The Development of the Military Aeroplane*

A Discussion of the Question of Size

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THE investigation forming the subject of the present article was embarked upon by the writer with a view to determining so far as is possible, as a generalization, the most appropriate size or weight of aeroplane to be employed for any given military duty.

There has been for some time past a belief current with the general public, and among engineers who have not studied the problem of flight closely, that future developments are to be expected in the direction of a great increase in the individual size and power of the aeroplane. This belief has been reflected in the work of several designers (notably in Russia), as evidenced by the construction of machines weighing 3 or 4 tons.

The writer has never believed in the probability of early developments in this direction; in 1908, in the second volume of his "Aerial Flight" (page 153), he gave the probable range of size of the flying machine (of the then "visible" future) as from ½ ton to 2 tons weight. This estimate was based on various considerations, both as concerning stability and as related to the aerodynamic and engineering outlook; the latter founded on data given in the earlier volume, where the possibilities of construction had been forecasted with considerable accuracy. Thus the weight of the power installation (without fuel) of the aeroplane is to-day commonly about 25 per cent of the gross weight. This is as given in 1907, on page 333 of *Aerial Flight*, vol. i. The gasoline capacity of the standard military machine of to-day is approximately 10 per cent of the gross weight. This is the basis given on page 331 of the volume aforesaid, and is that on which the final column in Table XV is founded. Again, on page 243 *et seq.* (§ 170), and on page 285 *et seq.* (§ 194), the question of aerofoil weight is discussed, and in an example given for illustration the wing weight is 22½ per cent of the gross weight. In one of the most popular of the British machines of to-day this figure is almost exactly that realized.

Although in the passages above cited the question of aerofoil weight was discussed, as affecting the conditions of least expenditure of work, it was not specifically discussed as a factor in determining the best size of machine; in other words, the relations between the "military load" specified for any given duty and the gross weight of machine best employed, and the gasoline capacity available. The establishing of this relation is the object of the present article.

The whole problem is one of considerable complexity, and in generalizing for practical purposes it is not necessary to take account of every factor which, strictly speaking, enters into the problem.

In dealing with the problem in its simplest form we may suppose the velocity of the design in contemplation to be an invariable. This assumption cannot be far from the truth, inasmuch that the highest admissible minimum flight speed is determined for military aeronautics by the landing grounds available under military conditions, and the maximum flight speed is determined by the horse-power installation which can be employed. Thus, if we take the flight speed as constant, it is fair to allot a certain definite proportion of the gross weight of the machine (the same in every case) to the power installation. In the present investigation this is taken at 25 per cent of the total gross weight, as in accordance with the writer's forecast and with present-day general practice. The fixing of this proportion is virtually tantamount to asserting that the gasoline motor can be designed to a given *horse-power/weight* factor, whether it be large or small, and this may be justified on the grounds that where a big power installation is employed, it is not unusual to duplicate the power unit rather than build a special larger type of engine; it is further justified by the fact that so long as a given size of cylinder is adhered to, the best which can be done in the way of weight reduction, with a given type of engine, is practically constant whatever be the power and size of the installation. Thus the lower powered engine will have a smaller number of cylinders, and the higher powered a greater number. If we consider ultimately the possibilities of design, it is improbable that the designer will be able to obtain a better horse-power/weight factor for an engine of say 200 horse-power than he can for one of 100 horse-power, and, as above remarked, the horse-power/weight factor can only be kept down in the big engine by employing a greater multiplicity of cylinders than in the smaller one, a course which beyond a certain point is open to objection.

The next point on which a convention may be made concerns the weight of the fuselage and alighting chassis; that is to say, the whole of the structural parts of the machine *excepting* the aerofoil itself, with tail and rudder, members whose weight varies in like ratio. These components again commonly total up to about 25 per cent of the total gross weight, and, generally speaking, it is not possible to obtain any relief in this part of the dead weight of a machine by making it bigger. There are, it is true, certain parts which can be relatively less weighty, such as those which relate to the pilot and seating accommodations, control mechanism, and so forth; but the alighting gear will have to be disproportionately heavier on the big machine than on the small machine, on the same principle, and for the same reason, that an elephant's legs have to be of a relatively greater diameter than those of a horse, or, going to an extreme, than those of a stork or flamingo. On the other hand, the weight of the fuselage itself may not necessarily require to be increased quite in the same ratio as the gross weight, though it is by no means clear that a serious saving can be made. It is not fair to assume, for example, that for a given military duty or purpose the same fuselage can be employed with bigger flight organs and heavier motor, etc., since the length of the fuselage has to be related in some degree of proportion to the flight organs themselves and to the general size of the machine; also the strength and scantlings of the fuselage have to be increased in proportion to the bending moments, etc., which may be taken as roughly proportional to the increase in weight, even if the size be not increased. The writer feels that it would be an optimistic designer indeed who would expect to save relative weight on the percentage of total on the combined fuselage and alighting chassis of the large aeroplane as compared with the small. He believes that in taking these combined weights as a constant proportion of the whole he is acting favorably, rather than otherwise, to the large machine. It would thus appear that, roughly speaking, half of the gross weight of an aeroplane is made up of its main structure and power installation with their associated parts, and the remaining half of the gross weight is available for the military load, the aerofoil weight, and the carrying of gasoline.

The next step is to formulate the law by which the aerofoil weight is related to the gross weight of the machine, that is to say, related to the total weight carried. The simplest basis is to assume an aerofoil of a geometrically constant form—that is to say, whatever type of aerofoil is selected, whether biplane or monoplane; and whatever method of construction is employed—that is to say, whether wood spars or steel tubular spars, or what not—the selected type of structure and method of construction is taken as applying to all possible designs under consideration, large or small.

Now, on the basis of constant velocity, the span must vary as the square root of the gross weight; this is a matter of aerodynamics. The aerofoil weight will vary as the cube of the span, for the bending moments at any point in the wing length or at any point in the wing structure vary as the weight multiplied by the span—that is to say, as the span cubed; and since with similarity of design the linear dimensions will vary as the span, the strengths of the members must vary as the span squared: in other words, the scantlings will be proportional and the aerofoil structures will be geometrically similar in every respect. Thus the aerofoil weight will vary as the span cubed—that is to say, if the gross weight $= W$,

$$\text{Aerofoil weight varies as } W^{\frac{3}{2}}$$

The above is the assumption which will be taken first, as it forms a simple introduction to the more complete investigation which follows:

In Fig. 1 a diagram is given representing the wing structure or aerofoil weight—the curve cCc_1 , the ordinates of which (axis of y) represent aerofoil weight, and abscissae (axis of x) gross weight of the machine. In accordance with the foregoing, the equation to this curve is

$$y = ax^{\frac{3}{2}}$$

where a is a constant.

Let the axis of y be extended to O_1 so that OO_1 represents to scale the constant load which it is required to carry; in other words, the *military load*, comprising pilot, observer, or gunner (if any), with machine-gun

or other weapon, ammunition, bombs, etc. Then a line O_11 drawn at 45 degrees will represent, by its ordinates, the gross weight, and lines O_12 and O_13 will represent, by the ordinates cut off, the proportion of the total (25 per cent in each case) assigned to the *fuselage*, etc., and to the power installation respectively.

The portion of the ordinate cut off by the line O_13 and the graph cCc_1 , and lying between these limits, will then represent to scale the weight disposable as gasoline, and the proportion as part of the gross weight is given by the per cent scale to the right hand of the figure, as determined by the lines directed to the origin O_1 .

Now, the gross weight corresponding to greatest relative gasoline capacity is defined by the point C at which a tangent drawn to the curve passes through the origin O_1 .

$$\begin{aligned} \text{Let } W &= \text{gross weight.} \\ w &= \text{aerofoil weight.} \\ M &= (\text{constant}) \text{ military load.} \end{aligned}$$

$$\frac{dw}{dW} = \frac{u + M}{W} \quad (1)$$

But

$$w = W^{\frac{3}{2}}$$

or

$$\frac{dw}{dW} = \frac{3w}{2W}$$

or by (1):

$$\frac{3w}{2W} = \frac{u + M}{W}$$

or

$$w = 2M$$

That is to say, the relative gasoline capacity is greatest when the aerofoil weight is double the military load. This is as given in Fig. 1 by the point C .

As in all ordinary cases of a maximum or minimum, there are always other considerations tending to make the practical engineering solution differ from that given by the mathematical solution, and the compromise to be adopted in any case will depend upon the relative importance of the various conflicting factors. On referring to the figure, it will be seen that anywhere in the region of the point C over a range of about 20 per cent, or 25 per cent of the gross load, plus or minus, the percentage of gasoline does not sensibly, or at least seriously, vary. Hence, since the duty performed is constant, it will be most uneconomical to employ a machine of gross weight as given by an ordinate at C (nearly eight times the military load), when a gross weight say five times the military load (as at point B) would do the same work with about 80 per cent of the maximum gasoline percentage, and therefore 80 per cent of the range of flight.

In some particular cases where the utmost range of flight is imperative it might be expedient to design to a somewhat higher gross weight, say six times the military load; but for the example taken in no case would anything much above this be warranted.

It is thus manifest that for the purposes of the aeronautical engineer or designer the mathematical solution for maximum relative gasoline capacity does not give sufficient information, or adequately act as a guide in settling the specification of a design for any stated duty. A graphic lay-out of the type given in Fig. 1 is necessary; it is just as important to know the extent of the sacrifice in gasoline capacity for values of W (the gross load), other than that of maximum, as to know the particular condition defining the maximum itself. Hence in the further development of the subject in the present article the mathematical treatment has been discarded in favor of a purely graphic representation.

The basis on which the graph cCc_1 , Fig. 1, is founded is only roughly approximate, since the aerofoil weight w included as part of the total may be considered as in

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reality borne locally, and as not giving rise to serious or sensible stresses within the aerofoil structure, so that the structural stresses within the aerofoil are due to the weight W minus the aerofoil weight. This introduces some complication, but the departure is easily dealt with by graphic construction. Thus, in Fig. 2, the corrected curve of aerofoil weight is obtained graphically from the curve given in Fig. 1 to comply with the new condition. The curve is first laid out as before, and increments of W are added equal to w at any selected points on the curve, the corrected curve being drawn through the points so obtained. The equation to the new curve is thus:

$$w = c(W-w)^{\frac{3}{2}}$$

In Fig. 3 an example is given with a curve (derived as in Fig. 2) representing a machine designed for a military load of 500 pounds and with an aerofoil weight which would correspond in practice (according to the ordinary current methods of construction) to a factor of safety of about 5 or 6, as recommended by the Advisory Committee for Aeronautics. Here it will be seen that the ultimate maximum percentage of gross weight which can be carried as gasoline represents about 18½ per cent, and the gross weight of machine corresponding to this is in the region of 6,000 pounds. Clearly from the diagram it would be absurd to build a machine 6,000 pounds in weight, for its actual consumption of gasoline would be twice as great as that of a machine 3,000 pounds gross for the same duty, and the latter machine would have over 80 per cent of the flight range of the other, as indicated by the relative gasoline capacity. According to the rule given in the simpler case, Fig. 1, the aerofoil weight = twice the military load, shown by point A in Fig. 3, the appropriate gross weight is about 4,700 pounds, and the loss of flight range as due to the lowered percentage of gasoline is a matter of about 2 or 3 per cent—that is to say, the gasoline capacity will be about 18 per cent of the gross load instead of about 18½. It is evident that no sane designer would go beyond this point.

If for ordinary military flying we take it that 75 per cent of the maximum relative gasoline capacity is good enough, then, for the machine in question, the gross weight will be about 2,800 pounds, as shown by point B, and the aerofoil weight will be approximately equal to the military load. The actual consumption of gasoline of such a machine for a given military duty will be less than half of that which would be necessary if the actual minimum (corresponding to 6,000 pounds gross weight) were adopted. From the diagram in question it is clear that for the military load of 500 pounds a machine between 1 and 2 tons weight is appropriate, 1 ton being sufficient where a 10 per cent gasoline capacity is all that is required, as in local reconnaissance or for defensive purposes, and 2 tons in the case of a machine for raiding or other purposes in which great range or radius of action is important. Thus the machine of 1 ton would have a flight range of between 300 and 400 miles, and that of 2 tons about 700 miles; beyond this no material advantage can be obtained.

As examples of two extreme values of military load Figs. 4 and 5 are given, the construction being identical to that shown in Fig. 3. In Fig. 4 the military load has been assumed as 150 pounds, a lower limit representing a pilot only, with virtually no equipment. In Fig. 5, as an extreme case, the military load has been taken as 2,000 pounds, this being a load beyond anything ordinarily required and would correspond to the carrying of a Whitehead torpedo, or it would represent a capacity of three bombs of 6 hundredweight each.

In both Figs. 4 and 5, as in Fig. 3, the factor of safety or dynamic load-factor of the aerofoil has been taken in accordance with the recommendations of the Advisory Committee for Aeronautics as about 5 or 6, and the weights are further based on present-day practice in biplane construction in which this factor of safety is embodied.

These figures speak for themselves; it is clear that if Figs. 3 and 4 be taken to represent the limits of ordinary military flying, the writer's 1908 estimate of the probably useful range of weight of aeroplanes is fully justified. The carrying of a load of over 2,000 pounds (as in Fig. 5) may fairly be regarded as duty of an abnormal kind, involving a special machine outside the ordinary run of experience. Such machines would form but a very small portion numerically of the total of the aeronautical forces.

It is now time to consider the extent to which the assumption of a constant flight velocity is, in fact, justified, and to point out the effect of the foregoing conclusions on departures from this condition. First, it may be remarked that the lower limit of flight velocity—that is to say, the lower limit for which it is possible to design as the normal speed of flight—is determined by questions of stability and by questions meteorological and military. The superior limit to which it is possible to design is, on the other hand, related to the

horse-power required, and by the area of the flight grounds, which, under practical military conditions, can be made available.

As to the lower limit, first on the question of stability, those best qualified to speak here are in disagreement; the crux of the matter is whether or not inherent stability is necessary or desirable. Ever since the formation of the Advisory Committee for Aeronautics in 1909 there has been a battle, if one may say so, in prog-

ress between the scientific constructor and the flying man; but the difference of opinion between the two is becoming less as time goes on. The scientific constructor, who has from the first maintained that machines should possess inherent stability, has virtually won the day. This, it may be said, is largely due to the efforts of the late Mr. T. E. Busk, who himself became a pilot in order to prove the then pilot's view as wrong. Briefly put, the argument of the pilot was that a machine with

inherent stability was less readily controlled than one which was neutral or actually unstable; further, that the inherently stable machine of necessity requires to be hand-controlled when alighting under difficulties, and if the pilot thus of necessity has to rely upon his own skill on occasions, it is better that he should always have to do so than only occasionally. The arguments on the other side, however, have proved too strong for this point of view to hold; the fact that an inherently

stable machine will fly itself through clouds and in the dark, and has its own sense of the true plumb as distinct from the apparent plumb, means that it is at an enormous advantage under many conditions which have to be faced by the military machine. Beyond this, for plain straightforward flying, the inherently stable machine requires comparatively little skill, and does not wear down the pilot under bad weather conditions. It is, perhaps, worthy of remark that, on the other hand,

there are particular cases in the military use of aeroplanes under which the conditions are better fulfilled by a machine whose stability is imperfect; but this is a case for a special type of machine for particular duties rather than an argument against inherent stability as a general proposition. From the standpoint of the present article it is enough to state that the smaller machine is at a great advantage over the larger one on

the score of stability. From the meteorological point of view (apart from stability) both large and small machines are on the same footing as to the minimum flight velocity. There is a certain agreed maximum wind velocity which the machine must be capable of exceeding in such ratio as will not too greatly upset calculations as to its time of flight. From the purely military point of view also the large and small machines are on approximately the same footing as to the lower limit of their designed velocity. The question here is mainly that of pursuit and that of a moving target. In the latter respect the smaller machine has some advantage owing to its ability to dodge more rapidly. Therefore it might be tolerated if its speed were slightly lower; however, this is hair-splitting. It may be said broadly that, from both the meteorological and military point of view, the minimum velocity admissible is independent of the size of the machine.

Now, as to the maximum velocity limit. Here, whether we consider the matter from the point of view of size of flight ground or from the point of view of the horse-power weight factor, the large and small machines are on, roughly, the same footing. It is quite true, however, that, for a given horse-power/weight factor, the large machine is capable of somewhat greater speed; the extent of this advantage, however, in any designs which have been so far produced is not great. It is impossible to take account, as a generalization, of this advantage; it is due to the possibility of a relative reduction in the body resistance. In practice, however, the designer can make his own estimate, and calculate, in view of the higher speed, what his reduction of span will be, and what saving in aerofoil weight this represents; he can then apply a suitable correction to the aerofoil weight curves given in Figs. 3, 4, and 5, and from this he will be in a position to compute to what extent it will pay to increase his gross weight for a given duty over that given by the uncorrected diagram. The writer will say here that in any case with which he is acquainted this will only amount to a moderate correction, and can in no case invalidate the method or general results.

It is thus abundantly clear that, for the purpose of broad theory, the assumption of constant flight velocity, no matter what the size of the machine may be, is fully justified. It is, however, of interest from two points of view to show the effect of designing for different velocities. First, we may take it that the weight of the gasoline motor per horse-power may be reduced by advance in knowledge and experience. The gross weight allotted to the power installation in Figs. 3, 4 and 5 may then be reduced, or alternatively the power of the given installation can be increased, and the flight velocity augmented accordingly. In the former case the solution is given by the general theory enunciated, assigning a different proportion of the gross weight in Figs. 3, 4, and 5, by giving a different inclination to the line from which the zero of gasoline capacity is measured, thus increasing the gasoline capacity to the extent of the weight saved from the improved power installation. In the diagram so modified, to comply with the new conditions, the minimum point is not affected.

If, on the other hand, the weight saving takes the form of additional motive power, then the designed flight velocity may be increased (but only with the provision of better flight grounds), and investigation shows the effect of this as an alteration in the scale of the diagram. The basis of scale alteration here is, if V = velocity of design in feet per second, multiply the scale

value of W as given by $\frac{V^2}{8000}$, or, assuming biplane construction, alternatively by $0.7 \frac{W}{s^2}$, where s is the span in feet.

It is of interest to take the case of a designer who, ignoring the considerations discussed in the preceding paragraphs, decides to maintain a constant span with increase of size and to furnish greater horse-power, and fly appropriately faster. If he takes this course, it is easy to show that his aerofoil weight now increases approximately as the gross weight, so that in the diagram the aerofoil weight may now be defined by a straight line directed from the origin O . The horse-power required for any given resistance/lift factor, however, and consequently the weight of the power installation, now goes up as $W \times V$, and since V increases as $\sqrt{W}$, the rate of the horse-power installation increases as $W \sqrt{W}$, or as $W^{\frac{3}{2}}$. Thus the position is fairly represented by a transposition in the interpretation of the construction given in Figs. 3, 4, and 5; the quantity formerly representing the power installation now represents aerofoil weight, and the quantity formerly representing aerofoil weight now represents power installation, and thus the big machine is at the same disadvantage as previously: