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Hang Glider Design and Performance

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Hang gliding represents a less known but sizable segment of the sport aviation community. This sport experienced a rebirth in popularity during the 1970s with the advent of new, simple wings developed by pioneers like John Dickensen based on a wing concept developed through NASA engineer Francis Rogallo's work. This paper will summarize hang glider technical development from the late 1800s to the current generation of designs. Hang glider structural and aerodynamic design features differ significantly from those of traditional aircraft design. This paper discusses these differences, including sail flexibility, structural design philosophy, and wing twist. Current hang glider design falls into two primary genres: Flexible and rigid wings. The flex-wings are the most popular and are direct descendents of the wings developed by Francis Rogallo and John Dickensen. Since the 1970s they have evolved into much safer, higher performing wings. They now have very pleasing handling qualities, and are capable of multiple-hour flights over great distances. The rigid wings have structural design features more similar to traditional aircraft, offer improved glider performance, and utilize composite materials extensively in their structure, all at increased cost and weight. The flex-wing product line of the Wills Wing company was evaluated in depth with a detailed build-up of drag and glide performance estimates shown.

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Nomenclature

α	=	angle of attack, degrees
CD	=	drag coefficient
CDi	=	inviscid induced drag coefficient due to wing planform and twist
CDmisc	=	parasitic drag coefficient due to miscellaneous items
CDprofile	=	profile drag coefficient
CL	=	lift coefficient
D	=	drag, pounds
γ	=	flight path angle, degrees
L	=	lift, pounds
L/D	=	lift/drag
ρ	=	air density, slugs/ft3
q	=	dynamic pressure, pounds/ft2
Swing	=	Wing reference area, ft2
θ	=	pitch angle, degrees
V	=	velocity, miles per hour
Vg	=	velocity over the ground, miles per hour
VG	=	variable geometry
Vs	=	sink rate velocity, miles per hour

I. Introduction

Hang gliding is an aerial sport whose participant pilots believe comes the closest to humankind mimicking the free flight of birds. What follows is a brief history of the sport, followed by a technical summary of the key design aspects of the most popular style of hang glider, the "flex-wing" which evolved from the original work of Francis Rogallo and John Dickensen during the 1950s and 1960s. Next, the performance of product line of the largest US based manufacturer, Wills Wing, will be analyzed. The drag of four Wills Wing gliders was independently estimated using classical techniques. This drag and the resulting glider performance data were compared to data from Wills Wing.

II. The Rebirth of Hang Gliding

The first heavier than air gliding flight likely took place in 1849 when Sir George Cayley launched his coachman in a flight across a valley in England. The first hang gliders flew during the late 1800s and were built and flown by famous pioneers such as the German engineer, Otto Lilienthal, Percy Pilcher of Scotland, and Octave Chanute and John Montgomery of the United States. Three of the four of these pioneers died piloting their experimental craft, evidence of the dangers faced by the pioneers of flight. Octave Chanute's biplane glider was the first successful human-carrying glider that set the pattern for biplane aircraft structure for decades to follow. Orville and Wilbur Wright experimented with gliders that improved upon Chanute's design in 1900-1902. They perfected their control system and basic turns with their 1902 glider before applying power to invent the airplane in 1903. The Wrights also experienced the first well documented, true soaring flight in October, 1911 at Kitty Hawk with a flight that lasted 9 minutes, 45 seconds. References 1 to 10 document many of these pioneering efforts.

After powered flight became a reality, gliding activity became more of interest for recreation. After World War I, Germany was prohibited by the Armistice from flying powered aircraft and gliding thrived as a sport. The first competition was held in Rhoen in 1920 and pioneer Willi Pelzner won in a biplane hang glider. The following years saw the advent of gliders that eventually evolved into the efficient sailplanes of today. Figure 1 illustrates the chronology of these early gliding aircraft.

Hang gliding experienced a rebirth in the 1960s and 1970s when John Dickensen of Australia developed a practical pilot support and weight shift control method coupled with the wing design invented by Francis and Gertrude Rogallo of the USA. Barry Palmer flew a foot-launched Rogallo wing prior to John Dickensen but it was not practical enough to be widely imitated. John Dickensen's wings were used by Australians Bill Moyes and Bill Bennett to promote hang gliding across the world and it really caught on in the early 1970s. By 1974 there were about 40 manufacturers of "Standard Rogallo" hang gliders in the USA. One could buy a ready-to-fly hang glider for about $400, and it usually came with little or no instruction on proper flying technique. There were many fatalities due to design deficiencies in these early wings as well as poor pilot instruction. Eventually the design technology matured and safety improved greatly with the advent of helmet usage, back up emergency parachutes, hang glider manufacturers agreeing on standardized full scale strength and pitch stability testing, standardized instruction and pilot ratings. The Hang Glider Manufacturers Association (HGMA) oversees the full scale testing of hang gliders in the US and the DHV does this in Europe (References 11 and 12). The sport has been successfully self-regulated in the USA for nearly three decades by the United States Hang Gliding and Paragliding Association., as evidenced by a greatly improved safety record.

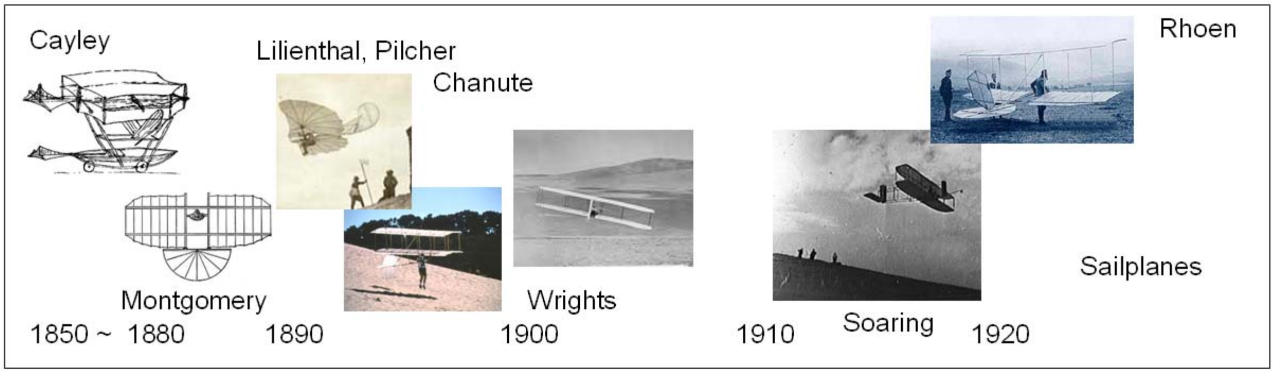

Figure 1. Early gliding aircraft through the 1920s.

The gliders evolved into two basic types of aircraft: More sophisticated, advanced Dickensen/Rogallo wings that are now called flex-wings, and gliders with rigid structure more like private aircraft that are known as rigid wings. In the 1980s and 1990s paragliders also arrived, evolved and have greatly increased in popularity. Figure 2 illustrates the chronology of hang gliders since their rebirth of popularity.

Figure 2. Hang gliders and paragliders since their rebirth in popularity

III. Flex-Wing and Rigid Wing Design Features

The typical flex-wing hang glider has structure and aerodynamic design features that differ significantly from typical lightweight private or ultralight aircraft. Figure 3 shows some of the design nomenclature.

Key design features include:

- A tail-less design that has adequate pitch stability, enabled by a combination of the low pilot position, wing sweep and washout twist.
- Pitch control is by pilot weight shift fore and aft.
- Roll/yaw control is by pilot weight shift side to side, causing differential sail twist.
- Lift loads are carried by the leading edge, side wires, keel and crossbar.
- Battens slide in pockets in the sail, held in tension at the trailing edge using special hardware or ties.
- A tight sail held in place by leading edge tube bending stiffness is used to control spanwise wing twist.
- Passive load relief occurs at high load factors by sail twisting and the outboard LE bending aft.

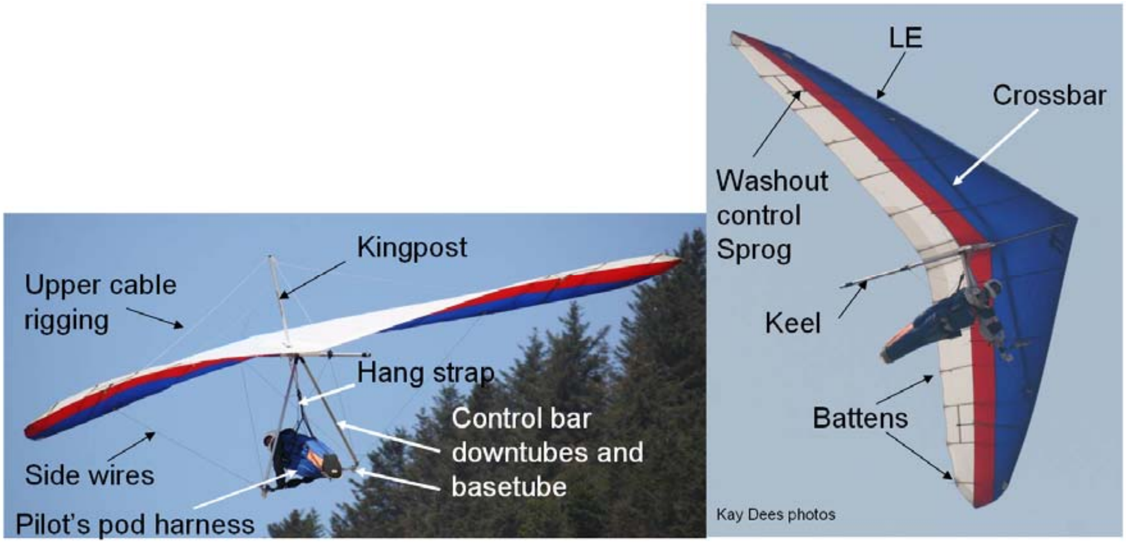

Figure 3. Flex-wing hang glider parts

There are complex aerodynamic and structural interactions that are known by active pilots and the few glider designers that work for the glider manufacturers but it would be difficult to get quantifiable measurements of them. Flex-wings vary from easy to fly and inexpensive trainers (Figure 4), to high performance wings capable of very good glide performance and cross country flights of hundreds of miles (Figure 5). The Falcon 3 of Figure 4 has an exposed crossbar that creates more drag, but also enables the glider to be very light weight and have superb handling qualities. The large wing area provides a low sink rate. The Talon 2's sail (Figure 5) encloses the crossbar and has a tighter wing of smaller area, requiring an advanced pilot rating to safely fly it and fully enjoy its capabilities. It has no kingpost or upper rigging and relies on a heavier, stronger composite crossbar to take negative g loadings in flight. The Talon weighs and costs more than the Falcon. Flex-wings are built in a variety of wing area sizes according to pilot weight. Typical harnesses are very comfortable and enable the pilot's body except for the head and arms to be enclosed for lower drag and for warmth at higher altitudes. The advanced gliders have a variable geometry (VG) feature where with the pull of a line, the pilot can tighten crossbar tension, reducing sail twist, and effectively trimming at a higher airspeed with lower drag.

Figure 4. Falcon 3 training glider

Figure 5. Talon 2 advanced flex-wing

Rigid wings provide a further improvement in glide performance over topless flex-wings like the Talon, although there is some debate regarding how much or if their cost, weight and greater fragility are worthwhile. A typical rigid wing is shown in Figure 6. Rigid wings typically have greater wing span, higher wing aspect ratio, lower sweep wing planforms and some designs also include winglets for a further boost in effective span.

The ATOS VR design represents state of the art rigid wing design that yields an L/D in the high teens, which is impressive considering the drag of an exposed pilot (Reference 13). Design features of the ATOS VR that differentiate it from the flex-wings include:

- Fully cantilevered wing structure with carbon fiber D-spar leading edge, carbon ribs attached to the LE and covered with sailcloth. It is fragile and must be carefully maintained.
- Less wing sweep so a small tail improves pitch damping and pitch stability.
- Roll/yaw control is by spoilers and is actuated by pilot weight shift side to side. Note that the weight shift by itself provides negligible roll effectiveness.
- Inboard simple trailing edge flaps of triangular planform.
- Ribs fold against D-spar when glider is disassembled. The airfoil is typically constrained to not have undercamber or chordwise curvature reversals.

Figure 6. Air ATOS VR rigid wing (photo via OZ report, vol 10., # 39)

Figure 7. Brightstar SWIFT (photo via http://aero.stanford.edu/Reports/SWIFTArticle1991.html)

The Brightstar SWIFT design, unlike the ATOS VR, integrates the pilot into the wing in a cage-like structure with the pilot in a supine rather than prone position. It has a higher L/D in the mid 20's if a fairing is used. It has been less popular than the ATOS line of gliders due to its higher weight, but the performance is improved. Design features of the SWIFT that differentiate it from other designs include:

- Fully cantilevered composite wing structure from leading to trailing edge.
- Wing with more sweep, less taper
- Optional fairing for supine pilot
- Pitch, roll control via TE devices actuated by side stick control.
- Inboard trailing edge flaps.
- The disassembled wing is transported in a large box.

IV. Wills Wing Hang Glider Product Line

The USA's largest manufacturer of hang gliders, Wills Wing, produces four models of flex-wings that are very popular with pilots. Wills Wing has sold thousands of gliders since the early 1970s. Flex-wing hang gliders make up the vast majority of gliders being flown today due to their lighter weight, lower cost and more robust design than rigid wings. There are only a handful of hang glider manufacturers world wide. Others in addition to Wills Wing include Moyes, Icaro, Aeros, Airborne, and Northwing (references 14 to 18).

The Wills Wing product line in order of increasing performance, cost, and weight is shown in Figure 8. The Falcon 3 trainer is a "single-surfaced" wing and is the most produced of the Wills Wing gliders. Many advanced pilots enjoy Falcons due to their convenient set up and superb handling qualities. The Sport 2 is an intermediate pilot's wing with a double surfaced sail that encloses the crossbar and has a variable geometry feature (as does the U2 and T2). The U2 has a higher wing loading, higher aspect ratio, and higher performance than the Sport 2. The Talon T2 eliminates the upper rigging present on the other gliders to further reduce drag. This results in a weight penalty in order for the structure to still meet strength requirements at negative load factors. All four models of gliders come in two or more wing area sizes to accommodate pilots of various body weights. In this paper a single wing size of glider of each model was analyzed, typically the closest size appropriate for a pilot weighing 160 to 170 pounds.

The generic glide and sink rate polars from the company's web site (Reference 19) are shown in Figure 9 and are for pilot weights 130% greater than the minimum weight rating for each glider. They assume the pilot is flying with excellent form, with wings level using proper technique to control yaw excursions. These polars are provided in a generic sense so pilots of different weights and sizes of a given model of glider can calculate their glider performance. Data were read from the curves of Figure 9 and by assuming a given glider size and pilot weight, the values of CL and CD could be calculated to generate plots of L/D versus CL (to be shown later in the paper).

Glider	Swing, ft2	Span, ft	AR	Weight, lbs
Falcon 3	170	30.6	5.48	48
Sport 2	155	31.5	6.36	59
U2	145	31.3	6.76	63
Talon T2	144	32.3	7.25	71

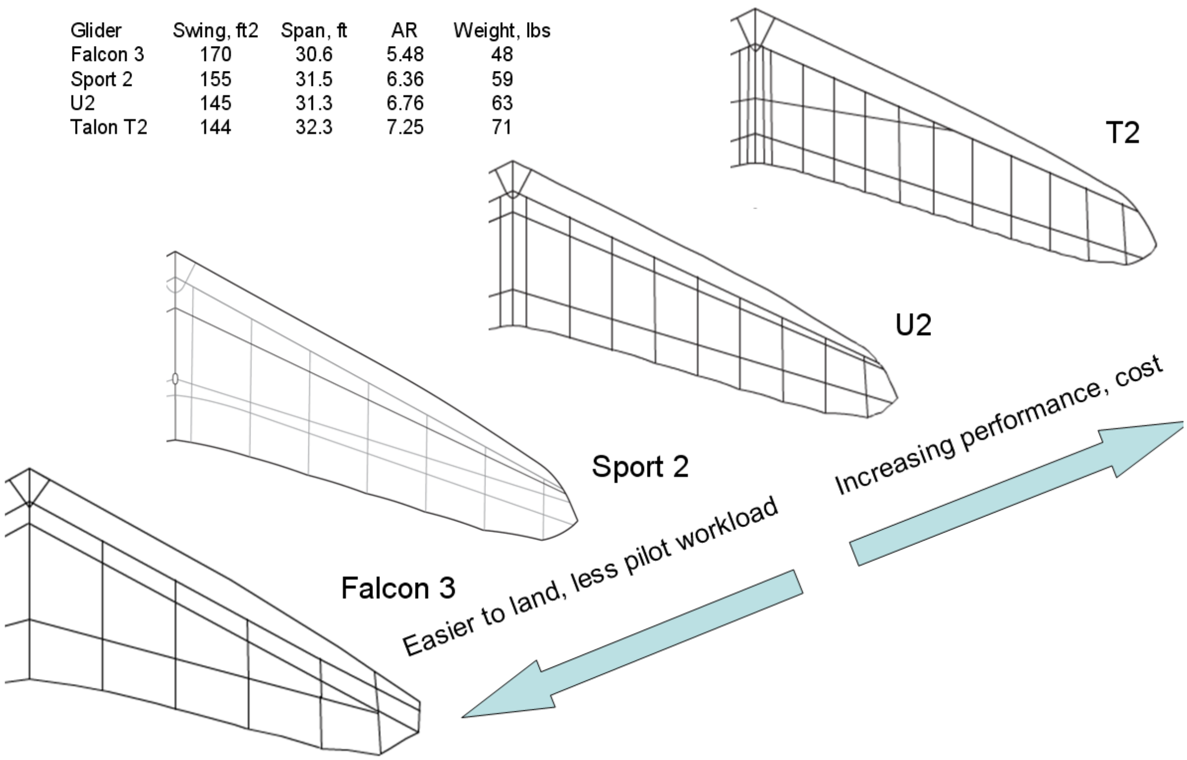

Figure 8. Wills Wing hang glider product line

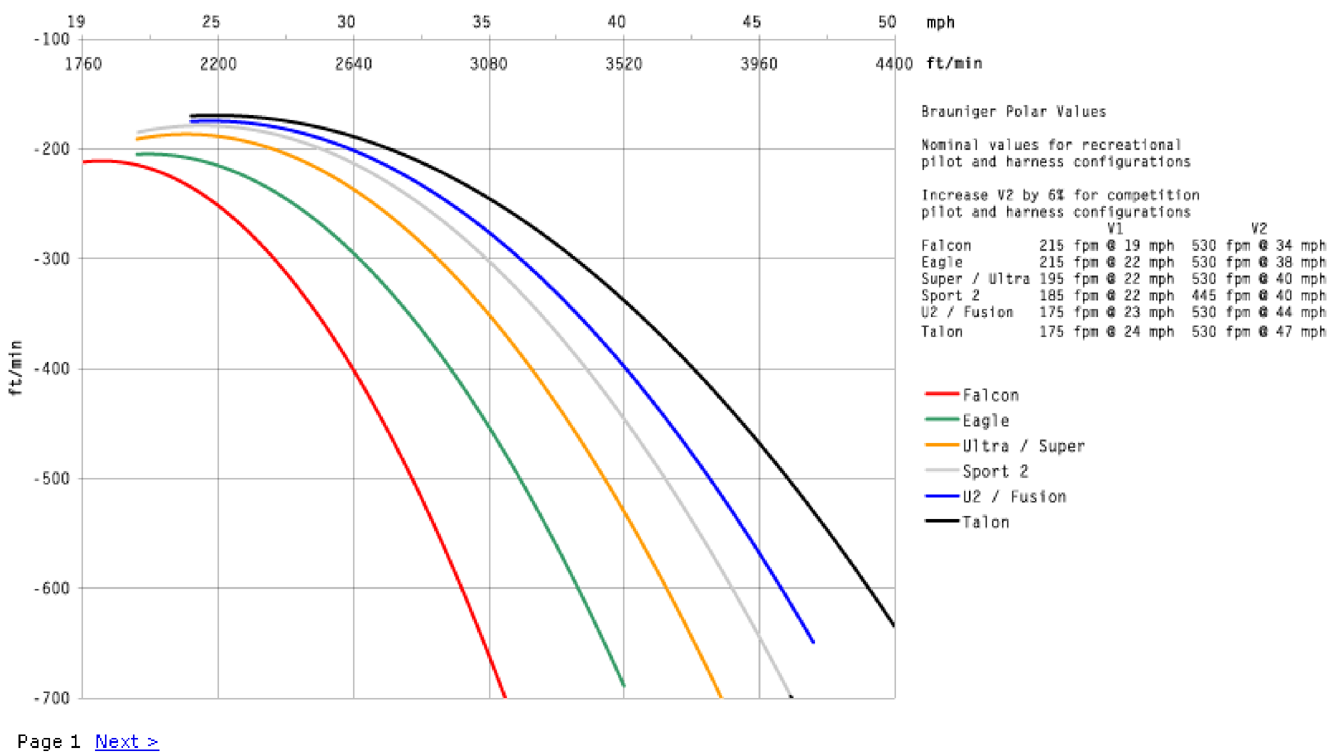

Figure 9. Glide performance of Wills Wing gliders (via Reference 19)

V. Drag and Performance of Four Hang Gliders

The equations for gliding flight are as follows with the geometry shown in Figure 10.

α=Angle of Attack, + as shown

θ=Pitch Angle, - as shown, $\theta=\alpha+\gamma$

γ=Flight Path Angle, - as shown

$L - W\cos\gamma = 0$

$D - W\sin\gamma = 0$

$$TAN\gamma = D/L = V_S/V_G = C_{D/}C_L$$

$$C_L = L/(qS_{REF}) \approx W/(qS_{REF}) \text{ for small } \gamma$$

$$C_D = D/(q\ S_{REF})$$

$$q = \tfrac{1}{2}\rho V^2$$

$$V = \sqrt{2L/(\rho SC_L)} = \sqrt{2W\cos\gamma/(\rho SC_L)} \approx \sqrt{2W/(\rho SC_L)}$$

$$V = \sqrt{V_s^{\,2} + V_G^{\,2}}$$

V_s ft/min=88 V_{MPH} $\sin\gamma$

$$L/D = (88/V_{sFT/\min})\sqrt{V_{MPH}^{\,2} - (V_{Sft/\min}/88)^2}$$

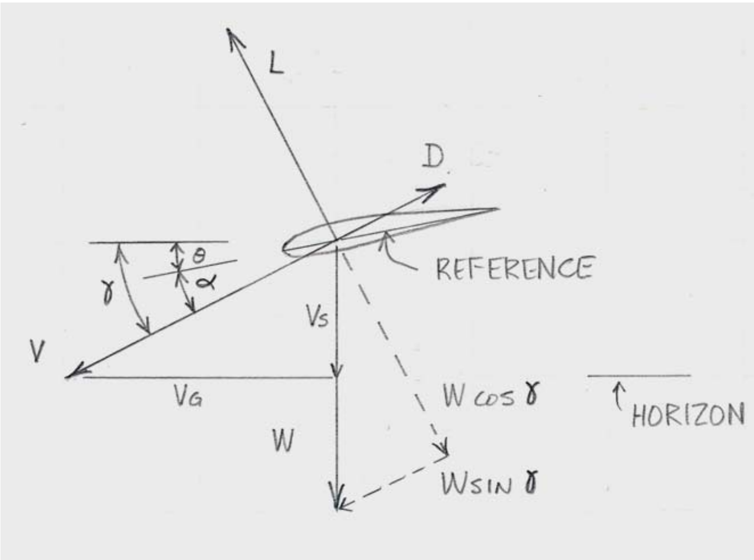

Figure 10. The geometry of gliding flight

The drag polars of all four glider models were estimated using classical aircraft design drag methods where the drag was broken down into three fundamental parts: Parasitic drag (CDmisc), induced drag due to lift (CDi or CDinduced), and profile drag (CDprofile). These three parts were then added together in a build up of total drag.

CDmisc is the miscellaneous parasitic drag originating from items such as the exposed pilot, cables, control bar, wheels, etc. Estimates were done using sources such as Reference 20. It is typically expressed as the product of CDmisc and Swing which is equivalent to the product of the drag coefficient based on frontal area and the frontal area itself. The pilot plus harness drag was derived from Reference 21 and adjusted using engineering judgment to more contemporary values. Figure 11 shows the assumed values used for this analysis.

CD assumptions, based on frontal area:

Exposed round crossbar near wing lower surf.	0.8
Round downtubes, basetube (F3)	1.0
Streamlined downtubes, basetube (S2, U2)	0.13
Streamlined downtubes (T2)	0.09
Wheels	1.0
Kingpost	0.3
Exposed cables	0.7 to 1.0

Components	Bottoms up build up of CD * S-frontal of Misc Drag Items, ft2 F3	S2	U2	T2
pilot and harness	1.70	1.70	1.50	1.50
exposed crossbar	2.05	0.00	0.00	0.00
downtubes	0.97	0.11	0.11	0.07
basetube	0.42	0.04	0.04	0.04
wheels	0.04	0.04	0.04	0.00
corner fittings	0.06	0.02	0.02	0.02
kingpost	0.09	0.09	0.09	0.00
lower side wires	0.17	0.17	0.17	0.17
fore/aft lower wires	0.18	0.18	0.18	0.18
top landing wires	0.15	0.15	0.15	0.00
top fore/aft wires	0.06	0.06	0.06	0.00
reflex wires	0.14	0.07	0.07	0.00
keel skin friction	0.01	0.01	0.01	0.01
misc	0.00	0.00	0.00	0.00
Total	6.04	2.64	2.44	1.99
Round off total	6.0	2.6	2.4	2.0

Figure 11. Miscellaneous parasitic drag estimates.

CDi, or CDinduced is the induced drag due to lift creation and driven by the wing planform and twist. Hang gliders have large amounts of twist, with intermediate gliders having nearly 20 degrees of twist change from the root to the tip airfoil sections. This is due to the structural arrangement as flex-wings have no rear spar and the only way to minimize sail twist is through a stiff sail and leading edge, which adds weight and stiffens handling qualities. CDi was estimated using a public domain vortex-lattice method called Athena Vortex Lattice, or AVL, developed at Massachusetts Institute of Technology (Reference 22). Typical results for the T2 are shown in Figure 12. The spanwise lift coefficient distribution is shown in yellow and indicates stall would begin approximately 25% of the way from the root to the tip. Gliders typically have tufts of yarn in the wing at this location so the pilot can get a visual indication in flight when flow separation first begins. The spanload distribution is shown in green and is close to elliptic, showing the level of refinement achieved through decades of incremental development.

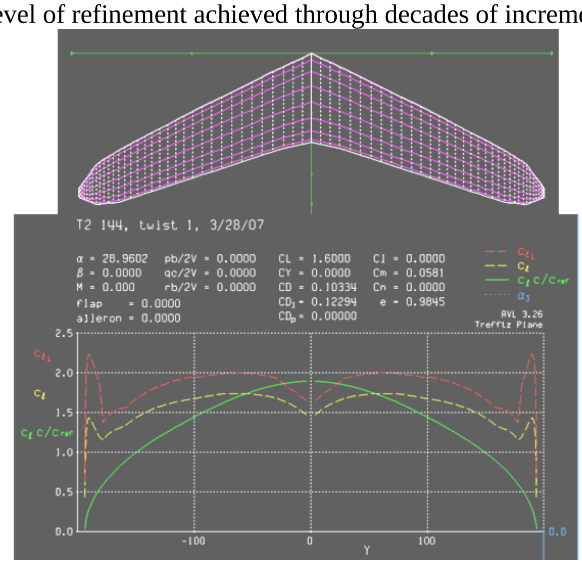

Figure 12. T2 Induced drag estimate using AVL.

Estimates of twist were made based on analysis of photographs adjusted after consultation with the glider designer at Wills Wing, Steve Pearson. Measurement of in-flight glider geometry would make an interesting study as from personal observation, sail twist and camber changes with changes in pilot weight, load factor, and airspeed. By intent, flex-wing hang gliders have selective geometric flexibility of their structure. The subtle nuances of how gliders have stiffness to take flight loads and perform well at high speed, yet have flexibility for pleasing handling qualities are only understood by a few successful hang glider designers. Rigorous engineering studies have not been conducted to document or further optimize these factors.

For this study, AVL was used to analyze the gliders with VG on and off to model two different twist distributions. A transition from VG off at low speed to VG full on (e.g. sail with less twist) was assumed based on the author's flight experience. In the case of the Sport 2, the AVL predicted CDi levels seemed excessively high and were adjusted downward to family with the other three glider models. (Figure 13). Curves were fit through these data so values could be calculated at any CL. Note that Figure 13 shows the difference between estimated CDi via AVL and the ideal induced drag.

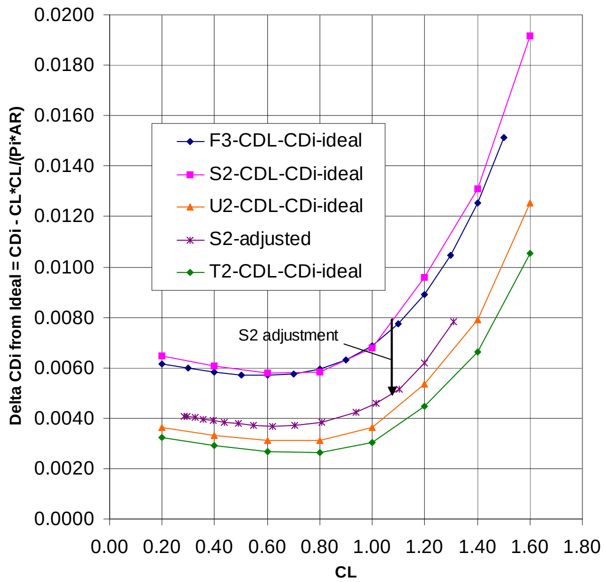

Figure 13. Induced drag estimates

CDprofile included the airfoil profile drag, including the effects boundary layer growth across various parts of the wing at either high or low CLs. It was estimated by first taking total drag polars derived from the Wills Wing web site shown in Figure 9 and then subtracting the parasitic and induced drags from the total drag. This yielded a residual drag coefficient versus CL that was assumed to include the profile drag. The raw data were in need of adjustment to assure that they formed a family of curves that represented a progression across the product line of Wills Wing gliders. Figure 14 shows these data after adjustment. Their minimum drag levels seem low to the author, given that even the best flex-wing hang glider sails tend to have some wrinkles and imperfections relative to a smooth theoretical airfoil surface.

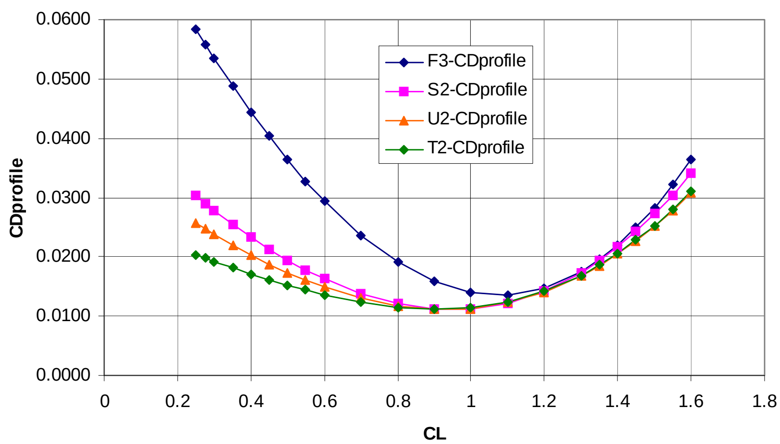

Figure 14. Adjusted profile drag estimates

These incremental drag estimates were then added as a build up to create estimates of glider performance for the closest glider size that would fit a 160 to 170 pound pilot. The build ups were used to create spreadsheets usable for different pilot weights or air densities. These spreadsheets were used to compare results with the original Wills Wing L/D data to see how close they were to each other (Figure 15). The build up maximum L/D estimates for the Falcon, Sport 2 and U2 gliders were slightly less than the original factory data, but the T2 built up L/D was greater than the Wills Wing data.

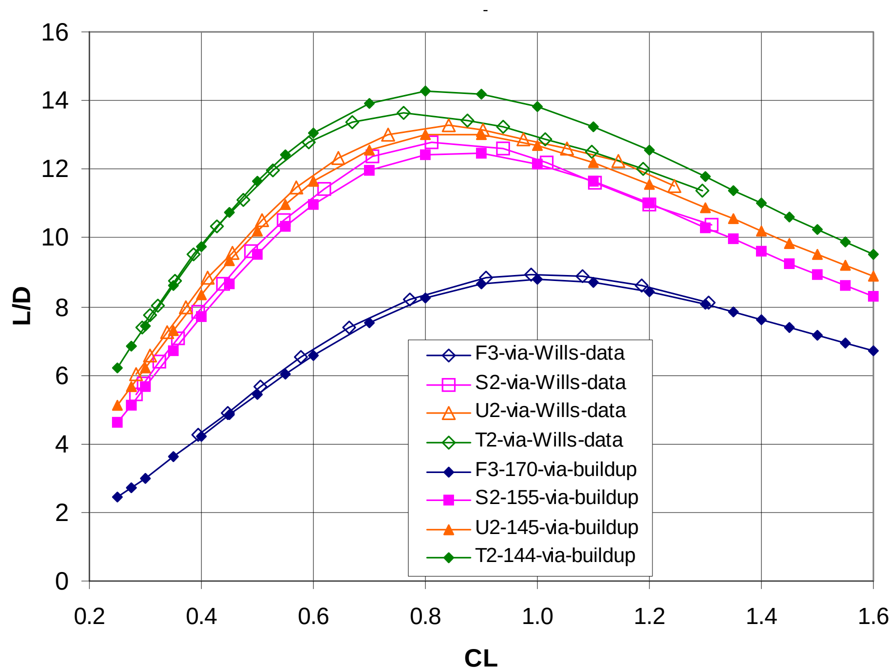

Figure 15. Comparison of L/D estimates with manufacturer's data

Figure 16 shows how L/D translated into glide and sink rate data. It should be noted that these performance levels have been validated by flight test by Wills Wing in some cases, but performance could easily be made worse by poor pilot technique or poor pilot position or a draggy harness. This could easily degrade L/D by a point or more. Typical flight data using a GPS and flown in calm air at constant airspeed in back to back flights can easily yield much larger uncertainty bands than the differences between the build up data and the Wills Wing data. The built up can be considered reliable regarding increments between the Wills Wing models. What is lacking is a rigorous and disciplined, independent flight test comparison amongst the various popular glider models of several manufacturers.

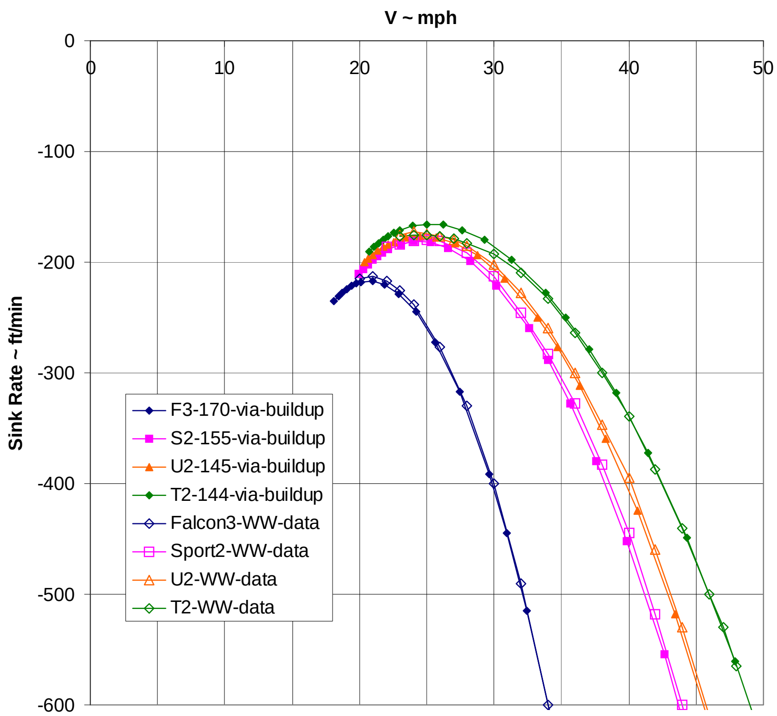

Figure 16. Glide performance comparison with manufacturer's data

The author's own crude attempt at this with a GPS device is shown in Figure 17. The two datasets were from the same flight in very calm evening air, one flying a different heading by as close to 180 degrees than the other as possible to eliminate any wind influence. Data indicated glide performance significantly worse than the Wills Wing data, but the flight was also in a recreational harness which had more drag than that assumed in the build up data. However, the differences shown here are more than can be explained by harness drag differences or flying in sinking air. If the Sport 2 induced drag adjustment for twist was too beneficial, removing it only improved sink rate by 20 ft/min. at 30 mph. Clearly a more rigorous experiment is needed with better instrumentation and test conditions limited to early morning calm, and including data at higher airspeeds to better capture the drag polar shape.

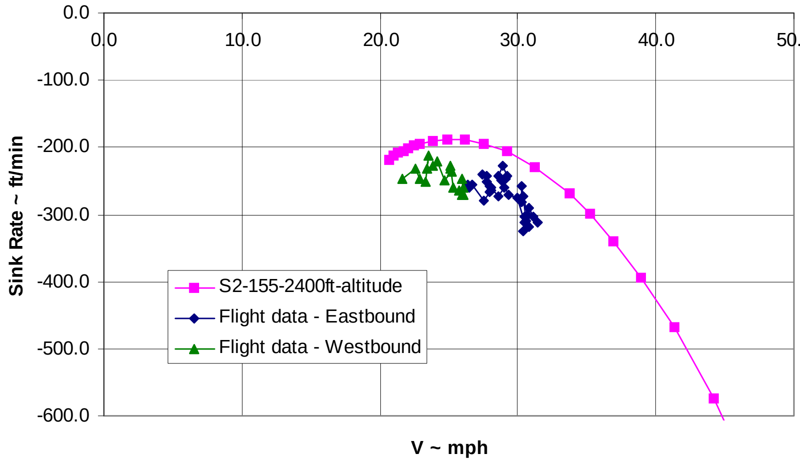

Figure 17. Author's crude flight test comparison with built up Sport 2 data

VI. Conclusions

- Hang gliders have evolved into safe, efficient, and fun sport aircraft.
- Flex-wing glider performance varies in L/D from 9 to 14 depending on complexity and degree of pilot skill required.
- Rigid wing gliders have achieved L/Ds in the 20s.
- Drag components can be estimated based on factory provided glide data, then adjusted to family better with each other.
- There is still a need for rigorous flight testing to better quantify in flight hang glider geometry and glide performance.

Acknowledgments

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