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The Man-Propelled Aircraft -
A Preliminary Assessment

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1. Introduction

It is the intention of this note to set down a few tentative, but (it is hoped) realistic, assessments of the problems involved in the design of an aircraft which by the crew's own muscular efforts shall take off from the ground and sustain steady flight, for a short period. The desire to fly is one of the oldest dreams of mankind, and it has of course found partial fulfilment with the help of external sources of power : but the ultimate achievement of unaided flight is yet to be realised. Everest was "conquered" with the help of the internal combustion engine in 1933 ; but the ultimate achievement was the greater glory of 1954. If the conclusions of this paper are correct, man-powered flight can surely be another "crowning glory" very soon.

These conclusions may of course be incorrect; the amount of work done hardly justifies unqualified confidence in their truth. Yet a useful purpose will be served by this note if it causes sufficient enthusiasm or distrust

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to stimulate researches by those better qualified than the author to dogmatise on many of the aspects of the problem treated.

To begin, we try to form some idea of the power a man can exert: the results quoted may surprise many people, but it will be appreciated that the figures refer to the exceptionally athletic, trained individual. After all nobody expected you or me to climb Everest, but evidently some can do so ; in the same way it is not suggested that Mr. Smith can fly-cycle into work each morning, but Mr. Reg. Harris might like to try. The opinion of medical authorities on the results quoted would be valuable : literature so far seen by the author (a couple of examples of which are quoted in the references) does not have the temerity to make such poorly qualified assertions as the author in his ignorance is bound to do; but it is believed the conclusions drawn are fair.

We next try to form some assessment, on aerodynamic grounds, of the minimum power requirement for sustained flight. Here the author is on ground much nearer home, and apart from the inclusion of unforeseen limitations or modifications, arising from the need for structural simplification (say), the feeling is that the results quoted are at least not optimistic and can, with the help of a wind tunnel investigation, be substantially improved.

To equate the power required with that available needs some assessment of structure weight. This seems the greatest unknown, and the results of flight duration are best quoted as a function of structure weight (section 4). Important issues such as the best wing span, the wing weight, and indeed the whole shape of the craft rest on the results of design studies which it is hoped may be accomplished at the College. For this is not a fully aerobatic plane for rough weather flying, but an exhibition piece to be brought out on a quiet afternoon in June. What year, I wonder?

2. Man Power

The power developed by a man is limited by his "aerobic capacity" - the rate at which he can take in

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oxygen. During strenuous effort (such as ski-ing, cycling or running) this rate of intake gradually rises until a steady state is reached, after about 5 minutes, which for an average healthy man corresponds to about 4 litres/min. The precise amount, of course, depends on the type of movement involved, on his physical condition, and on his size - there is evidently (for example) a strong correlation with his weight. An athlete, for instance, might have a rate of oxygen consumption of about 1/15 litres/min./Kg. weight compared with 1/17 litres/min./Kg. for the "average man". These figures refer to cycling or running exercise ; motion of the arms alone is less demanding, whereas movements involving both leg and arm muscles (as in ski-ing) are accompanied by higher rates of oxygen intake. We shall in what follows assume a cycling motion, though this may not necessarily be the best for our purposes.

However, oxygen intake rate is not the only criterion, for otherwise this would suggest that one's power increased with the duration of one's efforts, and no fatigue would be felt. Moreover the "athlete" would not be much better off than an "average man". As well as the energy extracted from the oxygen intake, there is a "potential energy" within one's system which, in violent exercise, is released. In this process lactic acid is liberated in the muscles until the alkali there present can no longer neutralise any more, and exhaustion ensues. In a powerful muscular athlete, in good condition, this "oxygen debt" which he can incur on his system is of the order of 1/4 litre/Kg. weight, and it is in this quantity that he differs most markedly from an ordinary person. He can use this at will, either expending a lot of it rapidly in the ten seconds of a sprint, or eking it out over a longer period. It is not capable of instantaneous release of course, but it appears it can all be made available in something like half a minute, if required. Once used, however, he is literally exhausted.

Of the oxygen which a man intakes and releases to his system, some is used of course in maintaining his basic metabolism, and it is difficult to quote realistic efficiencies of conversion. The calorific content of a litre of oxygen in mechanical units corresponds to 15,860 ft.lb. and for an untrained person in a pedalling motion working at a sub-maximal level (so no oxygen debt

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is incurred) it seems likely that his efficiency is about 23%. In other words of the 4 litres the average man inspires in a minute, calorifically equal to an energy of 63,400 ft.lb., only 14,600 ft.lb. are realised in mechanical work performed (corresponding to 0.44 h.p.) No figures have been found for trained cyclists with the optimum frequency of movement, and posture, but it is at least not optimistic to assume that their efficiency is about the same. Training seems to have most effect in enabling a person to work at a higher intensity before drawing on the oxygen debt - or in popular terms, before drawing on his "reserves of energy". Once this hidden store of energy is called upon, efficiencies measured relative to that amount of energy merely contained within the oxygen breathed in appear of course to increase, but this is misleading.

Supposing that the trained cyclist in fact has a true efficiency relative to the total energy released, - whether from the oxygen intake or the oxygen debt, - which is of the order of 25%, we find for the exceptional man of 150 lb.wt. (68 Kg.) a power output which is a function of the time before complete exhaustion as tabulated below. (As the oxygen intake and debt appear roughly proportional to a man's weight, figures for other weights can easily be derived.)

Time before complete exhaustion (mins.)	Oxygen intake (litres)	Oxygen debt (litres)	Energy available (ft.lb.)	Mechanical work done (ft.lb.)	Equivalent mean torque h.p.
1	2.3	17	3.05×10^{5}	0.76×10^{5}	2.30
2	6.7	↓	3.75×10^{5}	0.94×10^{5}	1.42
4	16		5.22×10^{5}	1.30×10^{5}	0.99
10	45		9.8×10^{5}	2.45×10^{5}	0.74
20	91		17.1×10^{5}	4.27×10^{5}	0.65
60	272		45.8×10^{5}	11.45×10^{5}	0.58

The "average man" of this weight might be able to generate about 0.45 h.p. over the longer periods, but even so his ability to yield more than half of this without becoming unduly fatigued would depend on his training. Between this figure of about 1/4 h.p. of average prolonged effort, and the figures quoted above for the trained man of unusual physical development, lies an enormous difference, and we here envisage the flight of a man-powered aircraft as being a possibility only for the physically exceptional - at least in the first instance. We then see that a demand of 1 h.p. for a four-minute flight is the most that could be expected of a pilot of 150 lb. weight. (Moreover, taking a propeller efficiency of 90% thrust to torque power, reduces the useful h.p. rating accordingly.)

As a check on these calculations we note that over a protracted (say an hour's) duration, the best road cyclists average a speed of 27 m.p.h. unpaced, and about 90 m.p.h. paced (with little or no wind resistance). If we take a coefficient of rolling friction of about 0.02 and a drag area[‡] of about 4 sq.ft. in the cycling position for a man of 150 lb. weight, these speeds are compatible with powers of 0.75 h.p. and 0.72 h.p. respectively. The figures tabulated, would appear rather smaller, and are therefore not optimistic viewed in this light.

We are left with one final loophole in our favour, even if our estimates are too great. If a protracted duration of flight appears an unreasonable demand, it would not be cheating to supply the operators of the machine with oxygen : in this condition something like a 50% increase in power is easily achieved in extended effort.

3. The Aerodynamic Problem

The thrust power required for steady level flight is given by

$$P = \frac{C_D}{{C_L}^{3/2}} \frac{W^{3/2}}{(\frac{1}{2}\rho S)^{\frac{1}{2}}} \qquad (1)$$

where ρ is the air density, W the all-up weight of the aircraft, S its wing area and C_D and C_L are the drag ...

[‡] Drag area is drag divided by the dynamic pressure.

and lift coefficients (based on this area). The problem is to find the conditions in which this is a minimum, and it is convenient to treat the wing area, span, and lift coefficients as variables to be selected as appropriate. Normally this selection would have to take account of the effect of these parameters such as span and wing area on the weight ; C_L would also be important in affecting the speed of flight. However, there is(as mentioned in the next section) no reliable way of estimating weights and the search for least power attempted here is based largely on aerodynamic considerations. Thus, aerodynamically, one would want as large a span as possible : of course structural considerations are bound to impose a limit here, and we somewhat arbitrarily assume a span of 60 ft. - which may be much too large. We have been guided here by sailplane experience and, although the aerodynamic criteria of sailplane design are rather different, the structural weights are relatively higher, and spans of 60 ft. or so would certainly not be used if they were not worth while.

The choice of lift coefficient, for a given area and wing span, can be shown to be largely a matter of obtaining as high a value of sectional (lift/drag) ratio as possible, and this usually means choosing a C_L at a value close to the stall. The remaining parameter is the wing area (which will determine the loading) : here one must strike an appropriate compromise between the relative magnitudes of fuselage drag (and other fixed items), wing profile drag and induced drag, and take account of the effect of speed on the power required (reflected in equation (1) by the term $S^{\frac{1}{2}}$ in the denominator). Preliminary assessments - again unfortunately making no allowance for the effect on the structure weight - suggest that the induced drag should be about 3 times the profile drag of the wing alone, for the fuselage size and sectional (lift/drag) ratios we shall shortly suggest.

The wing itself would best be highly cambered and fairly thick : of those sections subjected to tunnel tests so far perhaps the N.A.C.A. 65-618(a=0.5) is one of the best : operating at a C_L = 1.1 (with $C_{L\max}$= 1.3) at a Reynolds number of a million, the transition point is still well back along the surface and a profile drag coefficient of about 0.007 should be attainable. Putting the induced drag coefficient at about three times this figure, or say 0.021, would imply an aspect ratio of about 18 as an optimum, which is probably not far from the truth if experience on gliders is any guide ; the wing area is then determined in terms of the limit imposed on the span.

The rest of the drag is composed of three large components : the fin and tailplane drag, that of the undercarriage, and that of the fuselage. The minimum fuselage frontal area would not be required to be much in excess of that of the human body (8 sq.ft.). We take it as implying a cross-section of about 5 ft. height by 2 ft. breadth ; the best length would then be in the region of about $7\frac{1}{2}$ ft. The fuselage would resemble a thick low-aspect ratio "fin", and its drag area might conceivably be as low as 0.25 sq.ft.: however the interference with the wing would be adverse in the condition of high lift and a figure nearer 0.3 sq.ft. would be more realistic. The size of fin and tailplane needed can at this stage only be guessed at : in view of the short fuselage these would have to be mounted on a skeleton extension to provide an adequate arm ; something quite small would suffice as the wings have no flaps - perhaps a tail volume of about 0.3. With a tail arm of 10 ft., we would then put the tailplane area as at most about 20 sq.ft., and the fin would possibly require about half this. Thus the total drag area of the tail would be at most perhaps another 0.2 sq. ft., say. The undercarriage would probably employ a couple of bicycle type wheels, buried at least in part within the fuselage, and a couple of outboard stabilisers: the drag of these components would possibly amount at most to something of the order of 0.4 sq.ft. Adding a token 0.1 sq.ft. for wires and tail struts, this gives a total miscellaneous drag of one sq.ft. without account for imperfections, gaps, leaks and so on, which on an aircraft of simple construction might provide a severe penalty. Assuming the wing span is set at 60 ft., (typical of a twin-seat glider aircraft), and the area is consequently 200 sq.ft., this drag contribution is about 0.005, quoted as a coefficient on wing area, giving a total profile drag coefficient of 0.012. To account for these inevitable shortcomings between the ideal figures and those attainable on a practical aircraft we add 33% to this figure, bringing the total drag coefficient to about 0.037, including induced drag ; the exact efficiency of design is at this stage not known, though glider experience emphasises that the light-weight "stick and wire" type of construction imposes an uneconomic penalty on aerodynamic, and overall, performance.

As the limit on wing span is lowered, and so also the wing area, the drag coefficient tends of course to rise : the actual form of variation can quickly be worked out, but it is roughly in inverse proportion to $\sqrt{\text{span}}$. Taking this into account, from (1) we find that the thrust power required for steady flight at sea-level is approximately

$$P = 1.75\left(\frac{W}{10b}\right)^{3/2} \text{ h.p.} \qquad (2)$$

where W is the weight in lb., and b the span in feet.

4. Structure Weight

The total structure weight of an aircraft of the type envisaged is very difficult to determine : experience on gliders is not really relevant because it is fairly evident that the aircraft is only a kind of demonstration machine, meant for the exhibition or sporting occasion, to be flown only on calm days perhaps, and merely intended to accomplish a very limited flight plan. Any more than this would appear over-ambitious as a first specification which, as its primary goal, requires only the achievement of man-powered and man-sustained flight. Of course with aerodynamic and structural development it might be possible to turn it into a man-propelled glider independent of take-off assistance, but in the first instance it would not, as a necessity, have to be fully aerobatic. Thus some improvement on glider structure weights seems possible. The average empty weight of gliders is given by a formula of the type

$$W_e = (14.7b - 370) \text{ lb.} \quad (b = \text{span in ft.}) \qquad (3)$$

if the aspect ratio is 18, and rather less if the aspect ratio is greater. Where the load is less than 370 lb. equation (2) suggests that as high a span as possible is required, and vice versa ; but such niceties are probably not really predictable by a formula as crude as (3). What is probably true is that the span is after all not a very critical parameter and a figure as high as the 60 ft. previously suggested is unnecessary as a means of achieving flight for minimum power. However, we shall see later there are other considerations which tend to keep the span (and so the wing area) fairly high. (Section 5.1)

Keeping to this figure, by way of example, the empty weight is given by (3) as about 500 lb. ; on the other hand a really good design might achieve something like 375 lb. (One might cite here the Munich two-seat glider Mu-10, having a steel tube fuselage construction with normal wooden wings, - of aspect ratio of 16 and span of 58½ feet, - which has an all-up weight of 800 lb., half of which is load.) But as we have said, the structural complexity of the glider is unnecessary and can be simplified without at the same time detracting from the performance over the limited speed range and large turning circles expected of the craft we envisage here. It has in fact been suggested that the figure of 375 lb. empty weight might be halved : but without detailed investigation it seems best to leave this figure as undecided. The added complication of propeller and machinery on the man-powered aircraft must not be forgotten, of course.

Assuming the load to be one or two men each of 150 lb. weight - which appears a more realistic assessment[‡] of the likely size of the athletic individual than the usual 200 lb. - and a wing span of 60 ft., equation (2) can be used to calculate the necessary thrust power for flight as a function of empty weight, and reference to Table 1 then suggests the flight duration possible before the crew are exhausted, taking

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[‡] It is of course largely an immaterial assumption, because the heavier the man the more power we must expect from him.

a propeller efficiency of 90%. The results of such an analysis are tabulated below.

Empty Weight lb.	Min. h. p. required with a crew of		Max. duration of flight before exhaustion. mins.		Cruising Speed m. p. h.	
	1 man	2 men	1 man	2 men	1 man	2 men
500	1.97	2.70	1.1	1.8	34	38
400	1.54	2.20	1.5	2.5	31	35
300	1.14	1.75	2.4	4.1	28	33
250	0.96	1.54	3.4	5.7	27	31
200	0.78	1.33	5.4	9.2	25	30
150	0.62	1.14	14	25	23	28

It will be appreciated that the flight durations longer than about, say, a couple of minutes are artificial, as of course the distance flown would necessitate a considerable gain in height and some kind of turning radius, which would put up the power required. Nevertheless, it will be seen that man-powered flight is not merely a remote possibility, but a certainty if the quoted estimates are proved correct. It even appears a possibility using present-day glider construction figures, though this would be extravagance as the duration would be too small to take advantage of the performance permitted by the structure.

In some designs it is conceivable that the take-off might further limit the duration of flight below the figures quoted above - this is discussed in the next section. The ground run is to a large extent determined by the magnitude of the cruising speed which is given by

$$V = \sqrt{\frac{2AW}{\rho C_L b^2}} \qquad (4)$$

where A is the aspect ratio and b the span. Values are tabulated above.

In concluding this paragraph, one cannot resist the temptation to draw attention to the achievements of aeromodellers over the last decade in designing paper-covered craft whose wing loadings are between 1 and 2 lb/sq.ft. (as for the present project) and whose weights are something like 2 oz./sq.ft. of area. Perhaps this fact is irrelevant, but it is food for thought.

5. Miscellaneous Topics

5.1 Take-off

It might be desirable to provide a direct, variable-geared, drive to the undercarriage wheels (coupled to the propeller) on take-off as a more efficient propelling device than the simple fixed-pitch propeller, during the ground run. Once off the ground the shaft power would automatically be absorbed by the propeller and the undercarriage wheels could be disconnected at leisure. Alternatively, a variable-pitch propeller might be required, though the weight penalty could be important. With a direct drive to the wheels the efficiency would be greatest and certainly then no more power would have to be exerted during take-off than is needed for sustained flight. For, by trimming the aircraft to an appropriate lift coefficient during the ground run, the combined wheel friction and induced drag can be made less than the induced drag in cruising flight.

In the example of a man-powered aircraft previously mentioned, if the coefficient of friction is taken as 0.02 (corresponding to a concrete runway), this optimum trimmed condition in the ground run would correspond to a C_L of about 0.55, - half that in cruising flight. Thus at the cruising speed only half the weight is carried on the wheels and the induced drag is only a quarter of its free flight value. One would presumably unstick at this cruising speed, and a relatively unimportant burst of effort would soon gain a little height.

Conditions on take-off would be much more complicated, of course, if a grass runway was used, for then considerably more power would be required for take-off than in flight. It might well set the limit on the practicability of the whole scheme. Some alleviation of the problem, without "cheating", might then be possible using means of storing energy (such as springs) but these in practice involve many difficulties. Assuming a concrete runway, and the suggested relief of the wheel load as the speed (and lift) increases, use of the same power as is ultimately required in flight gives a ground run of a duration of

$$40 \frac{V}{g} \text{ secs.} \quad \text{where V is unstick speed (in ft./sec.)}$$

over a distance of about

$$30 \frac{V^2}{g} \text{ ft.}$$

Referring to the Table of paragraph 4, and taking the unstick speed as cruising speed, the above expression gives take-off durations of the order of 0.7 - 1.0 minute for the one-man aircraft, and 0.85 - 1.15 minutes for the two-man aircraft (which has to reach a higher speed because of its heavier weight). The take-off distances are variable between 350 - 750 yards and 520 - 960 yards respectively. In terms of durations of sustained flight it might well be profitable for the crew to exert extra power towards the end of the ground run* where otherwise the acceleration is low.

The above figures are valid whatever the span (or wing area) of the aircraft, provided that the aspect ratio, and the cruising lift and drag coefficients, are fixed. It will be seen from (4) that the unstick speed will vary inversely with the span : thus, if the span were reduced much below the figure of 60 ft. used as representative, the take-off time, speed, and particularly the distance, would all be increased. For then (with fixed aspect ratio) the wing area would be less, and the wing loading higher. It is difficult to see what would be a reasonable limit in practice, but this fact should be borne in mind.

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*Physiologically, releasing energy in any way but at a constant rate is inefficient ; psychologically it is, however, probably inevitable.

5.2 Control

Little thought has so far been devoted to the problems of control of the aircraft. It might be that conventional control surfaces were desirable, although as flutter might well be of prime importance in determining wing weight, alternative means may be necessary. Hinged tips, wing warping, or spoilers, suggest themselves as possibilities; or maybe C.G. movement - by the movement of the body - would be sufficient, although with such a large span as is conceived in the foregoing analysis, and with the trim change required at take-off this is probably not a sensible idea.

If mechanical controls are to be used, the question of the design of control column would be important. Assuming the usual cycling posture, the "handle-bars" could be converted into a stick with two rotations, about the vertical and longitudinal axes - to give yaw (rudder movement) and bank (aileron movement) respectively. As the cyclist exerts a considerable force (a pull) on his handle-bars, pitching rotations (to provide elevator movement) could not likewise be "natural" : they might be effected using clasp or twist grips. Whatever method is used, it seems possible that some loss in power would result, from the disturbance to the man's concentration and posture, and this might be a powerful argument for a two-manned aircraft as opposed to the single-seater - the second crew member at least being able to provide an uninhibited physical effort at all times.

5.3 The Airscrew

To derive the greatest efficiency from the airscrew it would have to be slowly rotating by ordinary aircraft standards : in fact, resembling (at a glance) something like a windmill. This slow rate of rotation inevitably implies, even at the low forward speeds used, a very large diameter. With a propeller mounted on the fuselage nose, one would be limited to about a 9 ft. diameter blade, assuming the propeller axis was close to the top of the fuselage. Then the optimum rate of rotation of a three-bladed propeller of this size would be of the order of 250 r.p.m. for operation at 1.5 h.p., at a forward speed of 30 m.p.h., close to conditions of ideal efficiency. The problem of sufficient disc diameter is eased of course if the operating speed is increased, or the thrust power output decreased. Alternative to this arrangement a couple of wing nacelle mountings for twin propellers could be conceived, but the added complication would probably be quite unreasonable.

The penalty of decreasing the blade diameter is of course not very severe, if the suggested arrangement is inconvenient (though there appears to be no reason why it should be). Thus an airscrew 7 ft. in diameter working at about 400 r.p.m. would only be about 1% less efficient than that cited above. However large the diameter, with the low disc loadings required, it is unlikely that the propeller would be a very heavy item of equipment.

5.4 The Overall Configuration

We have implicitly had in mind a monoplane arrangement in our discussion so far ; if this were adopted, a high wing position would be desirable to keep interference at a minimum. But it might be structurally desirable to use a biplane, cantilever, or even ring aerofoil configuration. These, like many other questions raised, must await some definite opinion on the structural advantagees which can be weighed against the aerodynamic detractions, and the proper compromise reached. There is no lack of problems, and their solution is surely a fascinating challenge to human intelligence and (ultimately) it is to be hoped, to human endurance, as well.

REFERENCES

Per-Olof Åstrand : Experimental Studies of Physical Working Capacity in relation to Sex and Age.
Ejner Munksgaard. Copenhagen. 1952.

A. V. Hill, D.Sc., F.R.S., : Living Machinery.
Bell, 1944.

Abbott, Doenhoff and Stivers : Summary of Aerofoil Data.
N.A.C.A. Report 824. 1945

S. F. Hoerner : Aerodynamic Drag. Otterbien Press 1951.

B. S. Shenstone, M.A.Sc., F.R.Ae.S. : Progress in Two-Seater Sailplane Design
Aircraft Engineering. Jan. 1953.