CIERVA MEMORIAL PRIZE ESSAY COMPETITION, 1958

The prize for the 1958 Competition was awarded to Mr E R Kendall, whose essay was published in the April Journal

From the very good response of essays sent in, the Examining Panel highly recommended two additional entries, a joint paper by Mr B S Shenstone and Mr R H Whitby and one by Mr C H Naylor, and it was therefore decided to publish both papers in this issue of the Journal

Is Man-powered Rotating Wing Flight a Future Possibility

By C H Naylor

(1) Introduction

Attempts at human flight go a long way back into history First success did not come by use of man's own power for propulsion but by the use of balloons for lifting Later gliders were made for descending flight It was only when a much greater source of power than man's own was developed that flight with heavier than air machines became really successful It was not until the 1930s that much serious attention was given to man-powered aircraft flight With the aeronautical knowledge that was then available successful man-powered aeroplanes were developed and built which flew a few hundred yards Little attention appears to have been given to the possibility of a man-powered helicopter, possibly because it did not appear to be as promising a line of development as the aeroplane

(2) Power Requirements

Compared with the creatures which fly, man's power/weight ratio is low and he is therefore ill fitted to imitate them It appears that the heavier a living organism is the more poorly off it is in this respect The largest flying creature the world has known is probably the tailless pterodactyl measuring 18 ft from wing tip to wing tip, but it has been extinct for a very long time

A number of measurements of man's maximum mechanical power output have been made and Ref 1 after analysis of this data takes a power output of 90% of that estimated to be required in achieving National Cycling Records for the purposes of evaluating performance of man-powered aircraft This corresponds to a steady power output of 0 44 H P plus a reserve of 0 35 H P minutes of energy (which can be spread evenly over any period from about half a minute up to thirty minutes) For one minute this gives a steady power output of 0 79 H P, which for man is a relatively high output, but as a source of power for a flying machine is very poor Power/weight ratio, assuming a most optimistic take-off weight of 200 lb total, would be about 0 004, and less than a tenth of that which would be required in a normal aeroplane or helicopter This figure demonstrates the magnitude of the difficulties of designing a man-powered flying machine but, even so, Ref 1 suggests that it is possible to design a two-man aeroplane having a limited duration of the order of a minute and a half Though two men may be better than one what follows is related to a single-seat helicopter

(3) Energy Losses

With so little power available it is evident that extreme measures must be taken to employ what power there is with the greatest possible efficiency and it is therefore necessary to examine what happens to the power Most of the power goes into the rotor, some of this power is lost in overcoming the skin friction and form drag of the blades and most of the remainder in imparting kinetic energy to the air

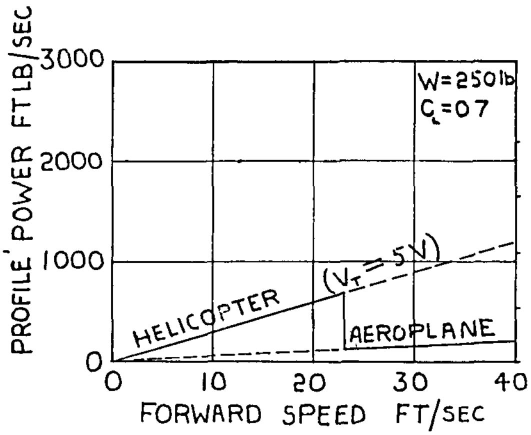


Fig 1
Variations of 'Profile' with forward speed

(3 1) *Power lost in skin friction and form drag*

In order to produce lift, a wing or rotor must work at incidence to its line of motion Assuming that the profile drag coefficient of an aeroplane is 015, and the lift coefficient is 0 7, that the machine weighs 250 lb, then the profile power is —

$$\text{(Aeroplane)}\ P_0 = \frac{W\,C_{D_0}\,V}{C_L} = 5\ 35\ V\ \ \text{ft lb/sec} \qquad (1)$$

For a helicopter assuming that the tip speed is 5x the forward speed, the speed at 0 7R will be 3 5x the forward speed, and the profile power is approximately

$$P_0 = 18\ 7\ V \times 1\ 62 = 30\ 4V \qquad (3)$$

The comparative profile powers are as in Fig 1 and the associated wing or rotor plan areas are as in Fig 2 The change over from aircraft to helicopter being arbitrarily assumed at a wing area of 600 sq ft

It will be seen that at any given speed the helicopter requires considerably greater profile power—but that for both types of machine profile power reduces as speed is reduced (on the above assumptions)

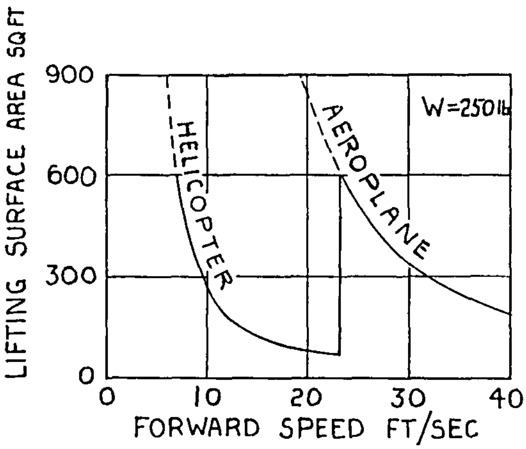


Fig 2

Lifting surface area for machine with design $C_L = 0\ 7$

(3 2) *Power lost in imparting kinetic energy to the slipstream or downwash (i e associated with the induced velocity)*

For a hovering helicopter, on momentum theory, the energy in the downwash/second

$$P_{i\,V=0} = L\sqrt{\frac{L}{2\rho A}} \qquad (4)$$

And in forward flight (deduced from Ref 2)

$$P_{i\,V=V} = x\,P_{i\,V=0} \qquad (5)$$

where

$$x = z\sqrt{\frac{(\sqrt{1 + 4/z^4}) - 1}{2}}$$

and

$$z = V \times \sqrt{\frac{2\rho A}{L}}$$

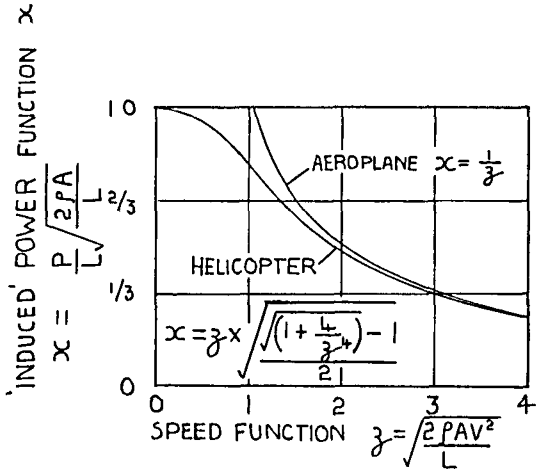
The corresponding expression for an aeroplane is

$$\text{Aeroplane } P_i = \frac{1}{z} \times L\sqrt{\frac{L}{2\,\rho\, A}} = \frac{1}{z} \times \Big[P_i\Big]_{v\,=\,o} \text{Helicopter}$$

These expressions are plotted in Fig 3 and show that when z is greater than 1½ there is little difference between a helicopter and an aeroplane (It is seen

Fig 3

Equations for estimating minimum 'induced' power



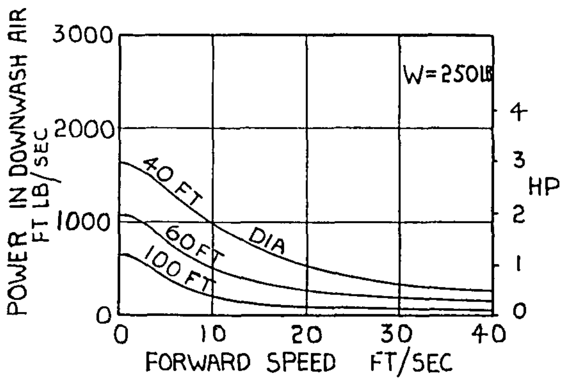


Fig 4

Power lost in K E of downwash air

later that this is the region where a man-powered helicopter must fly for least power in steady conditions)

Taking helicopter weight complete to be 250 lb the power requirements from slipstream kinetic energy losses only are plotted for a series of diameters in Fig 4 It will be at once appreciated from this figure that (in the absence of ground effect) (1) steady continuous hovering would require very large rotor diameters, (2) the reduction of power with speed is large and therefore gain results by designing on a forward speed case

(4) General Considerations

Ref 3 considers various proposals for taking out torque reaction and settles for two rotors rotating in opposite directions placed side by side The result was one of the first successful helicopters Propulsion by propellers on the rotor was the first of the various proposals dismissed on account of low propulsive efficiency (taken as 70 per cent) but apart from flapping rotors and tip reaction, which are here possibly even more out, it is the only way of obtaining rotation without reaction in a single-rotor helicopter It was decided to examine a single-rotor layout somewhat arbitrarily as it was thought that weight was likely to be less than with a multi-rotor system, and that weight was one of the most important factors (hence the desire to save the weight of a torque compensating system as well)

So far the way weight influences design has not been considered as a variant but it is clearly of great importance as it enters directly into equation 1 and to the power 1 5 in equation 4

(5) Optimum Design

It is desired to examine the effects of rotor diameter and solidity taking into account weight variation on the power required for steady flight over a series of forward speeds for a single rigid rotor helicopter driven by propellers on the rotor

(5 1) *Weight*

As the rotor in mind is of large diameter and slow rotation it was thought best to consider it for structural weight purposes as a wing Centrifugal forces will be small

The wing of Ref 1 is a convenient datum It is approximately 60 ft span and $2\frac{3}{4}$ ft mean chord $\frac{1}{32}$ birch ply covered spruce ribs and single box spar at 40 per cent chord Weighs 77 lb and has a total factor of 3 0 with a centre line load of 393 lb , spar 29 lb , cover and remainder 48 lb From this data a rotor weight formula of

$$W_R = 022\frac{b^2}{c} + 0\ 22\ b\ c$$

was arrived at for a single-seat helicopter rotor

Having arrived thus far it was decided to put the pilot on a conventional, though lightened cycle frame and saddle and mount the frame above the rotor hub and put the undercarriage below A total weight breakdown was then written down for a rotor of 60 ft span and 3 ft mean chord as —

Spar	26 lb
Cover	39 lb
Frame and undercarriage pedals, drive props	32 lb
Pilot	168 lb
Take-off weight	265 lb

or as a formula for any rotor diameter or blade chord as —

$$W = 200 + \ 022\ b^2/c + \ 22\ b\ c$$

(5 2) *Power*

With an 80 per cent, rotor propulsive efficiency (from the driving propellers on the rotor including mechanical transmission loss) and 15 per cent loss in power through additional kinetic energy losses through tip effects from span loading, the formula used for power required in steady level flight was —

$$0\ 8\ P = P_o + 1\ 15\ P_i + D \times V$$

where the last term is the drag power of the pilot and frame Or inserting earlier equations and constants total power required is

$$P = 1\ 25 \sqrt{\frac{b}{c}} \times W \sqrt{\frac{W}{b^2}} + 23\ 6W \sqrt{\frac{W}{b^2}}\ f(z) + \ 187\ V^2 \quad \text{(ft lb /sec)}$$

This equation has been evaluated in Table 1 for a range of speeds, rotor diameters and mean effective chords to give the three components of power The total power required is plotted in Figs 5, 6, 7 and 8 for four mean effective chords

Before this diagram can be used it is necessary to decide what tip speed ratio is reasonably attainable This is not easy so a limit of 0 2 has been arbitrarily assumed and the minimum power to fly this helicopter comes out at about 850 ft /lb /sec at 14 ft /sec forward speed where rotor diameter would be about 80 ft and mean effective chord 3 ft

By going to a larger mean effective chord or by increasing chord towards the tip it should be possible to operate at a higher tip speed ratio However, weight and power both increase so that the best combination may be that of Fig 7 at about 16 ft /sec forward speed

For a 70 ft diameter 5 ft mean effective chord rotor at 20 ft /sec forward speed we get —

" Profile " power	352	($z = 5\ 07$)
Induced power	344	
" Body " drag power	75	
	771 ≡ 1 4 H P	

which is more than can be obtained from one man However, with ground effect, a very low weight fairing for the man, and a really low drag wing section power could probably be reduced by the following factors —

× Induced power by	0 7	
× Profile power by	$\frac{008}{125}$	(Ratio of Section $C_{D_O}{}^S$)
× " Body " power by	0 25	
Giving Induced power	246 ft /lb	

TABLE 1

HELICOPTER WEIGHT AND POWER REQUIRED TO CARRY ONE 168 LB MAN IN LEVEL FLIGHT

V	Rotor Dia Ft	40				60				100			
Ft /sec	Mean Chord Ft	1	3	5	7	1	3	5	7	1	3	5	7
0	P_1	2230	2160	2330	2560	1960	1705	1860		2190	1470	1590	1780
	P_o	750	417	350	322	805	403	342		1155	450	372	356
	D V	—	—	—	—	—	—	—		—	—	—	—
	ΣP	2980	2577	2680	2882	2765	2108	2202		3345	1920	1942	2136
10	P_1	1360	1250	1375	1550	890	740	825		749	442	483	571
	P_o	750	417	350	322	805	403	342		1155	450	372	356
	D V	19	19	19	19	19	19	19		19	19	19	19
	ΣP	2115	1686	1744	1891	1714	1162	1186		1923	911	874	946
20	P_1	708	684	720	851	458	382	424		376	222	242	286
	P_o	750	417	350	322	805	403	342		1155	450	372	356
	D V	75	75	75	75	75	75	75		75	75	75	75
	ΣP	1533	1176	1145	1251	1338	860	841		1606	747	689	717
40	P_1	354	342	360	427	229	190	212		188	111	121	143
	P_o	750	417	350	322	805	403	342		1155	450	372	356
	D V	300	300	300	300	300	300	300		300	300	300	300
	ΣP	1404	1059	1010	1049	1334	893	854		1643	861	793	799
W lb		244	238	250	266	292	266	282		442	339	354	385

Profile power	220 ft /lb
" Body " power	19 ft /lb
Total power =	485 ft /lb ≅ 0 88 H P

which is approaching the 0 79 H P of our assumed pilot (for a flight of 1 min)

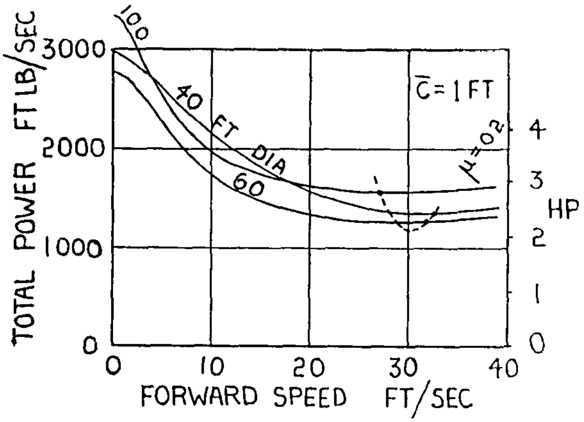
As more power is required to take off than is required to maintain steady flight the problem is how to get to steady flight conditions The kinetic energy required is not large as the speed is low and amounts to only about 2,000 ft /lb The machine could run along the ground until the desired speed was reached but it would perhaps be somewhat easier to put power into the rotor for a short while before flight by overspeeding and use this extra energy as well

(6) CONTROL

With a non-articulating non-flapping rotor, control can most easily be exercised by " ailerons " preferably under cyclic pitch control and with the

Fig 5

Power required for level flight in free air



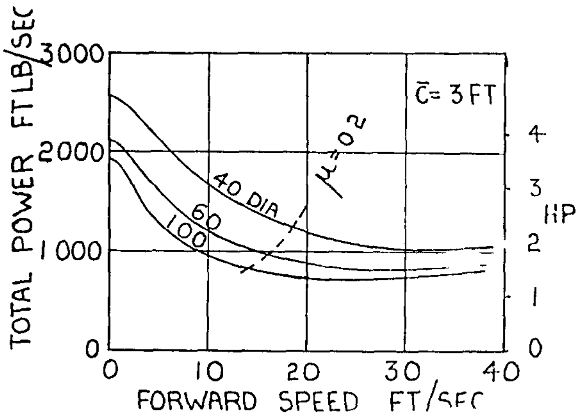


Fig 6

Power required for level flight in free air ability to operate "collectively" These ailerons would, from the point of avoiding discontinuities in spanwise loading, be of increasing chord towards the tip , probably full chord just before reaching the tip

The actual controls would be pitch, roll, yaw and up/down Pitch and roll by differential aileron, up/down by collective pitch The controls would not be easy to operate accurately when exerting much effort and it would probably be best to split control functions between the two hands Say roll and pitch with the left hand, yaw and collective pitch with the right The alternative is one, or no handed flight (which even on a bicycle on the ground is asking for trouble)

Yaw control could come from body twisting the saddle, reaction being taken by hands or feet, which would leave three hand operated controls Further simplification of control operation appears essential

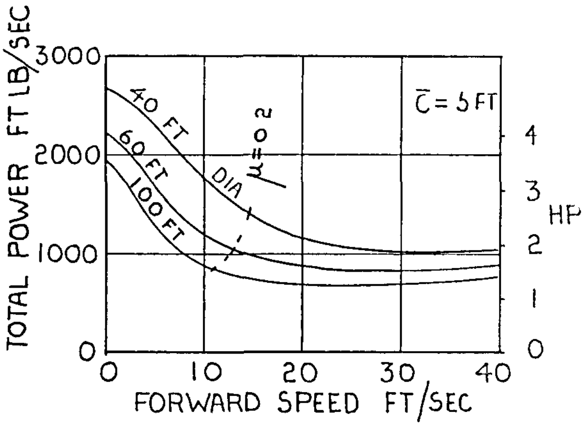


Fig 7

Power required for level flight in free air

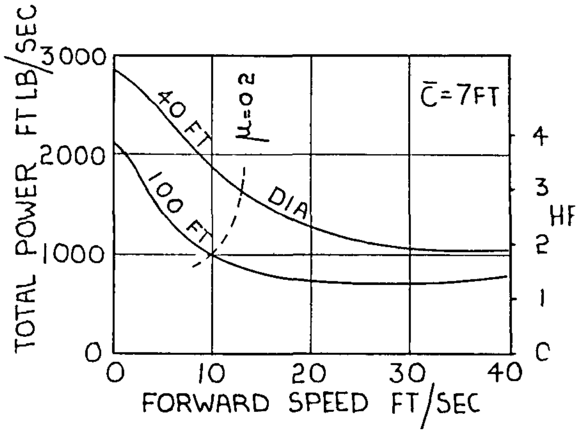


Fig 8

Power required for level flight in free air

(7) POWER DRIVE

To avoid torque reaction, power from the pedals could be taken to a differential and the two outputs taken by chain and sprocket to the hub One output to the propeller shaft drive and the other (which only carries a small proportion of the power) directly to the rotor hub which rotates in the opposite direction Any unbalance of torques in the two drives, through friction or non-steady conditions which would result in yaw (rotation of the pilot), could be balanced by a cross coupling between the two sides of the differential The action of the cross coupling being to transfer torque from one drive to the other This could be achieved by two connected rubber-tyred wheels rolling on the hub drives and acting as a small variable gear Control in yaw being obtained by varying the gear ratio (which would normally be 1 1 with zero " fuselage " angular velocity, and zero cross transference of torque)

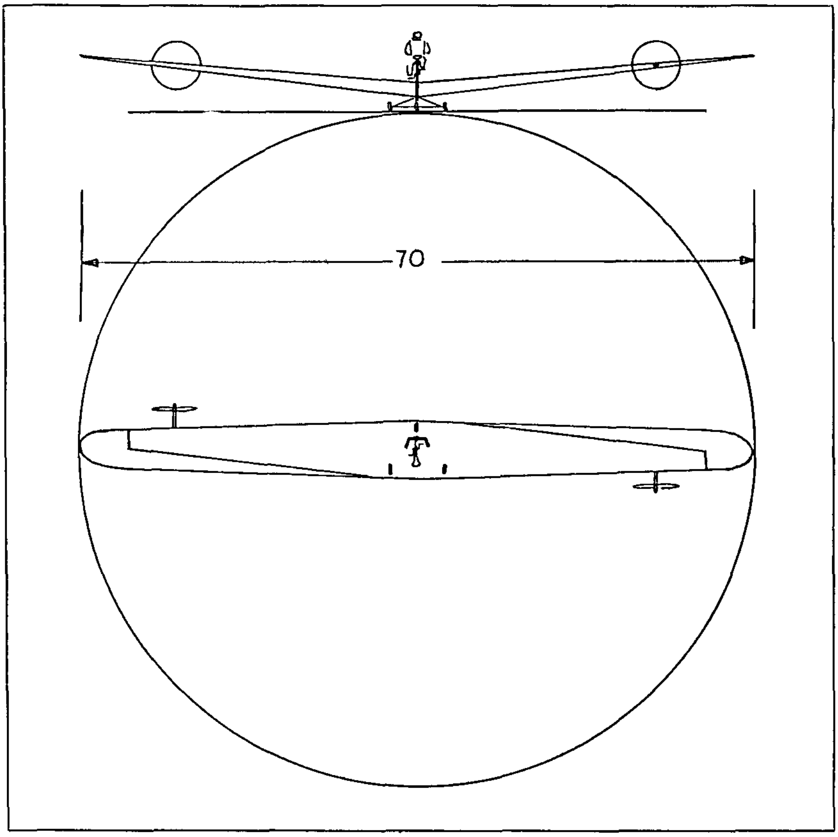


Fig 9 Sketch of possible man powered helicopter

(8) CONCLUSIONS

Fig 9 is a rough sketch giving the main dimensions of the type of machine considered here With good detail design, saving weight wherever possible and aiming for a good low drag surface finish, rotating wing flight of limited duration is a future possibility in the vicinity of fairly strong ground effect

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NOMENCLATURE

P	Power	Ft lb /sec
P_O	Rotor Profile Power	Ft lb /sec
P_i	Rotor induced power	Ft lb /sec
V	Forward speed	Ft /sec
C_{D_0}	Mean effective rotor section profile drag coefficient	
C_L	Mean effective rotor-lift coefficient	
L	Rotor lift	lb
A	Rotor disc area	Sq ft
ρ	Air density	
W_R	Rotor weight	lb
b	Rotor diameter	Ft
$\bar{c}$	Rotor mean effective chord	Ft
W	Take-off weight	lb
D	Drag of " fuselage "	lb

$$x = \frac{\text{Induced power at speed}}{\text{Induced power at zero speed}}$$