Tail-first (examples):	*Vari-Eze*,	canard, zero ± 1 deg wing, zero ± 1 deg (the planes must be within 0.5 deg incidence of one another).
	Long-EZ,	canard, ± 0.3 deg wing, ± 0.5 deg (the planes must be within 0.3 deg incidence of one another).

Biplanes

Biplanes dominated aviation into the 1930s, largely because of a series of catastrophic wing failures with early monoplanes. These happened because of an improper understanding of the complete role of the cabane bracing, consisting of a pylon structure above the centre section, from which bracing wires supported the weight of the wings on landing. The highly cambered wing sections of that period suffered powerful nose down pitching moments at high speed: in the language of the time, their centres of pressure moved a long way back. Wings began to fail downwards at high speed if the height of the cabane bracing had been reduced too far in an effort to cut drag and save weight, because the landing wires from the cabane pylon were taking tensile loads at high speed, keeping the wings in shape. Of course, the flatter the angle of the landing wires, the higher their tensile loading. In Britain, the War Office refused to have anything more to do with monoplanes and the biplane remained the mainstay of British military aviation for the next twenty years.

The biplane, on the other hand, was strong for several reasons. The reasons are still valid:

- ☐ They are compact, and their wingspans, which are shorter than those of comparable monoplanes, sustain smaller bending moments. Moreover, lift is shared between two planes instead of just one.
- ☐ Consequently, the wings of a biplane can be made 0.8 to 0.9 times the weight of a monoplane, with greater specific strength and stiffness (and the potential to make them lighter still (fig. 14.12)).

The modern metal monoplane, although superior in many areas, failed to oust the biplane completely. Figures given in table 4–1 show that one homebuilt aeroplane in four at the Experimental Aircraft Association Fly-In at Oshkosh in 1978 was a biplane.

TABLE 4–1 (ref 4.15)

Configuration	Percentage Present
Low wing	37
Biplane	25
High wing	19
Midwing	13
Parasol	5
Triplane (1), plus fractions left over above	1

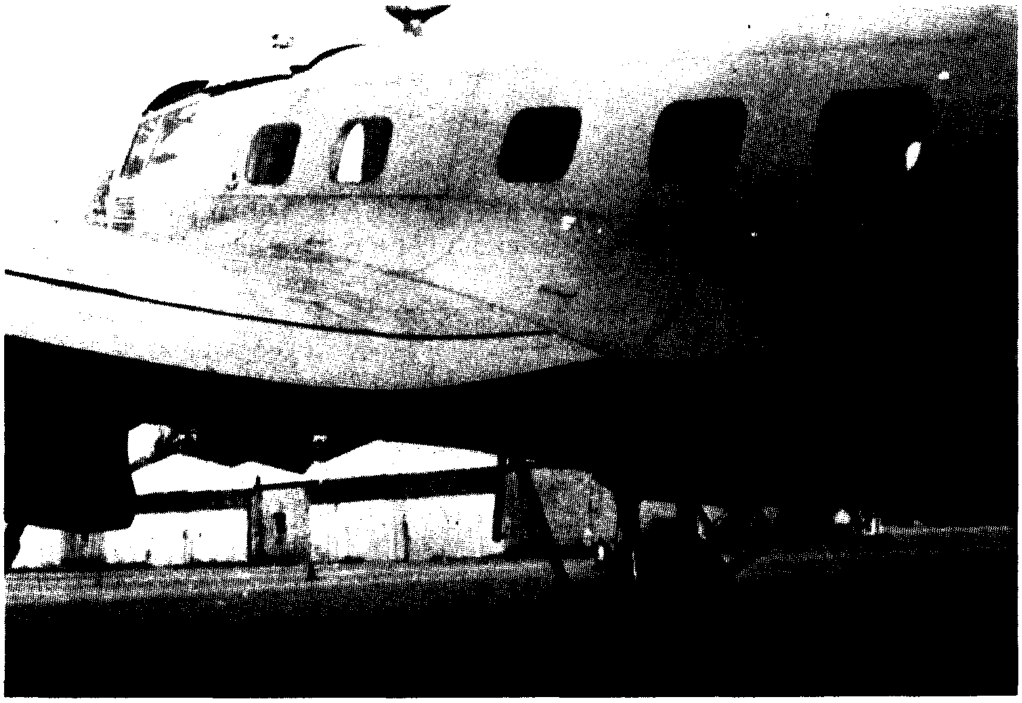


Plate 4–11 Unique fillet and 'bite' at the trailing edge junction of the basically elegant *Heinkel He III* (1934) which reduced interference and change of downwash with angle of attack from the wing upon the tailplane. This one is ex-Spanish Air Force. (*Author*)

As long as one can live with lower lift/drag and therefore less range than a monoplane, biplanes can be superior to monoplanes for similar tasks because:

□ They can carry more wing area for their size, can take off and land in shorter distances, and often have softer stall qualities.
□ They can perform well into and out of short fields without needing elaborate and costly high lift devices, and can therefore lift more payload.
□ They are more easily constructed for a lower price than a monoplane, all else remaining equal.

Some modern studies do not give such a pessimistic view of biplane lift/drag, suggesting that an unconventional layout, with proper choice of gap, stagger and negative decalage, can be aerodynamically more efficient than monoplanes (ref. 4.16). But their applications seem to be narrow and they may have unfavourable stall characteristics, because they differ considerably from conventional biplane arrangements.

Biplane theory is complicated by two factors. The most important is that mutual interference from the vortex system of each plane increases total downwash and induced drag, making it more than that of a monoplane with the same aspect ratio and wing area. Second, mutual interference from the curvature of the flow around each aerofoil section further increases downwash and induced drag, by an amount which depends upon the ratio of *gap/chord*.

Plate 4–12 *Westland Lysander* (1938) rebuilt from fragments, new materials, salvaged and refurbished parts, which now operates on a Permit to Fly. Wing is narrow at the root and in line with the pilot's eye, bestowing near-ideal field of view. The author, who is flying the *Lysander* here, found it to have remarkable low speed handling qualities and a wilful mind of its own. (*Flight International*)

Aspect ratio of a biplane is double that of a monoplane with the same span and total wing area:

$$\text{biplane aspect ratio, } A = \text{span}^2/\tfrac{1}{2} \times \text{total wing area}$$
$$= 2\,b^2/S \qquad (4\text{–}24)$$

which should be compared with eq (2–4). But we cannot apply this value to a biplane in the same way as with a monoplane, because it would make it seem more efficient, when the reverse is the case. Mutual interference between the planes causes a biplane to be flown at a larger angle of attack so as to generate the same lift as a monoplane with the same section and area. The increase in angle of attack, $\Delta\alpha$, is proportional to the increase in angle of downwash, $\Delta\epsilon$, and we may write:

$$\text{biplane downwash, } (\epsilon + \Delta\epsilon)/\text{monoplane downwash, } \epsilon = (1 + \Delta\epsilon/\epsilon)$$
$$= (1 + \sigma) \approx 1.5 \qquad (4\text{–}25)$$

If we now modify the equation for non-elliptic lift distribution by introducing the induced drag factor K or $K' = 1/e$, adapting it for comparison between the monoplane and biplane:

$$\text{monoplane downwash, } \epsilon = K'C_L/\pi A \approx 35\ C_L/A \text{ radians} \quad (4\text{–}26)$$
$$\text{biplane downwash, } (\epsilon + \Delta\epsilon) = K'C_L(1 + \sigma)/\pi A \approx 55\ C_L/A \text{ radians} \quad (4\text{–}27)$$

Biplane calculations can be simplified by replacing the wing arrangement by an *equivalent monoplane*, which has the same wing area and lift dependent drag. The concept was proposed by Max Michael Munk (1890–), a leading German aerodynamicist (who had been a student of Prandtl at Göttingen). Munk showed that in order to apply eq (4–8) to biplanes (and other multiplanes), the maximum span must be replaced by a monoplane wing of span kb having the same area and induced drag as the biplane. For a monoplane $k = 1$, but for a biplane k varies with the ratio of gap/span, the ratio of the spans, and the proportional area of the two wings.

If we use Prandtl's method of reducing any biplane arrangement to one that is orthogonal (equal span):

$$\text{mean span, } b = (\text{span of longer plane} + \text{span of shorter plane})/2 \quad (4\text{–}28)$$

then we may write the induced drag coefficients of the monoplane and biplane as:

$$\text{monoplane } C_{Di} = K'C_L^2(S/k^2b^2)/\pi \text{ from eq (4–9), and} \quad (4\text{–}29a)$$
$$\text{biplane } C_{Di} = K'C_L^2(S/2b^2)(1 + \sigma)/\pi \quad (4\text{–}29b)$$

To satisfy Munk's conditions, these are equal, and:

$$\text{Munk's span factor, } k = \sqrt{2/(1 + \sigma)} \quad (4\text{–}30)$$

For most practical biplanes $\sigma = 0.5$, with values varying between about 0.4 to 0.6.

There are various techniques for dealing with biplanes (refs. 4.3, 4.11, 4.17), but an easy geometrical way of solving the span of the equivalent monoplane is shown in fig. 4.17. This shows that the cylinders of air washed downwards by each wing of mean span b are reduced by the proximity of their overlapping cross-sections. Interference makes the total swept volume less than the sum of their swept volumes when separated. The equivalent monoplane has a span which sweeps out a volume equal to the remaining working volume (top and bottom lobes) of the biplane, *plus* an additional amount equal to that lost by interference. At first sight we might think that we have only to replace the shaded portion of the working mass in fig. 4.17b, approximately represented by the span × gap. In fact interference makes it necessary to add about $\sqrt{2}$ × gap × span (i.e. the mean span). When we draw the representative area as a ring around the circle circumscribing the mean span of the biplane, the overall diameter is that of the equivalent monoplane wingspan, within the range:

$$\text{gap/mean span} = 1/8 \text{ to } 1/4 \text{ (say, 0.1 to 0.25)} \quad (4\text{–}31)$$

Thus, if gap/mean span $= G/b$, it may be shown that:

$$\text{Munk's span factor, } k \approx \sqrt{[1.8(G/b) + 1]} \quad (4\text{–}32)$$

Fig. 4.18 shows the value of k for the range of gap/chord ratios in eq (4–31); it is pessimistic for biplanes with long wings. Table 4–2 shows how k is used.

Note that although we use gap/mean span when talking about interference effects, many other reference works employ the span of the longest wing for determining G/b. Generally the result is too small to be of much consequence now that biplanes are designed more for utility and sport than for aerodynamic efficiency. As a rough approximation, the loss of lift compared with a monoplane is about 3 to 9 per cent at large Reynolds numbers. The maximum lift of a biplane with gap equalling chord and no stagger is about 93 per cent that of a monoplane. Drag is 10 to 15 per cent more. This approaches a loss in total lift/drag ratio of 20 per cent. The lift slope, a, of a biplane is about 83 per cent of that of a monoplane with the same aspect ratio.

TABLE 4–2

Term	Finite monoplane span b	Orthogonal biplane span b	Equivalent monoplane span = $k \times$ biplane mean span, same total area
Aspect ratio A	b^2/S	$2b^2/S$ (i.e. double monoplane of same span and area)	$(kb)^2/S$ (i.e. $k^2\times$ monoplane of biplane span and area)
Downwash α_i or ϵ	$K'C_L/\pi A$	$K'C_L(1+\sigma)/\pi A$	$K'C_LS/\pi(kb)^2$
Induced drag coefficient C_{Di}	$K'C_L^2/\pi A$	$K'C_L^2(1+\sigma)/\pi A$	$K'C_L^2S/\pi(kb)^2$ (Munk's condition)

Munk's span factor k is taken from fig. 4.18(b), or by the approximation in eq (4–32), which relates it to the gap/span ratio of the biplane. In the equivalent monoplane column, where k^2 appears, we may introduce the term: $(1.8(G/b)+1)$

Location of equivalent monoplane wing

We need now to locate the equivalent monoplane wing relative to the pair of planes it is intended to replace. Figure 4.19 shows the method, using suffixes T and B for the top and bottom plane in each case. The mean chord of each plane is constructed as shown in fig. 2.5. When we have found the equivalent monoplane wing, it is necessary to assume that the aerodynamic centre is located about 2 per cent SMC further forward, at about 23 per cent $\bar{c}$, unlike the monoplane, which has the aerodynamic centre around 25 per cent. The reason for this is that the top plane generates more lift than the bottom.

The unmodified aerodynamic centre of the equivalent monoplane lies on a line joining the **ac** of the top and bottom planes. For simplicity, draw a line joining the quarter chord of each. The quarter chord of the equivalent monoplane will lie on the line. Now, to find the vertical position of the equivalent plane, distance Y above the bottom plane, take moments of the lift about the quarter chord of the bottom plane, using the gap, G:

$$\text{total lift} \times Y = (L_T + L_B)\ Y = L_T G$$

and, as lift can be expressed in proportion to C_LS, the lift coefficient and area respectively:

$$Y = (C_{LT}S_T/(C_{LT}S_T + C_{LB}S_B))G$$

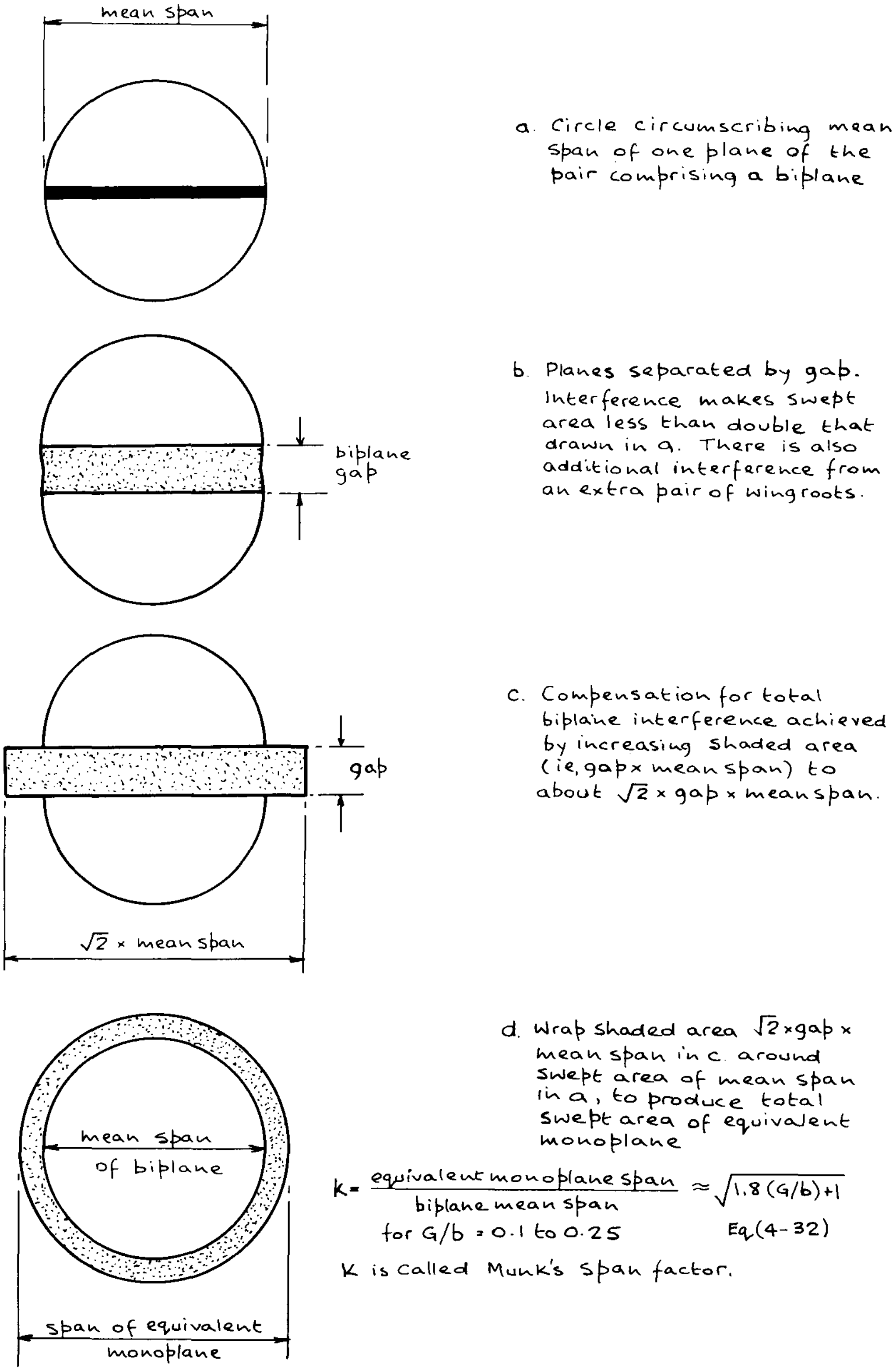


Fig. 4.17 Approximate construction of equivalent wing span of a monoplane having the aerodynamic characteristics of a biplane of given mean span.

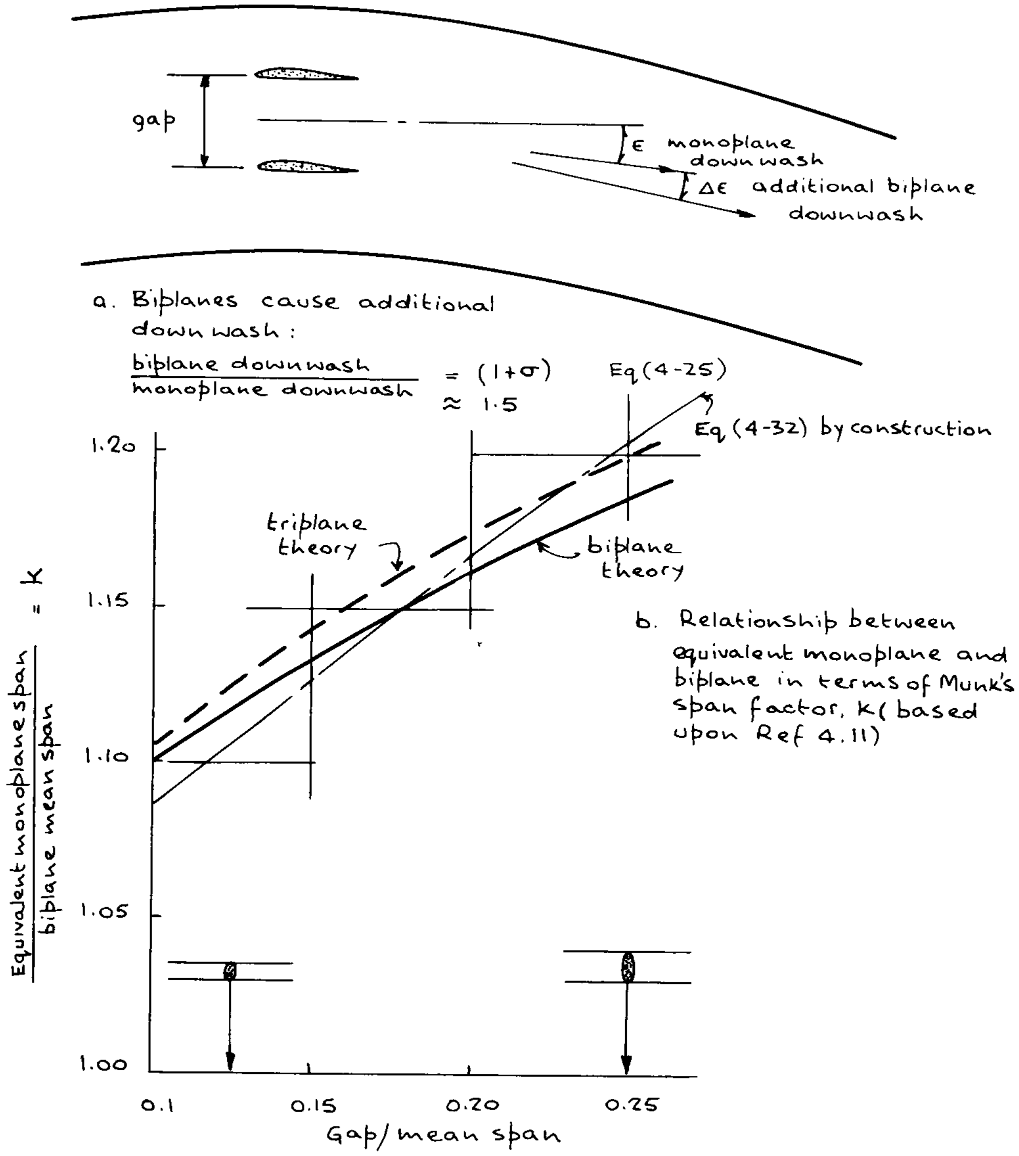


Fig. 4.18 Biplane (and triplane) characteristics.

$$= [pS_T/(pS_T + S_B)]\ G \qquad (4\text{–}33)$$

where $p = C_{LT}/C_{LB} = 1$ with zero or negative stagger to 1.35 with positive stagger. When both top and bottom planes are of equal size the lift of the top is about ⅓ more than that of the bottom, so that:

$$\text{orthogonal biplane } Y = 4/7\ G \qquad (4\text{–}33a)$$

and an orthogonal triplane can be shown to be:

$$y = 7/12 \text{ total } G \qquad (4\text{–}33b)$$

Similarly, for the standard mean chord $\bar{c}$ of the equivalent plane, area $S_T + S_B$:

$$\bar{c}(C_{LT}S_T + C_{LB}S_B) = C_{LT}\bar{c}_T S_T + C_{LB}\bar{c}_B S_B$$

i.e.

$$\bar{c} = (p\bar{c}_T S_T + \bar{c}_B S_B)/(pS_T + S_B) \qquad (4\text{–}34)$$

While for the pitching moment coefficient of the equivalent plane, C_{Mac}:

$$C_{Mac}\bar{c}S = C_{MacT}\bar{c}_T S_T + C_{MacB}\bar{c}_B S_B$$

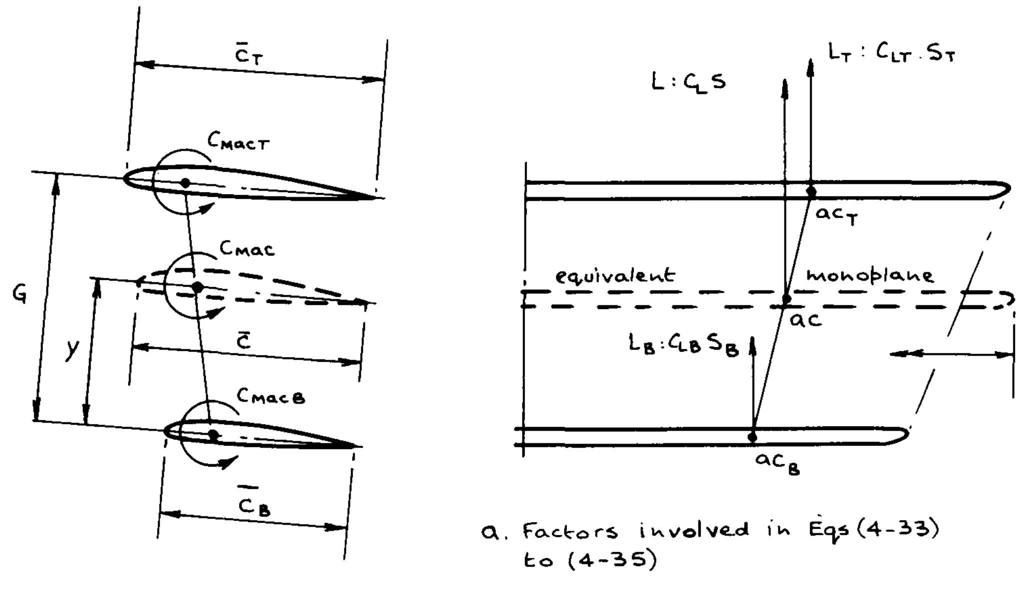
so that: (4–35)

$$C_{Mac} = (C_{MacT}\bar{c}_T S_T + C_{MacB}\bar{c}_B S_B)/\bar{c}S$$

Because the aerodynamic centre of the biplane lies about 2 per cent SMC further forward than a monoplane, it follows that a near-orthogonal biplane cellule must be mounted 2 per cent $\bar{c}$ further aft than a pure monoplane, to bring the centre of gravity of the aeroplane into the correct geometric alignment with the aerodynamic centre of the whole.

Wings are often staggered to improve the pilot's view. This has no effect upon the lift dependent drag of the whole, in theory anyway. The lift slope of each plane is modified slightly, as shown in fig. 4.20b and c (in which positive (top wing leading) stagger is employed).

Proportions of the most efficient biplane are given in fig. 4.20a (ref. 4.11), which is based upon the work of Munk. The diagram shows how to determine the best value of



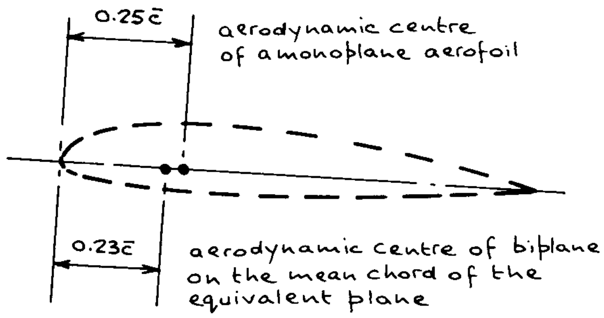


Fig. 4.19 Locating the equivalent monoplane.

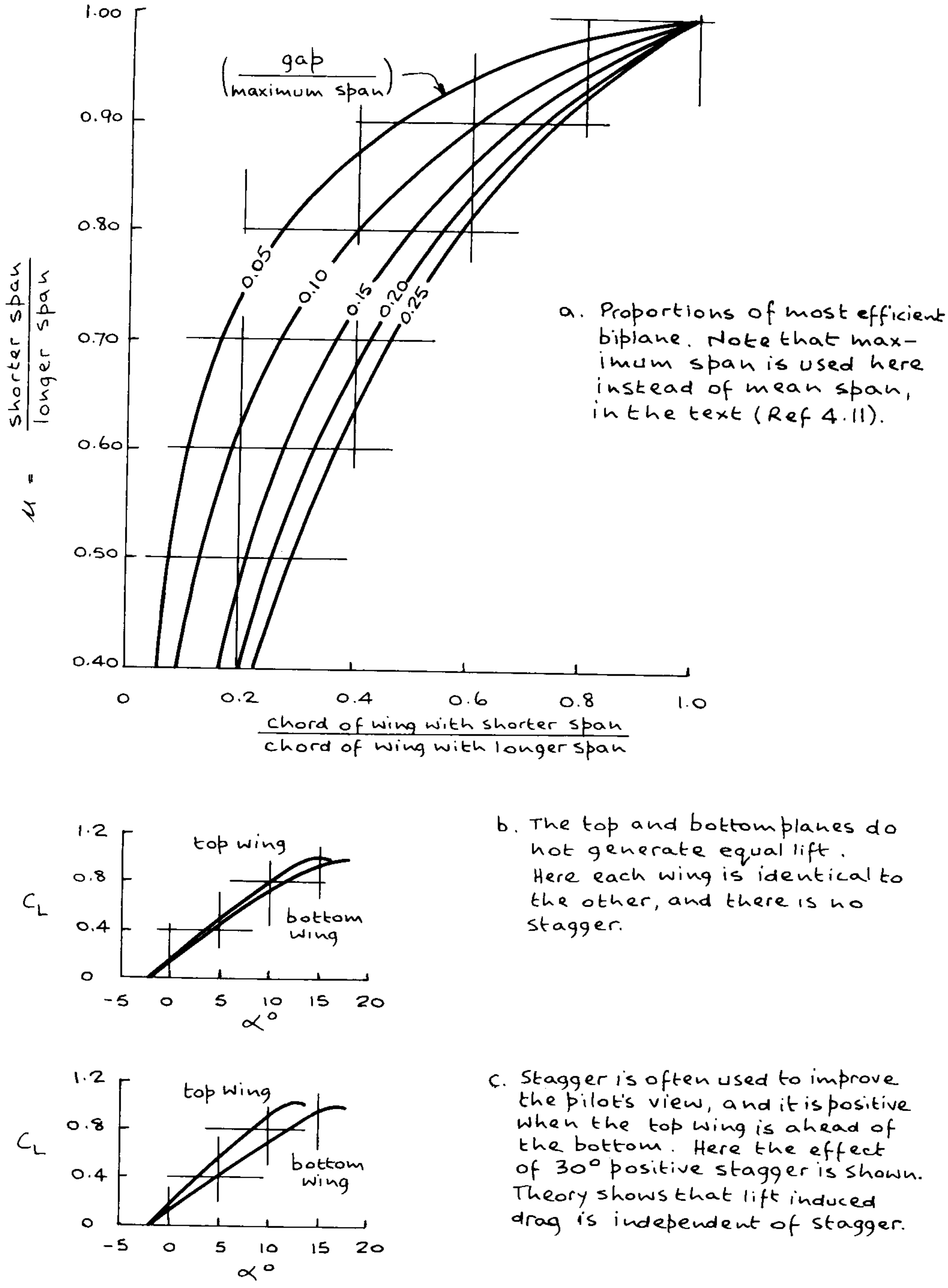


Fig. 4.20 Biplane geometry and its effects.

any one variable, $\bar{c}_2/\bar{c}_1$, G/b_1, or b_2/b_1 (where suffix 1 applies to the chord or span of the longer plane, and suffix 2 to the shorter), when the other two are assumed or known.

There is no place for triplanes, except as replicas of early aeroplanes – or perhaps for competition aerobatics (where low wing loading and plenty of drag might perhaps be combined with high power to produce an agile aeroplane, slow enough to keep within the box-like airspace limits). They can, nevertheless, be treated in a similar way to biplanes, and the curve for finding the span of the equivalent monoplane is shown in fig. 4.18b. The triplane has to be treated as two biplane cellules, so as to derive an equivalent plane between each pair. These equivalent planes are then used in turn to find the equivalent monoplane of the whole. Minimum drag is achieved when the lifts of the top and bottom planes are equal.

Rigging of biplanes

There is a conflict between theory, experiment and practice about the differing amount of incidence needed between the wings of biplanes. Induced drag theory suggests that the use of a small amount of negative declage (bottom plane at a larger angle of incidence than top) is needed for minimum induced drag. This is confirmed by ref. 4.16, but the use of negative decalage in practice is rare. The author discovered one example during a cursory search of records, the *Nieuport Scout* used in World War 1, which appears to have had about -2 deg between planes. The *Scout* had a large top plane and a small, narrow, bottom plane making it more of a *sesquiplane*, but this might not be significant.

Experiments, coupled with full-scale experience, show that a decalage angle of +1 deg for the top plane increases the minimum lift/drag ratio of the whole aircraft by +1 per cent (ref. 4.17). If decalage is increased further the effect is harmful to L/D. In many cases decalage appears to be 0 deg, with no difference between rigging with either forward or backward stagger.

A general summary shows the following values for decalage:

☐ Early biplanes (thin, undercambered wing sections):

average incidence of both planes,	+2 deg to +5 deg (extreme),
decalage between planes,	0 deg to +1 deg (with exceptions like the *Nieuport Scout*, with -2 deg),
longitudinal dihedral between wings and tail	about +2 deg to +3 deg.

☐ Triplane (e.g. *Sopwith Triplane* (1916)):

incidence of each plane,	+2 deg
decalage,	0 deg
longitudinal dihedral,	+½ deg.

☐ Later (post World War 1) biplanes with more advanced wing sections:

average incidence of both planes,	+2 deg to +3 deg
decalage,	0 deg to +1 deg
longitudinal dihedral,	about + 2 deg.

Comparing tandem with biplane wings

The arrangement of more or less equally sized wings in tandem has few applications, although there are now some exceptions: two are shown in plate 4.10. *Quickie* in fig. 6.9 is an example.

Biplanes and tandem planes are related by angle of stagger, θ, as shown in fig. 4.21a, in which a line joining the leading edges of the top and bottom planes is rotated forwards through 180 deg until the top plane is at the bottom. Munk's span factor, k, appears to vary with stagger from its value given in fig. 4.18b, to about 0.85 (minimum) in tandem, with the leading edges of equal planes 1.0 to 1.5 chords apart. This is sketched approximately in fig. 4.21a, while 4.21b is the tandem value of k for increasing distance apart of the planes (based upon ref. 4.11). Stagger is usually measured in chords.

Interference between the planes results in a moderate reduction in lift-dependent drag of the foreplane, and a marked increase for the rear. The consequence is an overall increase in drag for the whole.

An example of the result of interference between close-set tandem planes that was of historic proportion and is of importance to any designer and builder, was that of Henri Mignet's *HM 14, Pou-du-Ciel (Flying Flea*, in the carefree English translation), of 1933 (ref. 4.18). In its original form shown in fig. 4.22 it caused a number of fatal accidents from irrecoverable dives, and was ultimately banned in Britain and France. Later variants had the design faults corrected. After test flying one of these, the author believes that the configuration has much to offer anyone wishing to fly cheaply, for fun, with one of the simplest control systems that it may be possible to conceive (although it can be tricky when braking after landing for a conventionally trained pilot – as the author discovered).

Four factors appear to have contributed to the *HM 14* accidents, and they are worth recounting:

- ☐ The wings had a section invented by Mignet, with a sharp leading edge. Control in pitch was achieved by changing the angle of incidence of the foreplane by a direct linkage with the stick. Maximum incidence was limited to only about 4.8 deg on a specimen tested in the 24 ft (7.3 m) wind tunnel at the Royal Aircraft Establishment, Farnborough (ref. 4.19). It is possible that the pitch control lacked authority, and that the lack would have been worsened by the tendency of a sharp leading edge to force premature separation and loss of lift at moderate angles of attack.
- ☐ The foreplane trailing edge overlapped the leading edge of the rearplane. With the foreplane at its maximum incidence, a venturi effect might have been induced in the gap between the planes, increasing the lift of the rearplane, so that the nose-down moment of the rearplane about the centre of gravity could have become larger than the foreplane could counter.
- ☐ Longitudinal stability was dependent upon lift coefficient, being most stable at large angle of attack and high C_L, and least stable at low (due to the neutral point varying considerably with angle of attack).
- ☐ Inadequate control of the centre of gravity. The Farnborough tests showed the aeroplane to be unstable in normal flight with the CG further aft than 0.4 times the foreplane chord. In a dive steeper than −15 degrees, recovery could not be achieved.

There is also some evidence from later variants that the control power of the foreplane is affected by propeller diameter. Propeller tips have been sketched in fig. 4.22. A tip

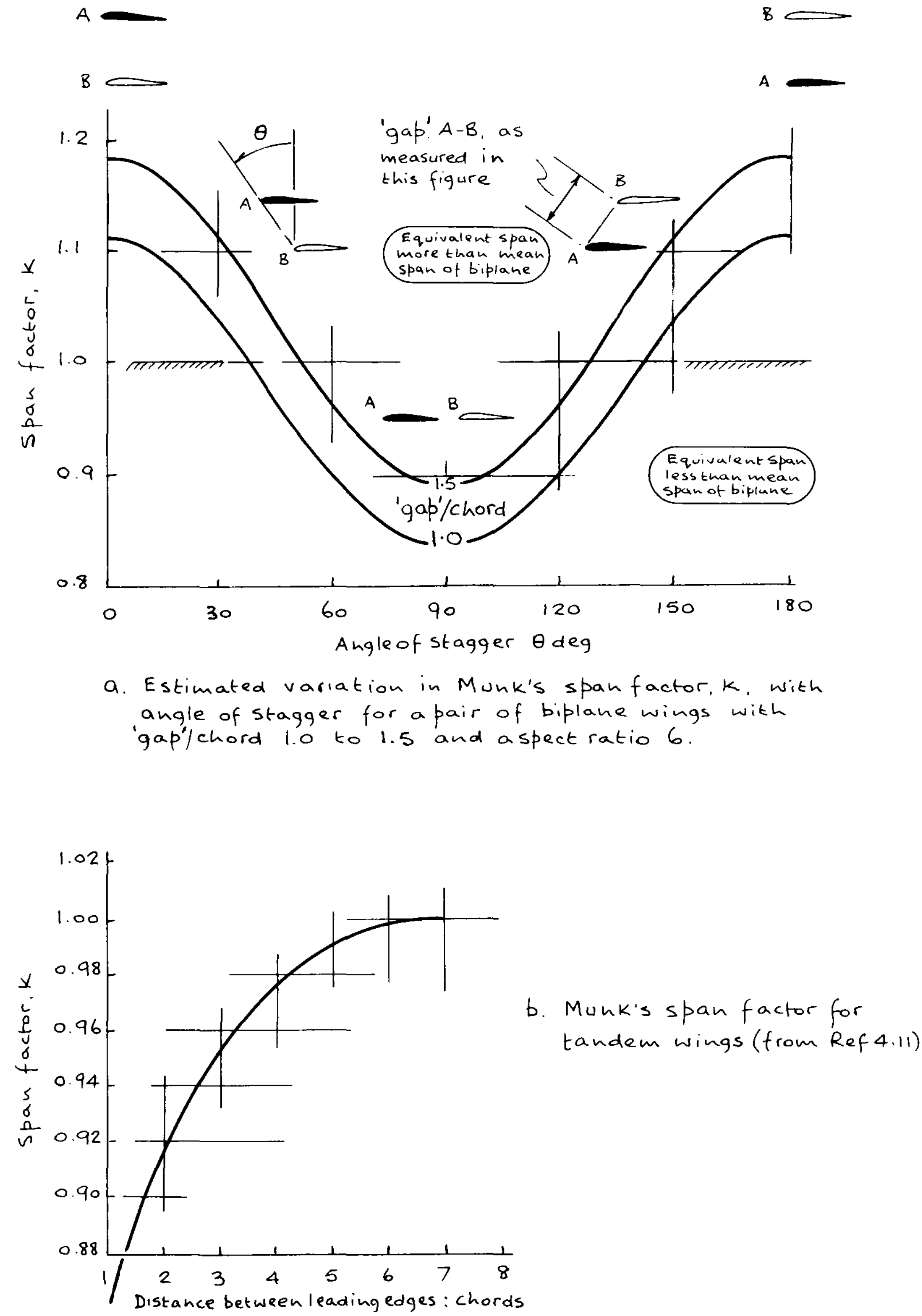


Fig. 4.21 Relationship between biplane and tandem wings.

that is not as high as the foreplane can cause a reversal of circulation beneath the centre section when power is applied, making it harder to lift the nose. A propeller tip should be about 4 in (10 cm) higher than the foreplane to maintain the authority of the control in pitch. Although *Flying Flea* variants can fly with quite low power engines, the small propellers used with such engines on gyrocopters, for example, should be avoided at all costs.

Among the cures applied to later variants of the *HM 14* were:

- □ The wing section was replaced by a tried design with a rounded leading edge.
- □ The distance between the foreplane and rearplane was increased, so that the overlap disappeared, being replaced by a gap.
- □ The rearmost position of the centre of gravity was limited to 0.25 times the total distance between the leading edge of the foreplane and the trailing edge of the rearplane.

Mignet's wing arrangement was close to that of a biplane with considerable stagger and a small gap. Or both wings could be taken as a single low aspect ratio wing, incorporating a slot, in which case aspect ratios varied between 3.2 and 3.43, depending upon the span of the foreplane. Zimmerman showed in 1932 that wings of very low aspect ratio have effective spans about 5 per cent longer than the actual span because of the closeness of the tip vortices, which dominate the aerodynamic picture. This caused him to advocate shapes like we saw earlier in the chapter. It is possible that the unusual, but effective, flying characteristics of the *Flying Flea* owe something to the phenomenon.

If the gap and stagger are increased in their proportions to wing span and chord, then another possible formula can be evolved for light aeroplanes. This is the configuration explored by *Arsenal Delanne* in the years from 1936 to 1939. Of eight tandem winged designs, two were built and flown. The foreplane was slightly larger than the rearplane, and they were located about two foreplane chords apart. The gap was about one foreplane chord. The advantages claimed were that such an arrangement provided a continuous slot effect. There is also some evidence that the *Arsenal Delanne 10C-2* tandem-wing two-seat fighter with retractable gear had a maximum level speed ratio, V_C/V_{SO} around 7.5, whereas conventional aircraft with piston engines and tails achieve about 3 to 3.5.

Westland Aircraft Ltd test flew a Delanne-type *Lysander* variant, designated the *P12*, in 1941. The layout is shown in fig. 4.23. The company found that its behaviour, stability and control were an improvement on the standard *Lysander* (plate 4.12), and the lift-slope was 29 per cent better. Using the figures given by Westlands (ref. 4.20) and Warner (ref. 4.17) enables table 4–3 to be drawn.

The *P12* had fixed gear and it appeared to have a maximum speed ratio, V_C/V_{SO}, about 5.17, compared with 7.6 for the *10C-2* given above. Certain other information obtained from the test flights showed that although the aeroplane was better longitudinally than the standard *Lysander*, directional control was degraded seriously at low speed, and when its tail turret was turned. Directional stability was reduced markedly when the centre of gravity moved aft. With the CG at 64.5 per cent chord the aeroplane was longitudinally and directionally uncomfortable. Further aft than that position the aircraft would spin. With the CG on the forward position at 45 per cent SMC take-off, general handling and stability were reported to be excellent, but full up elevator was needed to land. The design was not developed, although the *Westland* test

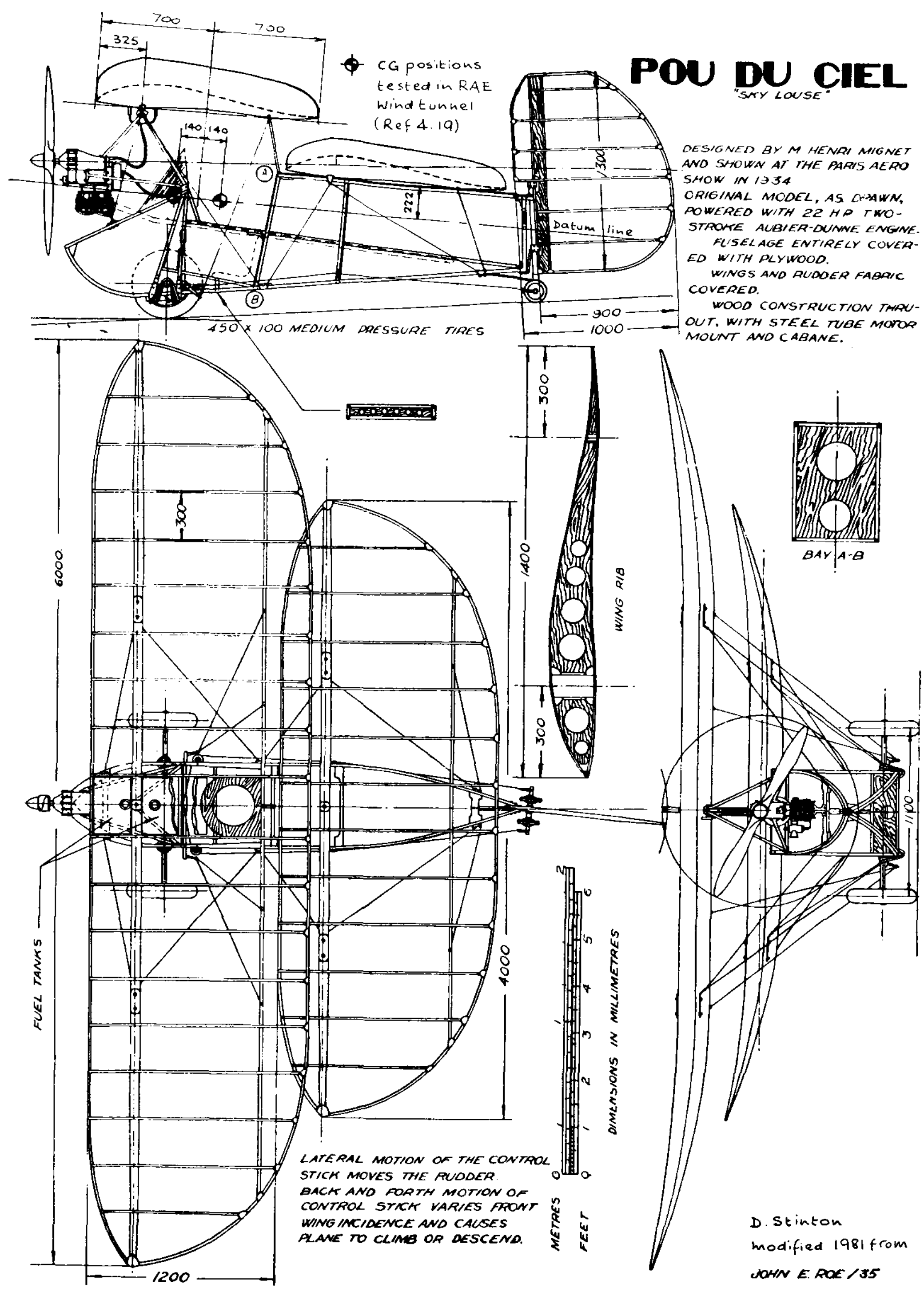


Fig. 4.22 General arrangement of Henri Mignet (1893–1965). *HM14 Pou du Ciel (Sky Louse* or *Flying Flea)*. Drawing based upon information given in refs. 4.18, 4.19 and 4.22.

pilot, Harald Penrose, proposed a light aeroplane with Delanne-type configuration around 1947.

TABLE 4-3

Configuration	Lift slope	Source
Infinite monoplane	$a_0 = 2\pi/\text{radian} = 0.1/\text{degree}$	eq (4-18)
Finite monoplane	$a_A = 2\pi A/(A+2)/\text{radian}$	eq (4-19a)
Biplane, $G/\bar{c} = 1$	$a_A \approx 0.83 \times$ monoplane	(ref 4.17)
	$= 1.65\pi A/(A+2)$ for the same aspect ratio	eq (4-36)
$\dfrac{\text{Westland Lysander}}{\text{monoplane}}$	$a_A = 0.075$ ($A = 9.6$, estimated)	(ref 4.20)
$\dfrac{\text{Westland P12}}{\text{monoplane}}$ (Delanne-type)	$a_A = 0.097$ ($A = 9.6$, estimated)	(ref 4.20)

Junctions, fillets and fairings

Junctions between surfaces are always sources of premature flow separation, aerodynamic buffet and drag. Mid-wing arrangements, and wings which meet relatively slab-sided bodies at right angles are the least likely to give trouble. With high and low wings, especially those which then meet curved fuselage skins, there is a natural tendency for wing and body surfaces to form an acute angle. Acute angles slow down flows, causing static pressures to rise and air to break away in small regions of high energy vortices left behind in the wake.

Losses with high wings are less than those which are set low on bodies with well curved cross-sections. The reason is that the increase in static pressure underneath the root of a high wing helps to generate and maintain lift. With a low wing, a rise in static pressure at the root of the top surface is anti-lift.

Wing fillets (and tail fillets) are designed to fill the volume between surfaces where they meet at an acute angle. A plot of cross-sectional area of such a trapped 'streamtube' shows a rapid contraction aft of the leading edge, to the point of maximum wing thickness, followed by a rapid expansion. Quite apart from adverse frictional effects, the air cannot cope with too rapid deceleration past the crest, so it separates. A fillet smooths and reduces the rate of change of cross-sectional area of the 'streamtube' between the leading and trailing edge of the wing, as shown in fig. 4.24.

Fillets give character to an aeroplane. A carelessly profiled wing root fillet can spoil the authenticity of a replica, quite apart from perhaps spoiling the flying qualities.

A particularly interesting fillet was the 'bite' at the trailing edge of the wing on the elegant and highly streamlined *Heinkel He 111* (1935), like that of the *He 70* (1932) before it. The marked 'bite' is shown in plate 4.14. It reduced the wing root chord, and gave a pronounced inverted-gull wing aspect to the trailing edge. The basic shape of both designs appears to have been so streamlined that the tailplanes lay almost in line with the crests of the wing root sections, where they were vulnerable to buffet. The bite was a geometric device which enabled the trailing edge of the wing to be swept