Aerodynamic Factors in the Design of Long Range Flying Boats

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THE PRIMARY AIM, in a flying boat design, after having satisfied the special conditions of a given problem, is to secure the maximum payload for a given range at the highest possible cruising speed. There are two aspects of the problem: flight at economical speed, *i.e.*, at or near $L/D_{\text{max.}}$, depending on the specific airplane engine characteristics; or flight at higher speeds, limited by permissible engine power. The solution differs somewhat in the two cases due to the varying relative importance of the induced and the parasite drag.

This paper endeavors to present a study of the various prime factors affecting cruising speed and range: namely, wing span, parasite drag, propeller efficiency, specific fuel consumption, altitude, headwind, and gross weight.

The basic law governing the drag of a wing or of a complete airplane is given by

$$C_D = C_{D_0} + C_{D_i} \tag{1}$$

where $C_{D_i} = BC_L^2$. The theoretical value of C_{D_i} is $C_L^2/\pi R$. This latter value is not strictly true, since neither the wing profile drag nor the structural parasite items are constant with varying angle of attack. The factor "B" corrects the theoretical to the actual induced drag, making allowance for mutual interference, departures from ideal lift distribution, and for the variation of profile and parasite drags with angle of attack. This expression holds very well within the normal flying range from $C_L = .2$ to 1.0.

Usually C_D is plotted *vs.* C_L giving the familiar polar, Fig. 1. Should C_D be plotted against C_L^2, as in Fig. 2, the graph is a straight line within the limits of C_L noted and the slope of this line is "B." The induced drag correction factor "e" may be defined as $\sqrt{1/\pi RB}$ and the effective span as $e \times S$. This conception of "e" and particularly the method of obtaining it are both simple and important.

Referring to the plot of C_D versus C_L^2, the intercept on the C_D axis for $C_L = 0$, represents the C_{D_0} term in Eq. (1) above, or the combined wing profile and parasite drag.

If A_p = A flat plate area equivalent to C_{D_0}.
C_p = .00327 = Drag coefficient of this area.
W = Gross weight.
V = Velocity of flight.
σ = ρ/ρ_0 = Relative density.

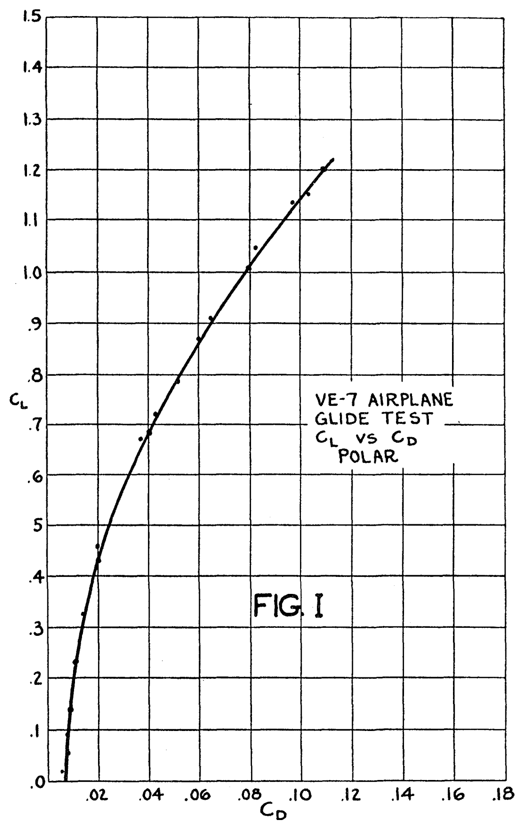

FIG. I

Then

$$\text{drag} = C_p A_p \sigma V^2 + 125 \left(\frac{W}{S_e}\right)^2 \times \frac{1}{\sigma V^2} \tag{2}$$

expressed in engineering units of lbs./sq. ft. and m.p.h. If this equation is differentiated and put equal to zero and solved for V, the speed of minimum drag or maximum L/D,

$$V = 13.95 \left(\frac{W}{S_e}\right)^{1/2} \times \frac{1}{\sigma^{1/2} A_p^{1/4}} \tag{3}$$

Another interesting relationship that may be determined by substituting V from Eq. (3) in Eq. (2) is that

$$D_{\text{min.}} = \frac{W A_p^{1/2}}{.782\, S_e} \text{ and hence } L/D_{\text{max.}} = \frac{.782\, S_e}{A_p^{1/2}} \tag{4}$$

If Eq. (2) is multiplied by V and divided by 375, the expression for the thrust power required is

$$P_R = .00000872\, A_p \sigma V^3 + \left(\frac{W}{S_e}\right)^2 \frac{1}{3\sigma V} \quad (5)$$

The Breguet formula for range is:

$$R = \frac{863 \times \eta_{\text{max.}}}{C} \times L/D_{\text{max.}} \times \log\,(1 + W_F/W_E) \quad (6)$$

$\eta_{\text{max.}}$ = Average propeller efficiency.
C = Average specific fuel consumption—lbs./hp./hr.
W_F = Weight of fuel.
W_E = Gross weight less fuel.

A study of these four simple equations, Eqs. (3), (4), (5), and (6), brings out some interesting points regarding range and the cruising speed at maximum L/D.

(1) V increases inversely as the square root of the relative density.

(2) V varies only as the reciprocal of the fourth root of the parasite drag, so that large changes in A_p are required to affect V appreciably.

(3) Due to the fact that decreased fuel consumption and improved propeller efficiency decrease the fuel used and hence increase the weight at the end of the trip, they each will slightly improve V_{average} if varied, favorably.

(4) V increases as the square root of the span loading but it is important to note that the power required varies with the square of the span loading.

(5) Theoretically, V varies inversely as the square root of the effective span. However, if some of the large fuel saving possible with increased span is used to fly at speeds greater than that of $L/D_{\text{max.}}$ such a change may increase both V and range substantially.

(6) The most economical speed is increased considerably when flying against a headwind, the power required to fly faster being counterbalanced by the shorter time which the airplane has to fly against the wind. The method of finding the correct speed is simple but time does not allow the presentation of the chart or equation here. For an airplane with a cruising speed of 135 m.p.h., a headwind of 30 m.p.h. increases the economical speed to 144 m.p.h. The increase is more on slower ships and less as the economical speed increases. The importance of high cruising speeds when flying against a headwind is clear due to the decreased percentage loss in effective speed. This constitutes one of the important advantages of a flying boat over a dirigible whose cruising speed is only half that of the airplane.

It is difficult to increase the true economical speed on a long range airplane because of its slow variation with parasite and the adverse effect of increased span. However, a large gain can be made by taking advantage of the relatively flat peak of the L/D curve. By flying at a higher speed where the L/D is 97.5% of the maximum the gain in speed is 11.2% with only a $2^1/_2$% sacrifice in range, and a power increase of 15%.

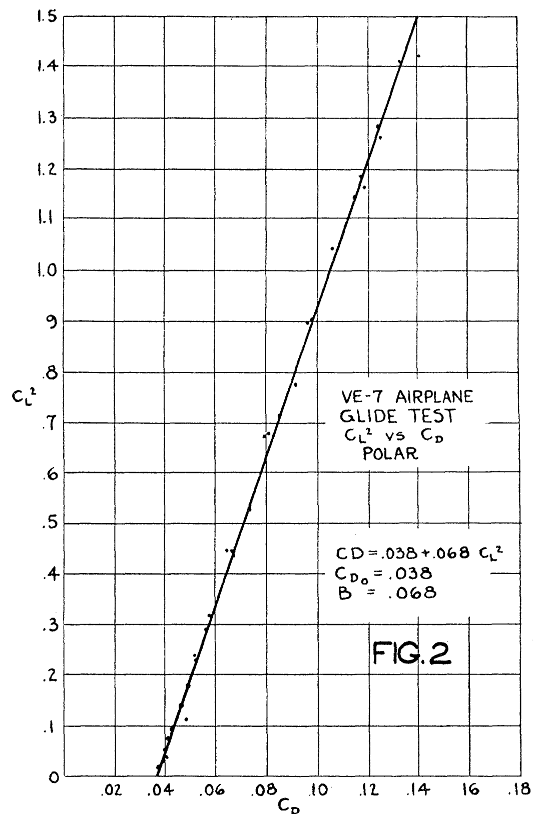

FIG. 2

It is an interesting point that at the speed of $L/D_{\text{max.}}$ the parasite drag exactly equals the induced drag, and at higher speeds the former predominates.

Having discussed the effect of various factors on economical cruising speed their effect on range as shown by Breguet's formula will be discussed.

(1) The range will increase directly as the propeller efficiency improves and the fuel consumption decreases. With a fixed pitch propeller the problem is simple and the results are pretty much beyond our control. With a constant speed propeller, on the other hand, the problem is quite complex because the propeller efficiency varies with both engine speed and power and with airplane speed while the specific fuel consumption varies with manifold pressure and engine speed. Usually engine manufacturers give only the specific fuel consumption determined from the basic propeller load curve starting from rated power and r.p.m. With a constant speed propeller it is not necessary and seldom desirable to throttle along this curve. There may be, as shown by Fig. 3, any number of such cubics giving constant power coefficient C_p starting at different points on the full throttle power curve. One engine manufacturer has made a thorough study of specific fuel consumption and found that the minimum specific fuel consumption at any power was obtained by following a line such as Line A of Fig. 3. Data for important engines sufficient to permit plots of contour curves

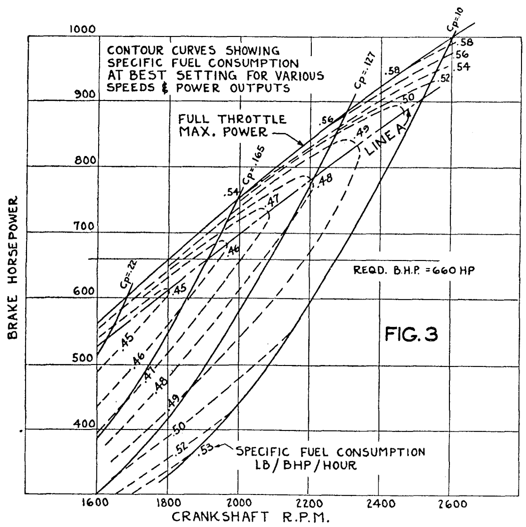

FIG. 3

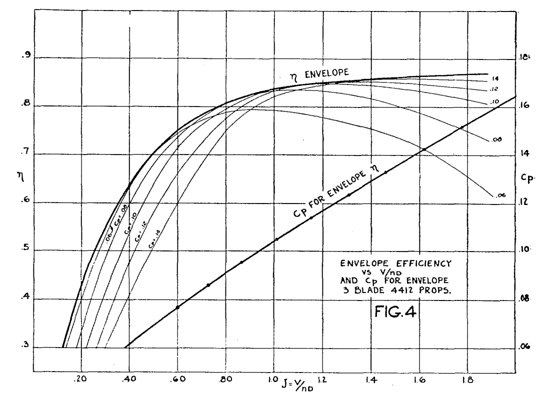

FIG. 4

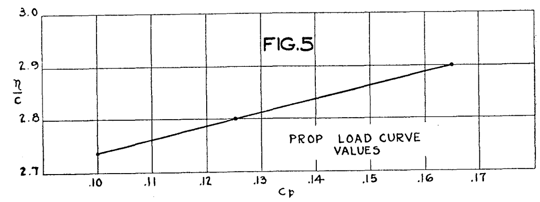

FIG. 5

of specific fuel consumption *vs.* engine power and speed are needed and must be had.

In a somewhat similar manner propeller efficiency at any V/ND will vary with power coefficient $C_p = P/\rho n^3D^5$. At any V/ND there is a value of C_p giving the maximum value of η. Fig. 4 shows an envelope curve of propeller efficiency based on these values of C_p.

For any airplane speed, by use of charts such as just described, the engine speed at any power may be chosen to give the best ratio of values of η/C or propeller efficiency and specific fuel consumption. Fig. 5 shows the variation in η/C with C_p. On long trips such studies will result in very appreciable payload increases.

(2) The range does not vary directly as the amount of fuel carried but as the log $(1 + W_F/W_E)$. This relationship works out so that the greater the proportion of the gross weight is fuel the greater will be the range *per pound* of fuel. In a specific case, if the fuel weights are 40, 20, and 10 percent of the gross weight so that the ratios of fuel load to each other are 1.00, .50, and .25, the respective ranges are 1.00, .437, and .206. The reason for this of course is the effect of induced drag, it being the least at the end of the trip in the case of the ship with the most fuel at the start.

(3) The other factor to consider is the L/D, to which the range is directly proportional when the airplane is flying at economical speed. From Eq. (4) $L/D_{\text{max.}} = .782\ S_e/A_p^{1/2}$. Here the predominant influence of *effective* span on range is clearly brought out. Again it should be emphasized that not geometric but effective span is the criterion.

(4) In contrast, range varies inversely only as the square root of the parasite drag. This and the preceding paragraph are the explanation of the range records that have been established by large span airplanes, not particularly clean aerodynamically.

Lest a wrong impression be given, it should be stated that commercial operation, even over the ocean generally requires speeds appreciably in excess of the true economical speeds, and hence parasite drag becomes more important. Probably the best criterion for comparing various designs of long range airplanes is the formula—Factor of merit = payload × speed × range—taking into account the fundamentals of payload, range, and speed. This is also useful in studying the effect of varying the speed on payload with a given range.

The discussion above applies to airplanes of about the same size, whether large or small. Overshadowing in its effect all the factors mentioned above is that of mere size and weight. Assuming the same general type of design, increasing the size and weight has a major effect on range for the following reasons.

(1) The structural and power plant weights are a definitely decreasing percentage of the gross weight, up to the maximum we have investigated carefully, leaving a greater proportion of the gross weight available for fuel if the payload is maintained a constant percentage of the gross weight.

(2) Scale effect has a pronounced influence on the parasite drag.

(3) With increasing size, the ratio between the structural portion of the parasite drag and the part formed by the wing profile drag steadily decreases. In other words, the drag of the hull, engine nacelles, floats, and miscellaneous items such as radio antenna becomes relatively less with increasing size until the ideal of the flying wing is approached. An L/D of 12 to 14 is good for a flying boat with a gross weight of 25,000 lbs. while a value of 18 is possible with a 100,000 lb. airplane and an L/D of 20 or more should be attainable on a still larger ship.

(4) It has been pointed out above that range is directly proportional to L/D and hence to effective

span. With larger airplanes, the nacelles and body affect a much smaller proportion of the span so that the correction factor applied to geometric span becomes more nearly unity. This is an important secondary effect of increasing size.

(5) The trends just noted make it possible to increase the power loading as the size increases, thus completing the beneficent circle of decreasing power plant weight percentages and nacelle drag.

Not only range but cruising speed is greatly improved as the size becomes greater due to these factors.

(1) The span loading rises very rapidly with gross weight, and as shown by Eq. (3), the speed at $L/D_{\text{max.}}$ varies as $(W/S_e)^{1/2}$. Even with constant wing loading the span varies only as $W^{1/2}$, and since the wing loading varies nearly as $W^{1/3}$ the span loading will increase as $W^{2/3}$ and hence if the parasite drag is constant, V at $L/D_{\text{max.}}$ will increase as $W^{1/3}$.

(2) Although the total parasite drag increases with greater size it does so slowly and since speed at $L/D_{\text{max.}}$ is inversely proportional to only $A_p{}^{1/4}$, this does not nearly counterbalance the influence of the higher span loading. To assume that A_p varies as $W^{1/2}$ is a reasonable approximation. Hence the net variation of economical cruising speed with weight may be taken as $V \propto W^{5/24}$. If V is 140 m.p.h. for a 50,000 lb. airplane it will be 160 m.p.h. and 186 m.p.h. for a 100,000 lb. and 200,000 lb. airplane, respectively. If the latter is increased by 11.2% by flying at 97.5% of $L/D_{\text{max.}}$ as discussed above, the cruising speed is is 210 m.p.h.

The first section of this paper deals with the effects of several basic factors on the design of long range flying boats. The application of these principles to the determination of some of the main characteristics of a design will now be discussed briefly.

The first step in the problem is a statement of the limiting requirements such as length of trip, velocity of headwind, additional hours of fuel reserve, cruising speed, payload, and type of accommodations required for passengers and cargo. The last item is important as it greatly influences the size of hull and hence its drag.

In case the cost narrowly limits the size, or if the payload is more than 15 to 20 percent of the weight, in the case of the non-stop transatlantic run, then the amount of fuel is limited. The design is importantly affected by this, since it means that the airplane must be flown at close to economical speed with the emphasis on large span and moderate wing loading. The capacity of the airplane to do the given job is really the determining factor in setting wing and span loadings. When the size is not limited or when speed is considered of first importance, the emphasis shifts from considerations of induced drag to parasite drag. Flying speed will be well above that of $L/D_{\text{max.}}$. The span and wing loading can be increased. Flight will be made at nearly constant power and hence the speed at the end of the trip will be considerably greater than at the beginning, the reverse of the condition when flying at $L/D_{\text{max.}}$. As in the case of land transports, speed will be fixed by the limiting cruising power of the engines.

Knowing the condition of the problem, the designer can calculate rather readily by chart or formula the wing loading and span to give the optimum desired result. The important matter of plan form must now be decided Weight and structural considerations lead to a very high taper ratio. However, both theory and experiment have demonstrated the marked tendency with high taper ratios, for the wing tips to stall, resulting in loss of lateral control when it is most needed. It may be brought out that the higher the aspect ratio, the larger the taper ratio may be. With long range aircraft another element in this connection must be considered and that is the effect of plan form on lift distribution and induced drag. The factor e, which is determined by the slope of the C_D versus $C_L{}^2$ curve, and its use in obtaining the effective span has been discussed. To secure a high value of e means that the lift distribution or the wing plan form must approach the elliptical. Span gained through improvement in e is just as useful as if added geometrically. It must be remembered that if a wing is given an aerodynamic twist this will affect e adversely or otherwise. Another powerful factor determining e is the interference between the nacelles and the wing or the hull and the wing. If the juncture is bad there will be a double loss: increased parasite drag and serious disturbance of the circulation about the wing reflected in a large decrease in e and consequent lowering of L/D. The need of a perfect juncture and melding of the two flows about the body and about the wing is particularly critical if the proportion of the span occupied by the nacelles and the hull is large. The Short "Empire" boats are excellent examples of clean design but my feeling is that this basic point in proportion has not received sufficient attention and if they do not prove efficient for ocean work the author believes this fact will be the underlying cause.