The Spitfire Wing Planform: A Suggestion

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Abstract

The paper concerns the aerodynamic design of the Spitfire wing and the involvement of the Canadian-born Beverley Shenstone in this. It is suggested that the wing's distinctive double-ellipse planform could have come from Prandtl's work at Göttingen on finite wing theory.

1. BEVERLEY SHENSTONE AND THE SPITFIRE

A recent book by Cole (1) deals with the career of the Canadian-born aeronautical engineer, Beverley Shenstone (Figure 1). Having graduated from the University of Toronto with both Bachelors and Masters Degrees in Aeronautics, in 1929 he moved to Germany to work for Junkers at Dessau. Whilst there, he became involved in gliding activities and through these he formed a life-long friendship with Alexander Lippisch. Cole (1) tells us that during Shenstone's stay in Germany he also met Ludwig Prandtl. By 1932, however, he had moved to Britain and joined Vickers Supermarine. From 1938 he served in the Air Ministry, later the Directorate of Technical Development, the British Air Commission in Washington and in the Ministry of Aircraft Production as Assistant Director of Research and Development of Air Transport. In 1948 he became Chief Engineer at British European Airways and in 1964 Technical Director at the British Overseas Airways Corporation. From May 1962 to May 1963 he was President of this Society.

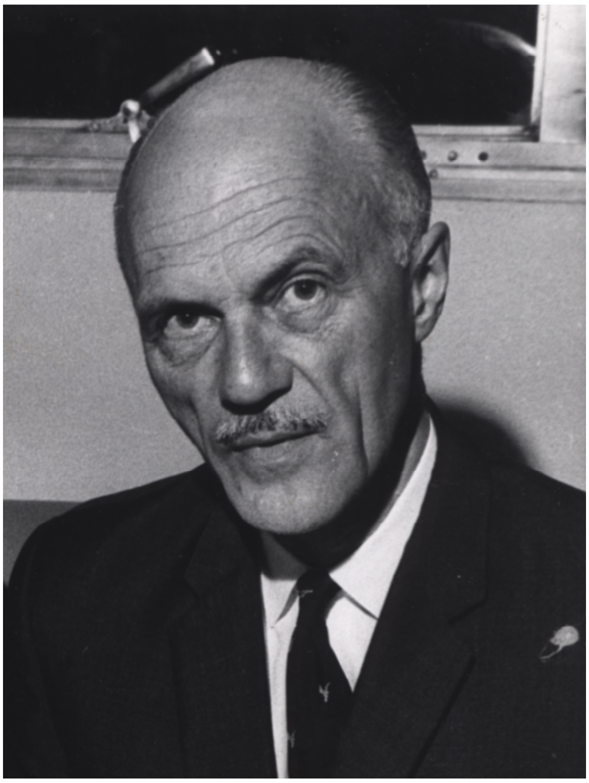
Figure 1 Beverley Strahan Shenstone (1906-1979), born in Toronto
Source: Royal Aeronautical Society (National Aerospace Library)

Much of Cole's book (1) concentrates on Shenstone's work at Supermarine with R. J. Mitchell (Figure 2) during the design evolution of the Spitfire (Figure 3). In particular, Cole seeks to demonstrate that Shenstone's involvement with the aerodynamic design of the Spitfire wing was more pervasive than hitherto supposed. Furthermore, he is at pains to scotch the belief that the Spitfire wing was copied from the Heinkel He 70. As to the latter, Shenstone himself stated in 1976 that that was not the case (see his letter to C. F. Andrews reproduced on page 32 of Reference 2). Moreover, in his far more extensive contribution to Reference 3 a year later he is even more definite in his refutation, stating,

> "It has been suggested that we at Supermarine had cribbed the Spitfire's elliptic wing shape from that of the German Heinkel 70 transport. This was not so. The elliptic wing shape had been used in other aircraft and its advantages were well known. Our wing was much thinner than that of the Heinkel and had a quite different section."

However, he admits that (3) (my explanatory addition in brackets),

> "The Heinkel 70 did have an influence on the Spitfire, but in a rather different way. I had seen the German aircraft at the Paris Aero Show and had been greatly impressed by the smoothness of its skin. There was not a rivet head to be seen….. When we got down to the detailed design of the F.37/34 (which was to become the Spitfire) I referred to the Heinkel 70 quite a lot during our discussions. I used it as a criterion for aerodynamic smoothness and said that if the Germans could do it so, with a little effort, could we."

Figure 2 Reginald Joseph Mitchell (1895-1937), born at Butt Lane, Kidsgrove, Staffs.

Source: Royal Aeronautical Society (National Aerospace Library)

Figure 3 Spitfire prototype K5054, first flight 5th March 1936
Source: Royal Aeronautical Society (National Aerospace Library)

So the He 70's only influence was in surface finish, not shape. As to the latter, Shenstone states (3),

> "The elliptical wing was decided upon quite early on. Aerodynamically it was the best for our purpose because the induced drag, that caused in producing lift, was lowest when this shape was used; the ellipse was an ideal shape, theoretically a perfection. There were other advantages, so far as we were concerned. To reduce drag we wanted the lowest possible wing thickness-to-chord ratio, consistent with the necessary strength. But near the root the wing had to be thick enough to accommodate the retracted undercarriage and the guns; so to achieve a good thickness-to-chord ratio we wanted the wing to have a wide chord near the root. A straight-tapered wing starts to reduce in chord from the moment it leaves the root; an elliptic wing, on the other hand, tapers only very slowly at first then progressively more rapidly towards the tip. Mitchell was an intensely practical man and he liked practical solutions to problems. I remember once discussing the wing shape with him and he commented: "! don't give a b….. whether it's elliptical or not, so long as it covers the guns!" The ellipse was simply the shape which allowed us the thinnest possible wing with sufficient room inside to carry the necessary structure and things we wanted to cram in. And it looked nice."

Shenstone (3) then turns briefly to the earlier and unsatisfactory Supermarine Type 224 (Figure 4) which first flew in 1934. This crank-winged fighter prototype, with a fixed and trousered undercarriage, was powered by a steam-cooled Rolls-Royce Goshawk engine. He comments (3) that this,

> "had had a thick wing section and we wanted to improve on that. The NACA 2200 series aerofoil section was just right and we varied the thickness-to-chord ratio to fit our requirements: we ended up with 13 per cent of the chord at the root and 6 per cent at the tip, the thinnest we thought we could get away with. Joe Smith, in charge of structural design, deserves all credit for producing a wing that was both strong enough and stiff enough within the severe volumetric constraints."

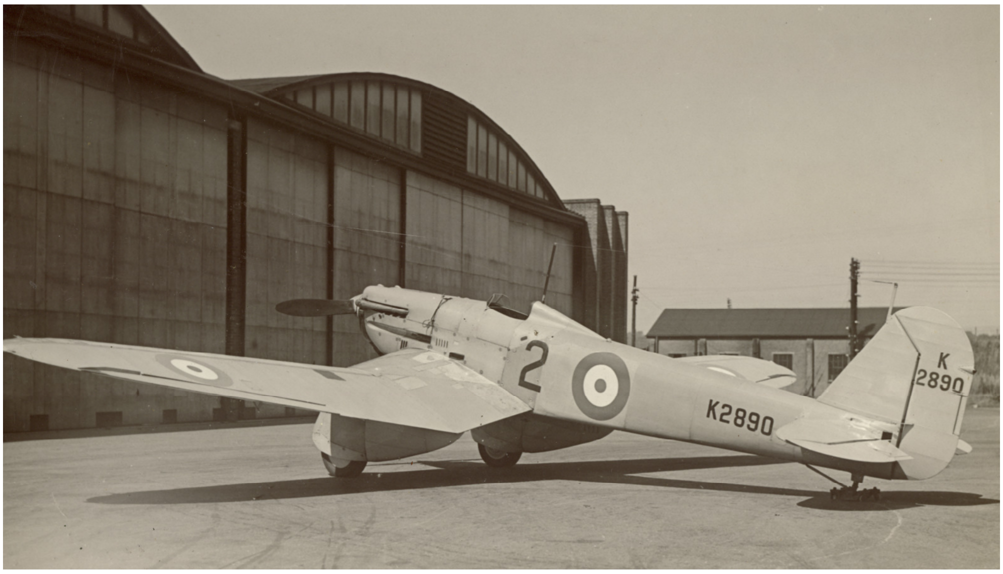

Figure 4 Supermarine Type 224 (Specification F.7/30), first flight 19th February 1934
Source: Royal Aeronautical Society (National Aerospace Library)

In his earlier note (2), Shenstone provides further thoughts on the later-realised advantages of the elliptic wing:

> "…the real advantage of the elliptical wing turned out to be its low induced drag at very high altitudes, such altitudes not having been considered during the design, but realised during the war, helping to keep Spitfire in the front line during rapid development under Joe Smith. The point here is that at great altitudes where the air is thin, the angle of incidence must be increased, resulting in more induced drag. The elliptical wing then becomes important - assuming subsonic flight."

All of the above accepted, it is clear that Shenstone was well aware of the aerodynamic advantages of the elliptic wing at the Spitfire's inception.

As Reference 4 shows, various planforms - at least three straight taper arrangements and the simple ellipse - were considered for the Spitfire design between May and December 1934. However, the interesting point is that the wing planform finally chosen in December 1934 was not the simple ellipse used on the He 70 and other aircraft but the combination of two semi-ellipses: the front of the wing is formed from a semi-ellipse having a small minor axis, this being wedded at a common major axis to a rearward semi-ellipse having a larger minor axis. It is this feature which makes the Spitfire wing not only so distinctive but also unique for its time. Yet this feature is scarcely remarked upon in the endless debates surrounding the provenance of the Spitfire wing. The questions then are: how might this unique feature have come about and, indeed, where might it have come from?

2. THE ELLIPTIC WING

Frederick Lanchester was the first to understand that a lifting wing creates trailing vortices which cause an additional drag force on the wing, what we now call lift-induced drag. In his *Aerodynamics* (5) of 1907 he provides a rather speculative argument that, from the point of view of reducing this induced drag, it is better not to have the kinetic energy of the trailing vortices concentrated at the wing tips but to spread this out along the span of the wing. He says (5),

> "We might thus take an elliptical form as a standard, with a pressure distribution appropriately proportioned. In general, the wing-plan of a bird has ordinates that approximate more or less closely to those of the ellipse."

Many of his model aeroplane wings had elliptic planforms.

Lanchester's speculations acquired a solid foundation in the finite wing theory developed during the First World War by Prandtl and his co-workers at Göttingen. In particular, analysis (6) by Prandtl's doctoral student, Max Munk, showed that induced drag is a minimum when the wing carries an elliptically distributed lift loading. The simplest means by which this loading can be achieved is by the use of an elliptic planform wing. However, in his Göttingen report (7) of 1918 on this and other work on wings, Prandtl illustrates the idea with a figure here shown as Figure 5. This depicts, not the simple elliptic planform, but that of the two semi-ellipses mentioned earlier as the shape of the Spitfire wing. Of this, he merely says (7) (Dr Brian Axcell has kindly provided the literal translation),

> "The form of an aerofoil of this type results when it is established that the profile form and the effective angle of attack α′ are to be constant, when bounded by two half ellipses, see Figure 5; since w is constant, the geometrical angle of attack α also becomes constant over the whole width of the span."

The effective incidence, α′, is that created by the trailing vortex field's downwash velocity, w, at the wing. However, the above comment gives little indication of a practical advantage in the use of this planform formed from two half-ellipses.

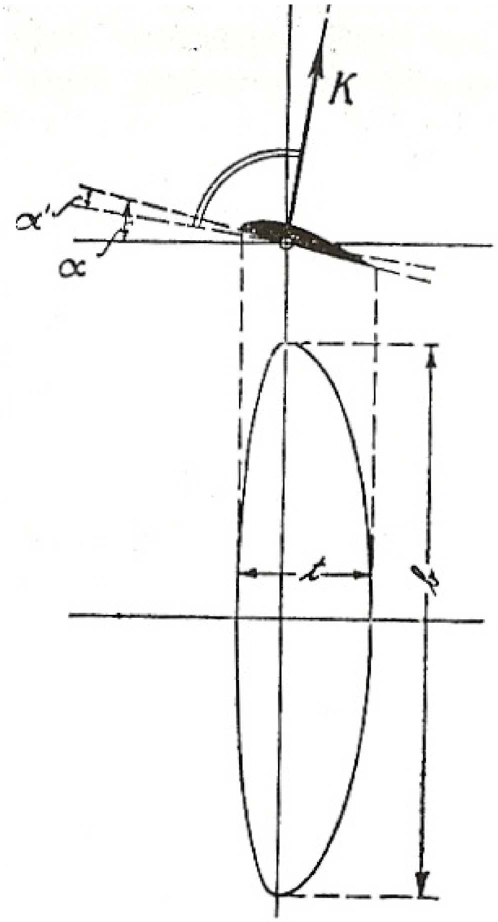

Figure 5 Wing planform shown in Prandtl (7), 1918

Prandtl's work on the finite wing reached an American audience through his NACA Report of 1921 (8). Although elliptic loading and its creation of minimum induced drag are dealt with there, the double ellipse planform of Figure 5 is neither shown nor mentioned. As to Britain, Prandtl's work was picked up by the German-speaking Hermann Glauert as a result of his visit to Göttingen after the close of the First World War (9). Subsequently, Glauert put the Göttingen work before the British aeronautical community through a substantial series of Reports and Memoranda provided by the Aeronautical Research Committee, keeping that community abreast of more recent German developments, devising improved mathematical methods and applying these to a wide variety of aerodynamic problems. From this came his widely-read textbook (10), *The Elements of Aerofoil and Airscrew Theory*, published in 1926. This deals with the case of elliptic loading and its advantage of minimum induced drag. It also mentions the use of wash-out, a feature used on the later Spitfire wing which contributed to its gentler stalling characteristics: the 2½° wash-out used helped to ensure that stall first occurred inboard so that the outboard ailerons still remained effective. Cole (1) claims this as one of Shenstone's contributions to the Spitfire's aerodynamic design and mentions that Shenstone had studied Glauert's textbook (10). However, the latter does not mention the use of Figure 5's double-ellipse planform.

So what then of Prandtl's double-ellipse planform of 1918? The current author has not had opportunity to study all of Prandtl's subsequent publications on the finite wing. However, one widely available publication stands out as being of particular interest to the present study and that is Prandtl's Göttingen lecture notes brought together and elaborated by his former doctoral student, Oskar Tietjens. Originally published in German, the second volume (11), of particular interest to the current study, appeared in 1931. Its English translation was published in 1934 (12).

It is here that the double-ellipse planform re-appears as Figure 166 on page 203 of the English edition. Concerning this, the text reads (12) (my emphasis in italics):

> "An elliptical lift distribution therefore can be realised by making a wing consist of two semi-ellipses as shown in Figure 166. By this special choice *the additional advantage is obtained that the centres of pressure of the individual profiles are all on a straight line* so that this particular wing can be approximated very well by a straight vortex filament."

Reference 12's Figure 166 is here reproduced as Figure 6. To put the above quotation's emphasised phrase in more modern terms, the aerodynamic centres of the individual aerofoil sections, located at or very near their quarter-chord points, will lie along a straight line. For a designer keen to use a single mainspar set, in plan view, perpendicular to the fuselage centreline, this would have vital practical implications over and above the aerodynamic advantage of minimum induced drag: the ability to set a single mainspar close to the line of section aerodynamic centres resulting in a strong but light structure, and attractive design features such as that the structure "covers the guns".

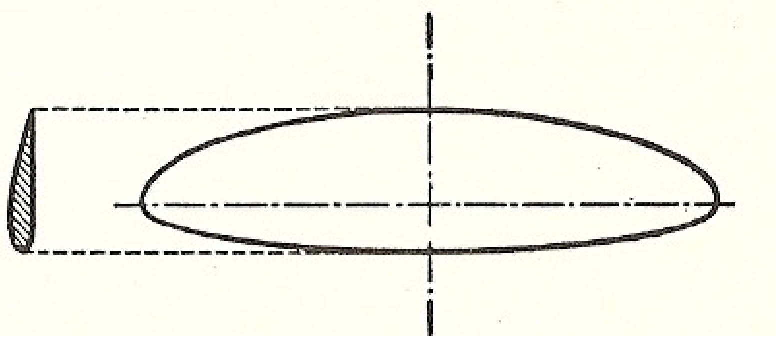

Figure 6 Wing planform shown in Prandtl and Tietjens (12), 1931/1934

It is possible that someone at Supermarine had seen either the original German edition (11) or its English translation (12) of Prandtl's notes and had understood the significance of Figure 6 when it came to the design of the Spitfire in 1934. The most likely candidate here is the German-speaking Shenstone. The alternative is that someone at Supermarine, and here again Shenstone is the most likely candidate, had independently arrived at the same idea. Weight is added to the first of these suggestions when the dimension ratios of Figures 5 and 6 are compared with those of the Spitfire planform. The semi-ellipses' semi-minor axes dimensions of those figures are both in the ratio of 1 to 2, identical to that of the Spitfire planform. Moreover, the span to root chord ratio of the figures is 4.1, again identical to that of the Spitfire when the fuselage width is excluded. Thus the semi-ellipse combination recommended by Prandtl is geometrically the same as that used on the Spitfire. Although the Spitfire's semi-ellipses' semi-minor axes dimensions are in the ratio of 1 to 2 so that the common major axis thus lies at one-third chord, the Spitfire's mainspar is positioned slightly further forward to lie closer to the structural ideal of the quarter-chord line.

3. OTHER CONDIDERATIONS

The structural advantage of placing the mainspars of windmill blades at the quarter-chord point had been grasped by the seventeenth century Dutch windmill builders. Drees (13) presents evidence suggesting that the blade mainspars were moved from mid-chord to one-third chord around 1550 and then, by about 1650, to the quarter-chord position. In addition, blade twist, giving greater incidence at the root, had been introduced together with a drooping of the leading quarter chord so as to give a slight camber effect. Drees (13) concludes that these improvements allowed the rotor diameter to increase from about 30ft to almost 100ft, producing a ten-fold increase in power.

Of course the detailed nature of the aerodynamic lift and its twisting moment on such windmill blades is unlikely to have been known to the early builders. In the case of the aerofoil, its lift and moment behaviour became clearer in the early years of the twentieth century. As mentioned in Reference 14's review (Section 5), in 1912 experimental evidence emerged to show that, whilst a cambered aerofoil's lift increases with increasing incidence, the lift force's centre of pressure moves steadily forward towards the quarter-chord position. Incidentally, that review (14) (Section 2) also draws attention to the strong similarity between Figure 5 above and the Spitfire's planform.

As Kutta-Zhukovskii aerofoil theory became absorbed within the aeronautical community, its results were seen to agree with the centre of pressure behaviour described above. Moreover, the theory revealed the remarkable feature described as follows: for a cambered aerofoil moving at constant velocity but with steadily increasing incidence, whilst the increasing lift force located at its centre of pressure moves steadily forward, the distance between that centre and the quarter-chord point steadily decreases such that the multiple of that distance and the lift force remains constant, independent of incidence. In other words, the aerofoil experiences a lift-produced nose-down moment about the quarter-chord point which is independent of incidence. Glauert's textbook (10) of 1926, for example, comes close to stating this. On page 86 he derives the following theoretical result, stated as "fully confirmed by experiment", for an aerofoil's moment coefficient, C_M, *measured about the leading edge*:

$$C_M = C_{MO} - C_L/4 \qquad (1)$$

Here C_{MO} is the constant moment coefficient at zero lift and C_L the variable lift coefficient. This result indicates that, had Glauert carried out the same calculation *but about the quarter-chord point,* then the term $C_L/4$ would have been lost. The final result would have shown that C_M *when measured about the quarter-chord point* is constant, equal to C_{MO} and independent of incidence, and thus in line with the above description. Two years later, in his work with S. B. Gates on the Westland Pterodactyl's swept-back wing (see Reference 9), the aerodynamic analysis is centred on each aerofoil section's quarter-chord point. Because of the extra geometrical complexity of wing sweep-back, the lines tracing out each section's quarter-chord point are themselves swept back. To deal with this, the concept of the "aerodynamic centre" is introduced as the point about which the complete wing's moment is invariant with incidence change.

In view of the behaviour of an aerofoil's lift force and centre of pressure movement described above, it is both entirely legitimate and very convenient to view this loading as follows. The incidence-dependent lift force acting at its varying centre of pressure position can be transposed so as to become the same force, but now fixed at the quarter-chord point, whilst accompanied by a pure moment, independent of incidence, acting about that point.

The structural implication of the above for those wishing to use a single mainspar is that its most structurally advantageous position is at the quarter-chord point. Placed there, it resists the lift load now considered as acting there, but provision must also be made to resist the nose-down, lift-induced twisting moment acting about that point. For the Dutch windmill blade, it was necessary to have a rectangular timber mainspar deep enough to resist the lift load whilst being wide enough to resist the twisting moment. For Mitchell's design masterpiece, the Spitfire, for which structural lightness was a major consideration, again the single mainspar was highly attractive and its most advantageous position was again along the straight line of section quarter-chord points. As Reference 4 shows, in the Spitfire's design evolution before the adoption of the double ellipse, this was the procedure adopted with all the straight-tapered and simple ellipse planforms considered. Consequently in all of these cases the mainspars were swept back slightly. This is evident in the straight-tapered example shown in Figure 7 taken from the first authoritative account (15) of the Spitfire's design and development provided by Joseph Smith (Figure 8). Smith, credited by Shenstone (3) above as supervising the Spitfire's structural design, succeeded Mitchell as Chief Designer after Mitchell's untimely death in 1937. Significantly, it was the double-ellipse adopted in December 1934 which finally allowed the structural simplicity of a mainspar set, in plan view, perpendicular to the fuselage centre line and along the almost-straight line of section quarter-chord points. This can be seen in the drawing (Figure 9) of the Spitfire prototype provided by Jeffrey Quill in his contribution to Reference 2.

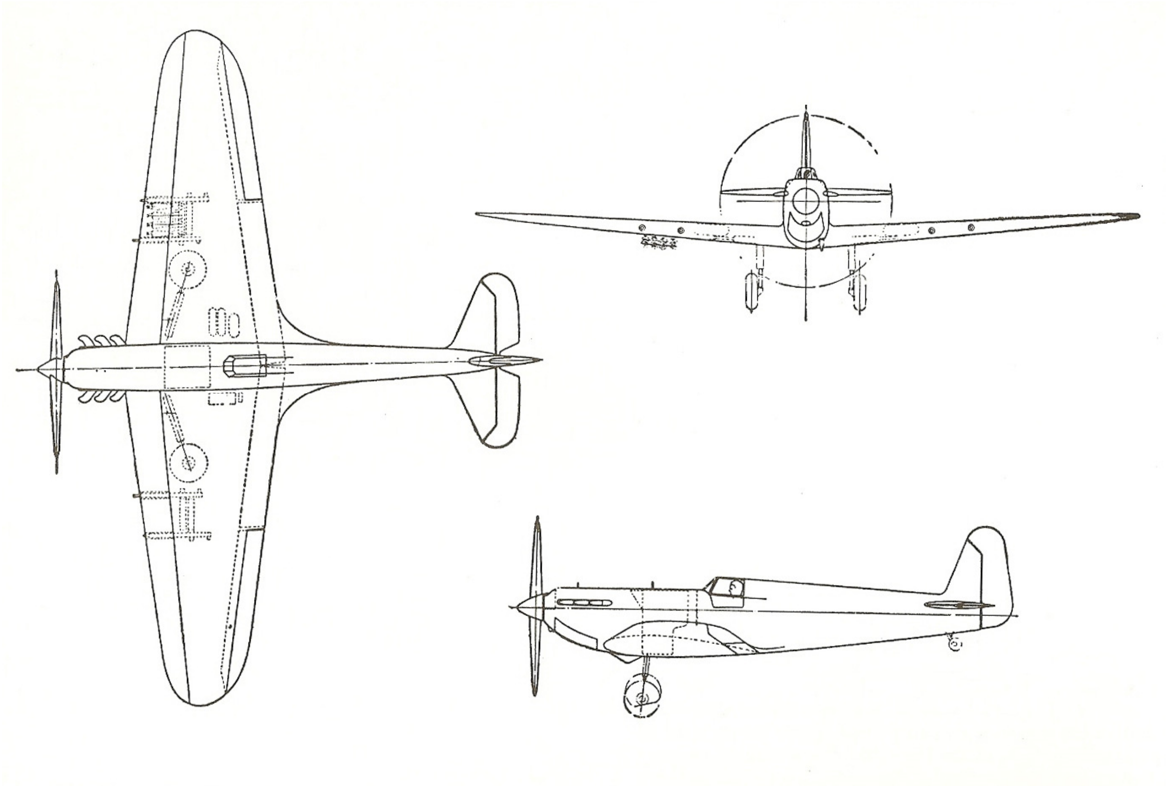

Figure 7 Supermarine Drawing No 30000 Sheet 11, dated September 1934 (4) from Smith (15)

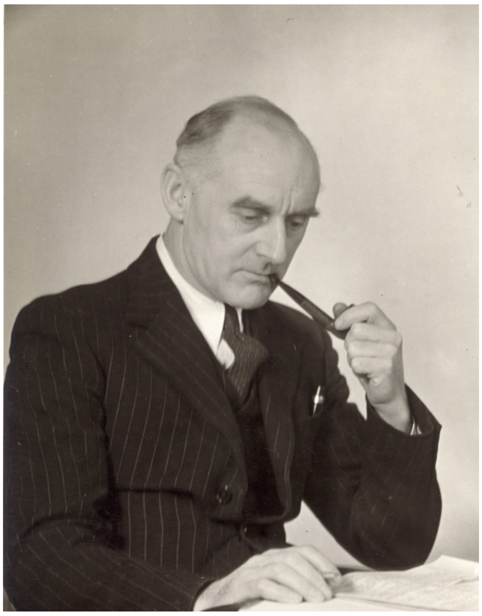

Figure 8 Joseph Smith (1897-1956), born near Birmingham
Source: Royal Aeronautical Society (National Aerospace Library)

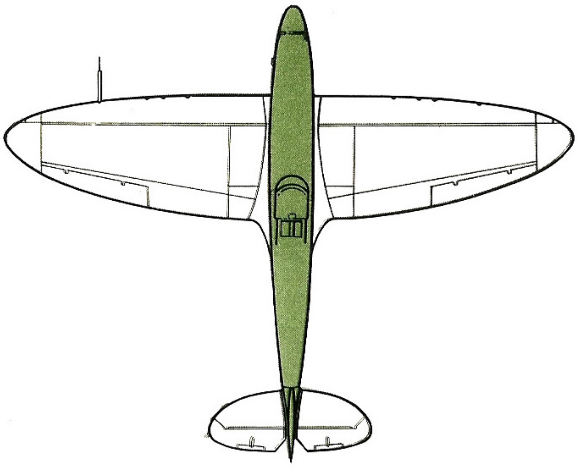

Figure 9 Plan view of Spitfire Prototype from Quill (2)

The Spitfire's mainspar provided sufficient boom area to resist the lift load and, with the Spitfire's solid-skinned structure, the wing's skin assisted in this. As to resisting the twisting moment, a torsion box was used for this. This D-nosed box was formed from the leading edge skin connected to the mainspar web separating the booms. Details of the ingenious method of mainspar boom construction are shown in Figure 10 taken from Reference 15. Figure 10 shows that, again for lightness' sake, the booms gradually reduce in strength as the lift load declines toward the wing tip. According to Reference 16's review (Section 2.4), on the advice of Pugsley at the RAE, the D-nosed torsion box was stiffened at an early stage so as to avoid wing flutter problems. This was accomplished by a thickening of the leading edge skin's gauge and a 2in rearward shift of the mainspar web.

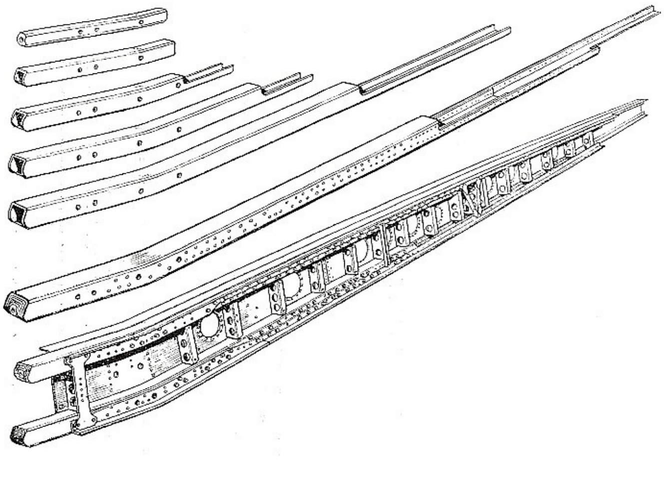

Figure 10 Spitfire mainspar, from Smith (15)

As to the "theoretical perfection" of elliptic loading in its minimisation of induced drag, it is important not to become too transfixed by this feature. The induced drag coefficient, C_{Di}, is given by (10)

$$C_{Di} = k\, C_L^2 / (\pi A). \qquad (2)$$

Here A is the wing aspect ratio. The factor k, having its minimum value of unity in the case of elliptic loading, increases by between 5% and 10% for other types of loading. The use of 2½°

wash-out, for example, would increase k slightly above unity. Moreover, elliptic loading can be achieved with, for example, straight taper combined with twist and change of aerofoil section camber. However, the important point is that C_{Di} only becomes significant at high values of C_L, i.e. at high incidences. As Shenstone (2) notes in the above quotation, one such case is at high altitude where reduced air density requires a compensatory high C_L. Another case is turning flight where C_L must be increased so that the lift's vertical component still counteracts the aircraft's weight. In estimating aircraft performance, C_{Di} is simply added to C_{DO}, the drag coefficient at zero lift, to calculate the total drag coefficient, C_D. In a horizontal turn at maximum C_L, for example, C_{Di} can be as high as 8 times the value of C_{DO}. In high-speed level flight, in contrast, C_{Di} is usually less than a tenth of C_{DO}.

In the light of Shenstone's comments (3) quoted above, one suspects that, for Mitchell, the retention of a broad chord outboard was the major attraction in his selection of wing planform since it allowed him to accommodate all the things he wished to cram within the wing. There were, however, other aerodynamic advantages in the use of the double-ellipse planform. One was the slightly higher wing area than might otherwise have been obtained from, for example, straight taper, leading to a lowering of wing loading. Since the latter is directly proportional to turning radius in horizontal flight (17), this was beneficial in combat situations. A further advantage, in stall behaviour, was pointed out to the current author in correspondence with Harry Fraser-Mitchell who has kindly consented to his comments being included as an Appendix. One practical disadvantage, however, lay in mass-producing the forward semi-ellipse which formed, together with the mainspar web, the wing's D-nosed leading edge torsion box. This leading edge panel possessed double surface curvature – along the leading edge and around it – so the mass-production problem of forming it from sheet alloy was subcontracted to the Pressed Steel Company (4).

After the unsatisfactory drag characteristics of the earlier Type 224 had become evident, Supermarine's urgent need with the Spitfire design became drag reduction. As Shenstone's comments (3) imply, part of the problem was thought to lie in the thick aerofoil section used on that aircraft - 18% thickness-chord ratio at the root - and, as he says, "we wanted to improve on that". Earlier experience with the S.6 and S.6B Schneider Trophy floatplanes using RAF 27 aerofoil sections of 10% thickness-chord ratio had been far happier. Consequently, Supermarine became inclined to ignore official advice that thickness-chord ratios of up to 20% showed no appreciable increases in drag. Cole (1) is scathing on this advice but the situation deserves rather more explanation.

After the First World War it was realised that a major problem in wind tunnel testing lay in achieving Reynolds numbers more representative of those at full-scale in flight. In a move to deal with this problem, the NPL built a large Compressed Air Tunnel which came into operation in 1932. The results obtained from this facility provided the basis of the above advice on drag. Unfortunately, what was not realised at the time was that this tunnel possessed a high level of turbulence which obscured the actual drag decrease with reducing thickness-chord ratio.

Sydney Camm at Hawker followed the official advice in selecting relatively high thickness-chord ratios for the Hurricane (19% at the root to 12% at the tip) and Typhoon and later passed the scathing comment that he had been "conned by the aerodynamists [sic]" when he learned the truth (see Section 4.2 of Reference 16 for more details of this sad episode). As indicated above, luckily Supermarine did not follow this advice.

Both Cole (1) and Reference 4 tell us that Shenstone visited the USA in 1934 in company with Vickers staff and there he acquired the details of the relatively new NACA 2200 series aerofoil sections (the first two digits specify 2% camber at 20% chord). The experimentally obtained aerodynamic characteristics of these NACA Four-Digit sections had begun to emerge in 1932 (18). The thickness-chord ratios then selected for the Spitfire, as Shenstone (3) notes above, were 13% at the root tapering to 6% at the tip. The resulting wing, relatively thin for the time, contributed to the Spitfire's notably low value of C_{DO}. In Reference 17 this is estimated as 0.018; the Hurricane's value, in contrast, is estimated as 0.021.

In describing Supermarine's search for drag reduction on the Spitfire, Cole (1) draws attention to the wing root fillet used to suppress the tendency for flow separation to occur in the corner between wing and fuselage. Such separation not only creates higher drag but also tailplane buffeting if the separated flow impinges on that surface. This fillet, he notes, is noticeably larger than those on many contemporary aircraft. Both Cole (1) and Reference 3 show Shenstone's photograph of a wool-tufted fillet being tested on the Type 224. Cole (1) suggests Muttray's paper (19) of 1934 as one possible source of information on fillets which Shenstone might have used. Muttray (19) refers to his own earlier work of 1928, to the use of large fillets on the Northrop Gamma of 1932 and also to undated fillet tests by Klein at Cal. Tech. The latter were used in the development of the Douglas DC-1 of 1933.

Von Kármán describes his involvement in this Cal. Tech. work in his autobiography (20), mentioning that he lectured on the fillets in Paris in 1933. Cole (1) tells us that Shenstone met von Kármán during his visit to the Douglas Company in California in 1934. Thus Shenstone had more than one opportunity to learn about this drag-reducing feature. According to Reference 4, flight tests with the Spitfire prototype, probably around March 1936, were used to check the direction and behaviour of the airflow close to the fillets. For this a surface oil film technique was used rather than wool tufts. Apparently all was well.

Cole (1) also draws attention to the remarkable performance of the Spitfire at high subsonic Mach numbers. In his contribution to Reference 2, Quill provides a graph, Figure 11, showing the variation of C_{DO} with Mach number for both the Spitfire XI and the

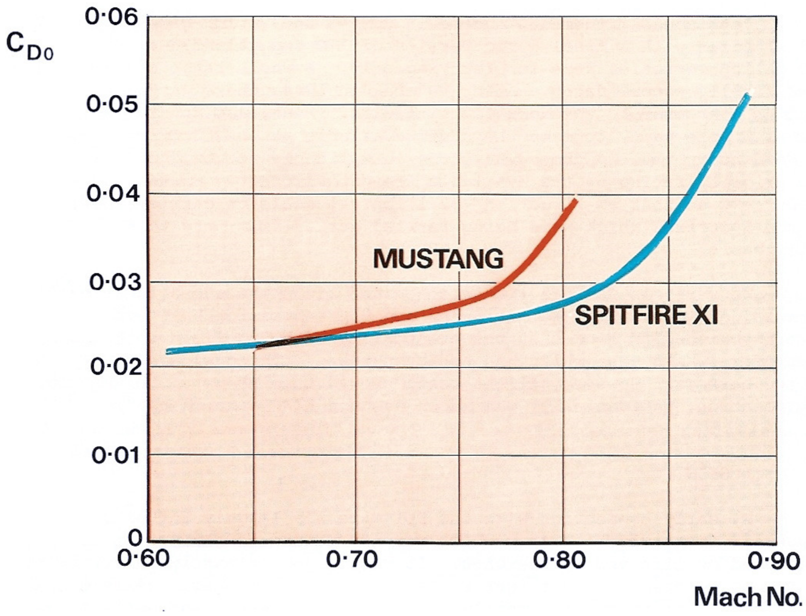

Figure 11 Variation of C_{DO} with Mach number for the Spitfire XI and the P-51 Mustang, from Quill (2)

P-51 Mustang. The data are drawn from RAE Report Aero 1906 of January 1944 (not seen by the current author). The Spitfire's superior performance above Mach 0.75 no doubt had much to do with its thinner wing, fortuitously so in this respect. For the Mustang wing, the maximum thickness at the root is 15% located at 40% chord, at the tip the figures are 11.4% at 50% chord. In Reference 2, when asked how much was known about Mach number effects at the Spitfire's design stage, Alan Clifton, Supermarine's Chief Designer after Mitchell and Smith, replied tersely, "Nothing, I'd say!" He later amplified that remark by adding (2),

> "We had in the late twenties, evolved a guess-work correction for the drag increase, due to compressibility of the tip sections of the Schneider Trophy planes' metal propellers, to enable us to analyse their performance. However we certainly saw no reason to apply this data to the Spitfire wing."

Having mentioned the P-51 Mustang, it is appropriate to point out that its uniquely low C_{DO} value at low Mach numbers (0.0163 according to Loftin (21)) probably had more to do with its employment of the Meredith Effect in its radiator design than its use of an early so-called laminar flow aerofoil section in which the maximum thickness is further aft than had been previous practice (see Reference 16). In the case of the Spitfire, although the Meredith Effect was used, because of its radiator's placement beneath the wing the Effect could not be deployed quite as thoroughly as was achieved with the Mustang.

The Spitfire design had to absorb enormous changes throughout the aircraft's operational life: prominent examples are a more than doubling of engine power and a near-doubling in weight. Consequently, considerable re-design was required, much of which is described in Smith's authoritative paper (15). As to the changes in wing planform, however, in his contribution to Reference 2, Quill shows that these were largely restricted to wingtip shape: examples are the clipped tips for the LF Mk IX, the extended tips for the HF Mk VII and the revised tip shape introduced on the F21. Yet throughout the Spitfire's extensive development the underlying planform geometry remained the same double ellipse.

4. CONCLUDING REMARKS

Cole's argument (1) that Shenstone was the source of much of the aerodynamic innovation in the Spitfire design seems perfectly plausible. The design grew out of a short period, less than a decade long, in which enormous advances in aerodynamic, structural and propulsion technologies were implemented. And here was a man *au fait* with much of the current thinking on aerodynamics, a man familiar with technical German who had seen many of the innovations emerging from the German glider movement, who probably kept a close eye on current German technical literature - another Glauert in this respect - and finally a man who had met a number of the key figures involved in current aerodynamic innovation: Lippisch, Prandtl and von Kármán. As to the truth of the matter concerning the selection of the Spitfire's now-iconic wing planform, however, this is now never likely to be known. That being accepted, if the selection had been prompted by the idea contained in Figures 5 and 6, there is a certain irony in that the design of an aircraft which foiled the Luftwaffe's intentions over Britain in the summer of 1940 had originated in a German professor's lecture notes.

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APPENDIX Trailing edge rake-forward

A. H. Fraser-Mitchell CEng, FRAeS, MIMechE
Chief Aerodynamicist (Handley Page to 1970)
Head of Aero (Hawk) (BAE Kingston to 1981)
Asst. Chief Airframe Engineer (BAE Kingston to retirement in 1989)

The ellipse also gave the Supermarine team a sharply raked-forward trailing edge at the wingtip. There had been a good deal of correspondence and articles in the aviation press in the mid-30's (then, proper technical publications, rather than the fairly trivial magazines one sees today) on the subject of the stall of tapered wings. In January 1936, Dr G. V. Lachmann contributed a longish article to "Flight" on the subject of stalling of tapered wings. He showed tuft pictures on a wind tunnel model of (probably) the wing of the HP 51 (forerunner of the HP 56 "Harrow"), which indicated good behaviour with flaps up, but needed leading edge slats on the outer wings with full landing flap deployed. The planform taper ratio was about 4:1 for this wing.

This produced a stream of correspondence from contributors, including W. R. Andrews (Avro), C. N. H. Lock (NPL) and C. H. Latimer Needham (Halton) mostly indicating that with a suitable choice of camber, twist and aerofoil section, the complication of slats was unnecessary – stoutly defended by G. V. Lachmann, of course.

The property of the raked-forward trailing edge in delaying the tip stall on these highly tapered wings was first mentioned in a note by the Editor in the 9th July 1936 issue of "Flight", as a result of a visit to the NPL, where H. B. Irving had illustrated this phenomenon on a wind tunnel model, but no details were given.

Nevertheless, this inspired the inestimable W. E. Gray, DFC, described as a "reader", to fly in a BA "Swallow" monoplane with tufted wings, and photographing their behaviour near the stall. He varied the forward rake of the trailing edge by putting on various degrees of yaw, positive and negative, and confirmed Irving's results. He showed a whole series of photos in "Flight", together with his theory of how it occurred in a series of three articles, published through 1936.

Lachmann had designed the cantilever monoplane wing of the HP 51, then the HP 56 "Harrow" and went on to do the "Hampden", which had even more forward rake on the trailing edge, and did not exhibit a tip stall either, in the flaps up case. But it was equipped with slats outboard for the flaps down case.

Hence the good behaviour of the Spitfire wing, assisted also with camber and 2½ degrees of washout.

Dr J A D Ackroyd CEng FRAeS

Born in Bradford, Yorkshire, in 1938, John Ackroyd graduated in Aeronautical Engineering in 1960 at Queen Mary College, University of London. After doctoral and postdoctoral research in shock tubes there, he joined the staff of the Department of the Mechanics of Fluids (later the Aerospace Division, Manchester School of Engineering) of the Victoria University of Manchester. He taught in aerodynamics, flight dynamics, aircraft structures and propulsion whilst carrying out research in boundary-layer theory. He retired in 2000 as Senior Lecturer. His interest in the technical history of aviation resulted in him giving the Royal Aeronautical Society's Lanchester (1991) and Cayley (2000) Lectures, and the Inaugural Cody Lecture (2003). Together with B. P. Axcell and A. I. Ruban, he is co-author of *Early Developments of Modern Aerodynamics* published jointly by the AIAA and Butterworth-Heinemann (now Elsevier) in 2001.