Man Powered Aircraft Group

Engineering Aspects in Man Powered Flight

by

B. S. SHENSTONE, M.A.Sc, F.R.Ae.S., A.F.I.A.S, F.C.A.I.
(Chief Engineer, British European Airways)

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1. Introduction

There are three practical aspects to the problem of man powered flight: aerodynamics, physiology and engineering. There are many more impracticable aspects to man powered flight, including the philosophical, the fanatical and the sceptical, which unfortunately have not yet been included in the lectures of the Man Powered Aircraft Group but which will no doubt find their places.

The engineering aspects are fortunately fairly clearly defined, although there is likely to be a slight threat of interference with the aerodynamic problems. I consider the engineering problems to be these:—

(*i*) the arrangement of the structure,
(*ii*) the details of the structure,
(*iii*) power transmission.

In all three of these one has aerodynamic limitations which may be illustrated in this way. The arrangement of the aircraft must be structurally sound and yet must be influenced by the aerodynamic requirements such as those of drag and interference. The details of the structure with regard to such matters as the wing thickness and the surface smoothness are limited by aerodynamic requirements. As for the power transmission, it may be influenced decisively by the aerodynamic requirements of the propeller position, its size and its speed of rotation.

It will already have been noticed by those interested in flapping flight that I have mentioned a propeller in such a manner as to exclude the use of flapping wings. This is done for reasons which have been expressed before over the past few years, and I think it is worth while mentioning them now so that my standpoint will be as clear as possible. I propose the propeller drive for the first generation of man powered aircraft because it is the easiest and best-known drive to adopt. This design brings us hardly outside our present knowledge. Practically all the factors can be calculated and those that cannot be exactly calculated can easily be tested in a wind tunnel or in the open air. Efficiencies are known and weights can be calculated. What more can one ask?

Although some people have reason to say that the flapping wing might be marginally more efficient than the propeller, it is unfortunately unproved at anything over 10 ft. span, even when driven by engine power. The complexity needed to enable the wing incidence to change in the proper way during flapping motion is complex and the weight of such full-scale mechanism is unknown. The aerodynamics of the rapidly oscillating tip are not known sufficiently so that one can calculate the performance of the flapping wing with any accuracy.

It is admitted that a natural rowing motion may be of the right order for easy transmission to a flapping wing, but even here the mechanism at this stage of development is far from simple. Therefore, without making any attempt to denigrate the future of the flapping wing, I would certainly say that it is a future development, not an immediate one. I may be criticised for looking for quick results, but that is my object; to get the men flying as quickly as possible, even though it may not be at the ultimate efficiency.

NOTATION

A	aspect ratio $= b^2/S$
b	span (ft.)
C_D	drag coefficient
C_{Dp}	profile drag coefficient
C_L	lift coefficient
D	drag (lb.)
L	lift (lb.)
P	power in horse power
S	wing area (ft.^{2})
V	air speed (ft./sec.)
V_s	sinking speed (ft./sec.)
w	wing loading (lb./ft.^{2})
W	weight (lb.)
W_e	empty weight (lb.)
W_w	wing weight (lb.)
ρ	air density $= 0{\cdot}00273$ (slug/cu. ft.)

2. Arrangement of the Structure

The structural and aerodynamic calculations indicate that the first man powered aircraft would have a wing of high aspect ratio, that is, of the order of 15. This is not an exceptionally high aspect ratio because cantilever wings have been built with an aspect ratio of 30[1]. It is also evident that the wing loading of man powered aircraft should be within the range of 1–3 lb./ft.^{2} This indicates roughly the size of the wing, which, depending on whether it is a single- or two-seater, will have an area between roughly 75 ft.^{2} and 300 ft.^{2}, with a span between 35 ft. and 65 ft. A large wing may be difficult to handle at low speeds, but if it were unfortunately necessary to have one, it must be accepted.

It is still an open question whether such a wing should be low on the fuselage or high. Aerodynamically it is far easier to deal with the high wing arrangement when considering the problem of interference and root stall at the high angles of flight which would be normal. On the other hand, a low wing would be closer to the ground and, if the ground cushion effect is to be

*The second lecture given to the Man Powered Aircraft Group —on 29th January 1960.

important, the closer the better. Whether a low wing arrangement could be devised with acceptable high angle of attack and flying characteristics is an important point which is as yet unsolved.

If we assume that the aircraft will fly at 10 ft. altitude, that is, 10 ft. from the bottom-most point, a low wing would be something like 4 ft. closer to the ground than a high wing, which would be of enormous importance if its effective aspect ratio can be maintained at the highest possible figure. On the other hand, most of the projects made public to date have been high-wing types because they are aerodynamically easier and, with wings which will tend to be very flexible in bending, they are less liable to damage on take-off and landing.

Leaving the wing for a moment, it is necessary to think of the tail/propeller combination as a unit. The first thing is that the propeller should not be in such a position as to disturb the free air flow over the wing, which in practice means it should be located behind the wing as a pusher-type propeller. This means it could be behind the tail of the aircraft, or it could be at the stern of a tail-less aircraft or a tail-first aircraft, or between the booms of a twin-boom aircraft, or above or below the boom of a single-boom aircraft, or by some ingenious means be incorporated in what might externally look like a normal fuselage.

It is essential that any layout must enable the propeller to be sufficiently large in diameter so that the best possible efficiency may be achieved. This diameter is bound to be over 6 ft. and may be as great as 9 ft. This large diameter member may well determine the fundamental layout of the aircraft.

As for the main structural material, I consider that for prototype aircraft, some form of wood construction would be the optimum. Whether or not wood in certain places is stabilised by honeycombs or foam plastic does not rule out wood as the main strength member. There may well be better materials than wood, but if anybody is starting now to design an aircraft which is meant to be a serious flying machine, he will not be able to afford fundamental research into more exotic materials. He can afford to use only materials which have proved themselves in the past. It is likely to be discovered that light-weight wood, that is, high-quality spruce and other woods even lighter, such as balsa, may take leading parts in the structure.

With wing chords up to 3 ft. and down to 1 ft., it will be realised that the rib loads at speeds of the order of 30 m.p.h. and an ultimate load factor of $2\frac{1}{2}$ will be very small indeed, and to get local structural stability a bulky structural material will be necessary.

It will also be clear that the lightest possible covering will be necessary with the proviso that the aerodynamic requirements of surface texture and continuity will have to be observed.

Perkins' use of an inflated wing design should not be ignored, but it requires special experience not generally available[(2)].

This leads one to the fuselage structure which, although it will have to have strong points involved with the wing attachment, pilots' weights, mechanical driving loads and landing and take-off loads, will need an aerodynamic fairing which must be as light as possible. This may inevitably lead to a light fabric covering. It is known that it is impossible to get a pure fabric covering to take an optimum aerodynamic form, but it may be necessary for considerable wind tunnel testing to be undertaken to achieve the optimum form for the designed cruising speed with the limitations on shapes achievable with fabric.

The arrangement of the structure is also influenced by the type of undercarriage, which again depends on the type of take-off visualised. The current condition laid down for the £5,000 Kremer prize is that the aircraft would have to take off without power storage and without outside assistance[(3)]. This probably means that during a large portion of the take-off, the drive will have to be through wheels in contact with the ground which has aerodynamic and structural complications apart from mechanical problems. If the take-off is accomplished by stored energy or by external power, the undercarriage need only be a skid with rubber buffers, which is a much simpler scheme.

3. The Details of the Structure

It is the details of the structure which weigh the most. The primary units, such as the wing spar and the fuselage skeleton, may be very light indeed, but the weight goes in wrapping these primary structures into an acceptable aerodynamic shape. If the load factors and the aerodynamic loads are large enough, it is quite easy to devise a thick-skinned wing which does not wrinkle under normal flying loads. In powered aircraft this can nowadays be accomplished by using metal skins and in sailplanes by using light-weight, fairly thick plywood, or sandwiches, because the ultimate factors and speeds are quite high (typically ultimate factor of about 8 and diving speeds of about 120 m.p.h.), but for the man powered aircraft, the ultimate factor may be only 2·5 and the speed to be catered for only about 50 m.p.h. (Fig. 1). Such low figures theoretically result in a very light aircraft, as indeed they could in practice, were it not for the aerodynamic difficulties, mainly connected with wing surface shape.

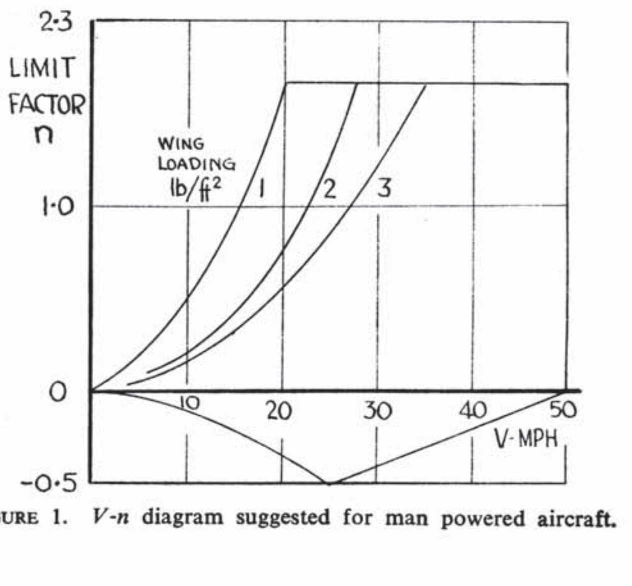

FIGURE 1. *V-n* diagram suggested for man powered aircraft.

At Queen's University, Belfast, a number of schemes have been studied and at the moment they feel it is most worth while using a single spar with a plywood "D"-type nose with fabric covering over the rear part of the wing which is the classical sailplane structure. They do not yet know the best way of stabilising the leading edge plywood.

We all have seen or read about new schemes for stabilised skins and much success has been achieved in using balsa-backed thin plywood, paper honeycomb backed thin plywood or glass fibre and many other variations of this scheme. Some schemes even go so far as to fill the whole interior of the wing with a light foam plastic or coarse paper honeycomb. Fig. 2 shows an impregnated paper honeycomb developed for a sailplane in Darmstadt.

There is no doubt whatever that a satisfactory aerodynamic surface could be obtained by a number of these methods. However, they vary widely in cost and difficulty in manufacture and also, in durability and mainly in weight.

It is very important to study the interaction between weight and drag in order to design the aircraft so that it will require the minimum amount of power for flight. There are many ways of expressing the power required and one of the simplest ways is as follows: —

$$P=\frac{W}{L/D}\frac{V}{550}\,.$$

It will be seen from this that one wants a low weight, low speed and a very high L/D or good gliding angle. This must be fairly obvious and it may be better to put the same formula into another shape, such as,

$$P=\frac{W}{550}\sqrt{\left(\frac{2W}{\rho S}\right)}\cdot\frac{C_D}{C_L^{3/2}}$$

(where $\sqrt{\left(\frac{2W}{S}\right)}\cdot\frac{C_D}{C_L^{3/2}}$ is the sinking speed)

and then $P=\frac{WV_s}{550}$.

It will be seen from this that the wing loading (W/S) should be low and that, quite apart from this, the all-up-weight should be low. It is also clear that the sinking speed must be as low as possible, which requires a low drag coefficient and a high lift coefficient. This expression shows clearly the extra difficulty of the man powered aircraft problem compared to the sailplane. Sailplane weight may be allowed to increase considerably and still achieve a better sinking speed. But for the man powered aircraft we have W the weight as an extra positive factor warning us clearly about the value of weight reduction in improving the power required. Here we see the usual inconsistent requirements of any weight versus drag problem, and it must be obvious, for instance, that to minimise the weight one dare not make the wing loading too low or the weight will begin to rise because of much larger wing. It was also easy to overdo the effort in getting the drag coefficient as low as possible because by doing so one can add weight, which would at least eventually counteract the effect of reducing the drag. A well-known analysis of reasonable approximation was that the minimum power required occurs when

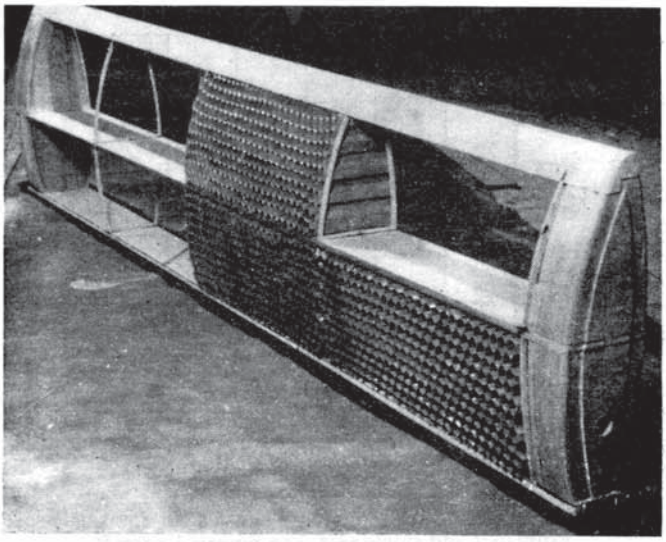

FIGURE 2. Impregnated paper honeycomb for sailplane wing (Darmstadt).

$$C_{Di}=3C_{Dp}$$

This means that, of the total power required, one quarter is needed to drive the aircraft and three quarters are required to sustain it.

This power for sustaining the aircraft is often called the induced power. This induced power may be expressed approximately as: —

$$P_i=\frac{W}{60A}\sqrt{(C_L w)}\text{ at sea level.}$$

and this expression instructs us to do some obvious things and some impossible things. We must keep the weight down. We must use a large wing aspect ratio. It tells us also, although in a somewhat more minor key, to use a low wing loading and to fly at a low value of the lift coefficient. At least this does show us how we might proceed in playing with weight and drag, but before we can do much about it, we have to know more about the weight problem.

The structure weights to be expected for properly designed man powered aircraft are not easy to foresee because there are so few data available on which to base them. The only information which is factual is the meagre information on the empty weights and some other weights of five single-seat man powered aircraft actually built, but none of them completely successful. Wing loadings come to an average of about 2 lb./ft.^{2} and aspect ratios average about 15, the ultimate load factors being something of the order of 5 or 6, but full details are lacking. If we plot the available empty weights against span, and compare them with sailplane empty weights, it seems reasonable to assume that the

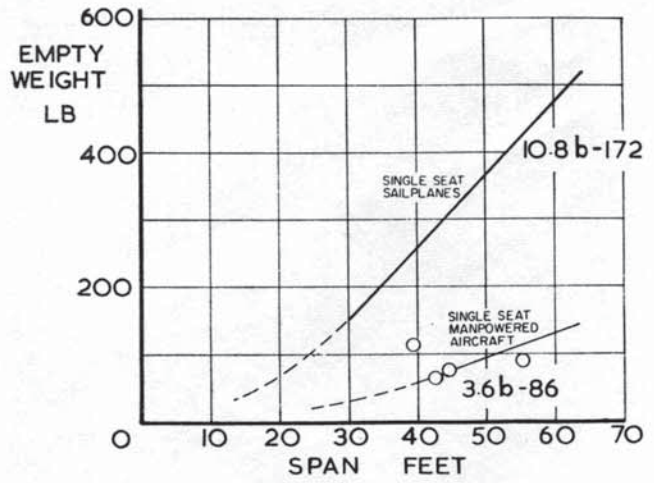

FIGURE 3. Empty weights plotted against span for single-seat sailplanes and single-seat man powered aircraft.

curve will be linear between the useful spans of from 40 ft. to 60 ft. From this we find that for such a single-seater:

$$W_e = 3{\cdot}6b - 86 \text{ in pounds and feet.}$$

However, this information, shown in Fig. 3, does not take us very far, because we want to have more information about these aircraft than just the empty weights and somehow we have to have some line on the variation of wing weight with span. There are not enough data available and we have to fall back on actual sailplane weights which, although of a slightly different order, are as near as we can get to our problem. Fortunately the publication of *The World's Sailplanes* by OSTIV in 1958 made it possible to analyse sailplane weights for the first time, and this has been done by Piero Morelli in an OSTIV paper[(4)]. The following notes are based on Morelli's analysis, although the conclusions which I have made have not been agreed by him.

In an attempt to obtain wing weights, we find that for single-seaters, based on 24 different types:

$$W_w/W_e = 0{\cdot}215 + 0{\cdot}0077b.$$

If we assume that this ratio based on sailplanes is applicable to man powered aircraft, we can then say that:

$$W_w = 0{\cdot}0277b^2 + 0{\cdot}115b - 18{\cdot}5 \text{ in pounds and feet.}$$

This is, as indicated above, for single-seater aircraft. However, there is some indication that a successful man powered aircraft may have two seats. To what extent then is the above expression acceptable for two-seaters? I think it can be accepted that a wing of the same dimensions for a two-seater would weigh more because the payload carried would be approximately twice as much. The wing, however, would not weigh twice as much. The problem is how much more? Theoretical concepts are complex and only as reliable as the basic assumptions. I want to be as simple as possible in my approach, and therefore would like to fall back again on what actual facts are available. Morelli's work fortunately gives reliable expressions for empty weight for both single- and two-seater sailplanes.

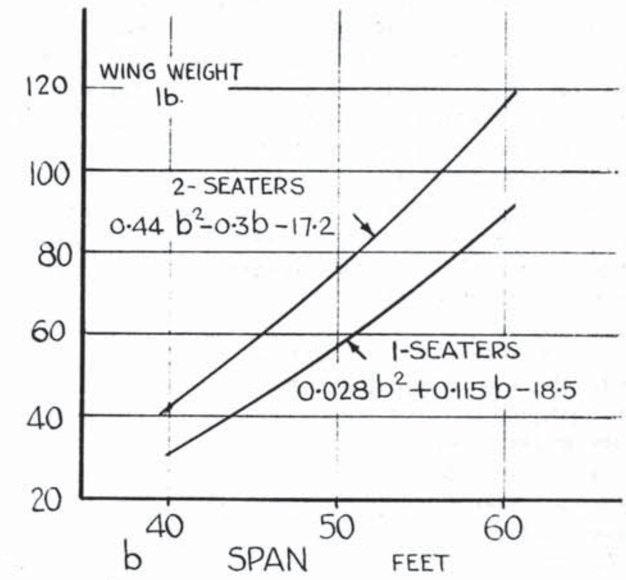

FIGURE 4. Wing weights for man powered aircraft.

It should, I suggest, be acceptably approximate if we examine how the ratio between these sailplane weights varies. An examination of the available data based on 24 single-seaters and ten two-seaters indicates that the empty weight of a two-seater is just about 1·5 times that of a single-seater. We may then take our original expression for a single-seat empty weight for man powered aircraft and multiply it by 1·5. The new expression would then be:

$$W_e = 5{\cdot}4b - 129 \text{ in pounds and feet.}$$

The ratio of wing weight to empty weight on Morelli's data on ten two-seaters is

$$W_w/W_e = 0{\cdot}133 + 0{\cdot}00815b$$

from which one can derive

$$W_w = 0{\cdot}044b^2 - 0{\cdot}305b - 17{\cdot}2.$$

We now have sufficient information to plot curves over the span range of from 40 to 60 ft. for man powered aircraft empty weights and wing weights for aspect ratios of the order of 15. These are shown on Fig. 4.

There being insufficient information available on the actual load factors used in the man powered aircraft built to date, it is considered to be unwise to try to vary these weights with differences in ultimate load factors. There is no doubt that the lower the load factor, the lighter the aircraft, but no information is available yet for load factors as low as 2·5 which have been suggested for man powered aircraft. It is probably safe enough to leave these expressions as correct, but in saying that, we must still admit that these weights shown in Fig. 4 are simply grasps at the unknown and are probably unreliable, but at least they are based on certain available data and are not entirely imaginary.

It should be mentioned here that to make this comparison between man powered aircraft and sailplanes valid, the man powered aircraft empty weights are based on only the following weights: wing, fuselage, tail, controls, skid undercarriage, ordinary pilot's seat, seat belt and canopy, and do not include the following: wheeled undercarriage, drive to wheels, propeller, drive to propeller. For a two-seater, Nonweiler estimates these items to weigh about 30 lb.[5] The figure for the single-seat Haessler-Villinger was 24·2 lb. and for the single-seat two-propeller Bossi Bonomi, 35·8 lb.[6]

We are now in a position to see what we can do about balancing weight against drag and to see the order of weight that can be flown by one man or two men. For the sake of this discussion, I will assume only a cruising condition as determining the size and weight of the aircraft and not deal with the more difficult take-off condition in this paper. This problem deserves a paper to itself.

It may be assumed that, under cruising conditions, it is possible to take out the entire cruising power through the legs of the crew, which is a different condition from that occurring during the sprint power conditions at take-off. We shall assume that each man can produce in cruising 0·5 h.p.[5] These powers have been measured on such equipment as Prony brakes and therefore imply that these powers include certain frictional losses in the drive. However, in the drive to a propeller there might well be additional frictional losses, let us say 3 per cent. The propeller efficiency might be as high as 85 per cent so we can say that the power we hope will be used for the actual drive to the aircraft will be for a single-seater $0{\cdot}5 \times 0{\cdot}97 \times 0{\cdot}85 = 0{\cdot}41$, or for two men, 0·82 h.p. The aircraft will be required to use no more power than this when in level flight, but since it needs to cruise only at one speed, it is a reasonable first assumption that the above thrust h.p. would be made available at any speed in an analysis such as this. This is reasonable, because the range of speeds from which one could choose is very small indeed.

This gives us the basic facts or near-facts needed for design studies. I shall not, however, carry out a great deal of such work for the purpose of this paper because in spite of basic assumptions that may be agreed, there are many secondary and personal assumptions that have to be made. For instance, what degree of approximation is necessary for an acceptable answer?

To show the results of rough approximation, I have made one short study, using Nonweiler's drag data[5] and the weights that have been discussed. For a given span of 50 ft. and all-up-weight of 420 lb. for a two-seater I have allowed the aspect ratio to range between 5 and 20 which results in widely differing wing loadings. It will be clear that the much larger wing area for the low aspect ratio wing will weigh much more than smaller wings of the same span, so that in this respect I have favoured low aspect ratio. But I have given all aircraft the same parasite drag coefficient which favours the low wing area aircraft. This rough shot shows that the higher wing loadings require less power than the lower. This is not to be expected and may be wrong, but it does lead one to try a more precise method of comparison (Fig. 5).

For the sake of general interest, I have shown one of the machines as at 10 ft. altitude and also the power available from two men. Apparently a machine built to the assumptions I have made would fly for ten

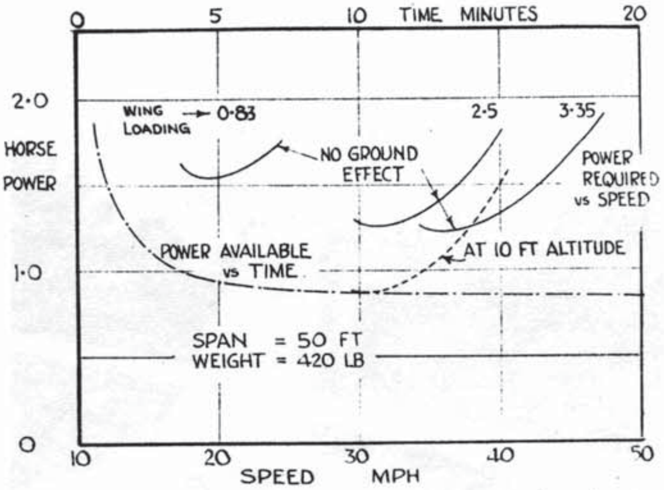

FIGURE 5. Performance curves estimated for a series of aspect ratios.

minutes and more at cruising man power with two men, using legs only.

If any general conclusion can be drawn, it is that the induced drag must be reduced as much as possible and that increase of span is the best way to do it even if the weight increases somewhat. It is, of course, the degree of "somewhat" which is unknown.

If span is to be kept as large as possible, the structural problem certainly becomes one of stiffness rather than strength and is therefore more complex.

4. Power Transmission

Pedals, chains and belts are the preferred methods for power transmission. This method is obvious to most people, except oarsmen who consider their motions more effective. Unfortunately, the rowing motion is not as effective as pedalling for driving a propeller[7]. Except for sprint conditions (up to a couple of minutes) there is no advantage in using more than your legs. Through the leg muscles, anyone can exert his full cruising power which is not limited by the number of muscles used but by the ability to use oxygen[8].

Examples of such transmissions which are worth studying are the Haessler-Villinger twisted belt scheme (Fig. 6) and the Bossi-Bonomi chain and sprocket scheme (Fig. 7). The chain shown leads through shafts and bevel gears to the propellers. The other sprocket was normally used to drive the undercarriage. Recently Perkins has used a plastic-covered rope as a belt. Nonweiler's scheme uses a series of chains and a final bevel gear (Fig. 8).

The problem of keeping the mechanism as compact as possible is so closely associated with aerodynamics that it cannot be dealt with by itself. On the other hand, I must try to deal with one thing at a time, so what I say about drives must be imagined within an aerodynamic scheme.

The final shaft is always above the heads of the crew, so there is always a gap of about 3 to 4 ft. between the crank shaft and the propeller shaft. The propeller tends to be well aft of the crew. The

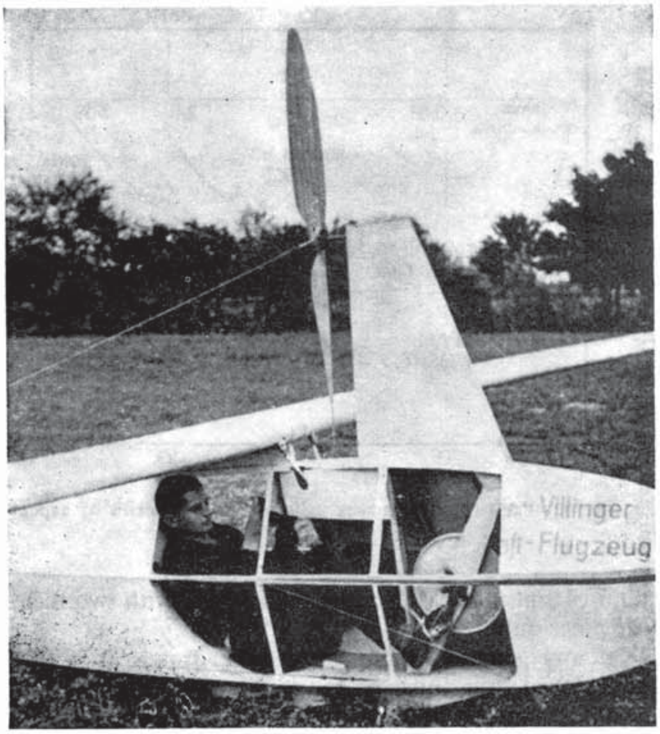

FIGURE 6. Haessler-Villinger transmission.

simplicity of the Haessler-Villinger drive leads to inefficiency. What is really wanted is a twistable bicycle chain in light alloy. Otherwise the use of bevel gears seems almost inevitable. A chain with single instead of double links and overhung rollers is said to be easily twistable, but I have not seen one yet. The modern bead-link chain used for wash-basin plugs and also for plastic Poppets is twistable and may have development possibilities.

The actual efficiencies of various drives are most important. Seehase[9] has measured the mechanical efficiency of an initial chain drive plus two pairs of bevel gears as only 74 per cent. To improve this poor figure, he did two things: he used a link type instead of a roller chain and claims that that improved the chain drive efficiency from 92 to 99 per cent. He replaced his bevel gears with a theoretically impossible mechanism, two double-cranked shafts at right angles to each other, one driven by the other by connecting rods. Dynamically this is "No Go," for the connecting rods would have to change their lengths slightly during the stroke. He overcame this by incorporating rubber buffers in the rods, thus allowing the changes in length to take place. This scheme, he claims, gave an efficiency of 97·5 per cent, an overall drive efficiency of 96·5 per cent as against the original 74 per cent. Seehase also claims that the simple twisted belt drive, as can be shown by theory and test, is no more efficient than chains and bevels at the sort of belt speeds necessary in this sort of layout.

There does not appear to be a great deal of data available on mechanical efficiencies, but fairly recent work done at Oxford[10] on a 3-speed bicycle hub gear is worth recording here. The variation of mechanical efficiency with torque is shown in Fig. 9.

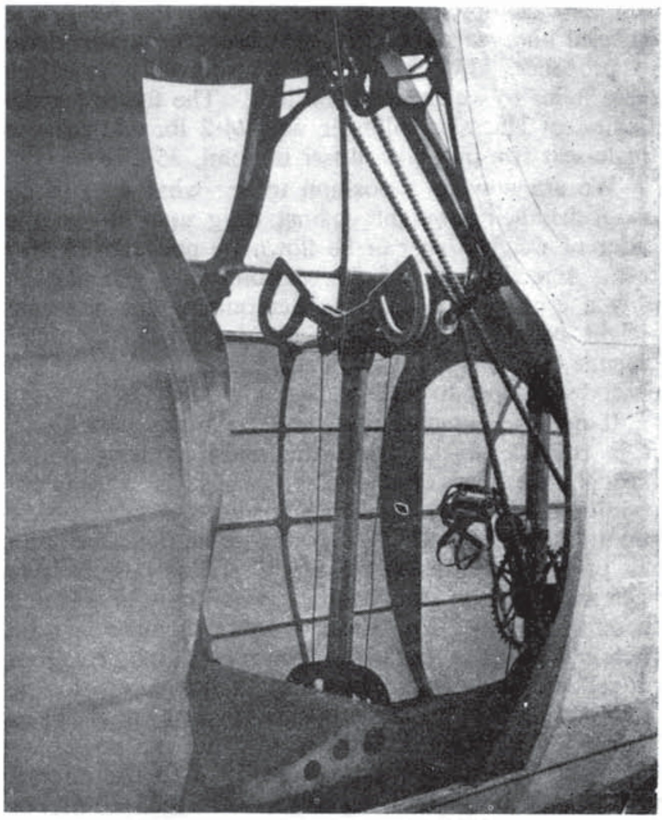

FIGURE 7. Bossi-Bonomi transmission.

The figures quoted in the foregoing paragraphs should not be accepted as gospel but are given to point out that any mechanism to be adopted should be bench-tested unless one does not care what comes out at the other end.

The propeller itself is a special problem. It should be as large as practicable, maybe up to 9 ft., and yet it has to deliver less than two h.p. It must be light and yet highly efficient, estimates showing that the efficiency should be somewhere in the 80s. If the drive is not very smooth the propeller will also have to act as a flywheel as it does for piston engines. Experiments and calculations have shown that the actual torque variations occurring with one pilot using arms and legs can cause a variation of two per cent in propeller efficiency through a revolution, although the net loss in

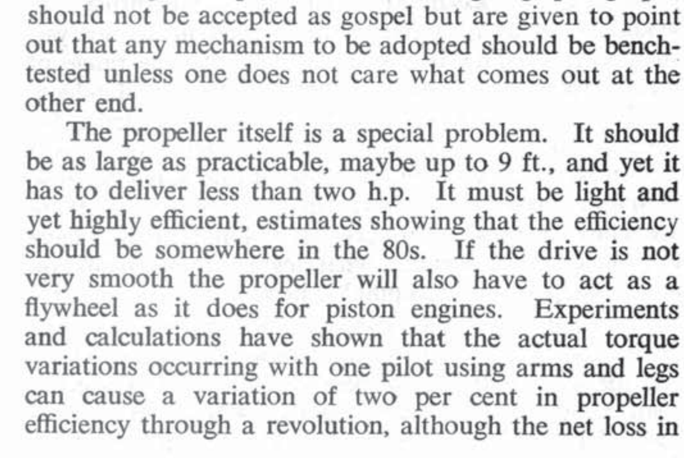

FIGURE 8. Nonweiler's transmission.

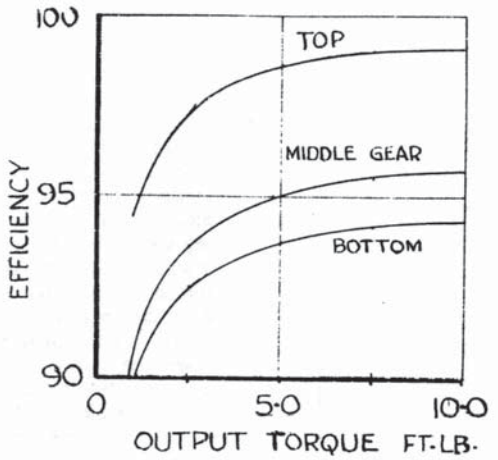

FIGURE 9. Efficiency of a 3-speed bicycle transmission.

this case was only 0·7 per cent. A larger diameter propeller with its weight concentrated near the tips would improve matters.

Conclusion

In devising a man powered aircraft, we have to struggle for every little gain that can be grasped. The structure must not cause aerodynamic losses, but the structure must be very light. The driving mechanisms must be light and unusually efficient and, in spite of a highly erratic torque, the propeller must not suffer. We have so little to play with, as in the years before 1910 when a flight was a flight and a great thing in itself. We have not even the consolation that our power plant will improve in foreseeable time. When success comes it will be only by good engineering, good planning and proper testing, rather than luck or the flash of inspiration.

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