The Man-Powered Aircraft

A Design Study

by

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SUMMARY—An appreciation is made of recent experimental and project work of relevance to the design of a very light weight aircraft capable of being taken off and flown by two men. The emphasis is on the aerodynamic problems involved. It is concluded that, although there are many difficulties still needing attention, all the information supports previous assertions that flight by muscular power alone is possible. The merits and de-merits of a particular projected design are studied, and its performance and stability assessed.

1. Introduction

Since the publication in 1956 of a provocative assessment of the possibilities of man-powered flight(1), and some tentative calculations by the author(2), a good deal of further thought and some experimental work has been devoted to proving its possibilities. Now that a Committee has been formed to promote the project, under the Chairmanship of H. B. Irving, it seems appropriate to summarise the work undertaken, to act as a guide to future investigators, and as persuasive evidence to convince those who are still sceptical of the possibilities of man-powered flight. It is hoped that, most of all, it will provoke constructive criticism which the author would be glad to receive.

Without intending to imply that it has any particular merit, we consider here only a *fixed-wing* version of the aircraft. A man-powered helicopter or even an ornithopter has possible advantages but would require quite separate and detailed study. Similarly we have not considered the employment of aerostatic lift.

2. The Power Generated by Man

We all know that one can work harder for a short period than for a long one but for some strange reason the power output of man and the way in which power decreases with increasing duration of exercise seem not to have been seriously studied by physiologists. If such studies have been made they have been lost from the stream of physiological knowledge. The only known systematic studies of the subject have been by engineers(3), (5).

In Ref. 3 details are given of measurements of the air resistance of cyclists in the posture adopted in racing, and since this source provides the bulk of the resistance to their motion on a hard track, these results can be used to provide reliable indications of the power output of record-breaking cyclists, as shown in Fig. 1. Over durations between one minute and half-an-hour the National records approximate to a level 0·49 h.p. output plus the ability to release an extra 13,000 ft. lb. of work at will; this corresponds with the concept that a man's power output depends in part on his oxygen intake (varying in proportion to time of effort), and for the rest on his "oxygen debt."

These results are compared in Fig. 2 with those of Ursinus(5), and fragmentary data from other sources, relating to other methods of power production. An opinion on the comparison has been sought from Dr. D. R. Wilkie of the Physiology Department, University College, London, who has made an extensive search of the literature and uncovered further results not shown in Fig. 2. His conclusion is that, although the cycling action permits large power outputs at all durations and is mechanically simple, nevertheless the legs cannot by themselves utilise to the full the short-term energy stores of the body. In amplification of this he writes(14):—

> "The muscles are a machine for transforming chemical into mechanical energy. The chemical energy comes ultimately from the oxidation of a carbohydrate, glycogen, to carbon dioxide and water. All the chemical processes take place at constant temperature *i.e.* the energy does not appear at an intermediate stage as heat, so muscle cannot profitably be compared to a heat engine. In spite of the complexity of the chemical processes involved, muscle achieves an efficiency of 20 to 25 per cent under favourable conditions.
>
> "Ultimately the energy production of muscle thus depends on an adequate supply of oxygen, which must be absorbed at the lungs and transported by the bloodstream. These organs have a limited capacity which in turn gives a limit to the steady-state energy production; healthy young men can absorb at the most about four litres of oxygen per minute while the maximum recorded (in an Olympic athlete) was about 5·4 l./min. These oxygen consumptions correspond to power outputs of about 0·4 and 0·54 horse power respectively."

Received September 1957.

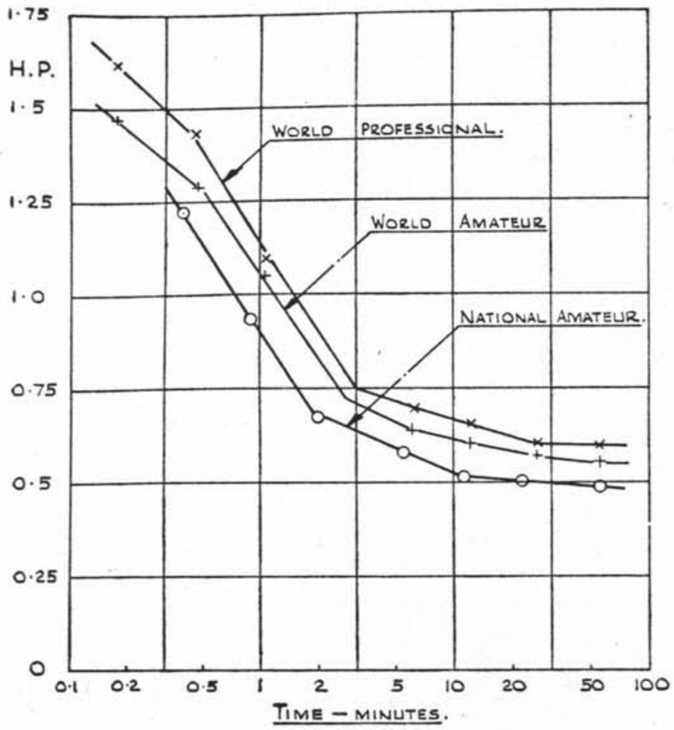


FIGURE 1. Powers to be achieved by a cyclist of average size to equal various record performances.

The latter figure agrees reasonably with the data of Fig. 1, indicating that the legs alone can generate the full-steady-state work production. Wilkie presents evidence, in support of the other figure, that training can add 20 to 30 per cent to an individual's power output. He goes on:—

> "The much greater power available for shorter periods is only obtained by going into "oxygen debt," that is, obtaining energy from the hydrolysis of chemical stores rather than from their oxidation. In order to replenish these stores at the end of exercise an extra amount of oxidation must take place—the "oxygen debt" must be paid back during recovery. For brief efforts the power output depends on the bulk of muscle that can be brought into use and on the availability of hydrolysable chemical stores. The maximum "oxygen debt" that can be accumulated is about 20 litres, equivalent to 60,000 ft.lb., and takes 2-5 minutes to be mobilised."

We have seen that less than a quarter of this "debt" is mobilised in cycling, but Wilkie finds that cycling with hand-cranking can nearly double this figure. In the only experiment on a cycling athlete, peak output was increased from 1·28 h.p. to 1·89 h.p., whereas the subject of Ursinus's tests, H. Gropp (who was not an athlete), was able to match Reg Butler's cycling performance at 15 seconds, by the help of hand-cranking. Wilkie reports:—

> "Four different types of machine for combined arm and leg movement were thoroughly investigated by Ursinus, who concluded that simple rotation of a 17·5 cm. crank by hand and foot was the most effective arrangement as well as being mechanically the simplest. Ursinus also established the optimum speed for each duration of effort, the correct phase relationship between arm and leg and the scope and limitations of postures ranging from lying on the back through normal sitting to lying face downwards."

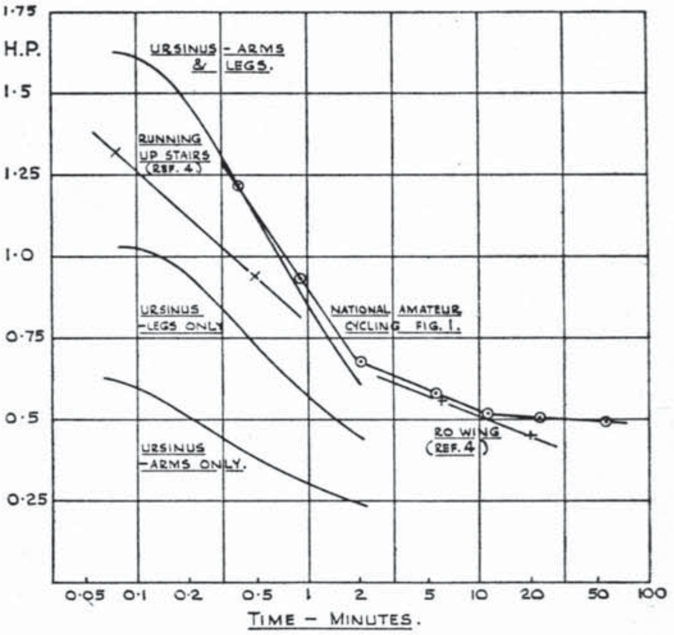


FIGURE 2. Various estimates of man's power compared.

Thus there seems to be little doubt that performance for the first two or three minutes can be substantially improved by combining arm and leg cranking.

For the purposes of the present study, it has been assumed however that the cycling action would be used, on the grounds (*i*) that it would enable one easily to find those athletes who excel in this particular exercise, (*ii*) that the performance of cyclists is well proven, (*iii*) that at least the pilot's hands must be free to control the aircraft, and (*iv*) that durations of flight would be long enough to make little difference if hand-cranking were adopted. It subsequently transpires that the last named is an inappropriate premise, and that a short duration burst of energy is what is required for flight. Hence one can expect some considerable improvement if one member of a two-man team derives additional power by hand-cranking. The actual figures used are 90 per cent of those quoted in the opening paragraph of this section—as of course it would be unreasonable to expect a record-breaking level of achievement on each attempt. Such figures are supposed relevant (as explained in Ref. 3) to a man of average size (height 70 in. and weight 150 lb.); insufficient is known as yet to deduce the relation of the power output to the weight of various individuals.

Apart from selection, training, and so on, only two ways have been suggested for increasing power output: warming the whole body by diathermy, or administering oxygen. The former would be effective but might be dangerous, the latter would certainly be of great

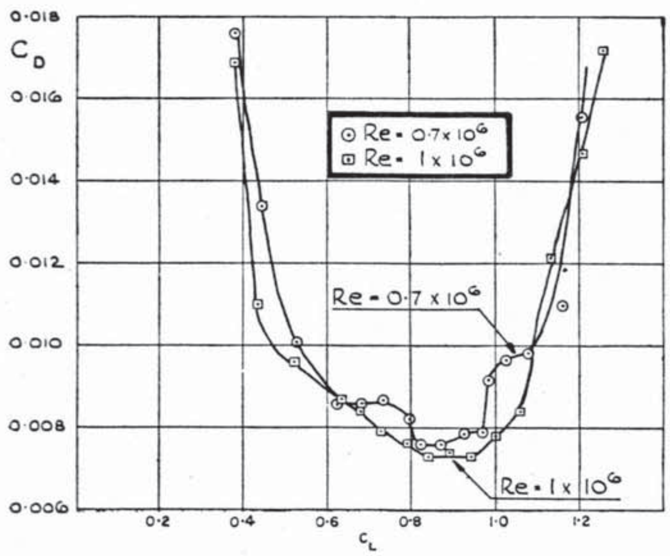


FIGURE 3. Profile drag of the N.A.C.A. 65A(10)12 section.

benefit if flights of five or more minutes' duration are envisaged, for oxygen administration is known to improve the steady-state power production. For durations of two minutes or less it may (Hill, Long and Lupton) or may not (Krogh) be effective. Curiously, 66 per cent oxygen is more effective than 100 per cent oxygen, but the reason is not understood.

3. Choice of Wing Section and Plan Form

The section (lift/drag) ratio is a convenient guide to its merit in the application envisaged, but the aircraft wing is expected to operate at a mean Reynolds number of 0·9 million and systematic information on sectional characteristics in this range is sparse. The highest (lift/drag) ratios recorded at this Reynolds number were thought to be those measured(6) on a N.A.C.A. 65A(10)12 section—a low drag wing with 6 per cent camber—and the lift-incidence, lift-drag polars and pitching moment characteristics of this wing are shown in Figs. 3 to 5. This section data has been used in the project analysis appearing later, but the camber is possibly excessive, because almost as good a (lift/drag) ratio has been achieved(7) on a section with a design lift of 0·6 (as shown in Fig. 6), and the lower operating lift coefficient, the lower C_{D_0} at low C_L (*i.e.* at higher speeds), the smaller value C_{M_0}, and the more easily constructed shape of the under surface are all minor and indirect advantages of its use.

In the other direction, more recent information has suggested that the low-drag profile designated FX05-H-126 by Wortmann(8)—which has a (t/c) of about 13 per cent, a camber of 5 per cent, a nearly flat undersurface, and a reflex curvature on the upper surface, extends the envelope of the drag minima, so well indicated by Fig. 6, up to a C_L of over 1·1. From the performance point of view alone this section is even more attractive, though working so near the stall might be a disadvantage.

The optimum operating lift coefficient of the N.A.C.A. 65A(10)12 section is found later to be around

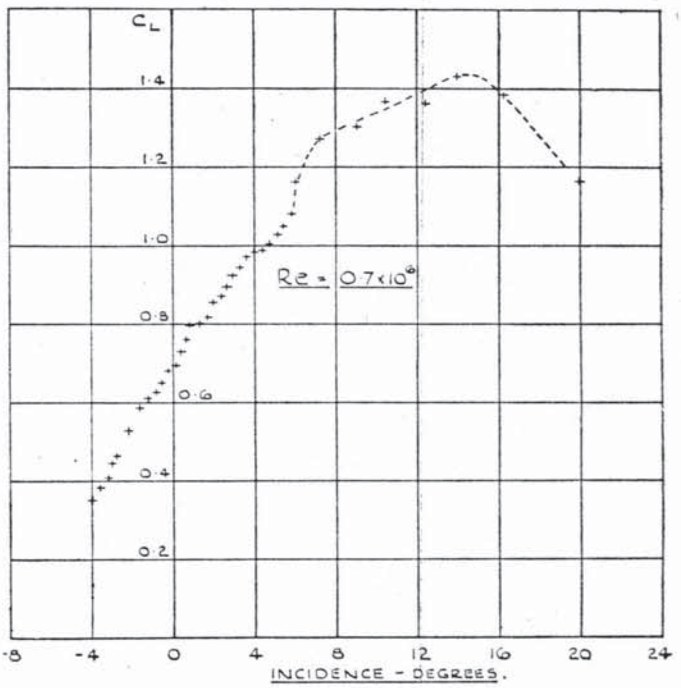


FIGURE 4. Lift-incidence behaviour of N.A.C.A. 65A(10)12 section.

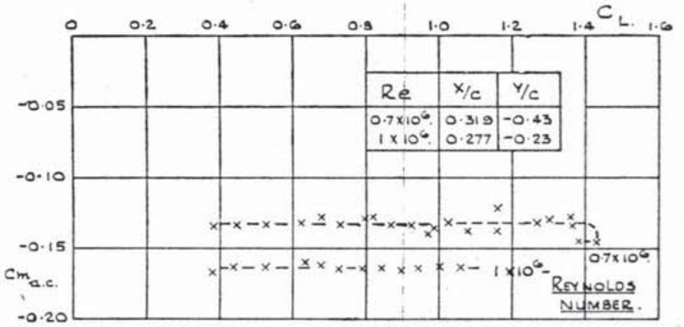


FIGURE 5. Pitching moment coefficient resolved about the aerodynamic centre position.

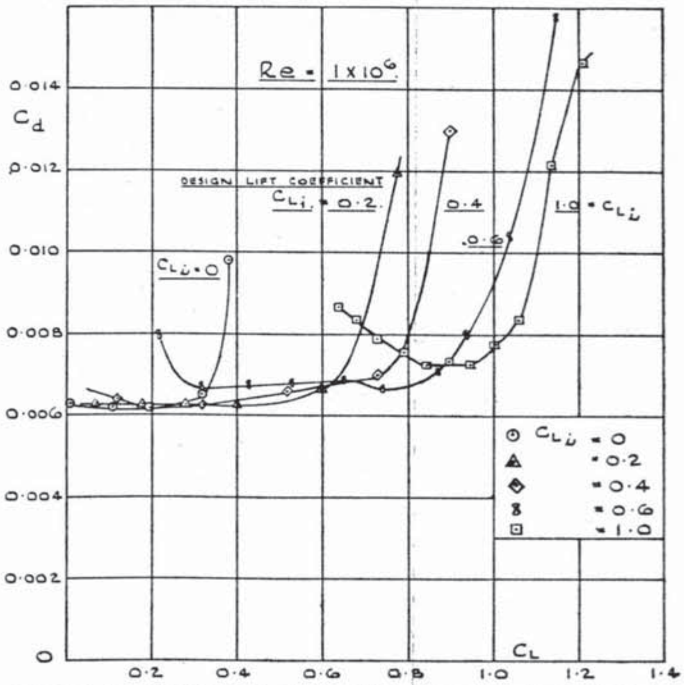


FIGURE 6. Profile drag of N.A.C.A. 64 series wings of various camber compared with that of 65A(10)12. (N.B. 64-series wings might be expected to produce about 0·0005 more in C_{D_0} than the 65-series at the Reynolds number quoted.)

0·94 (at a speed of 50 ft./sec.) and as it stalls at about $C_L = 1{\cdot}45$ at 10° greater incidence, gusts of more than about 6 knots could be troublesome. This, more than anything else, shows that man-powered flight is a calm weather sport, as the reserves of power and height to recover air speed are virtually non-existent.

It is not known how sensitive such low-drag sections may be to the maintenance of the correct profile at this scale, and it would be valuable to make comparative tests on practical construction wing-sections to discover this. Certainly it would seem that the Reynolds number is so low that surface roughness is of no concern. The wing profile drag transpires to be about 30 per cent of the total resistance, so that development of slot suction wings can be seen to be of particular advantage.

The main effect of plan form is on the induced drag which is an even larger proportion of the total drag—nearly one half. Thus savings here are of great importance. The construction of a wing with anything other than uniform taper was considered too elaborate for an initial survey. For an aspect ratio of 20, the minimum induced drag is achieved with a 4 : 1 taper ratio providing an induced drag factor of 1·02 (Fig. 7). In the subsequent project analysis a taper of 5 : 1 was selected under the erroneous impression that the saving of wing weight might compensate for the increased drag. The span loading of this wing is shown in Fig. 8, and it suggests that either washout or greater taper near the tips would be of advantage; of even greater importance—if some more elaborate plan form were considered—would be a local increase in chord near the root to counteract the adverse effect (on induced drag) of the negative lift on the tail.

Ground effect will later be shown to reduce greatly the induced drag. It is not exaggerating too much to say that the success of the project hangs on the reality of the correction adopted for this effect. That assumed in the subsequent project analysis is taken from Ref. 9 and is shown in Fig. 9. This figure refers to elliptically loaded wings to which that chosen in the present work only very roughly approximates.

A case can be made for the provision of sweepback on aerodynamic grounds, but it has been considered unwise owing to constructional difficulties and lack of certain knowledge of the likely effects.

4. Method of Wing Construction and Structure Weight

Structures of the dimensions of the envisaged aeroplane are of course common in glider design, where however the design loads are much heavier than any we need anticipate. Indeed it is quickly established that present day gliders could not be sustained by man-power alone, so that we must hope to gain something by sacrificing some measure of airworthiness. Indeed there would seem no reason to suppose that the pilot would want to apply more than tiny increments of acceleration, but he might inadvertently do so if he lost control. In view of this a limit load of $1{\cdot}5g$ would seem adequate. Conventionally a factor of 1·5 is applied to this, but in view of the possibilities of inaccurate stressing a total factor of 3 has been assumed here. (Later on, when more careful stressing is used, it might be safe to come down to a factor of 2·5.)

It seems advisable to design the wing with a rigid skin, at least until we know more about the aerodynamic effects of the distortion of fabric or paper covered panels. After several attempts to evolve a satisfactory method of construction combining fibre glass and foamed plastic, P. Jeffery (Design Dept., College of Aeronautics) decided that the more conventional $\frac{1}{32}$ in. thick birch ply covering is the lightest practical material. A rib pitch of 9 in. was considered necessary to support this, with ribs of conventional spruce construction. A single box spar at 40 per cent chord with variable boom thickness over the span, designed to carry an all-up weight of 490 lb. with an ultimate factor of 3, forms the largest item in the weight breakdown which is given for a specimen wing plan form in Table I, and the details of its construction are sketched in Fig. 10. The effects of

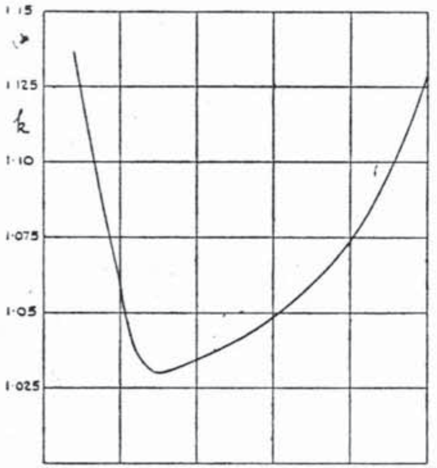


FIGURE 7. Variation of induced drag factor with taper ratio for wing of aspect ratio 20.

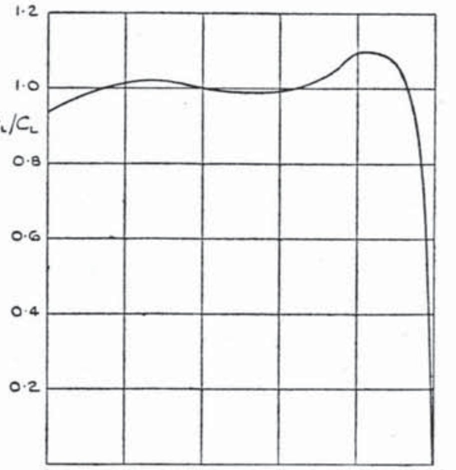


FIGURE 8. Variation of sectional lift coefficient on wing of aspect ratio 20 and taper ratio 5:1.

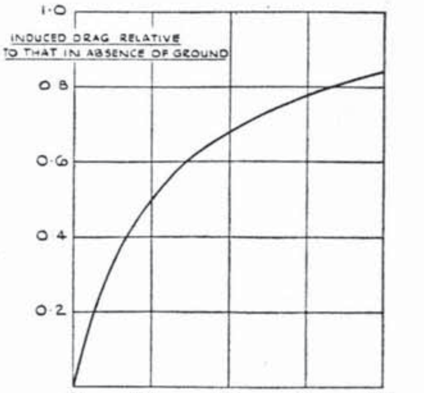


FIGURE 9. Ground effect on induced drag. (For wings of elliptic loading.)

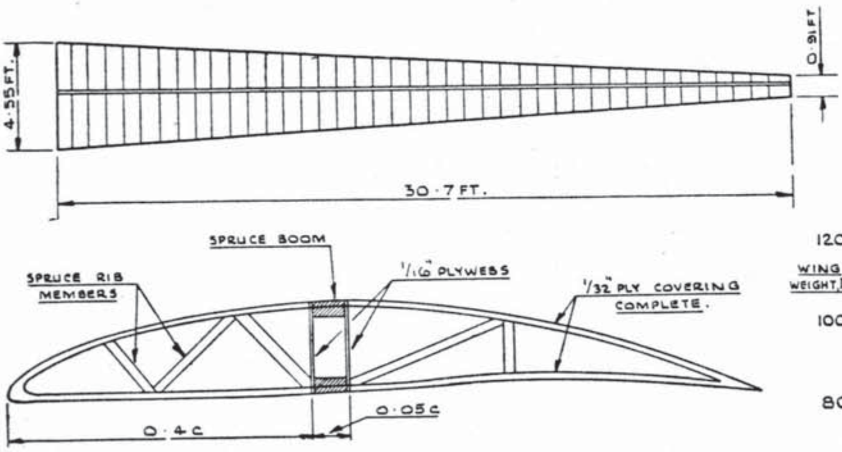
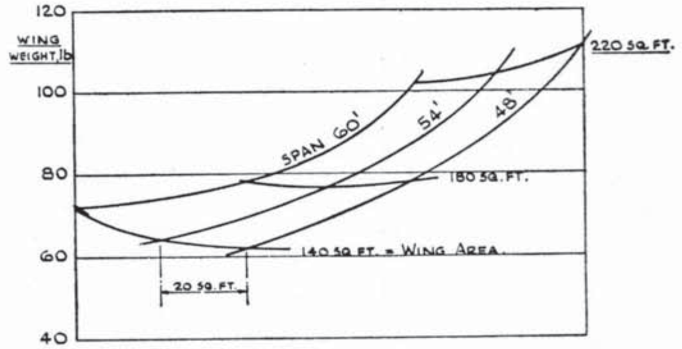


Figure 10 (*left*). Illustrating the assumed method of wing construction.

Figure 11 (*below*). Carpet plot of wing as affected by area and wing span.



variation in chord and span on wing weight is shown in Fig. 11.

No allowance has been made for the provision of control surfaces; indeed their form and size has not yet been established to enable this. Likewise, no careful consideration has been made of the other items of structure weight but tentative estimates of these are given in Table II, referring to the projected layout envisaged in making the performance calculations later (*see* Fig. 14). It has been considered that all the surfaces should be rigid to preserve a low-drag form; owing to its relatively small size, the tail-plane would probably have to be shaped from solid birch; the propeller blades are also supposed solid. Details of the other items will emerge from the following paragraphs.

5. General Layout

The fuselage layout presents a considerable problem; we shall suppose that it is necessary to accommodate two men in tandem in the cycling position, two men being the least required—one to ensure power continuity while the other is temporarily abstracted by controlling the aircraft—and three or more men seeming somehow to invite derision—although it may well be true that an "eight" is the optimum in flying as in rowing! As it is considered essential to the spirit of the enterprise for the aircraft to be propelled from rest to the take-off speed, wheels with low capacity high-pressure tyres would also need to be contained within it. One is therefore presented with the problem of fairing in what amounts in its geometry to two men on a tandem bicycle: the frontal projection being tall and thin immediately suggests that the form of this part of the fuselage should be like a fin, with a thickness/chord ratio adjusted to provide minimum drag for the given frontal area. Experience of wing shapes of higher aspect ratio and at higher Reynolds numbers suggests an optimum around $(t/c)=0{\cdot}2$, although as the fuselage drag is only 6 per cent of the total, such considerations are not important, and the precise figure would best be dictated by lateral stability characteristics (Section 9) which such a large fin shape severely modifies.

A high wing would seem to be more practical—to avoid impact of the wing tips on touch down or take-off, and the inevitable strengthening of the wing this contingency would require. In any case the relative loss in the alleviation of induced drag by ground effect is probably more than compensated in the high wing position by the reduction in wing-body interference, as contact between the upper wing surface (where there are strong adverse gradients) and the fuselage would

TABLE I

WING WEIGHT

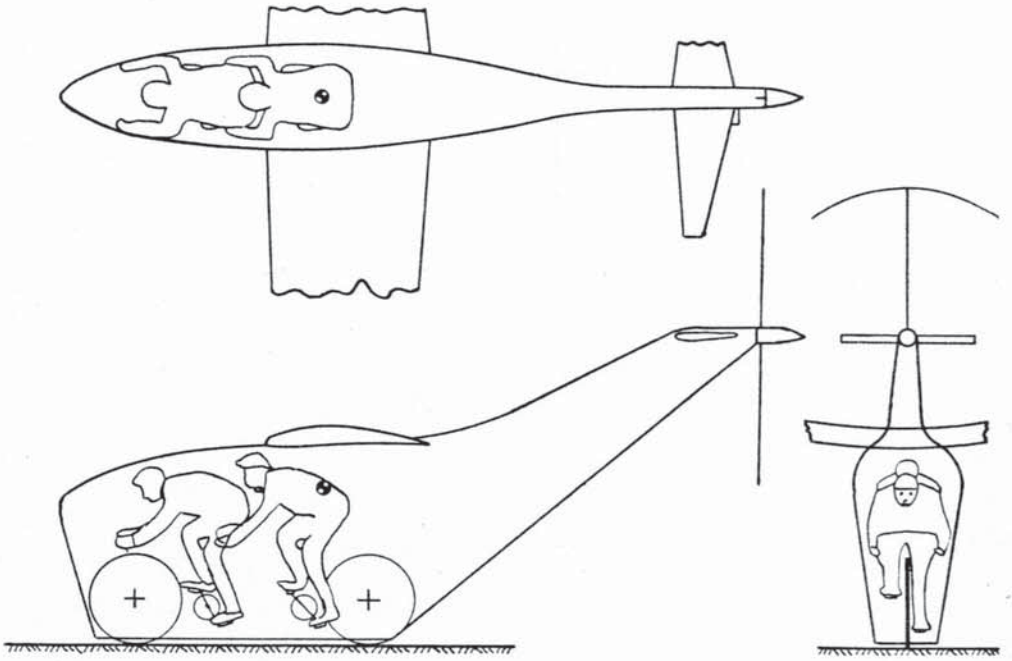
			Percentage	
Spar boom top	14 lb.		18	
Spar boom bottom	9 lb.		12	
Spar web	6 lb.		8	
Total spar		29 lb.		38
Covering		25 lb.		32·5
Ribs		18 lb.		23
Miscellaneous		5 lb.		6·5
TOTAL WING WEIGHT		77 lb.		

TABLE II

WEIGHT BREAKDOWN

		Percentage of empty	total
Wing (*see* Table I)	77 lb.	45	16
Fuselage-fin	40 lb.	23	9
Propeller	10 lb.	6	2
Tailplane	10 lb.	6	2
Transmission	10 lb.	6	2
Wheels	10 lb.	6	2
Controls	5 lb.	3	1
Contingency	8 lb.	5	2
EMPTY WEIGHT	170 lb.		36
Crew	300 lb.		64
TOTAL WEIGHT	470 lb.		

FIGURE 12. Fuselage and fin layout.



lead to trouble. In a low drag layout the major contribution to profile drag could arise from interference effects, and so it would seem essential to sweep the maximum thickness position of the fin-shaped fuselage backwards at its tip, so that the junction at the wing is between two surfaces supporting favourable pressure gradients. It would be helpful as well to give the fuselage a N.A.C.A. low drag section (say the 66-021) to stimulate these favourable gradients.

Such a side shape for the fuselage leads naturally to its extension into a true fin aft of the c.g., as shown in Fig. 12. This layout is made all the more inevitable by the fact that it can conveniently accommodate the pusher-propeller necessary to avoid spoiling the flow over the wing, which hazard would result from a conventional tractor position. No close study of propeller design has been made, but use of typical pre-war charts of low scale data suggests that a large diameter disc is essential for a reasonable efficiency (Fig. 13 from Ref. 10). To avoid fouling the blades with the ground, such a pusher must be placed high above the c.g., *i.e.* at the top of the fin. The elaborate transmission system necessary if the fuselage were connected to a true fin by a boom, let alone the difficulties of fairing the fuselage to the boom, inhibit consideration of a layout more conventional than that shown by Fig. 12. We shall see later that the high propeller position is troublesome to the longitudinal stability and control of the aircraft, but it appears to be an essential feature, and indeed appeared on all the man-powered aircraft designs of the pre-war era.

The length of the fin extension above the fuselage should be kept as short as possible, the critical interest lying in providing just an adequate tail arm rather than a large one (*see* Sections 9 and 10). The general arrangement shown in Fig. 14 has been assumed for initial assessment and its stability characteristics are discussed in later Sections, where certain important changes are suggested.

A summary of the leading geometrical features of this layout appears in Table III. It involves an optimised wing span and chord based on an examination of the effect of these variables on the minimum power needed to maintain level flight at an altitude of 35 ft. The

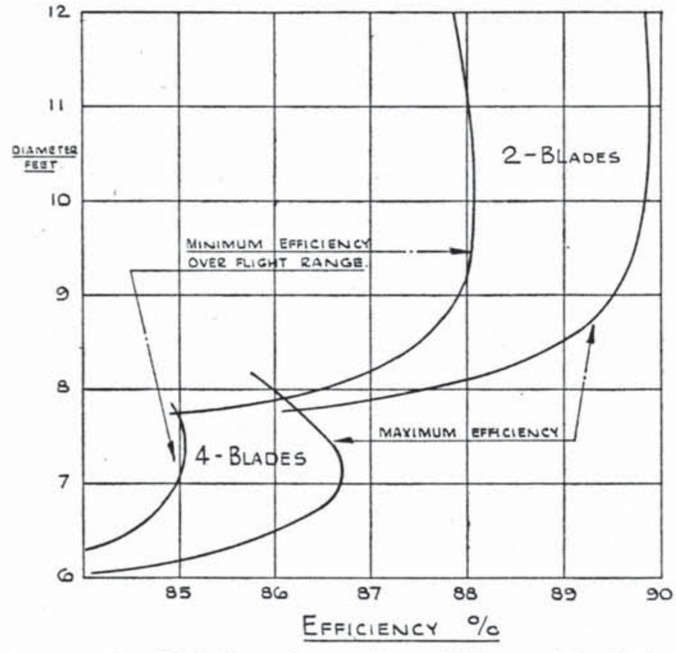


FIGURE 13. Variation of propeller efficiency with blade diameter.

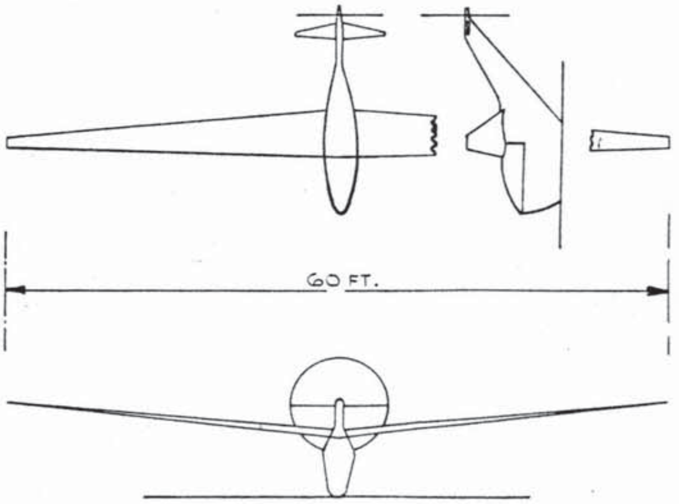


FIGURE 14. General arrangement of projected aircraft. For main dimensions—*see* Table III.

TABLE III

GENERAL DETAILS OF PROJECTED AIRCRAFT

Wing			
Section	N.A.C.A. 65A(10)12	Taper ratio	5:1
Area	168 ft.^{2}	Aspect ratio	21·4
Span	60 ft.	Dihedral	5°
Mean chord	2·8 ft.	A.C. position	0·28*c*
Line of zero sweep at 0·28*c*, 0·29 ft. ahead of *c.g.*			
Chord line parallel to ground line.			
Tailplane			
Section	N.A.C.A. 65-618	Mean chord	1 ft.
Area	8·6 ft.^{2}	Taper ratio	5/1
Span	8·6 ft.	Aspect ratio	8·6
Tail arm from wing a.c. 10 ft.			
Tail height above c.g.	4·2 ft.		
Tail volume	0·183		
Tail load, power on 17 lb. (negative lift) $C_{L_t} = -0{\cdot}66$			
power off 10 lb. (negative lift) $C_{L_t} = -0{\cdot}38$			
$d\epsilon/d\alpha = 0{\cdot}16$ without ground effect.			
Fuselage-fin			
Section	N.A.C.A. 66-021		
Height	5·5 ft. at wing junction 8·75 ft. maximum at tail		
Side Area	67 ft.^{2} total 13 ft.^{2} above wing t.e.		
Length	18·6 ft. to propeller disc		
Ground Line	4·3 ft. below c.g.		
Wheels			
1·25 ft. radius. Ground contact 5 ft. ahead of 1·25 ft. behind } c.g.			
Propeller			
Blades	2	Height above c.g.	4·2 ft.
P/D	1·6	Diameter	8·3 ft.

optimum span is found to be 60 ft. and the optimum wing loading a little less than 3 lb./ft.^{2}. However, the optimum span is sensitive to taper ratio, and it has already been suggested that this should be changed from 5 : 1 (assumed) to 4 : 1. Again, subsequent performance evaluation suggests that if the men are not to use assistance in the take-off, flight would be much closer to the ground where the reduction in induced drag would make it worthwhile to increase the wing loading. It is, of course, a nice point whether one would want to design the first aircraft to provide the easiest means of achieving man-powered flight, pure and simple, or whether one would prefer to look ahead to the use of some form of assistance which would lead to man-powered flight at higher altitudes (*see* Section 8). In any event a reassessment of the optimum wing loading and span now seems necessary.

6. Transmission and Propeller

Little complication would be involved by providing a drive to the propeller through the wheels so that during take-off the advance ratio of the propeller could be held at a constant value. As a wheel-drive is a much more efficient means of propulsion one would want to choose the gearing and this advance ratio so that only towards the end of the take-off run would the propeller take over full propulsion. If a free wheel is provided, the propeller could then achieve faster r.p.m. at this ground speed—and so generate higher powers for any further acceleration. (A free wheel would also be needed if the wheels are used on landing, although an extensible skid might be more appropriate.) The alternative would be a variable pitch propeller which would be far less efficient.

Though no serious difficulty is anticipated, little thought has yet been devoted to the transmission system to the propeller, which is over a length of about 12 ft., and must provide for the flight range in operating r.p.m. shown for a typical design in Fig. 15. A hydraulic system would be appropriate in view of the ultimate necessity of turning the torque axis through 90°, but its efficiency might not exceed about 92 per cent, and its overall weight would not be substantially less than that of a light-alloy chain and bevel or worm drive providing much higher efficiency.

Likewise, work needs to be done on evolving a satisfactory propeller. The operating conditions suggested by the later work are two power levels—cruise and maximum power—differing by a factor of 2·5:1—while the flying speed range is very small. The advance ratio and pitch would want to be chosen so as to provide as high an efficiency as possible in both conditions; at maximum power, the advance ratio used would therefore be slightly less than that for maximum efficiency. The data used in the project analysis subsequently quoted are based on the old charts of Ref. 13, as they are more likely to be relevant to the blade Reynolds number of about 4 × 10^5 involved, than more recent data. On the other hand, the propeller's range of operating conditions is to be relatively small and careful blade design might well provide even higher efficiencies than those assumed.

In considering the transmission and propeller design it is worth noting that an increase of one per cent

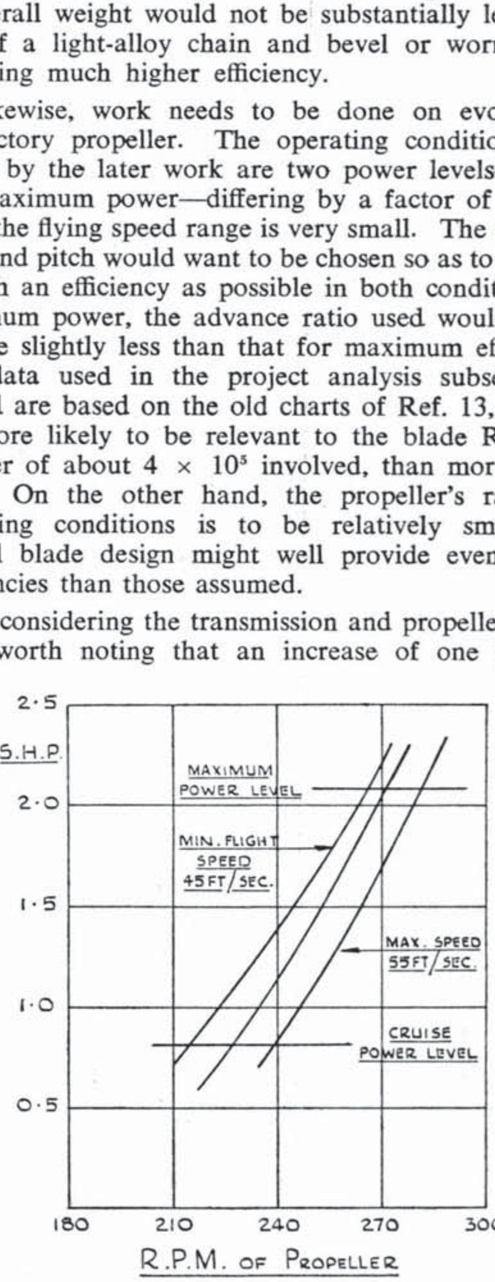


FIGURE 15. Operating conditions of propeller. (Tentative.)

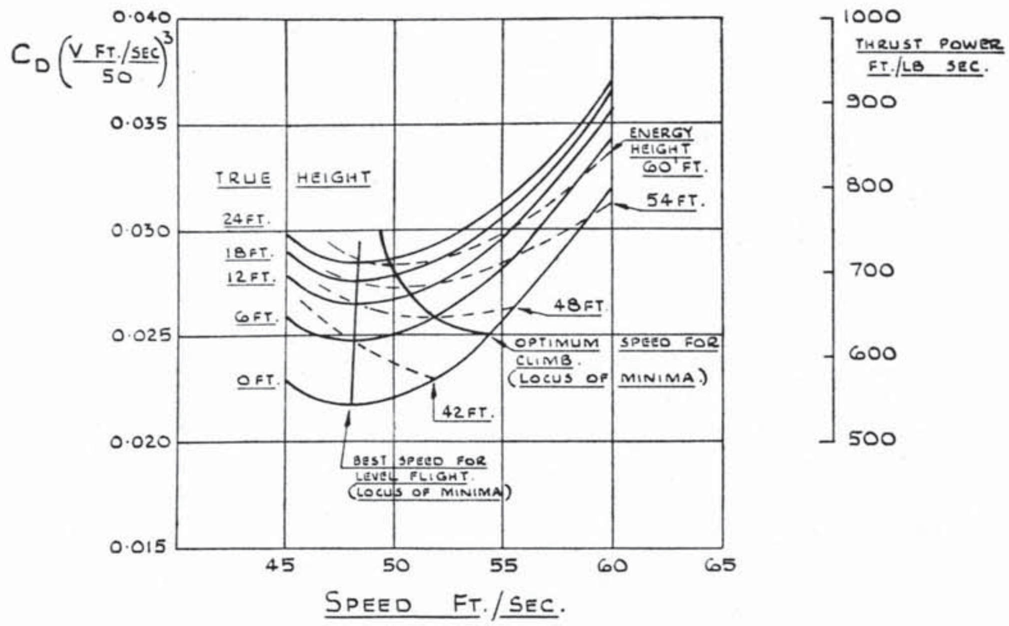


FIGURE 16. Power coefficient required for projected aircraft.

efficiency is worthwhile, provided it can be achieved at the expense of no more than $3\frac{1}{4}$ lb. of weight.

7. Take-off and Performance

One is forced to admit for a number of reasons that acceleration during the ground run is a far more efficient means of power absorption than flight, so that one would want to delay take-off at least until the optimum climbing speed is reached (which is about 55 ft./sec. at sea level, *i.e.* at $C_L=0{\cdot}78$). On the other hand it would be as well to choose the ground attitude of the aircraft so that (with both wheels grounded) some lift is developed on the wings and the proper balance is struck between the induced drag produced and the alleviation of rolling friction: careful determination of this attitude has not been made but it would appear to correspond to that required for take-off. As the speed builds up, the lift on the wings takes the weight off the wheels, and progressively more of the torque is absorbed by the propeller.

Given the power capabilities of the two men as an ability to maintain indefinitely a minimum ("cruise") level of power output, plus a potential to do a certain amount of extra work, it can be shown that the greatest *height* of flight will result from:—

(*i*) accelerating from rest on the ground at the cruise power level until the speed steadies (found in the worked examples to be at about 45 ft./sec. after a run of 900 yd. lasting 80 sec.) by which time the propeller has taken over full absorption of the power input—the wheels having freed;

(*ii*) increasing power to as high a value as possible (taken to be $1\frac{1}{4}$ h.p. in the worked example) and accelerating to the take-off speed (55 ft./sec. reached after 10 secs. in a travel of another 150 yd.); and

(*iii*) continuing at maximum power to climb on a path giving maximum rate of increase of energy height (Fig. 16), which involves a progressive loss in speed.

Upon exhaustion, the crew would return to the cruise level of power output and continue to ascend until nearing the stall.

Physiologically, this method of power output would be quite appropriate, the initial period of cruise power providing a "warm up" and the return to it after more violent exertion being a not uncommon habit of athletes. Whatever the total flight duration, it would be appropriate to employ sprint cyclists used to short, sharp bursts of power generation.

For the greatest flight *duration* the best flight programme is merely to take off and fly at the minimum power speed (48 ft./sec.) as close as possible to the ground; the power needed is then not much more than that of the cruise condition but would depend on the actual altitude.

To determine the heights and durations possible, it has been assumed that the air crew are of average size and develop 90 per cent of the National record level (0·49 h.p. plus 13,000 ft. lb.), that 4 per cent of this is lost in the transmission to the propeller, and that the efficiency of the latter is 87 per cent. In the ground run the thrust supplied by the wheels is reduced by a fraction 0·006 of the ground reaction, to account for rolling and mechanical friction(3).

The assumed profile drag breakdown of the aircraft shown in Fig. 14 is given in Table IV and speed and height variations are shown in Fig. 16. It will be appreciated that items "interference" and "leaks and gaps" can only be guessed at this stage. Control surfaces are likely to provide the bulk of the drag under the latter heading.

With the foregoing assumptions it can be deduced that in the flight path for maximum gain of height, some 15 seconds of maximum power are available after take-off during which time the aircraft reaches a height of 22 ft. and the speed drops from 55 to 50 ft./sec. Upon

TABLE IV

DRAG BREAKDOWN AT 50 FT./SEC. AND 12 FT. HEIGHT

	Drag area ft.²	*C_D on wing area*	*Percentage of profile*	*Percentage of total*
Wing profile	1·31	0·0078	55	29
Fuselage below wing	0·27	0·0016	11	6
rest (fin)	0·12	0·0007	5	3
Tailplane profile	0·11	0·0007	5	2
Spinner	0·12	0·0007	5	3
Wheels	0·04	0·0002	2	1
Gaps, interference, etc.	0·40	0·0024	17	9
Total profile	2·37	0·0141		53
Induced drag of wing	1·99	0·0118		44
Induced drag of tail-plane	0·13	0·0008		3
TOTAL	4·49	0·0267		

reduction of power, still further increase of height may be had (say about 5 ft.) at expense of speed. Or, the aircraft can glide downwards reaching ground level after 25 seconds, when its speed is 55 ft./sec.; further gradual deceleration down to 45 ft./sec. would occupy another 40 sec. giving a flight time of 80 sec. The greatest duration possible—by flying all the time just above the ground—is no more than about 90 sec., reducing more or less linearly with height to 10 sec. above 22 ft.

8. Power Storage

The flight duration and ceiling of the aircraft are so limited that some assistance by storage of power before take-off would be valuable although its use in the first attempts is regarded as detracting from the impact of the initial achievement. However, subsequently its use would be unobjectionable, and indeed a great advantage. Power could be stored at a relatively low and non-fatiguing level of input before take-off, and released optionally (as an overhead drive) through suitable gearing at whatever torque power is required. Of the suggestions examined, the use of compressed air appears to introduce unacceptable losses in the efficiency of the conversion process, and the most promising idea (the subject of a patent application by W. G. Holloway, College of Aeronautics) involves the use of rubber stretched in a helix on a cylindrical drum (Fig. 17). One end is rotated by the input to stretch the rubber and the other, when released, provides the output torque. Frictional losses are minimised by constructing the drum surface as a series of rollers. Examination of the mechanics shows that it is best to use heavy gauge vulcanised rubber thread of high elasticity(12) (with a maximum elongation of something like 900 per cent). Power sufficient for three minutes of flight can be supplied by two starts of unextended length 15 ft. each, and 0·4 in. square cross-section, giving 45 windings round a one foot diameter drum (18 in. long); the maximum radial compression on full extension would be 420 lb./in.² and the maximum gear ratio (on the output side) would be 18 : 1. Greater durations would require shorter, thicker lengths of rubber, necessitating higher gear ratios on both input and output sides, and generating higher compressions on the drum. A proper weight assessment of the device has not been made but it would seem likely to be about 10 lb./min. of flight duration. At least 150 ft. lb. of the stored energy is needed to compensate for the extra power required to carry each one lb. of the storage device's own weight.

9. Lateral Stability

The estimation of the stick fixed lateral derivatives has been aided by tunnel tests to determine the contribution of the isolated fuselage fin to the values of y_v, l_v and n_v (Fig. 19). The only remarkable feature of

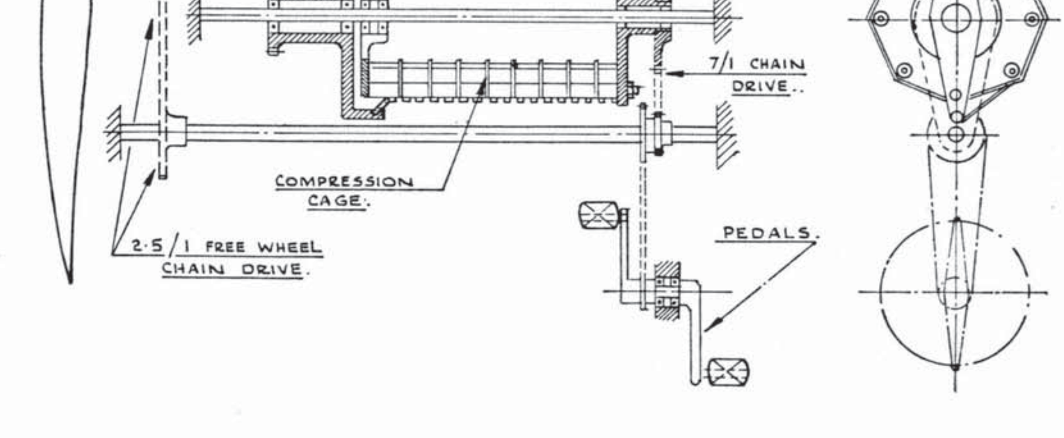


FIGURE 17. Helical rubber spring power storage unit. (*Patent applied for.*)

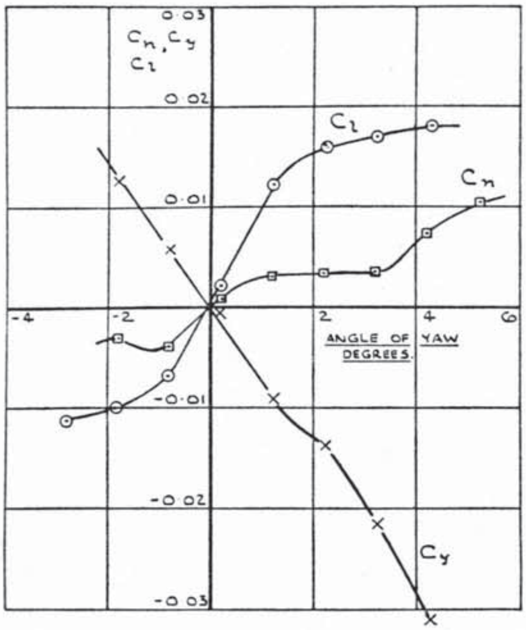


FIGURE 18. Tunnel results of lateral forces and moments on an inexact model of the fuselage-fin combination shown in Fig. 12. (Coefficient based on wing area and mean chord. Moments about c.g.)

these tests was the non-linearity of the rolling moment due to sideslip which increases suddenly in the destabilising sense up to 1° of sideslip, and then steadies off. (Thus the l_v contribution is something like 0·04 at zero sideslip — corresponding to $2\frac{1}{2}°$ of wing anhedral—and then tends rapidly to zero). This behaviour is not at present understood, but for the purposes of these estimates the destabilising value of l_v from the body is taken to be cancelled by the favourable effect of wing-fuselage interference. This leaves the contribution to the wing dihedral alone, which it will subsequently be shown ought to be large, and so we take it as 5°.

No oscillation tests on the fuselage have yet been made: its contributions are guessed as $y_r = 0·04$, $n_r = -0·015$. Table V gives a list of all derivatives relevant to gliding flight at 50 ft./sec.

The modes of disturbed motion of the aircraft as drawn, and with the assumed c.g. position, have a component which is unstable, and which can be identified as a very slow spiral divergence (doubling in 20 sec.). This is due to the rear equality of the terms $l_v n_r$ and $n_v l_r$, the latter being required to be less than the former for stability. An instability of this mode would not be unusual on aircraft operating at high C_L (due to large l_r), but in view of the special nature of the projected aircraft it would seem best to try to ensure stability. As much more increase in l_v (*i.e.* wing dihedral) is unreasonable, the easiest remedy is to decrease n_v which may be done by extending the fuselage forward. It is estimated that an extension of 2 ft. would move the c.p. of the lateral forces by half this distance and decrease n_v by 0·007 to half its present value.

If this is done the spiral motion is virtually in neutral stability. This should be adequate and the few response calculations attempted do not suggest any troubles resulting even from the choice of zero n_v. The other modes of motion are virtually unaffected by this measure, and consist of the very rapidly damped subsidence in roll (half amplitude time 0·04 seconds) and a "weathercock" motion damped to half amplitude in 0·7 sec. but with so long a period (8 sec.) that its oscillatory nature would not be noticed.

It is only when the recommended decrease in n_v is accompanied by a decrease in dihedral that the lateral motion becomes adversely affected, because of the closing-up of the stability boundaries (Fig. 19). For this reason it would seem best to preserve the present large dihedral, even if the destabilising l_v of the fuselage is a fiction. The stick-free stability has not yet been studied but the spiral damping could easily be improved in this condition (if considered necessary) by allowing the rudder to trail in sideslip(13)—so reducing n_v still further. It should be noted that the foregoing estimates (as well as those of the next paragraph) have included only a token allowance for propeller-fin effect based on a guessed value of $y_v = -0·02$. Its effect on n_v (and the spiral motion) is relatively important, but a more accurate assessment could only be made when its design is fixed.

10. Longitudinal Stability

The estimated stick-fixed logitudinal stability derivatives of the layout given in Fig. 14 are quoted in Table VI relative to flight at 6 ft. height and $C_L = 0·94$ (corresponding to a speed of 50 ft./sec.). The aircraft has been designed to provide a static margin of 0·05*c* without propeller-fin effect (and 0·08*c* with). The value of m_u is zero for gliding flight, and on the debatable assumption that constant power is maintained in any disturbed motion, equals 0·009 in the cruise condition, and 0·022 at full power (1.25 h.p.). If merely r.p.m. is kept constant, the value of m_u would be even higher. This increase in m_u unfortunately heightens an instability in the phugoid motion—increase in speed caused by a dive gives rise to a drop in thrust, and a nose-up

TABLE V

ESTIMATED LATERAL DERIVATIVES

$y_v = -0·235$ $y_r = 0·014$ $y_p = -0·003$
$n_v = 0·014$ $n_r = -0·022$ $n_p = -0·09$
$l_v = -0·087$ $l_r = 0·21$ $l_p = -0·56$
$i_A = 0·030$ $i_C = 0·038$ $i_E = 0·0052$ $\mu_2 = 1·21$

(Notation as in Ref. 14)

TABLE VI

ESTIMATED LONGITUDINAL DERIVATIVES

$x_u = -0·032$ $x_w = 0·41$ $x_q = 0·020$
$z_u = -0·94$ $z_w = -2·67$ $z_q = -0·45$
$m_u =$ *var.* $m_w = -0·059$ $m_q = -0·16$
$i_B = 0·109$ $\mu_1 = 3·66$ $m_{\dot{w}} = -0·02$

(Notation as in Ref. 14)

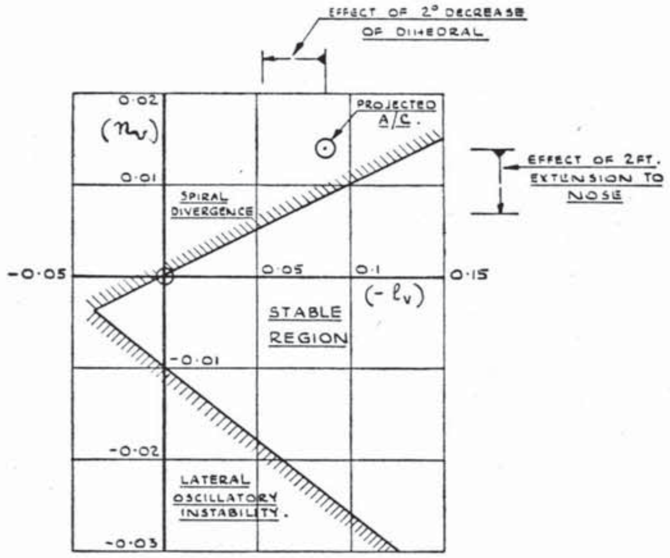


FIGURE 19. Lateral stability diagram for projected aircraft. (Illustrating the need for forward extension of the fuselage.)

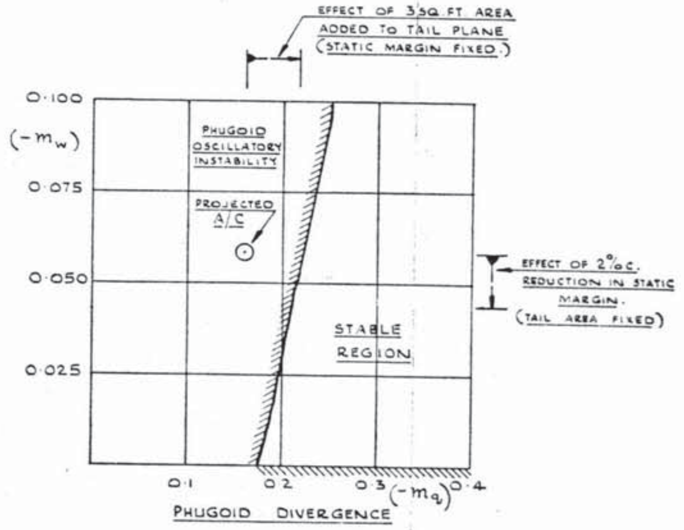


FIGURE 20. Longitudinal stability diagram for projected aircraft. (Illustrating need for more tail area, moving wing forward to preserve the same static margin.)

pitching moment is provoked (due to the offset thrust line) which over-corrects and amplifies the oscillation.

Even with power off—in the glide condition—the phugoid has a very slow divergence. At full power it diverges to double amplitude in 7 seconds with a period of the same time: an unpleasant motion, although it must be recalled that the duration at full power is no more than two periods. Apart from the contributory aggravation of the offset thrust line its root cause is the inadequate damping in pitch (Fig. 20). Tail arm cannot be increased without giving trouble in the lateral motion (since with the layout assumed this would mean increasing fin area and n_v), but an increase in tail area by 40 per cent or more (*i.e.* up to 12 sq. ft.), adjusting the wing position so as to keep the static margin unaltered (or perhaps decreasing it a little) would be quite acceptable, and would neutralise the instability even at full power, while in the glide the time to half amplitude would be 12 seconds, the period 4 seconds.

The rapid incidence adjustment is virtually independent of this effect or its remedy. It is well damped (to half amplitude in $\frac{1}{4}$ sec.) with relatively so long a period (3·5 sec.) as to be unnoticeable. As with the lateral motion, it is anticipated that the stick-free stability would be easy to guarantee.

11. Control

It is evident that—quite apart from its effect on the phugoid—the off-set thrust line is going to give some awkward longitudinal control problems. Simulator tests would be most valuable in determining just how much difficulty there would be. If it were decided that it forms too great an embarrassment, and it is admitted that the propeller cannot be much lowered, it is not inconceivable that some simple kind of servo control to the elevator, activated by a torque meter applied to the propeller shaft, could be evolved.

The problems under this present heading are those most needing attention on the part of the aerodynamicist. There is the general problem of what movement of the "handlebar" could be used for elevator control, since the cyclist pulls on his arms during strenuous action. There is the problem of size and shape of control surfaces, compatable with the likely restricted aerobatic qualities of the under-powered and fragile machine, and the need for low-drag: for instance, perhaps wing warping is preferable to the provision of ailerons despite the low rolling power implied.

12. Conclusions

(*i*) It is recommended that the cycling action be used on the grounds that men who are well practised in it, and the powers they can generate, are well-known. Hand-cranking by the second crew member would seem to give some extra advantage.

(*ii*) With the two cyclists capable of power outputs close to National record levels the performance of a projected fixed wing aircraft is assessed and shows that it can be taken off from the ground, flown for durations of up to 1½ minutes, and reach altitudes of up to 25 ft. by the sole use of muscular power.

(*iii*) For flight to maximum height a high rate of power output is required at the end of the take-off run and during the climb, while a low "cruise" level suffices at other times. For level, long-duration flights, intermediate and constant power output is most effective.

(*iv*) Considerable improvement of performance will result from the use of energy stored before take-off. A device using rubber as the energy storage medium is suggested.

(*v*) A wing section (the NACA 65A(10)12) has been tested at the flight Reynolds number, and has about as much camber as it would appear desirable to employ.

(*vi*) A high wing monoplane design has been considered and is shown in Figs. 12 and 14. Its novel features are a fin-shaped fuselage, single track wheels directly driven for take-off, and a high position for the pusher propeller. The optimum wing loading has been found as about 3 lb./ft.^{2} and the best span as about 60 ft.

(*vii*) Examination shows that the projected aircraft needs more tail area to ensure longitudinal stability, and an extension to the nose of the fuselage to provide lateral stability. The shape of the wing plan also needs detailed change.

(*viii*) A wing covering of $\frac{1}{32}$ in. thick ply is the best so far considered if its surface is to be rigid, and wing weights of about 0·45 lb./ft.^{2} have been calculated.

(*ix*) A number of specific suggestions for future work emerge. These include:—

- (*a*) A reassessment of the optimum wing geometry in view of the facts elicited by the present study.
- (*b*) Tunnel tests on practical construction, rigid and fabric covered, wing sections; on the lateral characteristics of a modified fuselage shape; and on the flow field at the wing-body junction.
- (*c*) Consideration of the design of a control system and control surfaces.
- (*d*) Simulator tests to determine the handling qualities, backed by response calculations.
- (*e*) The design of a suitable propeller.
- (*f*) A relevant theoretical study of ground effect.

(*x*) Longer term research work might be devoted to:—

- (*a*) An assessment of the advantages of helicopter, or other aircraft form.
- (*b*) An assessment of other methods of power generation.
- (*c*) The design of the power storage unit.
- (*d*) The development of wing suction.

Acknowledgments

The author would like to thank his past colleagues of the College of Aeronautics, and many other enthusiasts, for their help and stimulating criticism which find expression in this paper. In particular a special acknowledgment is due to B. S. Shenstone of B.E.A., who was primarily responsible for initiating interest in this remarkable problem.

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