) to determine fishtailing behaviour. The only approach would be to measure group width variation by moving forward and backwards around a specific distance.

It is unlikely, but possible that arrow fishtailing can give a false indication of a tuned button. With a badly tuned bow both the bareshaft and fletched arrow will fishtail and its possible that the two arrows could coincidentally hit at the same horizontal position. A walk back/up approach clarifies such a situation

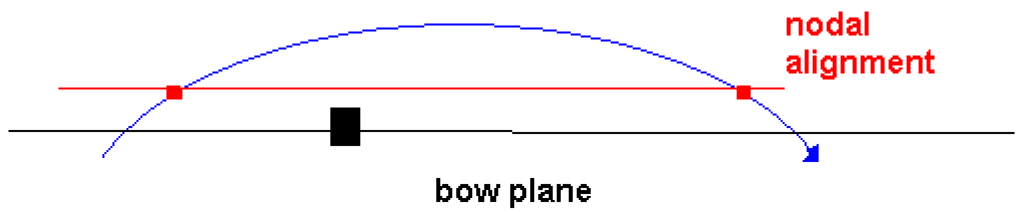


The attached graph illustrates how this 'false tune' can occur. In such a situation there is always going to be a significant lateral displacement of the arrow. When tuning getting the eye, plane of bow and sight pin in line will always reduce any problems.

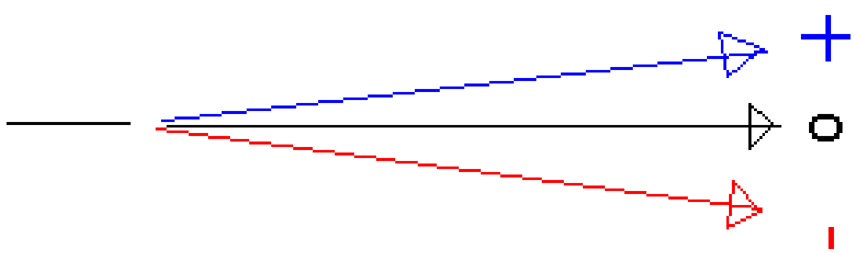
Summary

Distance tuning is as stated previously a bit of black art and requires understanding what you're doing combined with experience of doing it. While the above comments don't supply any answers they hopefully cover some of the considerations.

ARROW ALIGNMENT AND TUNING



Arrow alignment is defined as the angle, in the horizontal plane, between the direction the arrow is pointing and the plane of the bow at the moment the arrow exits the string. The direction the arrow is pointing is defined as the line linking the two shaft nodal points.



Re the diagram looking down on the arrow, for a RH archer, the blue arrow is regarded as positive alignment angle and the red arrow a negative alignment angle.(in reality the arrows are bent around the riser, not straight lines).

As reviewed elsewhere, on its own the arrow alignment at launch is fairly irrelevant to "tuning" and makes a neglible change to the overall arrow direction. However when you couple together the initial arrow alignment and the arrow rotation the arrow alignment does make a significant difference to the arrow flight behaviour.

For example it's easy to see that if the arrow was launched, rotating say in a clockwise direction, then the rotation and stabilisation of the arrow would be different if the arrow was launched at an initial clockwise angle as opposed to an initial anti-clockwise angle.

The consequence is that the results of say a 30 meter bare shaft tuning, in terms of group sizes, will be different with a negative, zero or positive initial launch angle. Having a zero initial launch angle will give the best result.

Suggested here is methodology for checking the arrow launch angle and to some extent correcting for its effects potentially reducing group sizes. This is a purely armchair theory and has never had any practical test. Practical testing is required to determine whether there is anything to the theory and if so to turn it into a practical method.

In the following it is assumed that the initial bare shaft tuning setup is made by crossing the bare shaft across the fletched shaft with the final button spring setting splitting the difference between these two points.

Suggested Procedure

- Carry out a normal 30 meter bare shaft tuning process
- Without changing anything except the vertical sight position shoot both fletched and barshaft arrows at the target at 50 to 60 meters distance.
    - If the fletched and bare shaft arrows are centered on the target then the initial launch angle is zero.
    - If the arrows fly left of center than the initial launch angle is negative.
    - If the arrows fly right of center the initial launch angle is positive.
- If the launch angle is zero then no further action required
- if the launch angle is not zero then one of following actions:
    - If the fletched arrow group is at a measureable distance sideways from centre then move the fletched arrow group to the center with the button spring.
    - If the fletched arrow group appears central but the bare shaft arrows are displaced laterally move the bare shaft arrows to the center with the button spring.

Ideally a mechanism to change the launch angle is what's wanted. Possible changing the center shot or brace height would do this, but any such methodology would only be determined by practical testing.

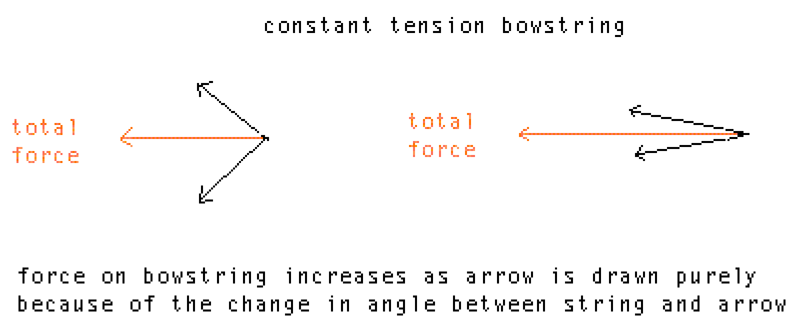
The following extract (from archery-interchange.net 14 January 2012) provides one archer's practical description of the alignment process

....during a phase of messing about about I tried to obtain nodal alignment from the initial departure of the arrow from the bow and at 10 and 20 yds and I sort of achieved it (based on locating nodal points on a bare shaft by methods established by Olympians and coaches from the 80's which coincided with positions obtained from a homemade "exciter" to oscillate an arrow) marking these nodes with chalk pastel crayons and shooting through paper, made GMB for the 1st time that year...
.....Well it was after reading McKinney's book, he said something along the lines that once you get your alignment right that the bare shafts will impact with the group but much straighter and also that wind drift would be reduced that I investigated further, he did describe some method of moving the plunger depth depending on which way the nock of the arrow was seen in relation to the point at the moment of loose, but I couldn't see it, so I thought up the

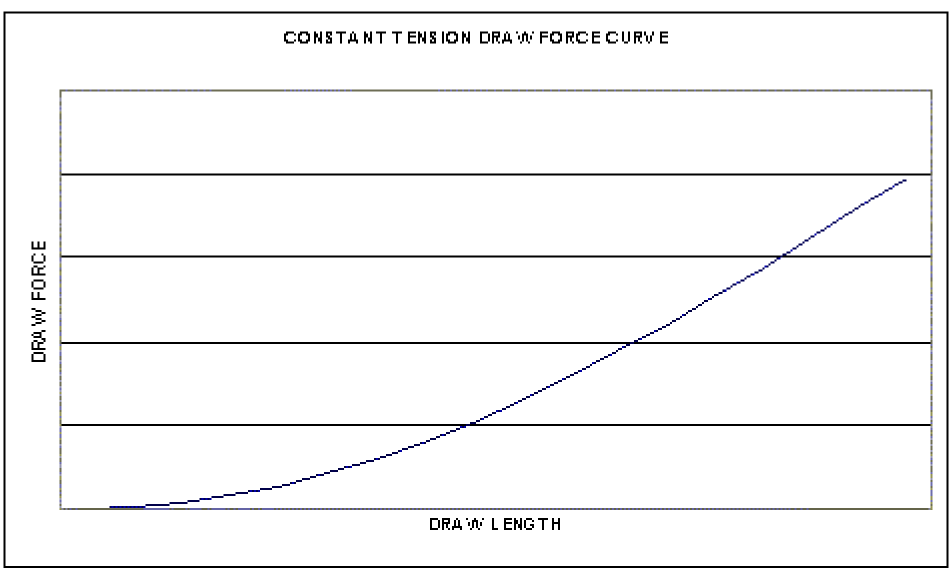
chalk/pastel trick, and yes I observed straighter bare shafts and less wind drift (subjective??) and the winner...better groups...
Blobs of chalk residue were in contact with each though not on top of one another which was the objective, tears were horizontal (which confirmed nock point height was correct to me) and about 1¼" long, point impacts were as expected in different positions (could see distinct embossing that could only have been made by the point).......
Had to make adjustments to the brace height too, plunger depth adjustments had to be compensated with tension adjustments to maintain central impact position in relation to point of aim.....
...Was not worried about length of tear as depending on how arrow is in its bending cycle at the time as it passes through the paper it could be a bullet hole or about three inches long and that can be the case by just moving the paper back 2", (that's why reading purely the tears and trying to obtain bullet holes at various distances during shooting through paper is a waste of time for recurve).....

Appendices

ADDING FORCES TOGETHER



Forces are what are called vectors having two properties 'amount of' and 'direction' e.g. an arrow travelling East at 300 fps could be represented by a vector like -------------------------> where the length of the line represents the speed and the line/arrow shows the direction of travel. When forces are added together both 'amount of' and 'direction' of each individual force affects the resultant total force vector. Suppose we have a bowstring which as we draw the arrow back has a constant tension. The force on the arrow changes as we draw it because the the angle the bowstring makes with the arrow keeps changing as per the diagram.



If instead of bow limbs we ran the bowstring over two pulleys with weights hung on the end to give a constant string tension then we would get a force draw curve something like the attached.

MOMENT OF INERTIA

Moment of inertia is a measurement of the 'rotatibility' of an object. If you apply a force to an object it accelerates. The relationship between the force and resulting acceleration is the Newtonian definition of 'inertial mass'. i.e. acceleration = force/mass. If you apply a force to an object which rotates it (a torque) then the relationship between the angular acceleration and the torque is the moment of inertia i.e. angular acceleration = torque/moment of inertia. If you apply a torque to an object and want to know how much it will rotate in a given time then you need to know the object's moment of inertia i.e.

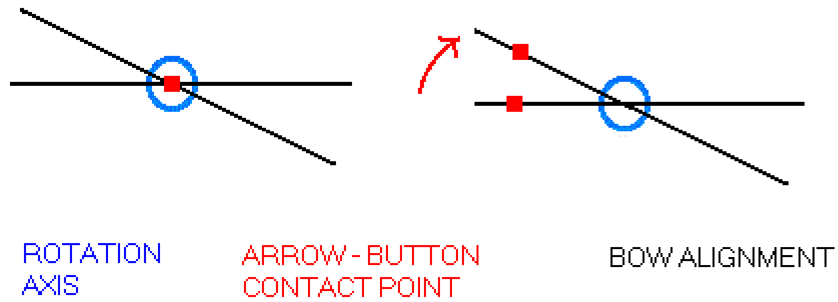
rotation angle = torque x time squared/ twice the moment of inertia.

The value of the moment of inertia depends on the axis around which the object rotates. If you hold a bow normally at the grip and twist it about the feel is very different to holding it at the end of the long rod and twisting it about. The respective moments of inertia are very different because the rotation axes are different. The moment of inertia of mass around an axis of rotation (assuming an infinitely stiff connection) is the mass multiplied by the square of the distance to the rotation axis. (In practice it will always be effectively less than this as the connection between the mass and the rotation axis, e.g. a long rod, will bend). The total moment of inertia of a complicated shape, e.g. a bow, is the momentum of inertia of all the individual small masses at different distances from the rotation axis added together.

The two main areas in which moment of inertia is important in archery is in how the bow rotates when you are shooting an arrow and how the arrow rotates when it's flying through the air. Both these rotations affect where the arrow eventually hits the target. The affect of arrow moment of inertia is covered in various other sections so I'll stick to some aspects relating to the bow. During the power stroke of the bow accelerating the arrow, the axis of rotation of the bow is the centre of pressure of the bow hand - bow grip contact. The main forces generating torque in the bow around this point of rotation result from the accelerations of the bow limbs, arrow and string.

Always what you are looking for in archery is consistency. If the bow hand position shifts about from shot to shot (or even during a single shot) then the axis of rotation shifts - the moment of inertia changes as well as the torques being applied to the bow and consequently the rotation behaviour of the bow changes. Result - the arrow hits at a different place. If the draw length or release varies then the forces generating bow torque will vary and again the bow rotation characteristics change. Result - the arrow hits at a different place. To cater for the natural variations of the archer the bow design is aimed at minimizing the effects of the archer variations.

The first point is the vertical position of the arrow - pressure button contact with respect to the bow axis of rotation.



If the pressure button -arrow contact point is vertically above the throat of the grip then it lies on the vertical rotation axis and any horizontal rotation of the bow will have less effect on the arrow-pressure button interaction. While the bow rotates, the arrow (inertia again) tends to stay where it is so any movement of the contact point with respect to the arrow will effect the action of the pressure button and hence where the arrow eventually hits. While the arrow has two contact points with the bow, nock and rest/pressure button then any rotation of the bow can affect the direction the arrow is shot as well as the rotation the arrow has when it leaves the bow. Once the arrow has only one contact point, the nock, then any bow rotation will affect the direction of the string force acting on the arrow as well as nock movement rotating the arrow in the horizontal and vertical planes.

The primary use of the bow stabiliser system is to position the bow centre of gravity to minimise the generation of torques acting to rotate the bow. While You can't completely eliminate these torques you can can reduce their effect by increasing the bow moment of inertia. The higher the moment of inertia the lower the angular acceleration for a given torque and hence the less the bow will physically rotate during the shot. Some moment of inertia is built into the bow design but the expectation is that stabilisers will be added to increase its value. The additional moment of inertia generated by a stabilizer depends on three factors: mass, distance of mass to the bow rotation axis and the stiffness of the stabilizer rod. Don't forget the last item. You won't get much benefit from a tonne weight on the end of 50 metres of string. This makes assessing stabilizers tricky. If you use the same end weight on a longer rod you could end up with less effective moment of inertia then with the shorter rod because of the increased flexibility of the longer rod. When shooting an arrow you have high torques over a short time time period, 10-15 milliseconds say, so waving the bow around in the air to assess its moment of inertia is not much help. Like a lot of things in archery it's play about and try to evaluate the effects of changes.

There is a simple stabiliser moment of inertia calculator on the "Downloads" page.

Measuring the Moment of Inertia of a Bow (MoI)

It is fairly straightforward to measure the 'static' bow MoI. By 'static' I mean that the bow is in the bracing height position and the accelerations of the bow are small so that components of the bow don't deform in any way. This 'static' measurement relates to the dynamic MoI so you can use it to look at the effects of e.g. different stabiliser configurations on how it affects the bow MoI.

The main requirement to measure bow MoI is having a solid pivot point from which you can hang the bow with the bow being free to swing (e.g. a nail in a doorframe. Tying a string loop on the bow and hanging the bow from a hook is a simple option). The following is a suggested procedure for measuring the bow MoI.

step 1 - Find the overall bow weight

Weigh the bow including all attachments. Call the mass of the bow **M** (in grams).

step 2 - Find the bow centre of gravity

Hang the bow at some point on the pivot and hang a plumb line from the pivot. With say masking tape, mark on the bow at two points the alignment of the plumb line with respect to the bow.

Hang the bow from the pivot at a different point and hang a plumb line from the pivot. Place a straight edge along the masking tape alignment marks. The point where the straight edge crosses the plumb line is the location of the bow centre of gravity. (you could say mark the plumb line at this point).

Measure the distances (in centimetres) from the bow centre of gravity to the throat of the bow grip (**b**) and to the pivot point (**h**).

step 3 - Measure the bow swing time

There are 3 possible axes of bow rotation and associated MoI values and the axes are assumed to run through the throat of the bow grip (approx. the hand - bow pressure point). Refer to the 'stabiliser' link on the main page for some nice drawings of these 3 axes if needed.

In order to measure the MoI about a particular axis the bow has to be swung (like a pendulum) around the pivot point (for which **h** was measured) parallel to this axis. The time (**T** secs) for the bow to swing forward and back to the same point has to be measured. The maximum amount the bow swings should be as small as possible (less than 10 degrees from 'vertical') and its more accurate to time a number of swings (say ten) and divide the total time by the number of swings to get the average swing time.

If you need to change the pivot point to get the bow to swing parallel to a given axis then the value of **h** needs to be measured for the new pivot point.

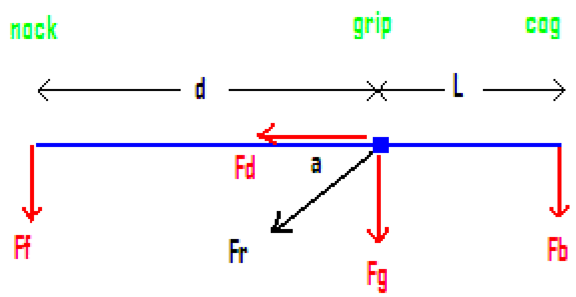
The bow MoI for a particular axis running through the throat of the bow grip $\mathbf{I}_{bx}$ is then given by

$$\mathbf{I}_{bx} = \mathbf{M}(24.85\mathbf{h}\mathbf{T}^2 - \mathbf{h}^2 + \mathbf{b}^2)$$

If you add/remove mass from the bow then you have to start from step 1 again. If you just rearrange the stabilisers then you have to restart from step 2.

Bow Hand Loading

There are three contributions to the force that the bow hand has to sustain, the force from drawing the bow, the gravity force on the bow and the balancing moment force exerted by the string hand.



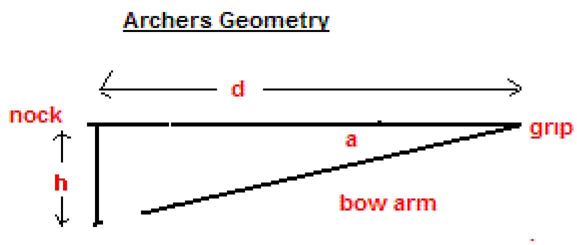
The diagram illustrates these three forces for the case where the gravity forces are at 90 degrees to the draw force.

Fb is the vertical gravity force on the bow mass which acts through the bow Centre of Gravity (cog). Ff is the vertical force that has to be exerted by the string fingers on the bow to balance the moment of the gravity force on the bow around the grip. Ff = Fb(L/d) where 'L' is the horizontal cog to grip distance and 'd' is the nock to grip distance. The total vertical load on the bow hand
Fg = Fb+Ff so Fg = (1+L/d)Fb.

As the vertical (gravity) load on the bow hand depends on the ratio L/d this has some implications for the bow setup. If you move the centre of gravity of the bow forward you increase the load the bowhand is required to carry. For a given gravity load on the bow hand there is a relationship between the draw length and the COG position. As the draw length increases, then to keep the bow hand loading the same the COG has to move forward (e.g longer draw length = longer extender bar).

The total force that the bow hand has to support Fr is the vector sum of the draw force Fd and the gravity force Fg. The direction of the force Fr (represented by angle 'a') is determined by the ratio Fg/Fd. i.e. Tan(a) = (1+L/d)Fb/Fd.

In Archery Anatomy Axford discusses how the stability of the bow arm shoulder is affected by the value of the angle 'a'. This can now be expanded to include draw length and bow centre of gravity position as factors in shoulder stability.



From an archer's geometry point of view, if we assume as previously that the nock to grip line is horizontal, then approximately Tan(a) =h/d where 'h' is the vertical distance from the arrow nock to a line through the shoulders. For the resultant force on the bow hand to run straight through the bow arm then you have the equality:

h/d = (Fb/Fd)(1+L/d)

The above equation gives some indication of how the various parameters affecting bow arm stability interrelate.

To express how heavy a bow aproximately needs to be for good balance a "power to weight" ratio factor is sometimes used. That is you divide the draw weight by this ratio to esimate the bow weight. As the power to weight ratio is by definition Fd/Fb the above equation can be used to give this ratio from some simple values. e.g. if h = 4", L = 2.5" and d = 28" the power to weight ratio is about 7.6. So if your draw weight is 40 pounds then the bow needs to weigh around 40/7.6 = 5.25 pounds.

In reality the bow will be raised (or sometimes lowered) for actual shooting at distance or uphill/downhill and this will have an effect on the overall bow hand loading. As the bow is raised above horizontal the value of Fr will increase and the value of 'a' decrease and vice versa as the bow is lowered.

While the bow hand load running through the bow arm may seem to be the mechanically the best option as the shoulder muscles need to exert minimum effort to keep the bow hand stationary, biomechnically this may not be the best option. I know zip about biomechanics. I've heard coach opinion that the bow hand load should run above the shoulder and coach opinion that the bow hand load should run below the shoulder. Take your pick but either way the force direction will be close to the line of the bow arm so the above equation can be subjectively useful.

How in practice do you set up a stabiliser system to get a balanced recurve bow. The only method I know of is "feel". If the balance is correct then at full draw the bow should feel mass neutral in the vertical plane. There is no sensation of vertical weight acting downwards or upwards on the bow hand. The benefits to a balanced bow to aiming stability are obvious. Stabilisers are used to do three things at the same time; balancing the bow at the aiming stage, dynamically stabilising the bow during the bow power stroke and dumping vibrational energy to protect the archer. So how do you balance a bow while optimising the other two stabiliser functions. The answer is the V bar and twin rod system.

Bow Balance - The V bar and Twin Rod System

If you look at any high class recurve archer shooting line then almost universally the same stabiliser assembly is seen on each bow, an extender a flat V bar and twin system and long rod usually fitted with end weights. Why this arrangement?

Fletchings were used on arrows, purely because of the performance increase achieved, thousands of years before how fletchings worked was understood. To some extent I believe the almost universal recurve stabiliser arrangement is experience based rather than knowledge based. The long rod, V bar and twin rod arrangement is used mainly because **it's what's found in practice to give the best results** . I've never seen a comprehensive description of why the V bar/twin rod assembly is so successful and I don't claim to have all the answers either. What I'll try to do here is take a reverse engineering approach essentially giving my opinions as to what the V bar/twin rod approach is for and why it's better than any alternative. On occasion I'll have to bring in aspects relating to dynamic bow stabilisation covered elsewhere and I'm not going to repeat the explanations.

Nearly all V bar/twin rod arrangements have a vibration damping function. At one time they all used "torque flight compensators (TFCs)" some still do in the classic approach of a chunk of rubber between the twin rod and the V bar, some rods have the equivalent of TFCs built in, some use the carbon rod itself as a damper but probably the most popular approach today is some form of Doinker incorporated into the end weights.

The typical weight arrangement on twin rods is solidly fixed weights with very often a doinker type arrangement at the end. As regards vertical load on the bow hand (bow static balance) both fixed weights and doinker weights contribute. As regards dynamic stabilisation only the fixed weights contribute significantly. With any movement of the riser during the power stroke the doinker rubber flexes so any mass beyond the doinker contributes very little to bow stabilisation.

OK, so the V bar/twin rod arrangement is used for static bow balance, dynamic stabilisation and vibration energy dumping. Is there an order of importance for these three functions. There are clearly simpler alternatives as regards vibration damping (e.g.doinkers in top/bottom risers bushings) so that is probably not it's primary function. As regards dynamic stabilisation while the twin rod weights make a significant contribution (around a vertical axis through the grip much greater than that from the riser) it is small compared to what you get from the long rod. The suggested conclusion is that the primary function of the V bar twin assembly is static bow balance.

The primary function of the long rod is dynamic bow stabilisation by increasing bow moi and pushing the bow centre of mass forwards of the grip. The limit on this is rod stiffness. We use an extender to effectively increase rod length while maintaining rod stiffness. The break between extender and long rod provides a convenient point to insert a V bar to carry a twin rod system. Now for the leap of faith (or my guess if you will). **When the long rod system on a recurve bow is maximised there is insufficient vertical mass load on the bow hand to statically balance the bow.**

Riser manufacturers don't know in advance what draw length and what draw weight any particular user is going to have so they have to make the riser light enough to cater for everybody. So when the archer has maximised the dynamic stabilisation with the long rod/extender additional mass is required for static bow balance. How do you add this mass. A consideration here is the overall force on the bow hand. The more mass we add the higher the force on the bow hand. So another rule is that **we want to minimise the amount of mass added to the bow to achieve static bow balance in order to minimise the force on the bow hand.**

In order to minimise the amount of mass added to balance a bow the mass needs to placed as close as possible in a vertical plane running through the bow pivot point (grip) at 90 degrees to the plane of the bow. The reason why is explained above with regard to the balancing moment required for bow centre of mass. Place extra mass anywhere else and the additional vertical bow hand load is greater than the physically added mass. When we shoot an arrow the riser accelerates away from the archer in a horizontal plane. **To increase lateral stability we want mass in the horizontal plane of the grip at 90 degrees to the bow plane.**. For We don't want to place the twin weights in front of the grip as this would increase the stress on the extender with respect to rotation about a horizontal axis (the major load on the extender presumably already maximised with respect to long rod dynamic stabilisation). Having the twin weights in front of the grip will also reduce the weight to grip distance unless you increase the V bar angle.I once tried reversing the V bar so the twin rods ran forwards. The result was hopeless as my (admittedly cheap) extender just flexed during the power stroke. The stabilisation system just went "mushy". We don't want to place the twin rod weights to the rear of the grip as this eats away at the dynamic stabilisation from the long rod (reduced gravity torque). By putting the twin weights in the horizontal axis through the bow pivot point at 90 degrees to the bow plane we can add as much weight as we like without penalty to the dynamic stabilisation of the bow from the long rod.

There are a number of solutions to how to add this extra mass. Adding mass directly to the riser is a possibility (screw in weights?), using a back weight attached to the bow is a used solution and using a V bar/twin rod system to add weights in the correct plane is the common solution. The down side to the back weight is that although in addition to achieving static bow balance it marginally adds to the bow moi about the grip being the wrong side of the pivot it reduces the gravity torque on the bow. The main advantage of the back weight is it creates more space on the shooting line. The advantages of the V bar/twin arrangement become clear.

- It puts the extra mass in the right place as regards lateral bow acceleration stabilisations with no detriment to rotational stabilisation.
- it's very easy to vary this mass by changing the screw on weights.
- We get an efficient vibration damping system.
- We get some additional dynamic stabilisation
- The mass of the V bar assembly and rods themselves, although they incur 'added mass' increasing bow hand force they do add to the gravity torque and to the bow moi about the grip.(The use of light carbon fibre for V bar and twin rods is explained)

The last point is the detail of the extender and twin geometry. The norm is a flat or slightly down angled V bar system with a 90 degree V bar angle. Why?

Too small a V bar angle and the rods start getting in the way; too large an angle and the rods get too long and wide for convenience or you have to shorten the extender which impacts on the dynamic stabilisation; angling the rods down has little impact on lowering the bow cog and you have the same issues as too large a V bar angle. Angling the twin rods upwards has the effect of marginally raising the bow centre of gravity which is never a good idea as regards dynamic stabilisation.And so on. By experience the "standard geometry" gives you all round the best solution.

Computer Models and Archery Mechanics Disinformation

Introduction

A lot of bad information about archery mechanics floats about particularly on the internet. A major source of this disinformation is the use of computer models and in particular "pin tape" and "arrow selection" programs. The problem is that these programs have very little, if anything, to do with actual archery mechanics. Unfortunately many of the people who use them, even many of the vendors who write them, don't seem understand this and misuse these programs (in all good faith it needs to be said). The result is computer produced garbage being presented as 'factual' archery mechanics information.

Pin tape programs have nothing to do with the real mechanics/aerodynamics of arrow flight and arrow selection programs have nothing to do with the real mechanics of the bow/arrow system. They are purely what are called 'empirical models'. Pin tape programs produce reasonable accurate estimates of pin positions for different distances and arrow selections programs produce reasonable estimates of what arrows will work for a particular archer/bow combination - So they must relate to the actual mechanics mustn't they? - Problem is they don't.

As stated above these types of archery computer programs are just empirical models so what's needed is to explain what an emprical model is and how in principle they work. This is maybe best done by giving an example of an empirical model.

An Empirical Model Example

Suppose, for whatever reason, we want to write a computer program which will predict how deep holes in the ground are. We don't know anything about gravity or the laws of mechanics. What we need is an empirical model. The one thing we do know is that if we drop a stone down a hole, the deeper the hole the longer it takes for the stone to hit the bottom.

The first step is to **invent a formula** (if we find it doesn't work we can always invent another one!) In this case the invented formula is;

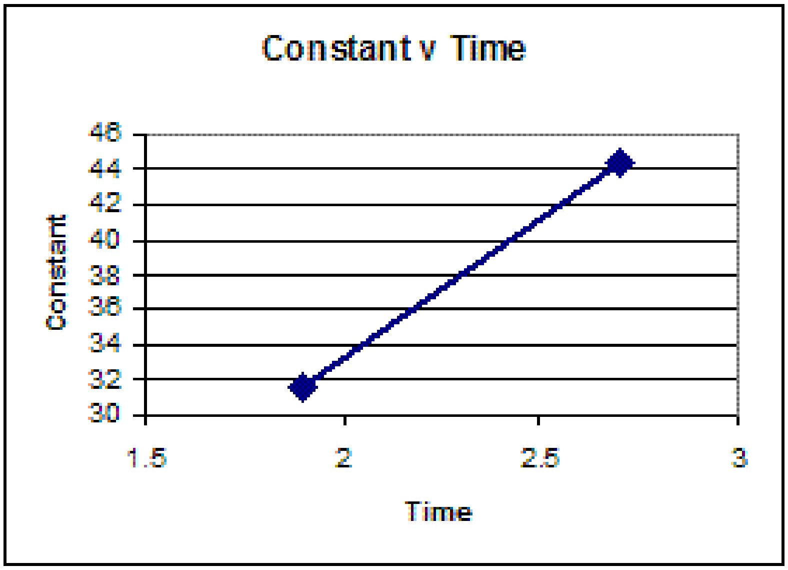
***Depth** of Hole = a **Constant** multiplied by the **Time** it takes for the stone to drop down the well*

If we measure the time it takes for the stone to fall down the hole we can calculate the hole depth as long as we know the constant.

The second step is to **calibrate the model**. This how we get the value of the constant. We find a hole and measure its depth **D1** and then drop a stone down it and measure the time of fall **T1**. The value of the constant **C1** for this hole can then be calculated using our invented formula as **D1/T1**. We then do the same with a second measured hole which gives **C2** =**D2/T2**. We then use these values of **T** and **C** to create a graph or a set of tables (If we want to be posh we could call them 'Ballistic Tables'). In this case we have two points on a graph and we just draw a line between them. In other cases we may need to have more calibration points and do a curve fit to them.

[At this point I'm going to cheat by actually using some mechanics as we need some example numbers. The hole depth is about half the gravitational acceleration multiplied by the square of the time for the stone to drop.]

Our stopwatch can measure time to one tenth of a second so let's say our measured values are **D1**= 60 feet and **T1**= 1.9 seconds (hence **C1** = 31.6) and **D2**=120 feet and **T2**= 2.7 seconds (hence **C2** = 44.4). This gives us the displayed graph of Constant against Time for drop.



To find the depth of an unknown hole we time how long it takes for a stone to fall down it. From the graph we look up the value of the constant for that time and then the hole depth is just the time multiplied by the value of the constant. So if our measured time was 2.5 seconds the corresponding value of the constant read from the graph is 40.5 which gives the hole depth as 2.5x40.5 = 101.25 feet. This is very close to the actual value.

So without any knowledge of or application of mechanics we can produce a computer model which can produce acceptably accurate results for a mechanical problem.

Pin Tape Programs

Pin-Tape programs relate the required bow angle (sight pin position) to the target distance to hit at a specific height. The two factors are the gravitational acceleration and aerodynamic effects on the arrow. Creating a computer model to handle gravity is very simple and pin-tape programs do use mechanics to do this. The problem area is the aerodynamic effects. Pin-tape programs replace the aerodynamics with an empirical model. The invented equation is:-

Drag Force = Constant multiplied by the arrow speed squared

In addition the Drag force direction is invented as being opposite to the arrow travel direction.

The Calibration of the empirical model is done by the archer himself. He shoots arrows at two distances and records the correct sight pin positions for them. This generates the constant as a function of distance in a similar way to the example model above. The estimate of pin positions for different distances is then done with the drag force generated from the invented equation combined with the gravity effect in a trajectory calculation.

Because there is no calculation of the actual drag forces on an arrow in a pin-tape program you cannot use these programs to say anything about the actual arrow flight. Even the arrow trajectories produced by pin-tape programs are not correct because they produce trajectories of objects which have the drag properties as defined in the invented formula. (to be fair at short distances the trajectories produced will not be that different from the arrow trajectory). When it comes to things like drag forces on the arrow or arrow components or wind effects than a pin-tape program is just going to produce nonsense.

An alternative approach used in pin-tape programs is to try to get the value of the constant in the invented equation from the properties of the arrow itself. So the main constant is made up by adding together constants for separate arrow components (pile.shaft etc) with these arrow component constants being derived from the arrow properties. These component constants have no physical meaning in themselves, they are just being used to created an overall invented arrow constant.

One of the earliest pieces of disinformation generated by the pin-tape method relates to arrow fletching drag. Fletching size has a big influence on the drag forces on the arrow as a whole so in terms of the overall Constant the fletching related sub constant is relatively quite large. This for years has been wrongly interpreted as frictional drag on the fletchings being a major contributor to slowing up an arrow.

Arrow Selection Programs

Selecting an appropriate arrow that gives good bow clearance and is tuneable by an actual mechanical model is currently not an available option. Arrow selection has to be based on an empirical model.

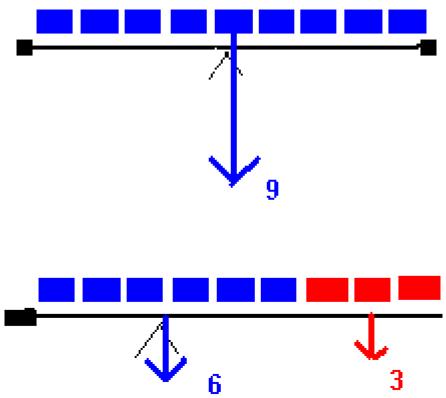
The invented empirical equation for arrow selection takes the general format:-
[Arrow Properties] = Constant multiplied by [Bow Properties]
Various approaches to how you invent something to put inside the brackets have been used.

Universally the approach used to specify the Arrow Properties in the invented equation is the arrow vibration frequency. The reason for this is the usual one in any empirical model, it seems to work fairly well. The only problem with this has been that some people have taken this to mean that arrow vibration frequency has to do with arrow selection or tuning in some real physical way. A confusion between the empirical approach and an approach based on actual real mechanics.

Various methods have been used to try to specify the [Bow Properties] part e.g. draw weight and draw length. One of the earliest empirical relationships suggested (Klopsteg) was:-
[Arrow Vibration Frequency] = Constant multiplied by [Time the arrow is on the bowstring]

The bow factors that play a part in how the arrow behaves on the string are many and are often equipment specific. Even different limbs from different manufacturers can change the arrow selection. It is in practice impossible to consistently and accurately select arrows using an empirical model. You hear endless comments about selection charts/programs being incorrect or one program recommending a different arrow than another program. Well that's just the way it is, it's not the fault of the program vendor. They are doing the best they can. The only way to improve the performance of arrow selection programs is to do more up front calibration with different equipment combinations.

A Guide to the Basic Concept of FOC

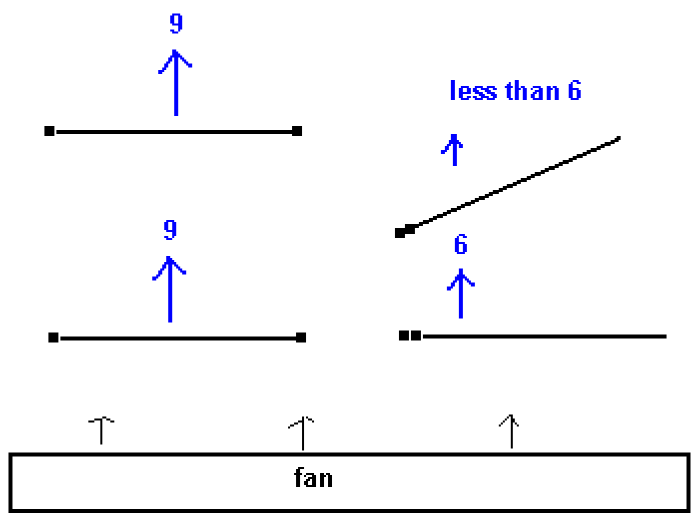


Suppose you have a two uniform beams of equal weight balanced on pivots. You have two equal weights. With one beam you attached a weight to each end - so the balance point remains in the centre of the beam. With the second beam you attach both weights to the same end - so the balance point is move nearer to the heavier end. The pivot is positioned so that both beams still balance.

Suppose you now add (blue) identical weights to the beam while keeping the beams balanced. With the beam with the balance point in the middle you can add 9 weights, the full length of the beam. With the other beam you can only add 6 blue weights. Add any more weights (the red ones) and the beam is going to tip up.

The balanced beams (blue weights only) don't move so there is an upward force by the pivot on the beam equalling the downward gravity force on the beam. Looking at the weights only and ignoring the beam itself then for the beam with the balance point in the centre (zero FOC) the force acting downwards on the beam is 9 times the value of each blue mass and for the beam with the balance point nearer one end (positive FOC) the force acting downwards on the beam is 6 times the value of each blue mass. In both cases this force acts through the beam balance point (its centre of gravity).

The red weights are identical to the blue weights, apart from the colour. We can add 3 red weights to the beam with the positive FOC. Obviously the downward force from these weights is 3 times the value of each weight. Because adding these red weights would tip the beam clearly the downward force from them doesn't act through the pivot but somewhere else as illustrated. (this point on the beam is what is called the 'Centre of Pressure').



OK, now for the conceptual jump. Instead of beams on a pivot suppose we have two arrow shafts magically suspended in mid air. Same as the beam, one has an identical weight at each end (zero FOC) and one has the two weights at the same end (positive FOC). We have a large fan and the arrows are initially the same distance from the fan. We switch the fan on so we get an airlow across the arrows. The air flow creates a drag force on the arrow shafts. We can replace the force generated by the weights on the beam with the force generated by the drag on the arrow shaft (each weight corresponds with the drag force over the corresponding length of arrow shaft).

So with the zero FOC arrow the force acting through the arrow centre of gravity is 9 and with the positive FOC arrow the force acting through the arrow centre of gravity is 6 with an addional force of 3 acting through the centre of pressure. Both arrows get blown downwind intially at the same acceleration. However the arrow with the positive FOC tips and this reduces the drag force blowing it downwind. Both arrows have the same mass so the zero FOC arrow which has a higher drag force acting on it gets blown downwind faster than the arrow with the positive FOC.

THE HEAVIER ARROW MAINTAINS IT'S DOWNRANGE ENERGY MYTH

The frequently heard expression of the form "A heavier arrow retains its energy at longer distances", usually implying e.g. that a heavier arrow will be travelling faster at 90 metres than a lighter arrow, is one of those awkward archery myths because the statement itself is true. It's only the understanding of the phenomenon and it's practical effect on arrow flight behaviour that is incorrect.

Using the 'Flight' arrow simulator I will try to put over a sensible interpretation of the comment.

The approach is to compare the flight characteristics of two arrows. Both arrows are 29" X10 650 shafts with identical fletching and nock assemblies. The only difference is that one arrow has a 100 grain point and the other arrow has a 120 grain point. It is of course impossible in real life to change only one variable for an arrow so the assumed arrow properties are:

100 grain pile

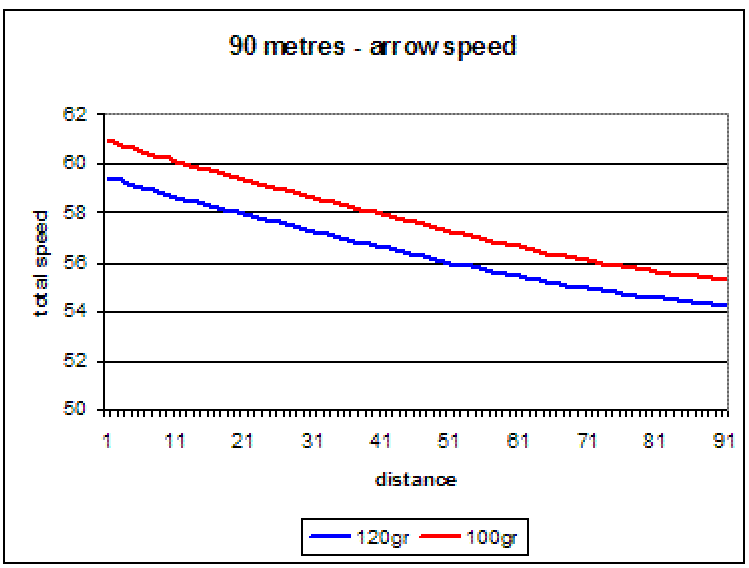
- Total arrow mass = 307.91 grains
- Arrow FOC = 14.57%
- Launch Speed = 60.96 metres/second
- Vibrational Characteristics not catered for in Flight model

120 grain pile

- Total arrow mass = 327.91 grains
- Arrow FOC = 16.73%
- Launch Speed = 59.47 metres/second
- Vibrational Characteristics not catered for in Flight model

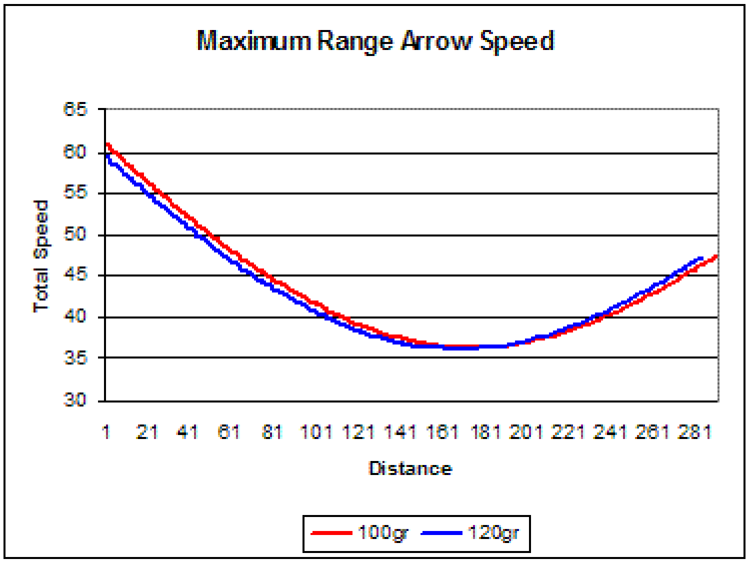
The different arrow properties are fairly consistent with a 20 grain difference in point weight.

For the first assessment the two arrows are perfectly shot at a 90 metre target distance and the 'Flight' simulator used to generate the total arrow speed over the distance. The following graph compares the speed over distance for the two arrows.



The lighter arrow has the higher launch speed and with increased distance the gap between the two arrow speeds decreases partly (mainly?) because of the effect of the mass difference on the relative arrow accelerations. However in this case at 90 metres the lighter arrow still has the higher speed.

For the second assessment the two arrows are perfectly shot at an angle to reach maximum distance and the 'Flight' simulator again used to generate the total arrow speed over the distance. The following graph compares the speed over distance for the two arrows.



The lighter arrow has the higher launch speed and with increased distance the gap between the two arrow speeds decreases partly (mainly?) because of the effect of the mass difference on the relative arrow accelerations. At around 187 metres both arrows have the same speed. At longer distances the heavier arrow has a higher speed. (In case you are wondering the arrow speed is increasing during the latter part of the flight because the arrow is 'falling down' and accelerating under gravity. The speed gain from this is greater than the speed loss from drag). Worth noting that the maximum range of the lighter arrow is about 7 metres greater than the heavier arrow.

You can see from the above simulation that 'the heavier arrow retains its downrange energy' statement is true and the corollary that the heavier arrow will end up travelling at a higher speed is also true. Where these *correct* facts are misleading is that you have to be shooting a lot further than 90 metres for this effect to become a practical reality.

Why do so many people get this relationship between overall arrow mass and speed variation wrong? My guess is that what people look at is the speed difference between different arrow shafts of which the difference in overall mass is only one of a large number of variables and they happen to 'pick' the one of lower relative significance.

So let's repeat the above assessment using this time three different shafts, the X10 650 as above and equivalent ACE 670 and Navigator 610 shafts. All arrows have identical point (100 grain), nock and fletching assemblies. In this case the respective arrow parameters are:

X10 650

- Total arrow mass = 307.91 grains
- Arrow FOC = 14.57%

- Launch Speed = 60.96 metres/second
- Arrow diameter = 0.195"

ACE 670

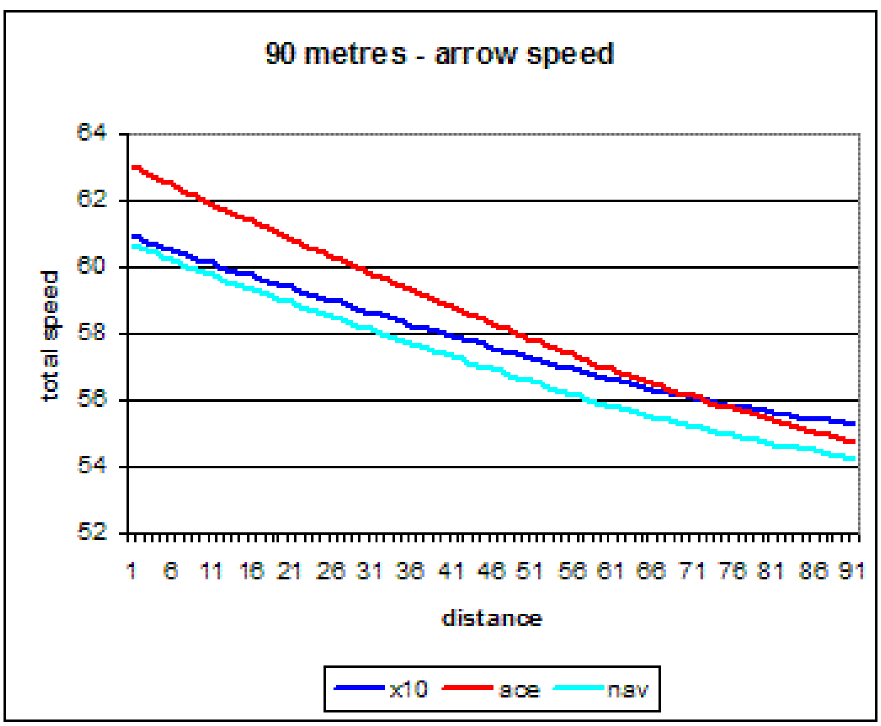
- Total arrow mass = 282.1 grains
- Arrow FOC = 15.91%
- Launch Speed = 63.07 metres/second
- Arrow diameter = 0.239"

Navigator 610

- Total arrow mass = 311.1 grains
- Arrow FOC = 14.42%
- Launch Speed = 60.71 metres/second
- Arrow diameter = 0.218"

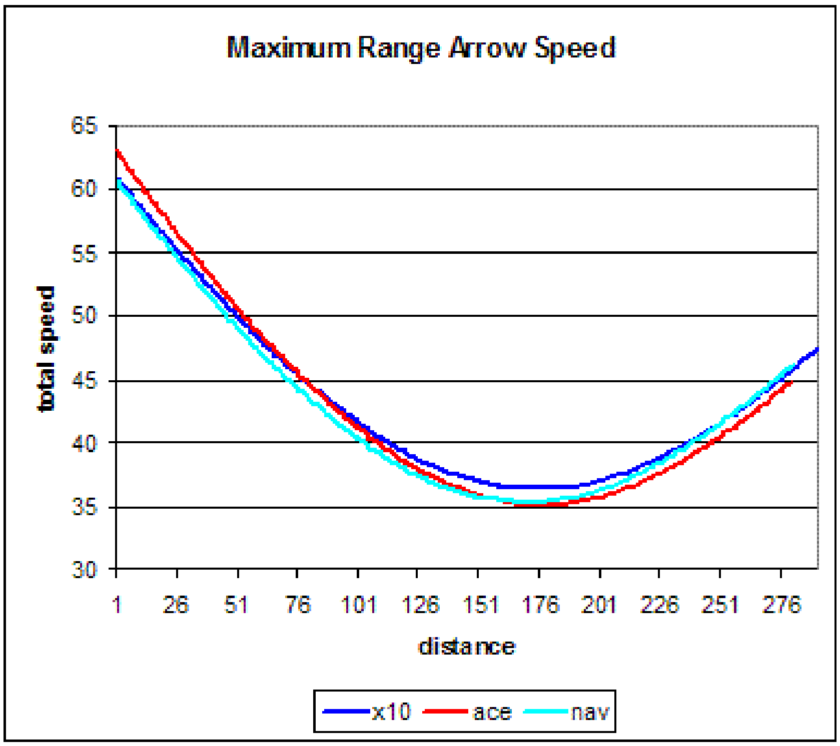
The differences in arrow mass are similar to the 20 grain difference we chose for the X10 shaft comparison. Need now of course to include the arrow diameter as a variable.

It is clearly impossible to define how much individual arrow components or individual arrow properties contribute to the overall arrow drag and hence to arrow speed variation. However I think you can reach some plausible views.



For 90 meters distance starting off with the X10 versus the Navigator they both have similar overall masses,launch speeds and FOC values but the Navigator loses speed much faster than the X10. This supports the X10 comparison above in saying that although overall mass has an effect on speed loss it's a relatively minor contributor. The big difference between the two shafts is the smaller diameter of the X10 which for sure is going to result in less drag slowing the arrow up. Highly suggestive that diameter is a major player as regards speed loss.

Whereas when comparing the two X10s above the lighter arrow had a higher speed at 90 metres, in this case the X10 speed overtakes the ACE speed at around 70 metres. While the higher FOC of the ACE will make a contribution to increased drag slowing the arrow up the FOC difference is less than the case for the two X10 arrows so again it seems that the smaller diameter of the X10 is the key property as regards speed loss between the X10 and the ACE.



While it doesn't add much to the argument for completeness sake I've included the speed variation for the three arrows shot at maximum range. As regards distance the X10 goes the farthest distance, the ACE the shortest, and the Navigator is between the two. That the maximum range is in the same sequence as the arrow diameter may or may not be a coincidence (always more questions :)) but clearly the maximum range does not match the sequence of overall arrow masses. The X10 speed overtakes the ACE speed before the Navigator speed overtakes the ACE speed, again raising a flag that diameter may be the the dominant parameter.

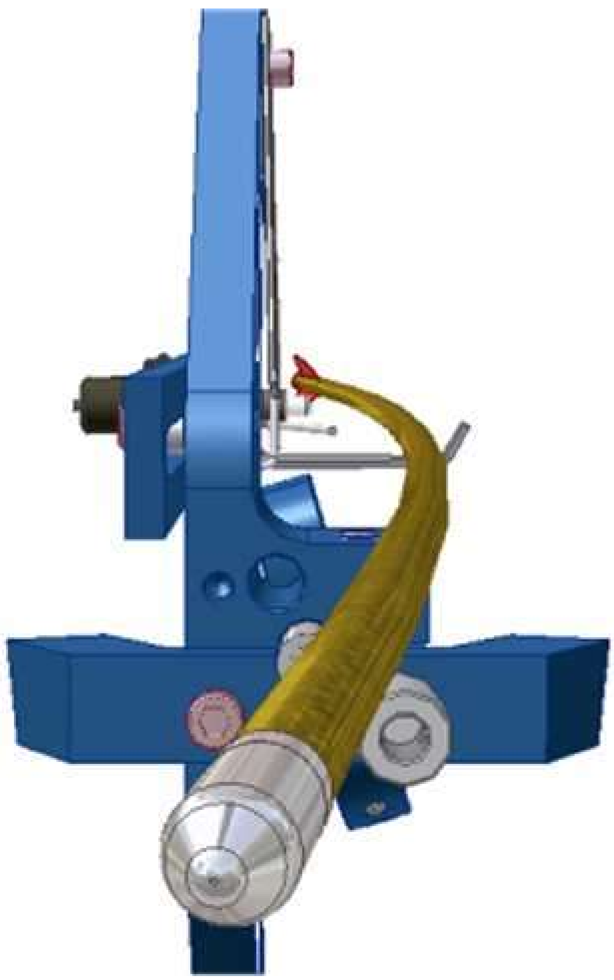
Drag affecting properties like FOC have much more of an effect at longer distances so any interpretations are going to be a lot less clear cut than at shorter distances.

The Mystery of Poor Arrow Flight Resulting in Good Groups

Two head scratching phenomena you find in archery are the cases where the arrow flight, as perceived by the archer, seems to be terrible yet the arrows end up nicely grouped in the gold and when the archer walks up to the target those arrows in the gold are at all sorts of different crazy angles.

As an illustration if you look at this (short) medium speed video you can see that while the arrow is fishtailing quite badly through the flight it still ends up scoring a ten. - how come?

Ignoring the effect of gravity and wind, which the archer can do nothing about, there are two contributions to the fishtailing/porpoising behaviour of an arrow resulting from the bow/arrow setup and how the archer shoots the arrow, launch alignment of the arrow and launch angular momentum of the arrow. This topic has already been covered under 'fletched arrows' but will expand on it a bit with respect to the current topic.



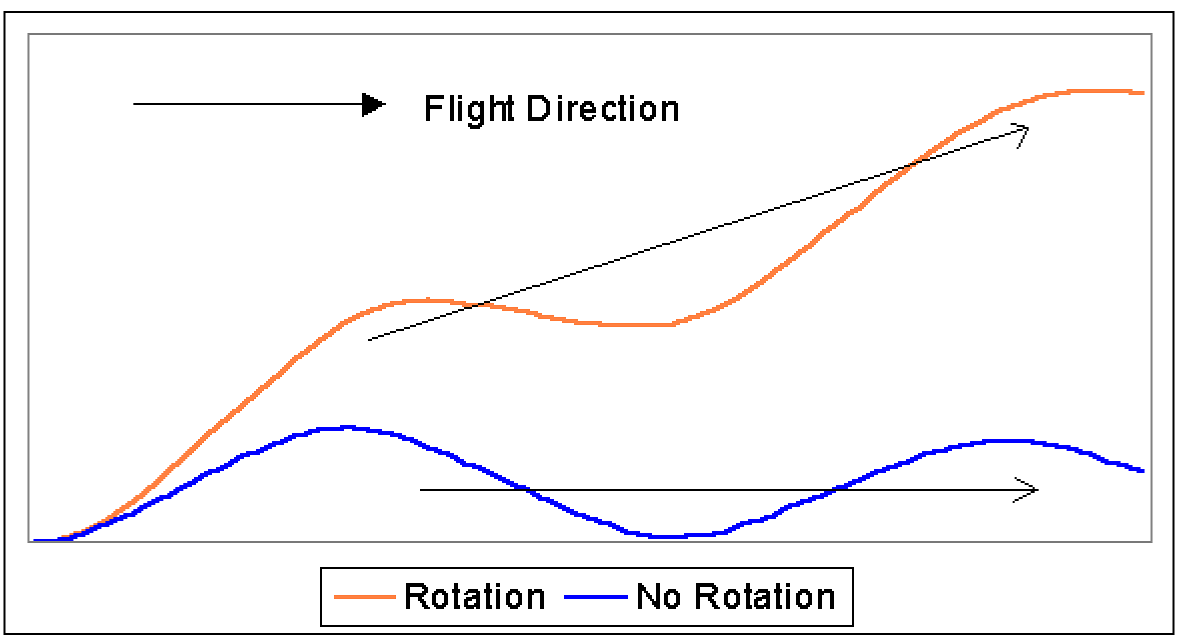
The attached (video based) image linked from Bertil Olssen's excellent site is a nice illustration of the arrow configuration at the moment the arrow leaves the string.

The alignment of the arrow at launch is a line drawn through the arrow's two (hypothetical) vibrational nodes. This alignment does not have to be in the plane of the bow. The arrow can be offset at an angle in either direction to the bow plane. The direction the arrow is travelling at launch will be very close to the plane of the bow. At launch the alignment of the arrow can therefore be at some arbitrary direction to the direction it is travelling.

The section on Fletched Arrows illustrated that while arrow (mis)alignment at launch can result in the arrow visibly fishtailing in flight the effect on where the arrow hits the target is fairly negligible. You need a big mislignment to push an arrow out of the gold even at 90 metres.
If an arrow is launched with angular momentum then after arrow stabilisation the arrow ends up with an angle between the arrow alignment and the arrow travel direction so again you will end up with a fishtailing arrow. In this case the arrow direction has been changed during the stabilisation process so the arrow can miss the gold (or the target!). The fishtailing behaviour again though has a negligible effect on where the arrow hits.

The figure illustrates the difference between the two fishtailing causing mechanisms. (horizontal axis is the distance and the vertical axis the horizontal arrow displacment from the the target centre). If the visual arrow fishtailing results only from launch misalignment (no rotation) the arrow still hits the middle. If the visual fishtailing results from launch angular momentum (rotation) then the arrow can hit anywhere. For the archer the arrow flight visually looks the same whatever the fishtailing causing mechanism. In reality the fishtailing will be a combination of the two sources.

The combined effects of launch misalignment and launch angular momentum may act to increase or decrease the amount of fishtailing (they can act in the same or opposite arrow alignment directions). It's possible for the two effects to largely cancel each other out so you can end up with an arrow that has visually good arrow flight but has poor grouping. This effect is another reason to doubt tuning methods that rely on looking at the physical orientation of the arrow i.e. paper tuning and arrow nock orientation in the target.



As far as arrows in the target goes, if the arrow is fishtailing then the whatever angle the arrow happens to be at in flight when it hits the target that's the angle you end up with. This angle will be a random combination of the effects of launch alignment and launch angular momentum.