Man-powered Helicopters

By

B S SHENSTONE and R H WHITBY

The present interest in man-powered flight has led to the consideration of whether man-powered flight can be accomplished by rotary wings If this could be done, it would be extremely convenient and in many ways much more attractive than man-powered flight by fixed wings or even semi-fixed flapping wings Support in the air by a rotor enables the forward speed to be as small as zero and, one would hope, as fast as a bicycle Not only it is attractive from this point of view, but such a machine could be small and compact and it is initially imagined as something on the lines of the small one-man helicopters under development in the U S A and France and possibly in other countries

Study of the problem involves two basic considerations Firstly, it must be made clear exactly what power can be made available from the human body to drive the rotor Secondly, it must be discovered how this power can best be applied in order to get the most out of it, in the hope that it will be sufficient for free flight by man-power

POWER AVAILABLE

Nonweiler (1) gives considerable information on the power that man can produce under various conditions and for various periods Although this information is scattered, it is probably sufficiently dependable to be used for design purposes, but anybody using the information will want to know how it was determined and should be able to satisfy himself whether the methods used for obtaining the power were the most efficient After all, the power available might be quite different for different end uses, and it is therefore necessary to discuss what work has been done to determine man-power and how it has been analysed

The most thorough work to date was done some time ago and it is worth reviewing this in some detail The work referred to was done under the direction of Oskar Ursinus who was for many years editor of " Flugsport " He formed the Muscular Flight Institute for the purpose of measuring the power available from man and published the result in six reports which appeared in the magazine " Flugsport " in 1935 and 1936 In these tests by Ursinus and Gropp, the man, the power source, was accommodated on a frame in various positions and his power output measured by a normal pony brake or a calibrated propeller Hence the powers given are nett powers which include the friction of pedals, bearings and, in some cases, chains Therefore, if only a little extra shafting or gearing is needed between this basic machinery and the rotor, only two or three per cent need be deducted to obtain the power available at the rotor head

The essential results that came from these tests were as follows

(1) Considerably more power is available from a person's arms and legs than from legs alone In other words, it is not possible to direct a person's entire power to the legs alone

(2) Rowing is an inefficient method of producing manpower

(3) Circular pedalling motion is the best method for producing manpower so far discovered

(4) The optimum speed for pedalling is of the order of two revolutions per second

(5) The power available for continuous work is only about one-third of that available for short periods of the order of a few seconds

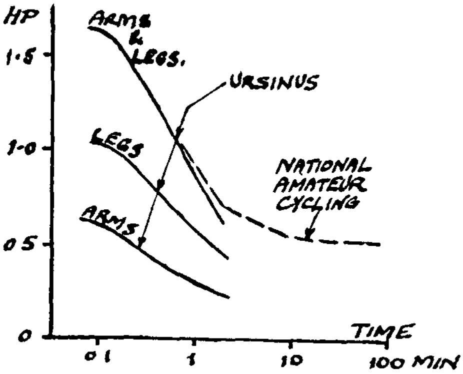

Fig 1 Power available

Fig 1 gives basic information in the form of man-power available against duration, pedalling at the optimum rate The results are for an average young man, and trained cyclists can do better as is shown by tests reported by Nonweiler (7) The tests he refers to were made on cyclists, keen but not professional, cycling over periods of the order of an hour The average speed around a closed circuit of a few miles (airport perimeter track) was carefully measured The cyclist and cycle were then placed in a wind tunnel and the drag measured at the same average airspeed From this the nett power output was calculated These results are not inconsistent with the Ursinus/Gropp data although they do show a somewhat higher power for legs alone

To summarize on the power available, one man can produce for take-off conditions (short spurt of effort for, say, five seconds) at least 1 6 horsepower using both arms and legs He can also cruise for 90 seconds with a legs' output of at least 0 5 horsepower or at least 0 74 horsepower with both arms and legs

POWER REQUIRED

To discuss the power required for flight, it is necessary to estimate the probable weight of a rotor system and associated structure and then, making reasonable assumptions about the aerodynamics, work out the hovering and forward flight performances

It is easy to make a weight estimate, but it is less easy to make a convincing one For this reason, the writers have chosen to take the actual weights achieved on a fixed wing aircraft intended for man-powered flight (2) and work from these rather than scale down existing larger and heavier rotor systems requiring many times the power available in the case under consideration

In addition, the alternative and ridiculous assumption that the man-powered helicopter has zero weight has been considered

The other way to do this job would be to make an analysis of a family of helicopter projects systematically varying in characteristics so that an optimum could be discovered Although this method is well recognised, the writers have decided against it and used what they consider to be the most down-to-earth approach, even if it leaves them there

In addition to simple direct man-powered flight, the effect of short-term power storage has been estimated on the assumptions of the use of a flywheel and alternatively by using Nonweiler's scheme of bunjy in tension

WEIGHT ANALYSIS

Seehase's man-carrying aircraft is sketched in Fig 2 The lightweight metal, wood and fabric wing construction gave the low weight of 1 kg /m^{2} or 0 205 lb /ft^{2} (*cf* Nonweiler's estimated value of about 0 46 lb /ft^{2} for a higher aspect ratio, unbraced wing with a ply skin) Preliminary estimates of the performance of the rotary-wing equivalent suggested that a rotor radius equal to the semi-span of the wing would give a reasonable disc loading, while the chord might be reduced to one half of that of the aeroplane wing Details

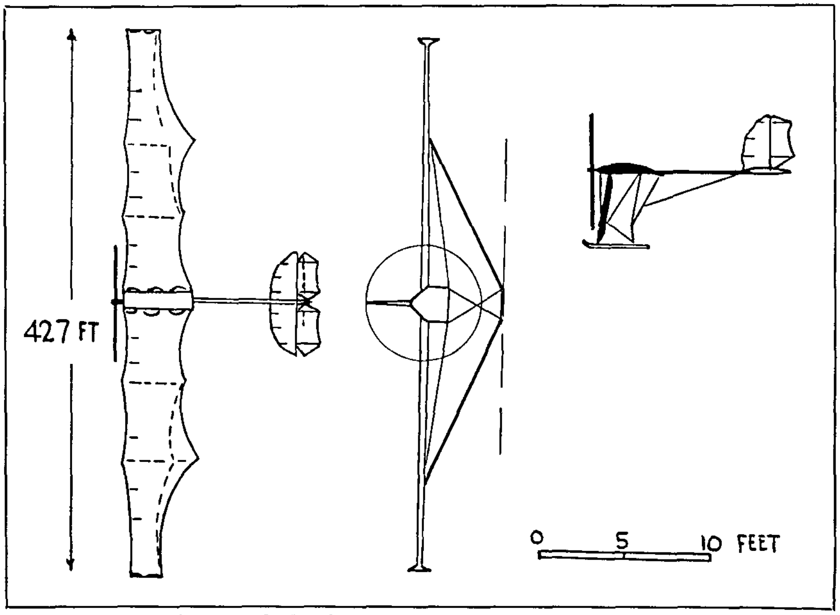

Fig 2 Seehase's man-powered aeroplane 3-view

are also given in Ref 2 of the weights of some other components as well as some constructional details and this allows an approximate weight analysis of the rotary wing aircraft to be developed It is assumed that directional control and torque balance of the main rotor is obtained by use of a tail rotor of which the thrust can be varied (by warping the flexible blade) Longitudinal and lateral control is by cyclic variation of the blade lift by a similar aileron to that used by Seehase, the cyclic movement being applied through a swash plate which is directly moved by a hanging stick

The following table gives weight estimate (in lb) for some man-carrying aircraft

	Aeroplane			*Helicopters*	
	Nonweiler	*Seehase*		*One-Man*	*Two-Man*
	lb	lb		lb	lb
Wing Struts	77	33 8 } 41	Main rotor	40	65
Tail	10	(7)	Tail rotor	7	10
Body	50	(13)		13	20
Controls	5	(3)		3	5
Transmission	10	(8)		16	25
Propeller	10	(7)		—	—
Contingency	8	—		—	—
EMPTY WEIGHT	170	79		79	125
Crew	300	155		155	310
TOTAL WEIGHT	470	234		234	435
$\frac{\text{Empty Weight}}{\text{Total Weight}}$	0 36	0 34		0 34	0 29

The first column (from Ref 1) is included for comparison The second column (taken from Ref 2) gives data on Seehase's actually constructed man-powered aeroplane The third column is the estimated weight of the parallel helicopter sketched at Fig 3 The last column is a rough estimate of the weight of a two-man helicopter to which reference will be made later

Detailed design analysis of the helicopters would probably show an under-estimate in some items, which might be expected to be offset by the availability of improved materials since 1923 when Seehase's aeroplane was constructed However, the helicopter weight estimates probably represent the lowest that could be achieved in practice

With half Seehase's wing chord for the two-bladed rotor the plan view is as Fig 2 giving a blade area of about 70 ft ^{2} and a disc area of 1,440 ft ^{2} Whence

Blade Loading $w_b = 3\ 35$ lb /ft ^{2}
Disc Loading $w = 0\ 17$ lb /ft ^{2}

POWER REQUIREMENTS WHILE HOVERING

Using a rather high camber on the blades, and a thickness of 12–15 per cent of the chord, despite the low Reynolds Number a section $C_{L_{max}}$ in excess of unity should be obtainable Ref 1 gives data for NACA 64 and 65 Series wings showing $C_{L_{max}}$ as high as 1 4 at Reynolds Numbers as low as

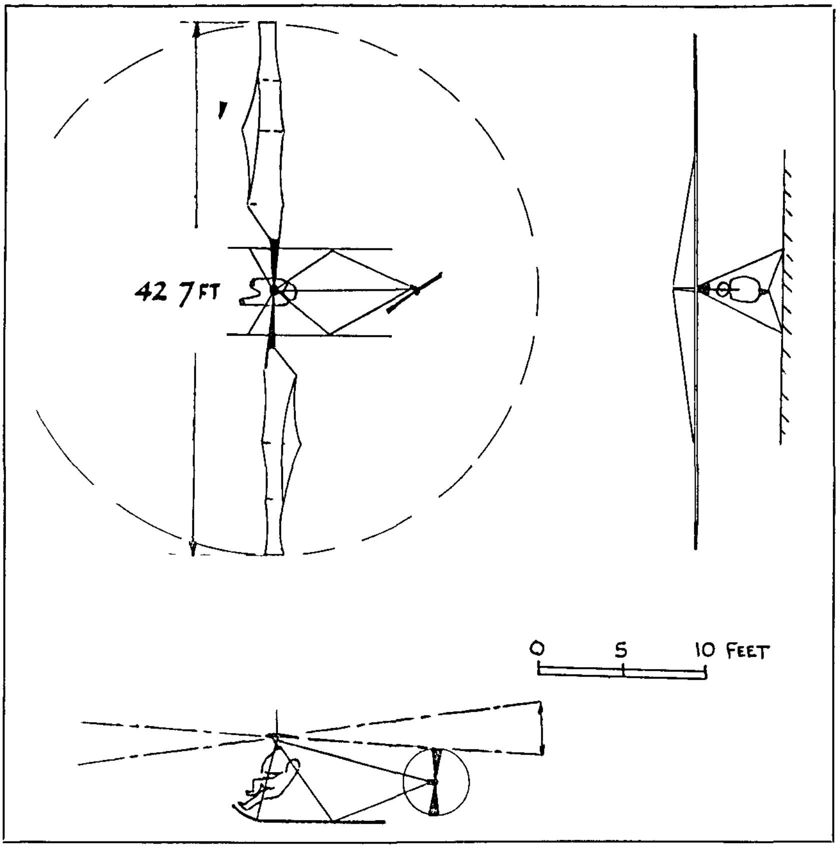

Fig 3 Man-powered helicopter 3-view

0 7 m However, some margin for non-steady flight manoeuvres and gusts is required, so assume a mean blade lift coefficient $C_{L_b} = 1\ 2$

Then

$$C_{L_b} = \frac{0\ 252 w_b}{v_{ti}^2} = 1\ 2$$

where v_{ti} is the indicated tip speed in 100 fps

Whence the tip speed is 84 fps and the rotational speed is 0 63 rps At 0 75 radius the Reynolds number will be about 0 6 m

From Ref 1 the profile drag coefficient, C_{D_b}, of an NACA 64 Series aerofoil with design $C_L = 1\ 0$, and at Reynolds Number of 1 0 m , is 0 0147 at $C_{L_b} = 1\ 2$ Allowing 10 per cent increase for imperfections in section, etc , and making an allowance for the lower mean Reynolds Number $C_{D_b} = 0\ 0175$ is estimated

The power required to hover is given by

$$\frac{\text{Rotor Horse Power}}{\text{1,000 lb weight}}\sqrt{\sigma} = 5\ 4\,\frac{v_{ti}^3}{w_b}(100\ C_{D_b}) + 26\ 5\,\sqrt{\frac{w}{\sigma}}$$

(The first term on the RHS being the rotor profile power and the second the induced power)

i e at sea level

$$\frac{\text{Rotor Horse Power}}{\text{1000 lb weight}} = 5\ 4 \times \frac{0\ 60}{3\ 35} \times 1\ 75 + 26\ 5\sqrt{0\ 17}$$

$$= 1\ 7 + 10\ 9 = 12\ 6$$

Whence for an all-up-weight of 244 lb the Rotor Horse Power required to hover is 3 08

The power absorbed by the anti-torque rotor for the layout sketched in Fig 3 is estimated to be 1 0 H P This high value results from the relatively short tail arm and the relatively high tail rotor disc loading Reduction in the tail rotor power would involve increasing the length of the body (which would require a good deal of weight if it were to be stiff enough) and an increase in rotor diameter is precluded by geometry The use of co-axial rotors is rejected on the ground of weight and complication It seems probable that the cost of balancing main rotor torque is fairly indicated by the above estimated value

Forward Flight

As the forward speed of the aircraft increases, the retreating blade will tend to stall Assuming that the blade is twisted in optimum fashion, then

$$\frac{C_T}{\sigma_e} = 0\ 137\ C_{L_b} \text{ (Ref 3)}$$

$$C_T = \frac{T}{\rho V^{2t}\pi R^2} \text{ and } \sigma_e \text{ is effective solidity)}$$

Then from Ref 4, taking body drag/lift $\lesssim$ 0 1 (to allow principally for forward acceleration, the parasite drag at the low forward speeds with which we are concerned being small) and taking the calculated tip incidence of 12° as the criterion for the onset of vibration we have (where μ is the ratio of forward speed V to the tip speed V_t)

μ	0	0 1	0 2	0 3	
C_T	0 164	0 123	0 089	0 062	
C_{L_b}	1 2	0 90	0 65	0 45	
V_t	84	97	114	137	fps
V	0	9 7	22 8	41 1	fps
	0	6 6	15 5	28 0	mph
$100\ C_{D_b}$	1 75	0 85	1 0	1 15	

In forward flight the power required is given approximately by

$$\frac{\text{Rotor Horse Power}}{\text{1,000 lb Weight}} = \underbrace{5\ 4\frac{v_{t1}^3}{W_b}(1 + 4\ 6\mu^2)(100\ C_{D_b})}_{\text{(Rotor profile)}} + \underbrace{4\ 15\frac{w}{v_1}}_{\text{(Induced)}}$$

$$+ \underbrace{0\ 18\left(\frac{D_{100}}{\text{1,000 lb Weight}}\right)v_1^3}_{\text{(Body Parasite)}}$$

Where v_1 is the equivalent forward airspeed in 100 fps and D_{100} is "Body" drag at 100 fps (assumed to be 50 lb)

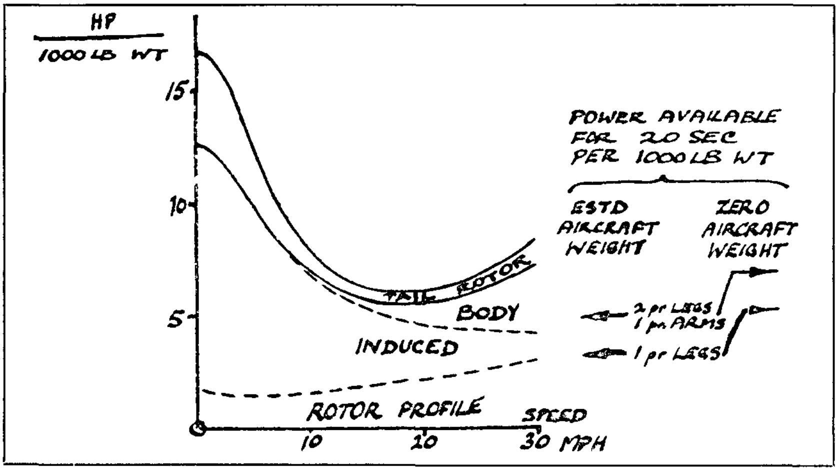

Fig 4 Power for steady level flight

The analysis of $\left[\dfrac{\text{Rotor Horse Power}}{\text{1,000 lb Weight}}\right]$ is then

Forward speed (mph)	0	6 6	15 5	28 0
Rotor Profile	1 7	1 4	1 9	2 6
Induced	10 9	7 2	3 3	1 7
" Body " parasite	0	0	0 4	2 6
Main Rotor	12 6	8 6	5 6	6 9
Tail Rotor	4 1	1 7	0 6	0 8
	16 7	10 3	6 2	7 7

These results are plotted in Fig 4 Neglecting transmission losses, the power required to hover by the 244-lb one-man helicopter is about 4 h p, while the power required to fly level at about 15 m p h is about 1½ h p On the right of Fig 4 the power available from the one-man helicopter (one pair of legs only) for a 20-second period is seen to be inadequate to allow the aircraft to fly level even if the weight of the helicopter is zero Assuming two men (one pair of arms, two pairs of legs) the power available is sufficient for level flight if the weight of the helicopter is very small, and in any case less than that of the estimated two-man helicopter quoted in the earlier Table

GROUND EFFECT

From Ref 5, if the rotor is near the ground, the thrust is increased and the power reduced as follows

	Thrust increment	*Power decrement*
Rotor 10 ft above ground	20%	18%
Rotor 20 ft above ground	6%	6%

For a given weight, the power required could be reduced by as much as one-third if the helicopter is hovered near the ground

USE OF ENERGY STORE

Assume that a flywheel weighing 10% of the all-up-weight of the aircraft and with a radius of gyration of 1 ft is installed

For an angular velocity of w the flywheel energy will be

$$\frac{\frac{1}{2} \times 23\ 4}{32\ 2}\,\omega^2 = 0\ 37\omega^2 \text{ ft lb}$$

It would be an elegant solution if the rotor itself could be used as the flywheel However, with the geometry assumed, to store the same energy it would be necessary to run the rotor up to $2\frac{1}{2}$ times the speed needed to hover Even at zero lift this would require more power than is needed to hover

Assuming that the pilot with legs alone can supply 0 5 horse-power for 90 seconds (Fig 1), working at an average 80% efficiency for one minute the flywheel could store 13,000 ft lb and $\omega = 190$ rdn/sec, *i e* 30 rps Assume that a clutch mechanism can be designed to engage the flywheel and transfer its energy into the rotor (which is required to rotate at about 2% of the flywheel speed) for a further 10% of the aircraft weight To accelerate the rotor to a speed of about 5 4 rdn/sec will require about $\frac{40}{64\ 4}(15)^2(5\ 4)^2 = 4{,}100$ ft lb (if the rotor radius of gyration is 15 ft) To raise the aircraft (now weighing

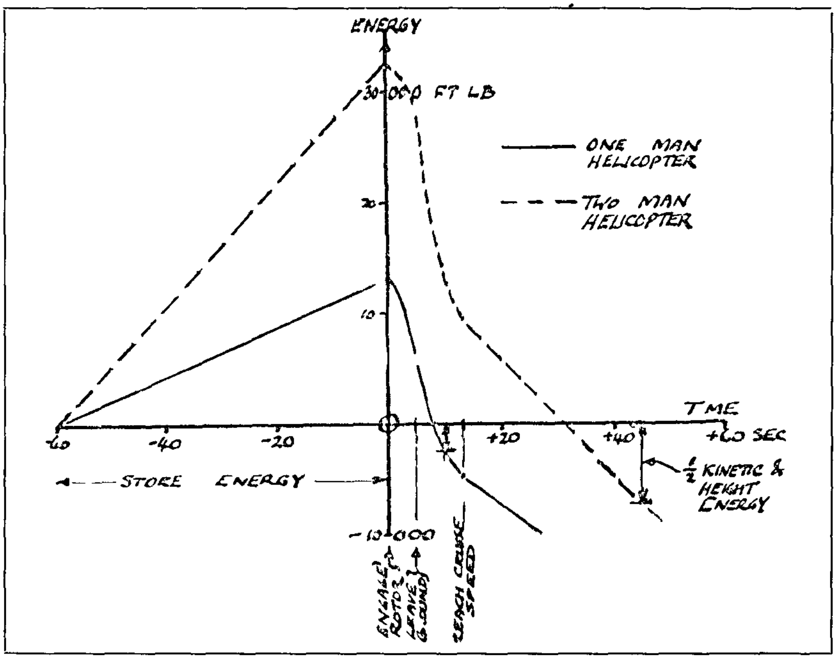

Fig 5 Energy vs time

293 lb) about 5 ft off the ground will take about 1,500 ft lb of energy To accelerate it at about 3 fps/sec to the minimum power speed (of, say 24 fps) will take 8 sec and $\frac{293}{64\ 4} \times (24)^2 = 2{,}600$ ft lb

Fig 5 shows a plot of the energy balance for the one-man helicopter (solid line), while Fig 6 shows the corresponding power required Use is made of Fig 4 to estimate the horse-power required for steady flight at any speed, the increased weight of the helicopter with flywheel being taken into account This method is crude, but since the helicopter of Fig 3 was not optimised for its weight, there is an even chance that the 20% increase of total weight due to the addition of the energy store raises or lowers the power/weight requirement of Fig 4

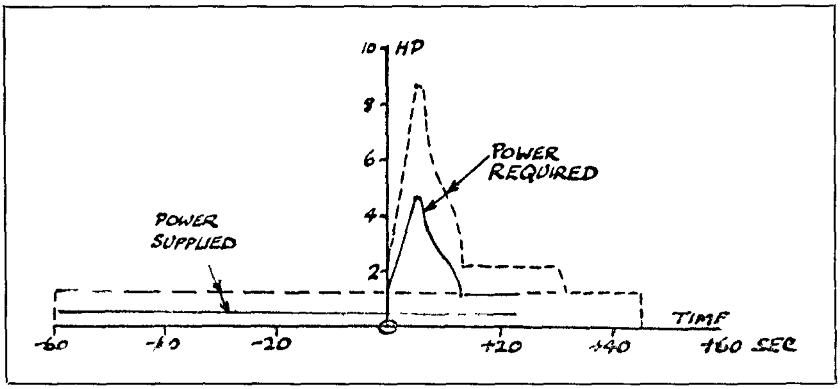

Fig 6 Power vs time

The " flight plan " would be as follows

(*a*) Store energy for 60 seconds
(*b*) Engage rotor and leave ground 5 seconds later
(*c*) Accelerate and climb to about 2 ft in 3 seconds
(*d*) Decelerate and touch down in 2 seconds, assuming that half the rotor and translation of kinetic energy and height energy are available to prolong flight during this phase through appropriate operation of the cyclic and collective pitch controls The overall effect is a flight of about 30 ft for about 5 seconds' duration after 65 seconds of steady working at the pedals

Also shown on Figs 5 and 6 is the energy balance and power required by a two-man helicopter (broken line) It is obtained on the simple assumption that the power available is increased by 2 48 times while the total weight only increases 1 85 times In this case, flight is more prolonged, being of 40 seconds' duration in which about 700 ft is covered, most of it about 5 ft above the ground

The problems involved in a clutch and gearing to transmit energy from the flywheel to the rotor in a controlled manner are obviously considerable The helical rubber spring power store of Ref 1 would be worth consideration Its weight might be lower than that of the flywheel and clutch assumed above

GROUND RUN WIND

If the helicopter could be pedalled along the runway until the minimum power speed was reached, the power-required peak of Fig 6 would be reduced This would require the added weight of an undercarriage and additional transmission , the nett saving might be small The presence of a quite modest breeze would serve to reduce considerably the energy required for flight However, difficulty of control in unsteady wind conditions would limit the extent to which advantage could be taken of natural wind

CONTROLS

The additional collective pitch control undoubtedly would make the task of the pilot more difficult than in the case of the man-powered aeroplane, particularly as his feet are occupied in pedalling

It was suggested above that rotor cyclic pitch should be handled through a hanging stick There remains collective pitch, control over the transfer of energy from the store to the rotor (" throttle ") and directional control It is suggested that these last three could best be combined for operation by the left hand The axis would be vertical, rotation giving directional control, up and down movement, collective pitch and fore and aft movement " throttle "

The acquisition of the necessary skill to co-ordinate these complicated movements in a changing situation will obviously present a difficult task to the pilot, particularly as at the same time he will be pedalling hard with his legs The complication of unsteady wind conditions would be likely to make it an insuperable task initial practice indoors out of gusts is indicated

CONCLUSION

The answers given above are not encouraging and there seems little prospect of achieving man-powered flight by using rotary wings This is not surprising when it is realised that man-powered flight, even with fixed wings, has not yet been achieved, although it is probably just possible at the present state of aerodynamic and structural development The advantages of the rotary wing arrangement are the zero or short take-off run and slow forward speed These advantages are not achieved without cost, and minimum power requirements for flight are in general higher for helicopters than for fixed-wing aircraft If man-powered flight were easy with fixed wings, the rotary wing would have a better chance At this stage of development, no future for the man-powered helicopter can be discerned To make such flight and future possible, the following developments would have to occur and their problems be solved

(1) Lower structure weight than now seems practicable
(2) Light power store and means of engagement with the rotor
(3) Simple and efficient transmission design to minimize frictional losses
(4) Construction and control techniques applicable to very light, low rigidity rotors

For the scales of size and speed here envisaged, these developments will not occur unless positive action is taken It may be that the Helicopter Association of Great Britain should encourage such action, since it has encouraged the writing of these papers, which no doubt if taken all together should give a sound appreciation of the present situation and provide a springboard for a dive into the future

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BOOK REVIEW

Helicopter Dynamics and Aerodynamics

P R Payne, Pitman, London, 1959

442 pp 84s

The increase in knowledge in any field is a slow process and early attempts to present a comprehensive survey are rarely successful In this volume, which is of some interest to those engaged in helicopter design, Mr Payne has tried to cover a very wide field and although he has achieved in some ways a very commendable result, it is doubtful whether he has been too successful

True, the general standard both of writing and production is high, but to be a complete success a book of this kind must be completely reliable No technologist likes to feel that there may be a doubt about the equations he is using or to wonder whether there is a fundamental error somewhere Proof reading of a high quality can eliminate typographical errors (a few still remain here and there in this book) but the author must take responsibility for errors of a general nature Unfortunately, these also exist in this book As an example of this, in the discussion of the blade motion in a gust in forward flight the author, faced with solving an equation with a cyclic damping term blandly averages it out Further, having gone to some lengths to develop the blade stability equation (5 7), he does not use it to study the gust case in forward flight but cites a report which omits some of the terms (5 16)

The performance section of the book is the use to which most readers will refer Here the author has tried to present yet another method of analysis In principle this is a good idea although most technicians have already tended to freeze on one or other of the existing techniques However, the section on presentation of performance curves leaves the reader with the impression of being patently unsatisfactory There is an art in representing data graphically It involves reducing information to the simplest form and avoiding presenting data in any way which is likely to obscure the trends which should be accentuated This is certainly not the case here—a most surprising situation in view of the large number of excellent explanatory diagrams sprinkled throughout the book

To compensate for some of the occasional lapses, it is refreshing to observe the author's careful study of many aspects too often ignored or taken for granted In this respect Mr Payne has really excelled himself

To sum up, this is a book which will provoke much discussion and some interest but is unlikely to find a permanent place among the other established books on helicopters