Problems of a Man Powered Rotorcraft*

R. GRAVES

(*A. V. Roe and Co. Ltd.*)

Introduction

We are at the moment at what is probably the most interesting phase of the battle between man and gravity. This battle has been waged since the days of the ancient Greeks when men dreamed of emulating the birds, and using various "stick and string" devices tried without success to fly under their own power.

In the present day we have much more sophisticated machines into which a great deal of careful thought and design work has gone. Much publicity and speculation is at present centred around the Southampton and Hatfield fixed-wing machines which are enjoying a certain amount of initial success. Whether either machine will ultimately be successful remains to be seen and I am sure that all of us are following their progress with interest and wish them all the best in their endeavours. These are not by any means the only two projects being pursued at present, although there is a definite preference for a fixed-wing machine.

There has been a certain amount of interest shown in a flapping-wing type of design and one or two of these have been built. However, there has not been a great deal of investigation into the possibilities of man powered flight using a rotary-wing machine. The results of the investigations which have been made, notably by Kendall, Naylor, Shenstone and Whitby, have not been very encouraging and so I have attempted to investigate this problem a little further and to try to devise some configuration of rotating-wing machine which would enable man to get off the ground under his own power and fly a distance worthy of the title of man powered flight. In this lecture I hope to show how the investigation proceeded.

Power Available

First, we must consider how much power a man is capable of producing. Several tests have already been made with this objective and the results obtained are readily available.

In Fig. 1 we have the results of tests made on various sportsmen by Dr. Wilkie, Nonweiler and several other people. This, of course, is the greatest stumbling block in man's attempt to fly, as so very little power is available. The tests indicate that cycling is the best form of power production. Running gives little external work and the cycling motion eliminates to a large extent the acceleration of limbs and mechanical parts which is necessary with rowing.

From these results we see that a National Champion cyclist is capable of producing 0·5 h.p. for something of the order of 20 minutes, while a normally fit racing cyclist can achieve this power output level for between 5 and 10 minutes. Consequently I have taken 0·5 h.p. as the steady state power output of the pilot and this figure is used as a basis for the following study.

We must remember that in addition to this steady state power the pilot is able to draw on a reserve of up to 0·6 h.p. minutes or 20,000 ft. lb. of energy by going into what is called "oxygen-debt." This energy can be used at will and may be required for take-off and climb away, the pilot returning to his steady state power output for the cruise.

We must also note that the psychological stimulus of achieving man powered flight with possibly a crowd of spectators encouraging the attempt will probably be a big factor in enabling the pilot to produce his maximum power output.

Preliminary Assumptions

Having decided upon the power output of the pilot, certain assumptions must now be made before the investigation can proceed any further. The weight of the pilot is to be taken as 150 lb. He is also to be taken as being approximately 5 ft. 8 in. in height and of average build. The target design weight of the machine is to be 100 lb. giving an all-up-weight of 250 lb. Any reduction in the weight of either the pilot or the machine is to be considered as a bonus resulting in a better performance than estimated. On no account, however, can any increase in these weights be tolerated.

Using these figures for the power output and the all-up weight it can easily be shown that hovering with a rotating wing machine is impracticable, as an enormous rotor diameter would be required. Naylor continued his investigation by considering the design of a machine under forward flight conditions where there is a reduction of the induced power requirements, more than compensating for the increased profile drag power up to the minimum drag speed. However, even with a 70 ft. diameter rotor the power requirements of Naylor's machine in forward flight are higher than the 0·5 h.p. basis being used in this investigation.

Ground Effect

It was necessary, therefore, to study what beneficial effects, if any, could be gained from the use of the ground effect on the rotor. For a helicopter the proximity of the ground to the rotor causes a reduction of the induced velocity through the rotor and hence, a reduction of the induced power necessary to sustain a given thrust. This phenomenon has been investigated theoretically by Knight and Hefner and their results compared with practical measurements. From these results the variation of the induced velocity through the rotor as the rotor approaches the ground is obtained.

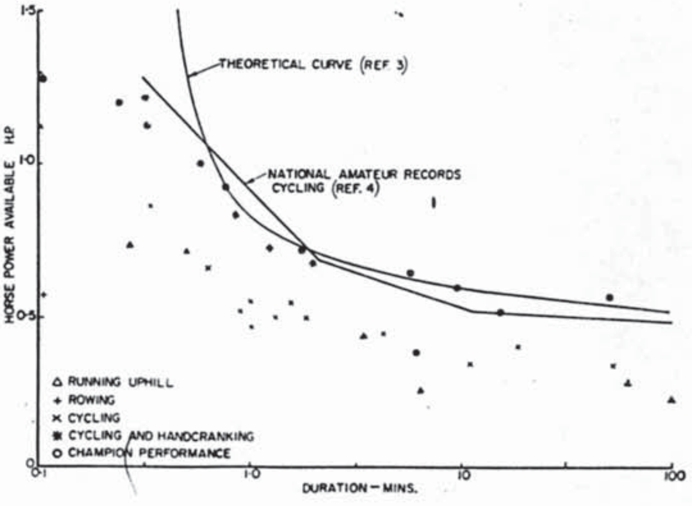

FIGURE 1. Power available plotted against time.

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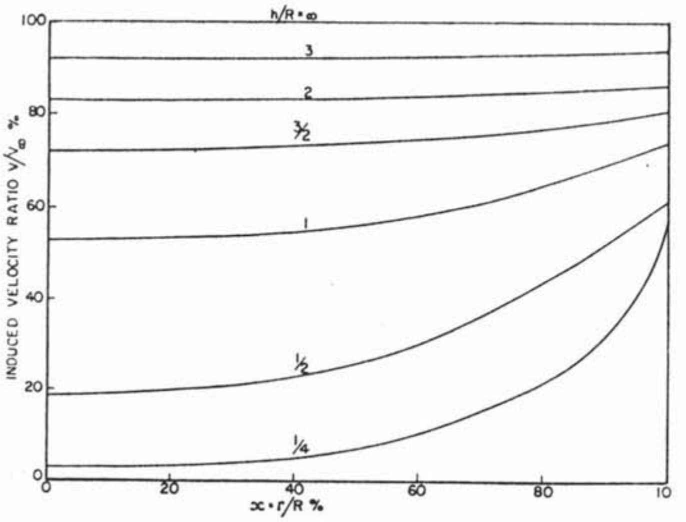

FIGURE 2. Induced velocity plotted against height.

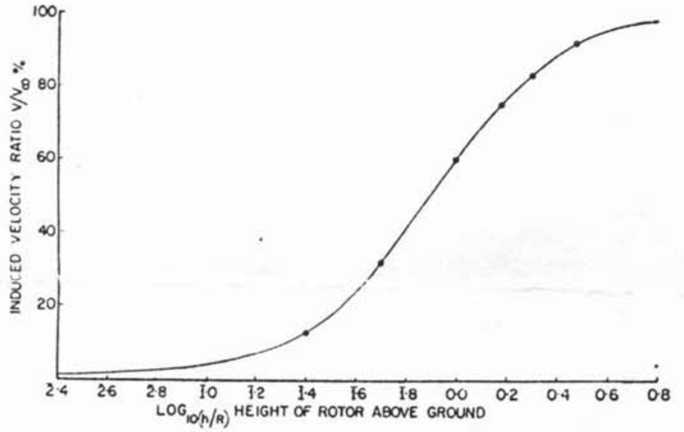

FIGURE 3. Average induced velocity through rotor disc plotted against height of rotor above ground.

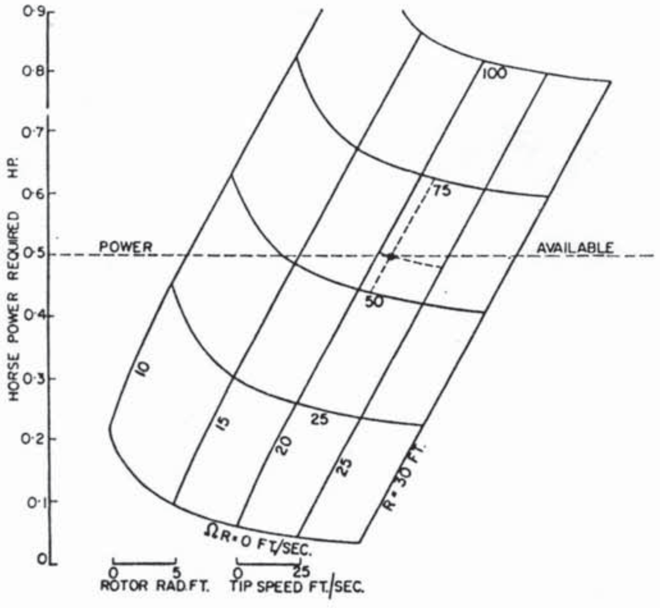

FIGURE 4. Hover power required plotted against rotor radius and tip speed.

From Fig. 2 we can obtain the average induced velocity across the rotor disc at each value of h/R and plot this against h/R. This result is shown in Fig. 3.

Hovering

As mentioned previously, there is a certain forward speed for which minimum power is required and the power required to hover is greater than this. Consequently, I first set out to study a basic machine which could hover just one foot above the ground, and then to find out what the forward flight performance of this basic machine would be. The basic machine was to consist of either one, two, three or four rotors mounted below the pilot so as to make full use of the ground effect. The aim of the investigation was to see whether there was any advantage to be gained by having one, two, three or four rotors. Five or more rotors were not considered as these would be far too complicated to construct, especially with regard to transmission.

Tests have been made which show that two rotors in ground effect have the same performance as two quite independent rotors, provided that there is no overlap. If there is overlap then the induced power requirements are greater than that of the two independent rotors and is as much as 41 per cent greater for co-axial rotors.

Now the power requirements for hovering flight are given by the equation:

$$P_{\text{hover}} = \frac{1{\cdot}25\,kT}{550}\sqrt{\frac{T}{2\pi\rho nR^2}} + \frac{T\delta\,(\Omega R)}{4a\left[\dfrac{\theta}{3}-\dfrac{\lambda}{2}\right]550}$$

where 1·25 is the hovering efficiency factor, K is the ground effect factor, from Fig. 3, T is the thrust and is equal to the all-up weight, n is the number of rotors, R is the rotor radius, and δ is the drag coefficient of the blade. Here we must stipulate the blade section and a NACA 23021 section has been chosen to give as much lift as possible at the low Reynold's Numbers involved, hence the thick, cambered section. The Reynold's Number for the rotor blade will be of the order of $0{\cdot}5\times10^6$ and hence δ is taken to be 0·015 for an incidence from no-lift of 8° and a lift curve slope of 4·9/radian. ΩR is the tip speed of the rotor, a is the lift curve slope of the

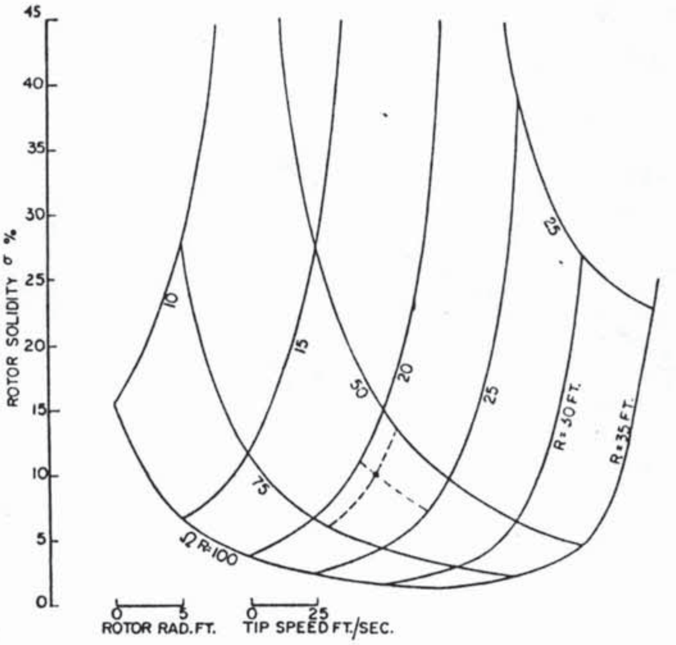

FIGURE 5. Solidity variation with rotor radius and speed.

blade section, α is the incidence and λ is the inflow ratio $(V \sin \alpha + v)/\Omega R$.

The calculations have been done assuming untwisted, untapered blades. However, it can be shown that blades with about 10° of washout and a 3: 1 taper ratio develop 5 per cent more thrust for the same power. This feature may be incorporated in the final design without adding to the weight or complexity of construction. It will also have the advantage of reducing the tip deflection.

Using this relationship together with the equation for the thrust developed by the rotor, which must, of course, be 250 lb. in this case, carpet plots can be obtained relating the rotor radius, solidity and tip speed for each configuration considered.

Figure 4 shows the power required to hover one foot above the ground for the two-rotor configuration. Similar plots are available for the one, three and four rotor configurations. For the single rotor machine it was assumed that 10 per cent of the available power was used in driving the tail rotor. Next we have the solidity necessary to provide the thrust of 250 lb. for various rotor radii and tip speeds, Fig. 5.

Again this carpet is for the two-rotor configuration and similar plots are available for the other configurations. A solidity of 10 per cent was chosen as being the maximum practicable and hence, using the two figures we have just seen that the necessary rotor radius and tip speed may be determined. This was done for each of the four configurations and the results were as shown in Fig. 6. This shows a comparison of the overall size of the machine for each configuration. As can be seen there is not much difference between any of them. It is also noticeable that the size of the machine is similar to the span of the current fixed-wing machines, that is about 80 ft.

Forward Flight

Now as hovering one foot above the ground does not really constitute man powered flight, the performance of each of the four configurations in forward flight was investigated. In this case the power requirements are given by

$$P_{\text{fwd. flight}} = \frac{Tk^2 C_t (\Omega R)}{1100\, \nu} + \frac{T \delta \sigma V}{440\, C_t} \left[\frac{1 + 4{\cdot}65\, \mu^2 + 0{\cdot}375\, \mu^4}{\mu} \right] + \frac{\rho V^3}{220}$$

Most of the symbols are as before. C_t is the thrust coefficient equal to $T/\rho\pi R^2 (\Omega R)^2$, ν is $(\mu^2 + \lambda^2)^{\frac{1}{2}}$ where λ is the inflow ratio mentioned previously and μ is the tip speed ratio $V \cos \alpha / \Omega R$.

The term $\rho V^3/220$ represents the drag horsepower of the pilot and the machine framework. It is obtained by assuming a "drag area" $A \,.\, C_d$ of 5 ft.². This is based on the results given by Nonweiler who measured this quantity on several cyclists in the wind tunnel at Cranfield. His results, for an average cyclist of similar proportions to the standard pilot considered in this investigation, give a drag area of the order of 3·5 ft.² and hence the figure quoted of 5 ft.² takes into consideration the extra structure required in the case of the helicopter.

Using this power relationship the forward flight performance of each configuration has been determined (Fig. 7). We see that in making use of the ground effect to reduce the induced power requirements there is not as much to be gained in forward flight by reducing the induced power still further. However, it can be seen that the basic machine—in this case the two-rotor configuration—is capable of flying at approximately 5 ft./sec. at a height of about 5 ft. Again, similar graphs have been obtained for the other three configurations. This performance is also shown by Fig. 8.

For each configuration it was found that the best forward speed and the height at which this could be maintained were

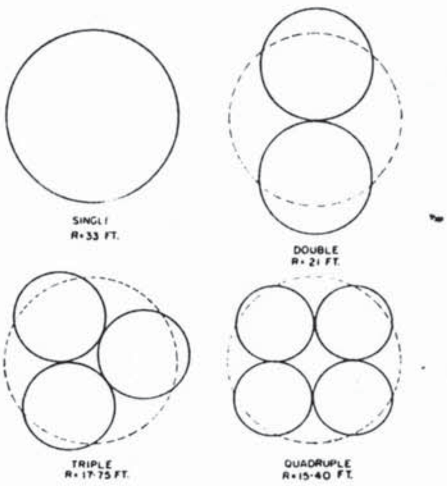

FIGURE 6. Comparison of configuration sizes.

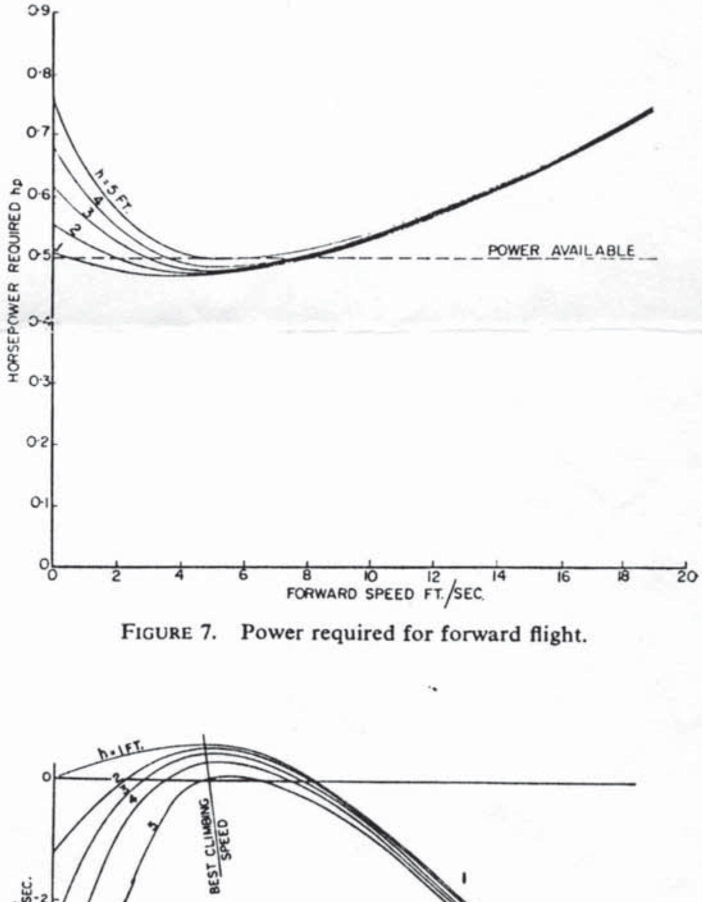

FIGURE 7. Power required for forward flight.

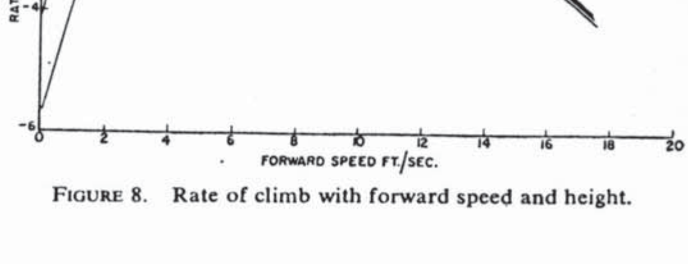

FIGURE 8. Rate of climb with forward speed and height.

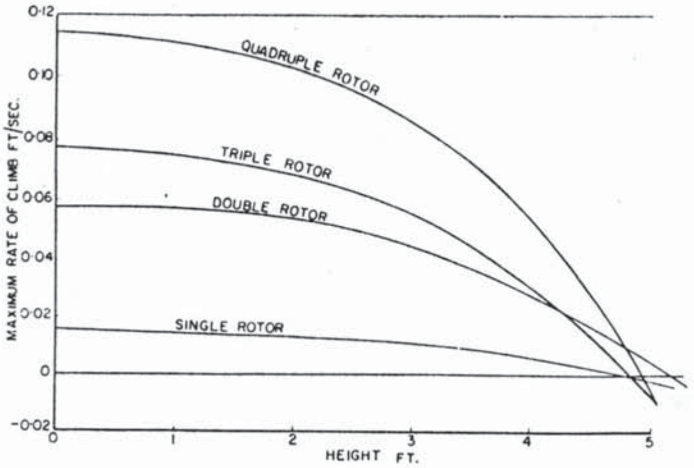

FIGURE 9. Rate of climb plotted against height; four configurations.

5 ft./sec. and 5 ft. respectively. However, the rate of climb of the machine varied somewhat as shown in Fig. 9.

In this case we see that the more rotors used, the higher the initial rate of climb. As these rates of climb are so small anyway, it would be better if the pilot used more than his 0·5 h.p. "steady state" output and made use of his extra store of energy to enable the machine to take off and reach height more readily.

Weight Estimation

So far there has not been any factor which definitely favours one configuration as opposed to any other.

It was then decided to investigate the weight of the four configurations to see if there was an optimum number of rotors from this point of view. A quick check showed that with the estimated light weight of the rotor blades, and their relatively slow rotational speed, tip speeds of the order of 50 ft./sec., the coning angle of freely mounted blades having the usual flapping hinges, was something phenomenal and completely out of the question. This meant that the flapping hinges had to be dispensed with and the blades rigidly attached to the hub. This move introduced the problem of making the blades stiff enough and strong enough to resist the bending due to the air loading on them and the resulting bending stresses involved. Three types of blade construction were considered and the results were as follows (Fig. 10).

The constructions considered were a light alloy skin, a light alloy channel section spar and a wooden box section spar. The weights shown are for a constant tip deflection of, in this case, 4 in. and we see that the wooden spar type is lighter than the other two. The section shape could be maintained by balsa ribs and the whole covered with light parachute silk. As the weight problem is so critical it would be a great advantage for a study to be made of the use of the light foam plastics, or sandwich construction, in an endeavour to obtain the lightest and strongest type of rotor blade possible.

Pilot		150 lb.
Fuselage, including frame, handlebars, saddle, chainset and pedals		15 lb.
Rotor system, including:		
2 rotors at 23·7 lb.	47·4	
2 hubs at 2·0	4·0	
Transmission	16·8	
Supporting structure	16·8	
	——	85 lb.
		——
All-up weight		250 lb.

FIGURE 11. Weight breakdown.

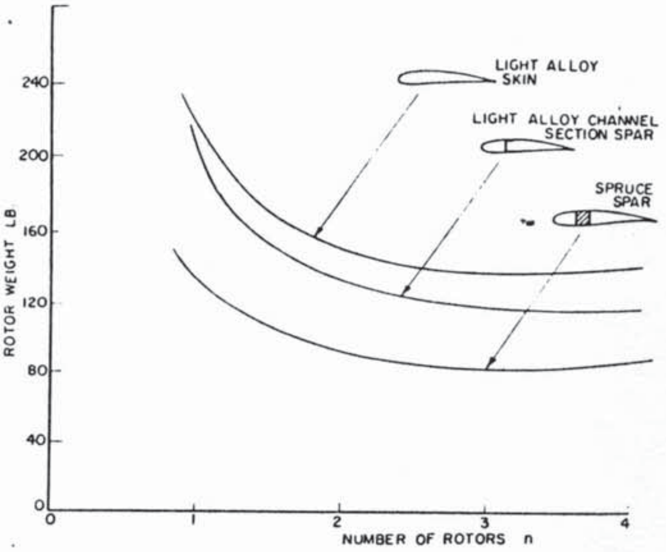

FIGURE 10. Rotor weights.

The results tend to favour either the two or three rotor configurations as being the lightest arrangement. Allowance was made in this comparison for the differences in structure and transmission weights of the various configurations, as well as the rotor weights.

Comparison of the Four Configurations

At this stage it was decided to take stock of the advantages and disadvantages of the different configurations.

For the single rotor we have very simple design of layout and transmission but a tail rotor is required to balance the torque of the main rotor. Alternatively, the rotor would have to be driven by means of propellers mounted on the rotor blades, which is not very efficient (of the order of 70 per cent) and is much more complicated in the design of the transmission. Also, since we have omitted the flapping hinges, there is the problem of the overturning moment due to the different lift on the forward going and retreating rotor blades.

By having contra-rotating rotors the two-rotor configuration eliminates the latter problem and also that of the torque reaction. The transmission is still simple and the overall weight of this machine is as low as, or lower than, that of the other configurations. The two-rotor configuration is constructionally much more simple than the three or four rotor configuration and the three-rotor configuration has the same problems as the single rotor as regards overturning moment and torque reaction. So far as performance is concerned there is little to choose between the four configurations.

Finally then, the two-rotor configuration was chosen and the estimated weight breakdown is as shown in Fig. 11. An obvious advantage could be gained by having a pilot weighing less than the 150 lb. assumed and a person such as a hill climbing champion would be ideal.

Layout of the Machine

We now come to the layout of the machine. This can be kept very simple and straight forward and consequently it should not be too difficult to meet the weight breakdown (Fig. 11).

In Fig. 12 we have what is basically a cycle frame minus front and rear forks. The pilot is in the usual cycling position as it is felt that any strangeness of position will detract from the ability to produce the necessary power output.

In this layout there is no canopy around the pilot and framework. Such a canopy would increase the forward speed for minimum power by reducing the drag of the pilot and machine but would obviously incur a weight penalty. At the low speeds involved the drag saving would not be great and therefore, unless an exceedingly light canopy could be manufactured, we are better off without one.

The layout is shown with chain drive as this is very efficient, with bevel gears at the rotor end. In a recent lecture to this Society it was claimed that chain drives are untwistable, but from another recent reference we are told that chains can be twisted and are more efficient than bevel gears. Further experiments should settle this point and the better of the two systems could be employed. Alternatively, a shaft drive (similar to that used in the Hatfield machine) to the two rotors mounted side by side might be either lighter, or more efficient, or both, than the chain drive (as shown in Fig. 12(*a*)). A flexible drive is suggested as being more efficient than either chain and bevel, twisted chain or shaft drives. Further tests in this direction would be beneficial. Also, the effect of the downwash field from the forward rotor in the tandem layout will probably be to increase the induced power requirements in the same way as rotor overlap does, but at the low speeds involved this effect is probably small. However, this factor could be resolved by wind tunnel tests.

Directional control could be effected by tilt of the rotors in opposite directions, the tilt being governed by the handlebars connected by cables to swash plates at the rotor heads.

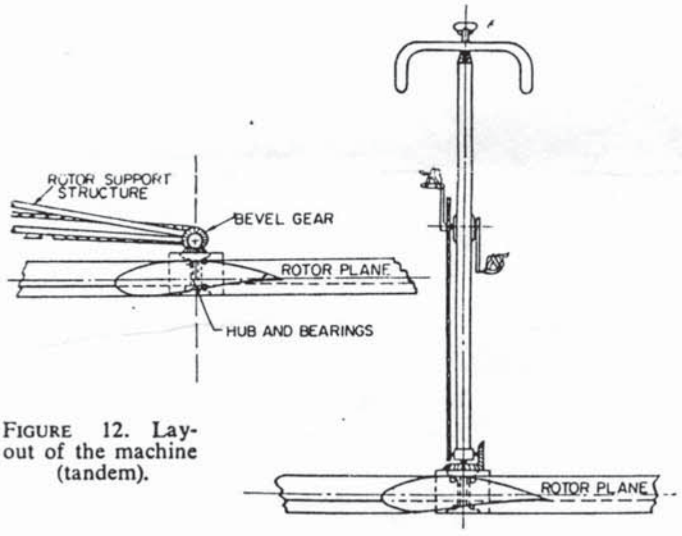

FIGURE 12. Layout of the machine (tandem).

Stability

The mounting of the rotor beneath the pilot leaves one very outstanding feature of this machine still to be discussed and that is the problem of stability. Machines of this "flying platform" type have been built and flown in the U.S.A. and it has been proved that this type of machine can be quite stable, provided certain requirements are met and adhered to. It can be shown that if the pilot's reaction time is slow then the machine will be unstable, but if his reactions are quick then the machine is stable. In between these two limits is a "critical reaction time" for which the machine is neutrally stable. Control of these machines is effected by the pilot providing correcting moments about his ankles to counteract any disturbance of the flying platform in the same way that a man standing corrects the disturbances to himself. As long as his reactions in providing the correcting moments are faster than the critical time, then the machine is stable. Applying this argument to the man powered rotorcraft, the pilot must react to any disturbance of the machine by applying correcting moments to the frame in the same way that a cyclist manages to control his machine when cycling. His reactions to any disturbance must be quicker than the critical reaction time, which is given by the relation:

$$t^2 = \frac{\Sigma I_r \times I_m}{W_m h_{mg} (\Sigma I_r + I_m)}$$

where ΣI_r is the moment of inertia of the rotor system about an axis in the plane of the rotors. I_m is the moment of inertia of the machine about this axis, W_m is the weight of the machine and h_{mg} is the height of the centre of gravity of the machine above this axis. The machine in this context includes the pilot. The pilot in this case is in the position shown in Fig. 13, and an estimate of his moment of inertia and centre of gravity position while in this position was made.

Using these results, together with the weight breakdown and layout of the machine, the critical reaction time for this machine was calculated and was found to be 0·43 secs. Quoted times for a man's subconscious reactions, *i.e.* when he does things involuntarily, such as applying correcting moments when standing or cycling, are of the order of 0·03 secs. For conscious reaction times when a definite effort on the part of the man is required, the figure is 0·4 secs. Consequently, the machine should be quite flyable whether the pilot consciously effects control or not. It is worth noting the report of one incident in America when a man was flying one of these flying platform machines. The stability of the machine was such that he found it virtually impossible to fly and in trying to do so he got tangled up in the harness he was wearing. He then let go of the controls and struggled to release himself from the tangle. While concentrating upon this task

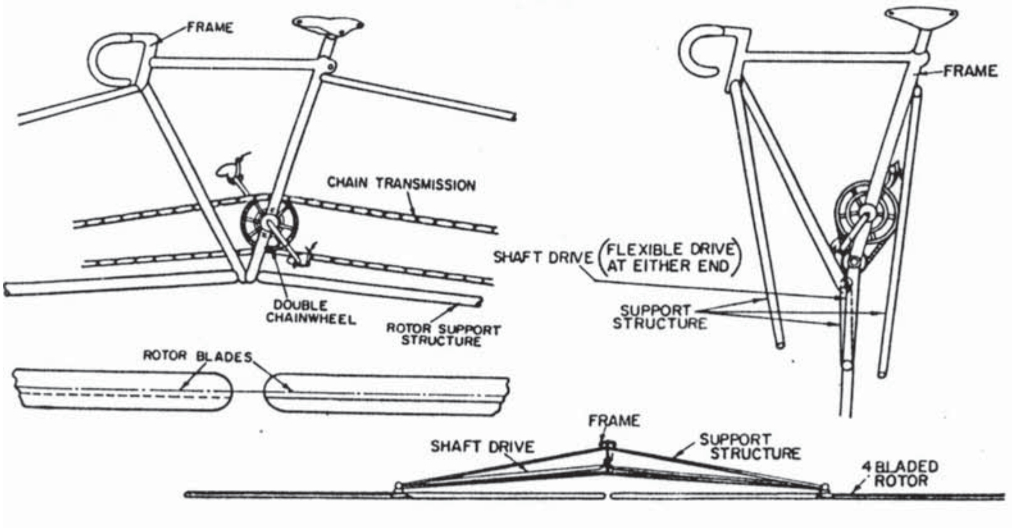

FIGURE 12(*a*) (*left*). Layout of the machine (side-by-side).

FIGURE 13 (*below*). Cyclist in racing position.

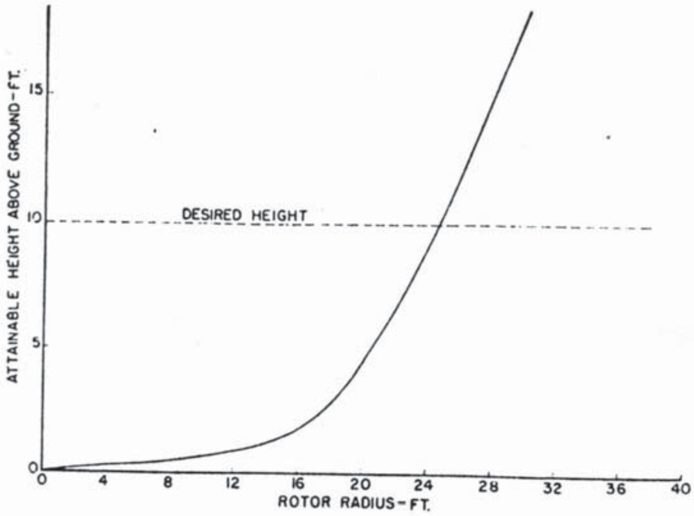

FIGURE 14. Attainable cruise height plotted against rotor radius.

he flew the machine perfectly, indicating that the stability must have been such that the critical reaction time was in between the conscious and subconscious reaction times of the pilot.

Improving the Performance

We have seen that with careful weight-conscious design it should be within the capabilities of a reasonably fit racing cyclist to take off and fly a rotating-wing machine. The machine envisaged so far is to fly at 5 ft./sec. at 5 ft. above the ground. This performance is very modest and a brief investigation was made to see how the performance could be improved upon by increasing the rotor radius. This is shown by a curve of attainable cruise height with increasing rotor radius (Fig. 14). From this we see that in order to cruise at the height of 10 ft. required by the Kremer competition, a rotor radius of 25 ft. is needed. This machine size is now larger than the fixed-wing machines but it has one very distinct advantage. The initial trials of a helicopter machine could be made very simply and with little or no danger of damaging either the pilot or the machine, since there is no question of attaining flying speed along a runway.

The machine is readily developable into a two-man machine and if the design of this could be made at less than twice the single machine weight an obvious improvement in the power-weight ratio would result and hence, an improvement in performance. Time has so far prevented this course of study. However, I hope that I have shown that man powered flight of a modest nature is practicable, and we must remember that Orville Wright's first flight was also a modest performance.

The requirements as I see them are, therefore:

A careful study of the design of very light weight, non-flexible rotor blades.

A study of whether a two-man machine has a better power-weight ratio than the single man machine without the machine size increasing too much.

Wind tunnel tests on a twin-rotor configuration in tandem and side-by-side layouts, while in the proximity of the ground.

Further tests on transmission systems. The lecture by Dr. S. S. Wilson on Powered Transmission Systems which is to be given in the 1962–63 Session could be very enlightening.

Wind tunnel tests on a model of the machine and pilot, with and without a canopy. These would indicate whether the weight penalty of the canopy is justified by an improvement in the forward flight performance of the machine.