HELICOPTER RESEARCH

a review of outstanding problems together with an account of some recent work at A & A E E

By

F O'HARA, M A (Member H A G B)

SUMMARY

In the first part of the paper a brief review is made of major items for research in the helicopter field, the subjects touched on including rotor aerodynamics, stability and control, evaluation of configurations, vibrations and fatigue, and operational aspects An outline is given, in the section on stability and control, of work being done at A & A E E in connection with the assessment of the longitudinal handling characteristics of helicopters The second part of the paper contains an account of recent work at A & A E E on the low speed and take-off performance of a helicopter An empirical method of low speed performance estimation is described, and the variation with wind speed of the ground effect on a rotor is discussed theoretically and on the basis of experimental results A theoretical analysis of the forward take-off motion of a helicopter is briefly presented, and the final section is concerned with the performance of a multi-engine helicopter in the event of failure of one engine, with particular reference to the possibility of safe operation from the type of site proposed for civil use

1 *Introduction*

This paper was originally intended to consist wholly of a general review of the current position in the helicopter research field, with particular emphasis on aspects on which a major effort is at present required A comprehensive paper on a subject of this kind, however, tends to degenerate into largely a catalogue of numerous items and I have chosen, therefore, to devote the first half of the paper only to what appear to me to be major items for research in the general field , the items selected are treated very briefly except in the case of stability and control, the section on this subject including an outline of work at present being done at A & A E E in connection with

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the assessment of helicopter handling characteristics The second half of the paper is devoted to an account of work in a rather specialised field, that of the low speed and take-off performance of a helicopter, which we have recently been doing at A & A E E

Work is known to be already in progress at various centres on some of the aspects high-lighted in the review to be given here of helicopter research items, and it is to be hoped that contributions will be made in the discussion to follow this paper on recent advances in knowledge both on these items and on other problems considered of outstanding significance in the helicopter field A more detailed treatment of some aspects has been given recently by R H MILLAR in his paper to the Anglo-American Aeronautical Conference on " Some factors affecting helicopter design and future operations " (Ref 1)

PART I

MAJOR ITEMS FOR RESEARCH

2 *Rotor aerodynamics*

On a single rotor helicopter, the rotor thrust provides lift, forward propulsive force and control moments , the thrust is produced by giving a downwards and backwards momentum to the air An illustration of the force system in the longitudinal plane of the helicopter is given in Fig 1,

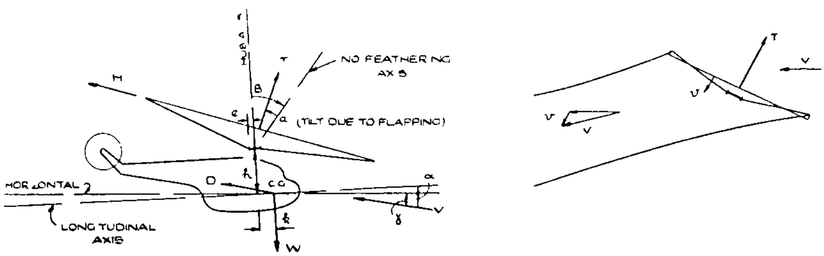

FIG 1 HELICOPTER LONGITUDINAL FORCE SYSTEM AND AIRFLOW RELATIVE TO ROTOR

together with a diagram showing the airflow relative to the rotor in forward flight , the significance of the rotor angular co-ordinates is indicated later in a theoretical discussion of stability and control (Section 3) The forces on the rotor blades, and the general motion of the blades, which determine the blade stresses, and basically govern the helicopter's flying characteristics, are dependent on the distribution of the induced velocity over the rotor On a multi-rotor helicopter such as the now common tandem configuration, the performance and stability are in addition affected by the interference at the aft rotor from the downwash of the front rotor

The actual induced flow distribution through a rotor is therefore important, but early analytical work dealing with the aerodynamic loading of a rotor was for simplicity developed on the assumption of a uniform induced velocity over the rotor Various attempts have now been made to give a more accurate analysis of the downwash , the most realistic appears to be that by Mangler (Ref 2), who has derived the induced velocity fields for various assumed pressure distributions over the rotor area Mangler's analysis shows considerable downwash variation over the rotor, and the possible importance of this has been shown in a later investigation of rotor blade stresses, by Daughaday and Kline in America (Ref 3) They observed large periodic forces of frequencies up to ten times that of the fundamental rotor frequency (high frequency forces are of course significant from the point of view of fatigue) and comparison of the experimental results with values estimated from one of Mangler's downwash distributions indicated that the primary source of the higher order of blade force excitations was probably downwash variations

Much more information is required however on the actual induced velocity field of a rotor and on the aerodynamic loading of rotor blades This does not appear to be the type of investigation which can be made in quantitative terms in flight tests and the most likely method seems to be by wind tunnel tests , a study of downwash distributions is particularly required at the present time for tandem rotor arrangements as well as for single rotor layouts An alternative method of determining the aerodynamic loading distribution is by means of pressure plotting on a rotor blade and some useful results have already been obtained in this way at M I T in America (Ref 4) It should be possible in this way to determine something of the effect of the aerodynamic interference between the blades of a rotor and of varying the number of blades , the theoretical analysis referred to above is still limited to the assumption of a flat disc with effectively an infinite number of blades

It is pertinent at this stage to point out that there is great scope for development in the application of wind tunnel testing in helicopter research There is as yet not a great deal of information available on the general techniques to be used, and such questions as the minimum size of rotor for reliable results, and the correlation of wind tunnel and full scale characteristics require further investigation

Other aspects of rotor aerodynamics at present relatively unexplored include the effect of variations in rotor geometry or layout, like the use of offset blade hinges, and of different control arrangements such as the servo tab system, on rotor blade loading Insufficient is known also of rotor operating limitations, including the effects of blade stalling and compressibility, and of operation at high tip speed advance ratios

3 *Stability and control*

The stability characteristics of helicopters are not yet satisfactory and their operational use has been in consequence restricted, particularly in blind flying conditions Efforts have been made to improve the stability by the use of such devices as the Bell stabiliser bar and the Hiller servo rotor, but recently on larger machines, the trend appears to be towards auto-stabilisation

Much basic work has been done to analyse the stability and control characteristics of helicopters and to study ways in which the stability may be improved The stage now appears to have been reached where more attention should be given to developing methods to assist in designing helicopters with selected handling properties , in support of this, more information is first required on desirable handling qualities for helicopters Some notable work on the flight assessment of handling qualities has been

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done at N A C A (Ref 5) and the test there proposed for assessing longitudinal manoeuvre stability, based on the shape of the acceleration-time curve, is now widely known Acceptable characteristics depend on a "divergence requirement" that the normal acceleration-time curve shall become concave downwards within 2 seconds, and an "anticipation requirement" that the slope of the curve must be positive until the maximum acceleration is achieved However, this test is of a fairly complex nature and it appears desirable if possible to make a quantitative assessment of the characteristics in simple manoeuvres like a pull-out or turn

An effort is at present being made at A & A E E to correlate pilots' impressions and quantitative measures of the simpler aspects of handling on a single rotor helicopter For the longitudinal motion in forward flight, an analysis has been made similar to that developed by Gates for fixed-wing aircraft (Ref 6) We start from the fact that the general longitudinal dynamic stability of a helicopter can be shown to depend on the roots of the standard form of stability quartic (Ref 7),

$$\lambda^4 + B\lambda^3 + C\lambda^2 + D\lambda + E = 0$$

where B, C, D, E are functions of the aircraft inertia and aerodynamic characteristics

The mathematical conditions for a stable dynamic motion include the requirement that the coefficients B to E should be positive The condition for static stability in a steady state of motion is simply that E should be positive From the general forms of the aerodynamic derivatives it is found that

$$E \backsim -\frac{dC_m(\alpha, V)}{dC_T}$$

subject to the condition for steady flight equilibrium that

$$\frac{dV}{dC_T} = -\frac{V}{2C_T}$$

where C_m and C_T are the pitching moment and thrust coefficients respectively

The static margin for a helicopter can therefore be defined in the same way as for a fixed-wing aircraft as

$$K_n = -\frac{dC_m(\alpha, V)}{dC_T}$$

Further, the actual static margin can be determined from the variation with speed in flight tests of the longitudinal cyclic pitch control application B_1 B_1 is in fact the longitudinal tilt of the control plane of the rotor, which results in an equal tilt of the no feathering axis of the rotor, forward tilt being produced by a forward movement of the control , because of blade flapping due to forward speed, the rotor plane and therefore the thrust vector are tilted back by an angle, a_1 (see Fig 1) The pitching moment equation for steady trimmed flight may be written,

$$C_m = O = -C_T\left[(B_1 - a_1)\frac{h}{R} + \frac{k}{R}\right] + C_H\frac{h}{R} + C_F - C_S\frac{e}{R}(B_1 - a_1)$$

where h, k are the C G distances below and forward of the rotor head ,

C_H is the transverse force coefficient and C_F the fuselage pitching moment coefficient,

C_S is the blade centrifugal force coefficient and e is the blade flapping hinge offset

It follows that, for constant pitch,

$$K_n = -\left(\frac{dC_m}{dC_T}\right)_{B_1} = -C_W\left(\frac{h}{R} + \frac{C_S}{C_W}\frac{e}{R}\right)\left(\frac{dB_1}{dC_T}\right)_{C_m = 0}$$

$$= \left(\frac{h}{R} + \frac{C_S}{C_W}\frac{e}{R}\right)\frac{V}{2}\left(\frac{dB_1}{dV}\right)_{C_m = 0}$$

Illustrative examples of cyclic pitch to trim and the corresponding static margins are shown in Fig 2 For the pilot, the static margin is a measure of the change of stick position to trim in steady flight at a speed differing from the original trimmed speed, and a positive static margin results in a forward stick displacement for a higher speed The manoeuvre characteristics however are probably of still greater importance to him, and here, as a first step, we have considered accelerated motions at constant speed and have shown that, as for fixed-wing aircraft, a pitching divergence in a quick manoeuvre is not to be expected if the coefficient C in the stability quartic is positive Now

$$C \backsim -\frac{dC_m(\alpha, q)}{dC_T},$$

with the condition for steady acceleration at constant speed

$$\frac{dq}{dC_T} = \frac{V}{R}\frac{1}{2\mu_1},$$

where q is the rate of pitching in the longitudinal plane and

$$\mu_1 = \frac{W}{g\rho R\pi R^2}$$

The manoeuvre margin for a helicopter may therefore also be defined in the same way as for a fixed aircraft, namely by

$$H_m = -\frac{dC_m(\alpha, q)}{dC_T}$$

The stick fixed manoeuvre margin can be determined from the observed variation of the longitudinal cyclic pitch with normal acceleration in near level flight at the same speed, the acceleration increment is assumed to be ng and the rotor thrust (n + 1)W approximately Then from the pitching moment equation for trimmed accelerated flight

$$H_m = -\left(\frac{dC_m}{dC_T}\right)_{B_1} = -C_T\left[\frac{h}{R} + \frac{C_S}{C_T}\frac{e}{R}\right]\left(\frac{dB_1}{dC_T}\right)_{C_m = 0}$$

$$= -\left[(1 + n)\frac{h}{R} + \frac{C_S}{C_W}\frac{e}{R}\right]\left(\frac{dB_1}{dn}\right)_{C_m = 0}$$

The latter equation shows the relation of H_m to the cyclic pitch application per g, a positive value of H_m results in a backwards movement of the stick for a pull-out

Flight data for dB_1/dn cannot be satisfactorily determined in pull-outs if the steady acceleration is not achieved in the time taken for the manoeuvre It appears easier to obtain satisfactory results in steady turns and the control application required in a pull-out can then be determined by making allowance for the effect of the difference in the rate of pitching in the two states Thus

$$(B_1)_{\text{pull-out}} = (B_1)_{\text{turn}} + \frac{16g\,(C_T - C_W)}{\gamma\,\Omega\,V\,C_T}$$

where γ is Lock's inertia number,
and Ω is the rotor speed,

and

$$H_m = -\left[(1+n)\frac{h}{R} + \frac{C_S}{C_W}\frac{e}{R}\right]\left[\left(\frac{dB_1}{dn}\right)_{\text{turn}} + \frac{16g}{\gamma\,\Omega\,V\,(1+n)^2}\right]$$

To eliminate some of the secondary pitching moment effects from the main and tail rotors it is convenient to take mean values for B_1 from turns made in both directions If the flight path deviates markedly from level flight

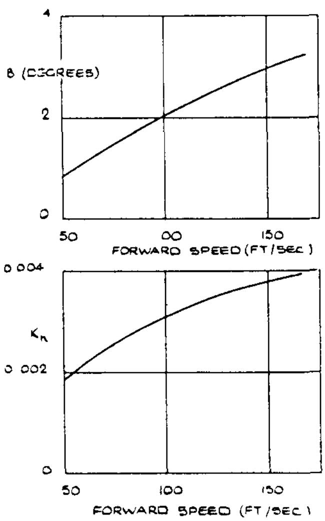

FIG 2 LONGITUDINAL TRIM AND STATIC MARGIN CURVES

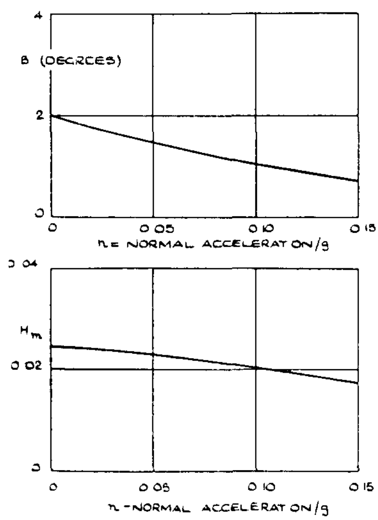

FIG 3 STICK POSITION AND MANOEUVRE MARGIN VARIATION WITH ACCELERATION

it may also be necessary to make allowance for product of inertia pitching moments Illustrative examples of curves of cyclic pitch and manoeuvre margin are shown in Fig 3 The practical significance of the maneouvre margin in helicopter testing has not yet been assessed and it may still prove necessary to make use of the time-history of acceleration

The suggestion has recently been made that rate of pitch might be a better criterion of manoeuvrability than acceleration because extreme change of attitude is frequently the disturbing feature in a manoeuvre Acceleration and rate of pitch, however, are not independent , in the type of pull-out we have considered, for example,

$$q = \frac{ng}{V}$$

Thus at high speed the rate of pitch is normally small and the pilot probably more conscious of acceleration, but at low speed the pitching rate may be large when n is small, and more important to the pilot

Considering again the general stability field, the theory so far developed applies on the whole to stick fixed conditions, and refers to control displacements , there is a real need for extension of the theory to the stick free domain, to analyse stick force characteristics, which are probably of greater importance to the pilot, particularly in blind flying conditions

Some proposed developments in control arrangements require investigation There is growing interest for example in the use of combined rotor and elevator controls and a general study of such systems is required, particularly in manoeuvres at high speeds Understanding of the problems involved in combined control systems will be required if convertiplane projects are to be tackled

4 *Evaluation of helicopter configurations*

In the early days of helicopter development, attempts were made to develop helicopters of many and varied configurations The field has now been narrowed down considerably but there are still aspects requiring systematic study and evaluation to provide guidance for future development The relative merits of single and multi-rotor systems, for example, require impartial investigation , the interference effects with tandem rotor arrangements are of particular interest, and experience with the Bristol 173 should provide valuable information on this point Estimates for a representative twin rotor helicopter of the variation of the interference losses with rotor gap and stagger are given in Fig 4 , for comparison the power required for torque reaction on an equivalent single rotor machine is also included The tandem arrangement without overlap appears more efficient than the single rotor in hovering but is less efficient even at fairly low speeds , overlapping reduces interference losses at higher speeds but is less efficient in hovering For an overall assessment of the configurations other factors have of course to be taken into account

Rotor design itself requires continual study, with emphasis on aspects like increased disc loading, the number of blades, the use of rigid rotors and so on The effectiveness of various schemes designed to permit higher speeds, like second harmonic control, offset hinges, auxiliary fixed wings, forward propellers, should be assessed , possible stability and control problems associated with the various schemes should also be investigated

A study of the various types of rotor propulsive systems would also be of great value and help to define the most favourable applications for piston engines and gas turbines with shaft driven rotors, and for the various pressure and combustion tip jets at present being considered This would enable the necessary impetus to be given with confidence to power plant developments for helicopters, along the most promising lines

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5 *Vibrations and fatigue*

Vibrations are still the cause of considerable difficulty on helicopters Much of the trouble arises from the rotor systems in which freely articulated blades subjected to fluctuating loads are the source of vibration excitations which may be communicated directly through the control system, or may for example result in resonance disturbances in the fuselage Aerodynamic interference between rotors, or from rotor downwash on the fuselage are also possible sources of vibration excitation In addition, mechanical units like the engine, or complex and lengthy transmission systems may be other potent sources of vibration

A low level of vibration is important for crew and passenger comfort, but the vibratory characteristics are of greater significance in their effect on

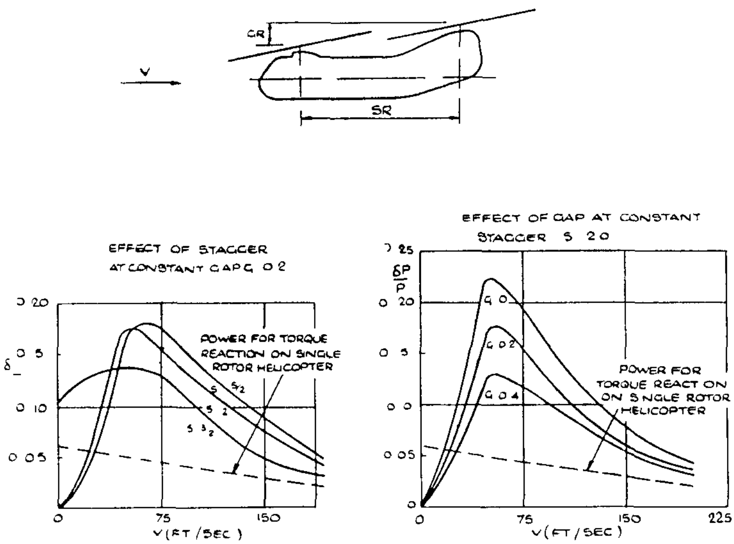

FIG 4 ROTOR INTERFERENCE LOSSES ON TANDEM ROTOR HELICOPTER

fatigue stresses A comprehensive study should be made of the origins and character of helicopter vibrations, with the main aim of providing guidance on how vibration troubles may be avoided At the same time it is important for fatigue assessment to be able to determine the points on the helicopter, and the flight states, in which critical stresses are most likely to occur A general study of rotor dynamics, including aero-elastic effects, is required in this connection

Another type of vibratory disturbance which has caused trouble on several aircraft is the phenomenon known as ground resonance This usually occurs with the aircraft on the ground partly supported by the rotor, and appears to arise from resonance between the motion of the aircraft on its undercarriage and oscillatory in-plane motions of the blades Some theoretical and experimental work has been done on this problem but ground resonance accidents continue to occur and it is clear that ways for controlling

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tendencies to resonance are not yet fully understood for all types of helicopter configuration

6 *Operational aspects*

The wider use of helicopters in both military and civil roles requires operation in blind flying conditions and in all except the most severe weathers Until recently it has been generally agreed that blind flying on helicopters must await improvements in their stability and control characteristics However, while it is still true that further improvements would be of great assistance it now appears that the stage has been reached where instrument flying in a limited flight envelope is at least a near-possibility on some current types of helicopter, providing the question of limited panel flying, in the event of instrument failure, is satisfactorily answered In this connection the possibility of flying with the artificial horizon out of action but with a turn and yaw indicator in addition to the other standard helicopter blind flying instruments is to be investigated The possible application to the helicopter of more recently developed flying aids like the Sperry Zero Reader should also be investigated For instrument flight at low airspeeds, instrument improvements in themselves will hardly be enough, and the only real immediate hope appears to lie in auto-stabilisation of the helicopter

The navigation of helicopters by means of radio aids does not appear to present great difficulties, but such aids may not always be available in military roles Insufficient is yet known of methods of dead-reckoning navigation and of the possible accuracy that may be achieved

Other outstanding operational problems still to be adequately solved include de-icing, blade motion control for rotor starting and stopping in high gusty winds, the suppression of noise for civil operation and so on Some aspects of operation from restricted sites in built-up areas are discussed in Section 11 of this paper

PART II

Low Speed and Take-off Performance

7 *General*

Much emphasis is commonly placed at the present time on the need to increase the speed of helicopters, mainly for the purposes of civil operation and generally on the assumption that the take-off performance is adequate or can be made so in a straightforward fashion by increasing the power However, current employment of helicopters is mainly in military roles and their application in this field is primarily due to their low speed flying properties Reliable methods of determining the low speed performance are particularly important because for most existing and foreseeable types it is at best marginal in some operating conditions

8 *Steady low speed performance*

Methods of estimating low speed performance are required for example in connection with the assessment of vertical take-off performance in different wind speeds In general, the analysis of performance in any flight state depends on knowledge of the induced flow at the rotor, and a mean value over the disc is normally assumed to be sufficiently accurate for this purpose

The simple theory for a single rotor helicopter is based on the momentum theory formula for the rotor thrust

$$T = 2\pi\rho_0 R^2 V_1' v_1$$

where v_1 is the mean induced velocity and V_1' the resultant airflow velocity at the rotor

This equation is in effect a relationship between the induced velocity and the main airstream velocity and the rotor disc incidence. At low speeds however this formula has been found to be inaccurate and to replace it a set of empirical curves has been established from flight data for current single rotor helicopters relating values of v_1/v_T to $V_1 \sin i/v_T$ and $V_1 \cos i/v_T$ where $v_T = (W/2\pi\rho_0 R^2)^{\frac{1}{2}}$ (Fig 5, Ref 8). Theoretical curves from the momentum theory, which are of semi-circular form, are also included in the diagram, and it will be seen that these give lower values for the

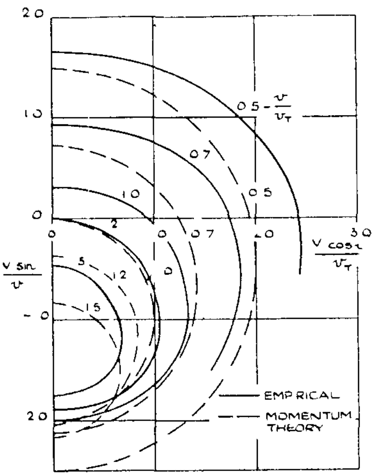

FIG 5 COEFFICIENTS OF INDUCED FLOW AT A HELICOPTER ROTOR

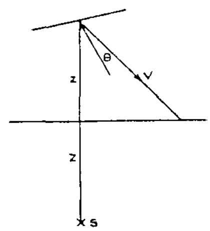

FIG 6 REPRESENTATION OF THE GROUND EFFECT BY AN IMAGE SOURCE

induced velocity for a given climb or level flight condition. To ensure continuity over the speed range the empirical curves have in fact been faired into the momentum theory curves at higher speeds, this was done by plotting the data as curves of constant u_1/v_T [$= (v_1 + V_1 \sin i)/v_T$]

9 *Variation of ground effect with wind speed*

In some roles, such as rescue winching or sonar dipping, the helicopter is required to hover a spot near the ground or sea surface. The power required in these circumstances is affected by the ground cushion effect and although information has been available for some time (Ref 9) on the effect in still air conditions, there has been a lack of knowledge of its variation with wind speed

An indication of the way this effect varies can be obtained from a development of the simple theory proposed some time ago by Betz (Ref 10) for the zero speed case The rotor is replaced by a point source (not a sink as assumed by Betz) of velocity distribution $Av/4\pi d^2$, where A is the rotor area and d the distance from the source, together with an image source at a distance Z below ground level equal to the height of the rotor above it For constant power, there is a reduction of downwash at the rotor due to the image source, and an increase of thrust given by,

$$\frac{T}{T_\infty} = \frac{1}{1 - \frac{1}{16}\left(\frac{R}{Z}\right)^2}$$

where T_∞ is the thrust away from ground effect
Estimates from this formula are in reasonable agreement with the experimental results, although the latter also show variation with rotor disc loading and solidity , some allowance for these effects could be made in the theory

The theory has been generalised for application to low forward speeds by Dr Cheeseman, who suggested replacing the rotor by a form of jet source with variable induced velocity distribution, $3A\ v\ \cos^2\theta/4\pi d^2$, where θ is measured relative to the resultant airflow direction at the rotor, together with an equal image source at a distance Z below ground level (see Fig 6) the source assumed gives a not unreasonable induced velocity distribution with a total flow of Av and satisfies the physical requirement for zero velocity normal to the ground As in the previous case, there is a reduction of downwash through the rotor due to the image source, and a thrust increase at constant power given by

$$\frac{T}{T_\infty} = \frac{1}{1 - \frac{1}{16}\left(\frac{R}{Z}\right)^2 \quad \frac{3}{(1 + V_1^2/v_1^2)}}$$

Estimates from this formula for zero airspeed are greater than from the simpler formula above, and its principal value is in indicating the relative fall-off in ground effect with speed Theoretical estimates made on this basis, given in Fig 7, show a marked reduction with speed in the effect at a given height For comparison, estimates are also included in the ground effect on the lift of a wing in equivalent conditions and this is somewhat larger than the theoretical rotor effect, in the region where the wing theory is valid

Values of T/T_∞ have also now been obtained from analysis of flight test data from different wind speeds near the ground and curves based on the results are given in Fig 8 The experimental results show variation with C_T's, but the mean trend is comparable to the theoretical variation in Fig 7

The significance of these results can be seen from the estimates given for a typical single rotor helicopter in Fig 9, of the power to hover in the ground cushion in different wind speeds Normally away from the ground the power required decreases with wind speed, but very near the ground it may actually increase

10 *The forward take-off of a helicopter*

A helicopter should ideally be capable of ascending vertically from the ground in all conditions but in practice it is often necessary to gain speed before climbing away either because of inadequate vertical climb performance or to provide a greater degree of safety in the event of power failure, and an analysis of the accelerating and climbing motion in a forward take-off has recently been made (Ref 11)

Consider a stage of the motion with the helicopter flying at velocity V at a flight path angle γ to the horizontal, the rotor thrust T acts normal to the disc which is at angle α to the horizontal, the transverse force H is parallel to the disc and the body drag D is assumed to act along the

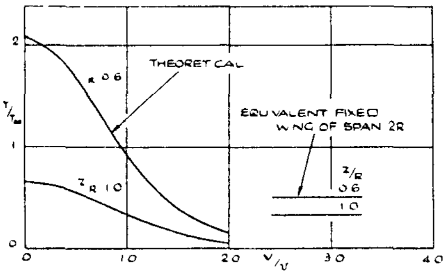

FIG 7 THEORETICAL ESTIMATES OF THE GROUND EFFECT AND COMPARISON WITH FIXED WING THEORY

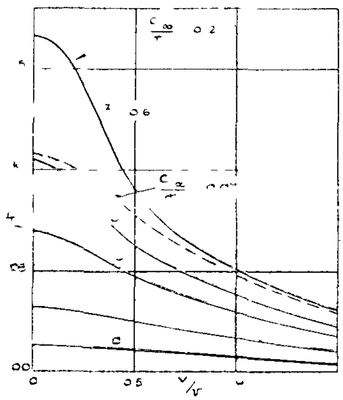

FIG 8 EMPIRICAL CURVES SHOWING VARIATION OF THRUST AT CONSTANT POWER FOR VARIOUS HEIGHTS AND SPEEDS IN THE GROUND CUSHION

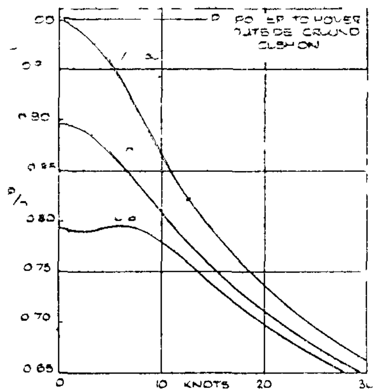

FIG 9 GROUND EFFECT ON POWER FOR A TYPICAL SINGLE ROTOR HELICOPTER

direction of flight (see Fig 1) These forces vary to some extent during the take-off, but the analysis is made in stages in which constant mean values are used In addition during each stage either the disc attitude to the horizontal, or the flight speed, is assumed to be constant The aerodynamic forces can be determined by the normal methods using suitable approximations to obtain the mean values , however, these methods are not discussed here, but only the forms of the motion for known values of the forces

The motion is considered with reference to ground axes, x horizontal forwards and y vertical upwards For flight with constant disc attitude, the equation of motion along the flight path leads to the following relation for the speed range from V_0 to V,

$$Ay + Bx = \frac{V^2 - V_0^2}{2f} \qquad (1)$$

where A, B, f are constant functions of the disc attitude a_m and of the mean forces T_m, H_m, D_m (see List of Symbols)

The equation of motion normal to the flight path may be written,

$$A - \tan\gamma = \frac{V^2}{f}\frac{d\gamma}{dx} \qquad (2)$$

It may be seen that a special solution of (2) is $\tan\gamma = A$ which gives a straight flight path This solution is basically the condition that the resultant force normal to a straight path is zero,

$$T\cos\imath + H\sin\imath - W\cos\gamma = 0$$

where $\imath = (\alpha + \gamma) =$ rotor incidence to the flight path
This special solution applies to the case therefore where the resultant force is along the flight path, and in particular it applies to motion from rest when with the assumption of constant mean forces, the helicopter moves off in the direction of the resultant force Since the path is a straight line

$$\frac{y}{x} = \tan\gamma = A$$

and the distances x, y from V_0 to V follow simply from (1) For $A = 0$, that is in horizontal flight, there is a relation between T and α, namely $T\cos\alpha = W$ approximately, and x can be expressed as a function of T/W, V_0 and V If $T\cos\alpha < W$, the helicopter is not fully airborne and ground friction forces have to be included in estimating the ground run

In the more general case when $\tan\gamma = A$, the solution of equations (1) and (2) give γ, x/S and y/S as functions of $V^2/2fS$, A and B, where S is a function of the initial conditions V_0 and γ_0 (see List of Symbols) The shapes of the curved paths starting from $\gamma_0 = 0$ are shown in Fig 10, for a range of values of A and for $B = 1$ (this corresponds to the case of negligible fuselage drag)

Now consider motion at constant speed This occurs generally in the take-off technique in which the helicopter is accelerated horizontally near the ground up to a speed safe in the event of power failure and then climbed away at this speed During a constant speed stage, the pilot must vary the disc attitude in a way to keep the resultant force along the flight path zero , the equation of force along the path is,

$$T\sin\imath - H\cos\imath - D - W\sin\gamma = 0$$

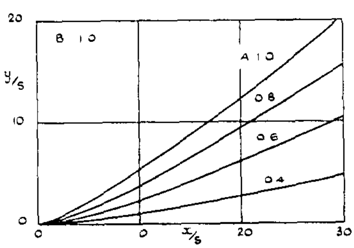

FIG 10 CLIMB AWAY AT CONSTANT DISC ATTITUDE

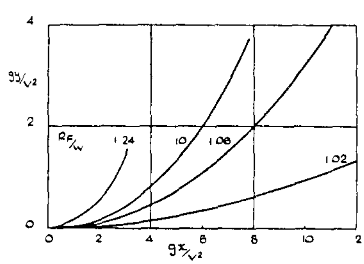

FIG 11 CLIMB AWAY AT CONSTANT SPEED

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This relation together with the equation of motion normal to the path is used to determine the motion, and the solutions are obtained with gx/V^2 and gy/V^2 as functions of γ, T/W and D/W These solutions can be combined to give gy/V^2 as a function of gx/V^2 for a range of values of T/W as in Fig 11, for a specific value of D/W , the curves give an indication of the shapes of the take-off paths from $\gamma = 0$

The above theory is being used for the development of methods of reducing observed take-off data to standard conditions

11 *The performance of a multi-engine helicopter following failure of one power unit during take-off or landing*

It is essential for civil operation that if one engine fails during take-off or landing, the helicopter can either climb away over surrounding obstructions or make a safe landing on the take-off or landing area The type of site proposed for operations in built-up areas is comparatively small, being 300 ft square with a surrounding clearance angle of 1 in 2 Current single engine helicopters cannot operate safely from such sites but no flight data are yet available for multi-engine machines and a theoretical study has been made therefore to assess the possibilities (Ref 12)

An analysis has been made of the performance of a twin engine helicopter, generally comparable to the twin rotor Bristol 173 Its maximum vertical rate of climb is assumed to be 1,200 ft /min , for half power, the steady rate of descent is 1,900 ft /min and the minimum speed to maintain height is 36 knots A sudden cut of one engine is considered during vertical take-off, and in landing including a slow speed approach to 150 ft followed by vertical descent to the ground , a 2 second delay is assumed for completion by the pilot of corrective control action This includes reduction of the blade collective pitch to prevent a large fall-off in rotor speed, and for the climb away case, a forward tilt of the rotor disc—subject of course to overall aircraft control—to produce rapid acceleration to the minimum climb speed

In the transition to climb away the rotor speed may be stabilised below the initial value to reduce the height lost, but for landing a higher rotor speed is desirable for an effective pull-out just prior to touch-down

An illustration of the estimated motion in the transition to climb-away, with a disc attitude of 12°, is given in Fig 12 The rotor speed falls off rapidly in the first 2 seconds and the rate of descent builds up to 25 ft /sec before sufficient speed is developed, climbing flight being achieved at a speed of 38

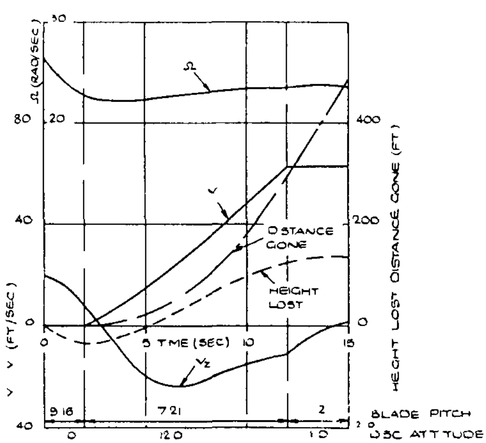

FIG 12 PERFORMANCE DURING TRANSITION TO CLIMBAWAY FOLLOWING FAILURE OF ONE ENGINE DURING FULL POWER VERTICAL TAKE OFF

knots , the loss in height during the motion is 125 ft The variation of the height loss with the assumed disc attitude, α, is shown in Fig 13 , it varies from a large value for $\alpha < 5°$ down to 100 ft for $\alpha = 16°$ However, the greatest attitude compatible with aircraft control is assumed to be about 8° and the corresponding height loss is 200 feet To clear surrounding obstructions up to 150 ft , the critical height for climb away following engine failure is thus about 350 ft

Below this height a return landing is required, and estimated touch down rates of descent following failure at lower heights are given in Fig 14 If the maximum acceptable rate of descent is assumed to be 10 ft /sec , it is necessary to utilise the rotor energy down to rotor speeds below the normal flight minimum , this, however, is probably acceptable in an emergency landing Near the ground immediate use can be made of the rotor energy following engine failure The performance is estimated to be adequate for emergency landing in this way from heights up to at least 20 ft for rotor speeds not below the normal minimum at touch down

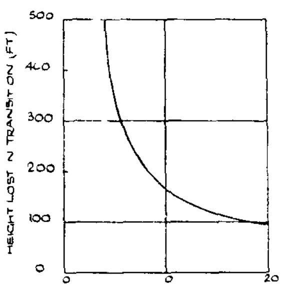

FIG 13 VARIATION OF HEIGHT LOST DURING TRANSITION WITH DISC ATTITUDE

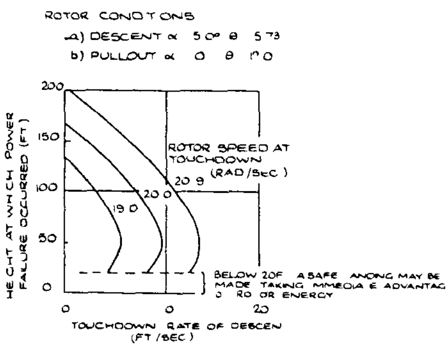

FIG 14 VARIATION OF TOUCHDOWN RATE OF DESCENT WITH HEIGHT AT WHICH POWER FAILURE OCCURRED DURING VERTICAL TAKE OFF

Similar results have been obtained for the case of engine failure during approach and landing The critical height for climb away is again estimated to be about 350 ft , and safe landings can be made from lower heights providing the rotor energy can be used down to rotor speeds somewhat below the normal flight minimum

These results indicate the performance of the twin engine helicopter to be just adequate for safe operation from the type of site proposed for civil operation The performance however may be difficult to achieve because of the fine judgment required of the pilot , in addition handling problems are possible in low speed powered descent It has been suggested (Ref 13) that a backwards take-off offers a greater degree of safety than a vertical take-off because it enables the airstrip to be kept in view throughout It is considered however that the acceptable backwards flight path angles will be limited and the performance in return landings effectively the same as in vertical take-off

The possible difficulties of effecting a landing following engine cut makes it clear that it would be preferable if the helicopter could climb away following engine failure at any stage except very near the ground This would only be possible with a twin engine helicopter by having a very large reserve of power or by the use of an emergency source of power , the critical aspect of such schemes is the time lag for the build up of the emergency power and their use has not yet been assessed We have however estimated the performance of a four engine helicopter with the same effective total power as the twin engine machine , the full power vertical rate of climb is unchanged but the steady rate of descent with one engine inoperative is reduced to 700 ft /min and a rate of climb of 200 ft /min is obtained at 16 knots The critical height for a straight path climb away is now only 100 ft and for failure below this height a climb away clearing surrounding obstructions can be made in turning flight, requiring only about 6 0 deg of bank at 16 knots If the power of the four engine version is increased by 10% (the full power vertical rate of climb then being 1,700 ft /min), the helicopter will be capable of a straight path climb-away following failure of one engine at any height , in addition, however, it will have sufficient performance to hover with one engine inoperative and could make a safe vertical take-off

The performance estimates given relate to I C A N atmospheric conditions and lower performance would be obtained in higher temperature conditions

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List of Symbols

Section 3 Stability and Control

a	—	slope of blade lift coefficient curve
a_1	—	longitudinal tilt of rotor plane due to flapping, positive backwards
B_1	—	longitudinal tilt of control plane, positive forwards
C_F	—	fuselage pitching moment coefficient
C_H	—	transverse force coefficient, $H/\frac{1}{2}\rho V^2 S$
C_m	—	helicopter pitching moment coefficient, $M/\frac{1}{2}\rho V\ SR$
C_S	—	blade centrifugal force coefficient, $^1F/\frac{1}{2}\rho V\ S$
C_T	—	thrust coefficient, $T/\frac{1}{2}\rho V^2 S$
C_W	—	$W/\frac{1}{2}\rho V^2 S$
e	—	blade flapping hinge offset
F	—	centrifugal force on blades
h	—	distance of C G below rotor
H	—	transverse force on rotor
H_m	—	manoeuvre margin
I_B	—	blade moment of inertia about flapping hinge
k	—	distance of C G forward of rotor hub axis
K_n	—	static margin
M	—	helicopter pitching moment
ng	—	normal acceleration increment
q	—	rate of pitching
R	—	rotor radius
S	—	rotor area, $-R$
T	—	rotor thrust
V	—	flight speed
W	—	helicopter weight
α	—	fuselage incidence to the flight path, positive upwards
/	—	Lock's inertia number, $C\rho\ a\ R^4/I_B$
μ_1	—	$W/g\ \rho\ S\ R$
ρ	—	air density
Ω	—	rotor angular velocity

Differences from and additions to the above notation in the remaining sections are as follow —

Section 8 Low speed performance

i	—	rotor disc incidence to flight path, positive downwards
u	—	airflow velocity normal to rotor
u_1	—	$u\sqrt{\sigma}$
v	—	mean induced velocity at rotor
v_1	—	$v\sqrt{\sigma}$
v_T	—	$(W/2\ \pi\rho R^2)^1$
V_1	—	$V\sqrt{\sigma}$
V'	—	resultant air velocity at rotor
V_1'	—	$V'\sqrt{\sigma}$
σ	—	relative air density

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Section 9 Ground effect

A — rotor area, πR
b — number of blades
c — blade chord
d — distance from rotor
s — rotor solidity, $bc/\pi R$
T — rotor thrust away from ground
Z — height of rotor above ground
θ — angle relative to resultant air velocity direction

Section 10 Forward take-off

A — $$\frac{\frac{T_m}{W}\cos\alpha_m + \frac{H_m}{W}\sin\alpha_m - 1}{\frac{T_m}{W}\sin\alpha_m - \frac{H_m}{W}\cos\alpha_m}$$

D_m/W

B — $1 - \frac{T_m}{W}\sin\alpha_m - \frac{H_m}{W}\cos\alpha_m$

D — body drag

D_m — mean body drag

f — $g\left(\frac{T_m}{W}\sin\alpha_m - \frac{H_m}{W}\cos\alpha_m\right)$

$G(\gamma, A, 1)$ — $\frac{1 + \tan\gamma}{(A - \tan\gamma)^2}$

H_m — mean transverse force on rotor

S — $\frac{V_o}{2fG(\gamma, A, B)}$

T_m — mean rotor thrust

V_o — initial flight speed

x, y — co-ordinates relative to ground axes, x horizontal forwards, y vertical upwards

α — rotor disc attitude to horizontal positive downwards

α_m — mean disc attitude

γ — flight path angle to horizontal, positive upwards

γ_o — initial flight path angle