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The Performance of a Multi-engine Helicopter Following Failure of One Engine During Take-off or Landing

By

A. L. Oliver, B.Sc (Eng.)

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

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A.L. Oliver, B.Sc.(Eng)

30th October, 1953

Summary

A theoretical analysis is made of the performance of multi-engine helicopters following failure of one engine in take-off and landing from the type of site proposed for Civil operation in built-up areas. The performance of a twin engine helicopter of similar class to the Bristol 173 appears to be just adequate for safe operation from such a site but the nicety of handling judgement involved in return landings may make the performance difficult to achieve. A take-off technique allowing climb-away after engine failure at any stage is preferable but this is not possible for the twin engine machine within the space available. It is possible if the twin engines are replaced by four of the same effective total power but only if a turning climb-away is made after engine failure. A helicopter with sufficient performance for a straight climb-away can in general hover with one engine inoperative.

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/1. Introduction.....

1. Introduction

It is essential for the civil operation of helicopters from restricted sites in built-up areas that, in the event of failure of the critical power unit during take-off or landing, the helicopter should be capable either of climbing away wer surrounding obstructions or of landing on the take-off area. For a helicopter with an adequate rate of climb at forward speed in the reduce?. power condition it is in general true to say that there is a critical height above which a satisfactory climb away may be made, and below which it is necessary to consider the possibility of a return landing.

The type of landing site proposed by the Interdepartmental Helicopter Committee (Ref.1) is comparatively small, being 300 ft. square with an obstruction clearance angle of 26 deg. (1 in 2) from the edge of the landing area. It is known from observed flight data that current types of single-engine helicopter do not meet the requirements for safety in the event of power failure when operating from such sites. No flight test information is yet available on the capabilities of multi-engine helicopters in this respect sc, in order to provide guidance on the subject, a theoretics1 analysis has been made of the performance of a helicopter following the failure of one engine. The analysis has been used to make estimates of this performance for a twin-engine helicopter of similar class to the Bristol173, and for a four-engine machine of similar type.

A list of symbols is given at the end of the Report.

2. Theoretics1 analysis

2.1 General. The analysis of both transitional and landing performance has been based on that given in Ref.2 for the engine-off performance of a single-engine helicopter. The motion of a multi-engine helicopter is considered relative to axes fixed in space, Ox horizontal forwards and Oz vertical upwards. The forces acting on the helicopter are the rotor thrust T, the transverse rotor force H, the weight W and the fuselage drag D. The flight velocity is V, with components V_x (positive forwards) and V_z (positive upwards), and the mean rotor axial flow velocity is u. The disc incidence to the flight path is i and the disc attitude to the horizontal is α, both being measured positive upwards from the disc. The system is shown diagrammatically in Fig.1.

The assumptions made in the analysis are in general similar to those in Ref. 2. In addition, engine power at constant boost is assumed to vary linearly with rctotionol speed; this is a reasonable approximation and simplifies the analysis.

2.2 Analysis of transitional performance

2.2.1 Forward flight. Using the nototion given et the end of the Report, and neglecting the rotor transverse force H and terms in μ of higher order than the first, the equations of motion of the system are:

$$\frac{dV_x}{dt} = \frac{g}{W}\left[T\sin\alpha - \frac{D}{10^4}\cdot VV_x\right] \quad \ldots\ldots\ldots (1)$$

$$\frac{dV_z}{dt} = \frac{g}{W}\left[T\cos\alpha - \left(W + \frac{D}{10^4}\cdot VV_z\right)\right] \quad \ldots\ldots\ldots (2)$$

$$\frac{d\Omega}{dt} = \frac{1}{I}\left[\frac{n-1}{n}\cdot\frac{EP_o}{\Omega_o} - \left(\frac{Tu}{\Omega} + \frac{\pi}{8}\rho\; C_D s\, R^5\,\Omega^2\right)\right] \quad \ldots\ldots\ldots (3)$$

Additional relations are used to determine the thrust T and axial velocity u. From the blade element thrust formula it can be shown that

$$\frac{T}{2\pi\rho\, R^2}\cdot\frac{1}{V^2} = \frac{\Phi}{\mu_1^2}\left(\frac{2}{3}\theta - \mu_1\cdot\frac{u}{V}\right) \quad \ldots\ldots ? \ldots\ldots (4)$$

/where.....

where $\delta = a.s/8$ and $\mu_1 = V/\Omega R$. It is also possible to express $T/2\pi\rho R^2V^2$ as a function of i and u/V, using the momentum thrust formula (as in Ref.2) for values of $\mu_1 > 0.12$, in the form

$$\frac{T}{2\pi\rho R^2} \cdot \frac{1}{V^2} = \left[\frac{u}{V} - \sin i \right] \left[\frac{u^2}{V^2} + \cos^2 i \right]^{\frac{1}{2}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

For $\mu_1 \leq 0.12$ the relation is given graphically in the empiric31 charts of Ref. 3. The letter relations and (4) enable T end u to be determined for given values of the helicopter constants at known values of V, μ_1 and i, i being obtained from

$$i = \sin^{-1} \left\{ (V_z \cos\alpha + V_x \sin\alpha) / V \right\} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

This is conveniently done by presenting the relations as in Fig.2. Since for large values of u/V the curves of constant i become asymptotic to $V. \left[2\pi\rho R^2/T \right]^{\frac{1}{2}} = 0$, Fig.2 is plotted in two ports using u/V as abscissa for $u/V < 1.0$ and V/u for $u/V > 1.0$.

The motion during a transition stage can therefore be determined by numerical integration of the differential equations (I), (2) end (3) using values of T end μ as estimated from Fig.2.

2.2.2 Vertical flight. For vertical flight, using the rotor thrust equation for steady aerodynamic conditions, the following relation between the operating coefficients f_1, F_1 and μ_1 is given in Ref.2:-

$$\mu_1 = \frac{\delta}{2f_1} \left\{ \left[\frac{1}{F_1^2} + \frac{8\theta}{3\delta} \right]^{\frac{1}{2}} - \frac{1}{F_1} \right\} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

The equations of motion in this case may be written

$$\frac{dV}{dt} = g \left[\frac{2\pi\rho R^2}{W} \cdot V^2 f_1^2 - 1 \right] \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

$$\frac{d\Omega}{dt} = \frac{1}{I} \left\{ \frac{n-1}{n} \cdot \frac{EP_o}{\Omega_o} - \pi\rho R^5 \left[\frac{\sigma\delta}{8} + \frac{2\mu_1^3 f_1^3}{F_1} \right] \Omega^2 \right\} \qquad \ldots\ldots\ldots (9)$$

Equations (8) and (9), together with the relation given in (7) and the empirical $f_1 - F_1$ curve (Ref.3) define the transition performance following the failure of one engine; solution is achieved by numerical integration.

2.3 Landing performance. The analysis of 2.2.2 may be used to determine the landing performance following failure of one engine but allowance must be made for the ground effect on the rotor thrust. An approximate relationship for the ground effect in vertical flight based on the empirical curves of Ref.4, is given in Ref. 2 in the form

$$\frac{T_g}{T_\infty} = 0.95 + 0.2 \frac{R}{h} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

where h is the height of the rotor above the ground. The value of T_g/T_∞ becomes 1.0 at h equal to 4R; above this height the ground effect is negligible in practice. The limited information available on the variation of ground effect with forward speed at constant height and power suggests that equation (10) is sufficiently accurate for horizontal velocities up to 15.0 ft/sec.; the effect falls off at higher speeds and is small for horizontal velocities greater then about 50 ft/sec. The value of T_∞ from which T_g is determined can be found for the known rotor operating condition by the appropriate method of either para. 2.2.1 or para. 2.2.2.

/It is......

It is possible, owing to the neglect of unsteady aerodynamic effects, that the estimated landing pull-out performance may be pessimistic because the rotor induced flow does not instantaneously build-up as the pitch is increased. This is to some extent counter-balanced however by the assumption that there is no delay in the development of ground effect.

The equation of motion given in para. 2.2.1 can be simplified if the horizontal velocity is small (less than about 15.0 ft/sec.) by neglecting the fuselage drag terms.

3. Estimated performance of a twin-engine helicopter

3.1 General. The analysis given in para. 2 has been used to estimate the performance in I.C.A.N. sea level conditions of a twin-rotor, twin-engine helicopter having the choraoteristics given in Table 1. it has been assumed that in vertical or nearly-vertical flight there is no interference effect between the rotors, and that the performance of the twin-rotor machine is the same as that of a single-rotor helicopter of half the total weight.

The estimated verticalperformance of this heliopter in still air gives a rate of climb of 1190 ft/min. at full power and a rate of descent of 1920 ft/min. with one engine inoperative. At half power, height can be maintained at speeds between 37 and 63 kts. E.A.S., the best rate of climb being 150 ft/min. at 50 kts. Preliminary considerations led to the assumption of an approach path angle of approximately 45 deg. The helicopter approaches from 500 to 150 ft. above the ground at a speed of IO kts. E.A.S. and a rate of descent of 700 ft/min.; this is followed by a vertical descent tn the ground at 300 ft/min. In the first stage 70%, and in the final stage 80% of the tot31 power is required .

Estimates hove been made of the performance following an instantaneous cut of one engine during both vertical take-off and the landing described above. It has been assumed thzt there is a 2.0 sec. delay following engine failure before corrective control action by the pilot is effected; this allows for pilot reaction time and the time required. to move the controls. Partial power failure on either take-off or landing is followed by a loss of rotor speed and thrust, and a reduction in collective pitch is necessary to counteract this. From preliminary considerations it may be seen that for the case of climbaway a rapid acceleration towards the minimum climbaway speed is desirable, and a forward tilt of the rotor disc will be required - subject of course, to overall aircraft control. it may also be advisable to stabilise the rotor speed below its original value and thus make use of some of the rotor energy to reduce the height lost in the transition. For the landing case, on the other hand, it would appear advisable to aim at a high rotor speed in order to provide greater arresting power from the rotor energy in the pull-out prior to touch-down. These points arc taken into account in the assessment given in the following paragraphs of the performance following power out.

All pull-out performance was calculated for a blade pitch of 12.0 deg, which it has been estimated will not involve any blade stalling problems in the flight conditions considered in the analysis. The performance has been estimated with reference to a landing area of the type defined in pare.1 with the added assumption that the maximum obstruction height is 150 ft. It is also assumed that the maximum acceptable rate of descent at touchdown is 10 ft/sec.

3.2 Performance following failure of one engine during vertical take-off.

The performance following engine failure during vertical take-off has been determined for initial conditions of full power climb at 1190 ft/min. with a rotor speed of 26.2 rad/sec.

Estimates have been made of the height lost in the transition to climbaway when using a blade pitch of 7.21 deq. which corresponds to a steady rotor speed of approximately 23.5 rad/sec. The technique considered was to

/accelerate.....

accelerate to 37 kts. forward speed, and then to reduce the disc attitude to 1.0 deg; this reduced the horizontal acceleration to about 0.5 ft/sec² and led to a small positive rate of climb. A range of values of disc attitude were investigated for the acceleration stage, and the variation of height lost in the transition against disc attitude is shown in Fig.3. The transition performance for a typical case is shown in Fig.4. The greatest disc attitude that can be maintained for an adequate period will probably be about 8.0 deg. for a helicopter of this type; the height lost in the transition for this value of disc attitude is 200 ft. The "critical height" on take-off is therefore 350 ft. when allowance is made for clearing a 150 ft. obstruction.

It is not possible to clear the surrounding obstructions in a climb-away if engine failure occurs below this height, and the performance during return landings has therefore been investigated. The height lost in attaining steady vertical descent followed by a vertical landing with reduced power was calculated first. Using a blade pitch of 5.73 deg., which corresponds to a rotor speed in steady conditions of 26.2 rad/sec. the height required to make a landing is 25 ft., the rotor speed at touchdown being 20.9 rad/sec. and the touchdown rate of descent 9.0 ft/sec. A safe vertical descent and landing can therefore be made following failure of one engine at any height above 175 ft.

A safe landing can be made from heights below 175 ft. if forward speed is developed. Estimates have been made for the performance following engine failure below 175 ft. using a blade pitch of 5.73 deg. as before and a disc attitude of 5.0 deg. for the transition; pull-outs were made with a pitch of 12.0 deg. and the disc horizontal. Using this technique the horizontal distance travelled during a descent and landing from 175 ft. is 100 ft. and a safe landing may be made following engine failure between 175 and 110 ft., for a touchdown rotor speed of 20.9 rad/sec; the results are shown in Fig.5.

Failure below 110 ft. results in high touchdown velocities at the normal minimum flight rotor speed. It is considered, however, that rotor speeds below the normal minimum (probably as low as 19.0 rad/sec.) may be safely used in an emergency landing and Fig.5 includes curves for 20.0 and 19.0 rad/sec. as well as for 20.9 rad/sec. It will be seen that, if the rotor speed is allowed to fall to 20.0 rad/sec before touchdown, the rate of descent at touchdown is less than 10 ft/sec. following engine failure at any height.

Near the ground, in the early stages of take-off, the rate of climb of the helicopter (before engine failure) will be less than the ultimate steady value. In addition, it may be preferable in an emergency landing to make immediate use of the rotor energy. It is estimated that for a vertical rate of climb of 300 ft/min. and a touchdown rotor speed of 20.9 rad/sec, the helicopter can make a safe landing in this way from a height of 20 ft. (Fig.5). Landings of this type are possible from greater heights if the rotor speed is permitted to fall below 20.9 rad/sec.

3.3 <u>Performance following failure of one engine during the approach and landing.</u> Estimates have been made of the height required to gain a speed at which the helicopter can climb following failure of one engine during an approach down to a height of 150 ft. made at 10 kts. and 700 ft/min. rate of descent. Using a blade pitch of 7.21 deg. and a maximum disc tilt of 8.0 deg. the critical height below which it is impossible to climb away is 350 ft.

As in the case of take-off, engine failure below the critical height means that the helicopter must land. Calculations show that for a blade pitch of 5.73 deg. and a disc attitude of 1.0 deg. the aircraft can land on the airstrip following engine failure at any height above 1.50 ft. As before, pull-outs were calculated for a blade pitch of 12 degrees with the disc horizontal,

/In......

In the event of engine failure below 150 ft. when the helicopter is assumed to be in vertical descent, the pilot is assumed to use a pitch of 5.73 deg. and a disc attitude of 5.0 deg. for the transition, and to make tho same pull-out manoeuvre as before. The resulting touchdown rate of descent at a rotor speed of 20.9 rad/sec. is high (Fig.6) but this can be reduced to on acceptable value if the rotor speed is allowed to fall to 19.0 rad/sec. at touchdown.

4. Discussion

The performance of a multi-engine helicopter following the failure of one engine during take-off or landing must be considered in relation to the space available for landing and the possibility of damaging the aircraft during such 3 landing. With these criteria the performance of the helicopter considered in pore.3 is adequate for an engine out occurring above 110 ft. on take-off or above 150 ft. during landing, if the rotor speed is not to drop below the minimum permissible figure of 20.9 rad/sec. during the pull-out. It is assumed again however, that the rotor speed may be allowed to fall below this figure during an emergency lending and Figs. 5 and 6 include curves of touch-down velocity against height et which power cut occurred for touchdown rotor speeds of 20.0 and 19.0 rad/sec. The curves show that if the latter rotor speed is acceptable, a safe landing may be made following engine out at any height. The performance will, however, be difficult to achieve because of the fine judgement required of the pilot; in addition, complications may arise from the problem of handling and control in low-speed power-on descent.

It has been suggested (Ref.5) that a backward 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 backward flight path angles will be limited and the performance effectively the same es in a vertical take-off, although there may be some loss due to interference between the rotors.

The difficulties of effecting a return landing following engine cut in teke-off make it clear that it would be preferable to be able to use a take-off technique in which the helicopter continues its climbaway following the failure of one engine 3t any stage. With a twin-engine helicopter this would only be possible by having a large reserve of power in normal operations for the present all-up weight, or by making a large reduction in weight nt the present power; accordingly, estimates have been made of the performance of the helicopter of para. 3 at 10,600 lb. when fitted with four engines instead of two, but with the effective power at the rotor maintained constant in full power operation.* The helicopter has full power rates of climb of 1190 ft/min. in vertical flight and 1250 ft/min. et 16 kts. as before; but the vertical rate of descent with one engine inoperotive is 690 ft/min. while the corresponding rate of climb at 16 kts. is 200 ft/min. Assuming a mean forward acceleration of 5.0 ft/sec^2, the distance required to reach 16 kts. from hovering is about 75 ft; the helicopter would therefore have about 130 ft. of runway in hand when it starts to climb and about 90 ft. in hand when it reaches 100 ft, which is the critical height for a straight path climbaway.

The helicopter can climb away after engine failure below that height only by making a Rate 2 turn (about 6.0 deg. of bank at 16 kts.), because the straight path angle of climb is less than the obstruction angle. If sufficient power were available to permit climbaway without turning at low forward speed, the helicopter would generally be capable of hovering with one engine inoperative and a safe vertical take-off could therefore also be made. This can be achieved with the four-engine helicopter by increasing the power by about 10%, which corresponds to a full-power vertiool rate of climb of 1670 ft/min.

No estimates have been made of performance in atmospheric conditions other than I.C.A.N. sea level. It should be noted, however, that a 5% decrease in power, which is approximately equivalent to a rise in ambient air

/temperature.....

* Note: the payload would, of course, be reduced by an amount corresponding to the difference in weight between the four engine and the twin engine installation.

temperature at sea level at 20°C for piston engines, results in the twin engine helicopter being unable to climb with one engine inoperative. The effect of a 5% decrease in power on the performance of the four engine helicopter is to increase the speed for 200 ft/min. rate of climb with one engine-inoperative to 21 kts.

5. Conclusions

The estimated performance, following partial power failure during take-off from or landing on a restricted site, for a helicopter of similar class to the Bristol 173, shows it oon climb-way or make a safe return landing in the event of engine failure et any height, provided the rotor speed may safely drop in the touchdown slightly below the normal flight minimum. The performance in return landings may however be difficult to achieve end a take-off technique allowing climb-away following failure at any stage is desirable. This is not possible for the twin engine helicopter within the space available but is possible for a four-engine helicopter of the same effective power if a climbing turn is ma-de after power failure. If the performance is increased to allow climb-away without turning, the helicopter will generally be able to hover with one engine inoperative.

6. Further developments

An assessment is to be made of the usk of emergency sources of power as a way of obtaining adequate performance in the event of engine failure. A critical aspect of such schemes is the time-lsg for the build-up of the emergency power.

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2	O'Hara and Mather	The performance after power failure of a helicopter with blade pitch control. R & M 2797. September 1951.
3	Oliver	The low speed performance of a helicopter. C.P. 122. May 1952.
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5	Whitby	Some operational problems of public transport helicopters. Journal R. Ae.S. January 1951.

List of Symbols

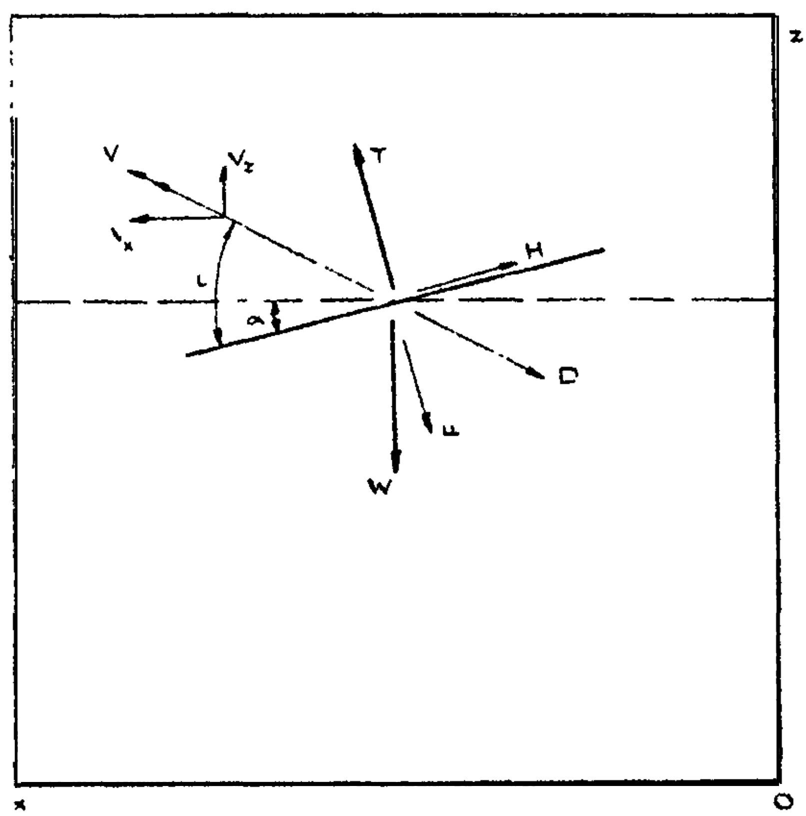
a	slope of blade lift coefficient curve
b	number of rotor blades per rotor
c	rotor blade chord at $r = 0.7R$
C_D	blade profile drag coefficient at mean effective lift coefficient
C_L	mean effective lift coefficient; $C_L = L/\frac{\pi}{2}\rho s\Omega^2 R^4 \left(\frac{1}{3} + \frac{\mu^2}{2} + \lambda^2\right)$
D	fuselage drag at 100 f.p.s.
E	ratio of effective power at the rotor to total engine power
f_1	$\left[T/2\pi\rho R^2 V^2\right]^{\frac{1}{2}}$ } vertical flight coefficients.
F_1	$\left[T/2\pi\rho R^2 u^2\right]^{\frac{1}{2}}$ }
h	height of rotor above the ground
H	transverse rotor force: $H = \frac{\pi\rho}{8} C_D s\Omega^2 R^4 (2\mu)$
i	rotor disc incidence to flight path positive upward from disc
I	rotor moment of inertia
L	rotor lift
n	number of engines
P	engine power
R	rotor radius
s	rotor solidity; $s = bc/\pi R$
T	rotor thrust
T_g	rotor thrust within the ground effect region } calculated at constant power.
T_∞	rotor thrust outside the ground cushion }
u	total velocity of flow normal to rotor disc
V	flight speed of helicopter
$V_x\ V_z$	components of flight speed
W	helicopter all-up weight
x, z	space co-ordinates
α	rotor disc attitude, positive upward from disc
θ	rotor blade pitch
λ	axial flow ratio; $\lambda = u/\Omega R$
μ	tip speed ratio; $\mu = V\cos i/\Omega R$
μ_1	$V/\Omega R$
ρ	air density
Φ	a s/a
Ω	rotor speed

Table 1

Characteristics of helicopter used far estimations

All-up weight	10,600 lb.
Number of engines	2
Maximum power at I.C.A.N. sea level, per engine	525 HP
Number of rotors (tandem)	2
Details of rotors	
Number of blades	3
Diameter	48.56 ft.
Solidity	0.0464
Maximum permissible rotational speed in normal flight	26.2 rad/sec.
Minimum permissible rotational speed in normal flight	20.9 rad/sec.
Mean blade profile drag coefficient	o.olo
Gear rntio, engine : rotor	11.98 : 1
Effective power at rotor: total engine power	o. 926
Body drag at 100 f.p.s.	320 lb.

FIG. 1.



VELOCITY AND FORCE SYSTEM

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FIG. 2.

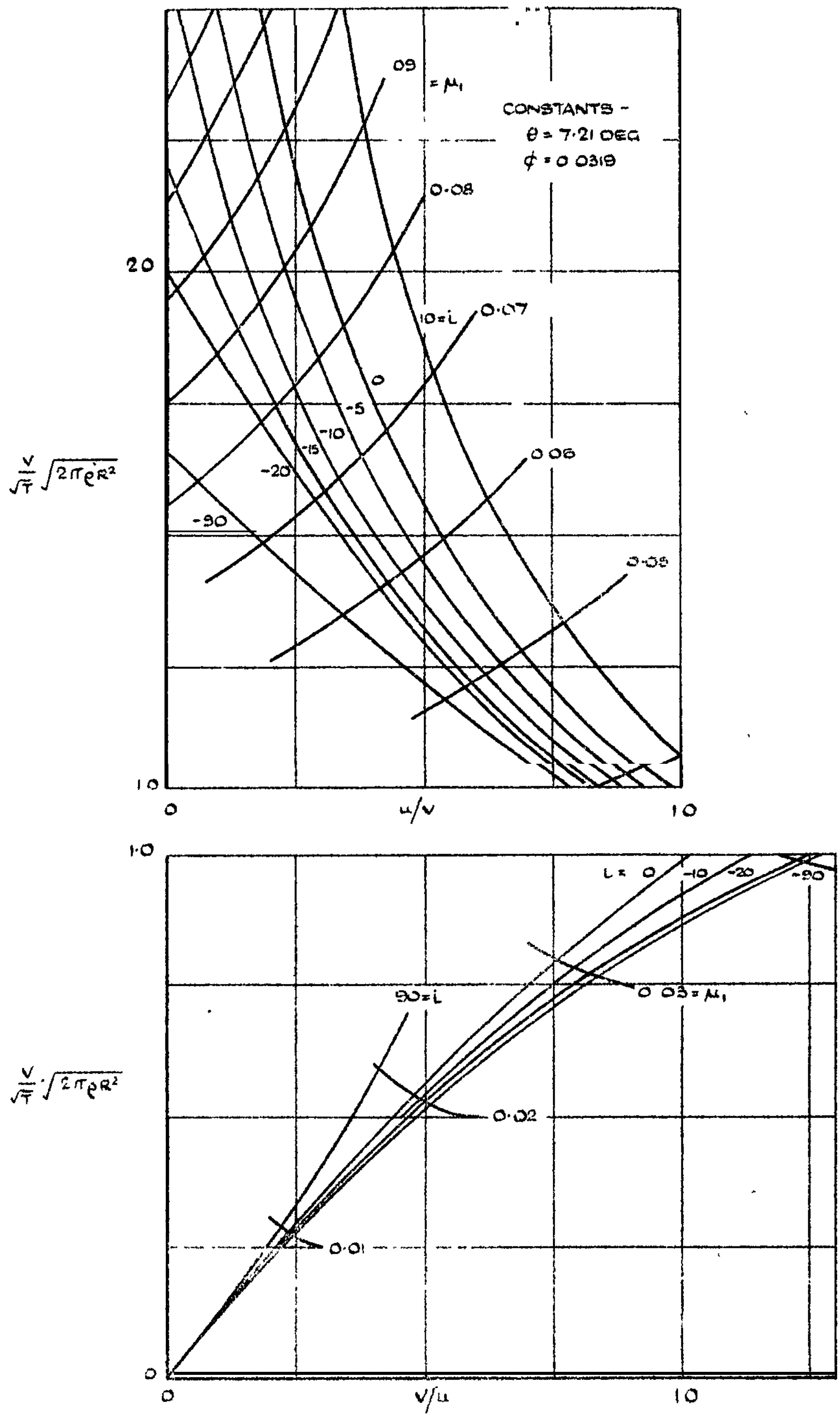
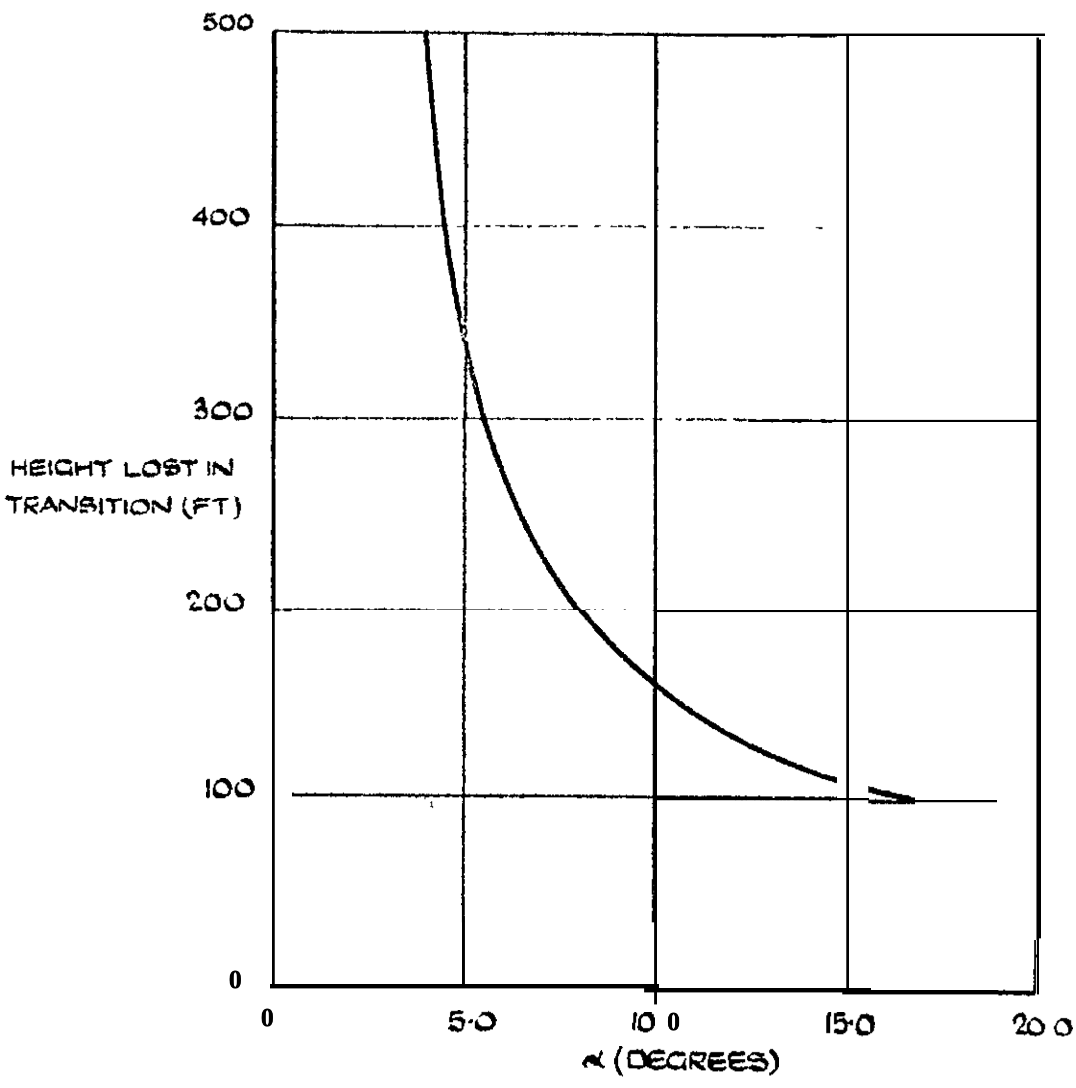


CHART FOR DETERMINING ROTOR THRUST IN FORWARD FLIGHT.

FIG. 3.



VARIATION OF HEIGHT LOST IN CLIMBING AWAY WITH DISC ATTITUDE.

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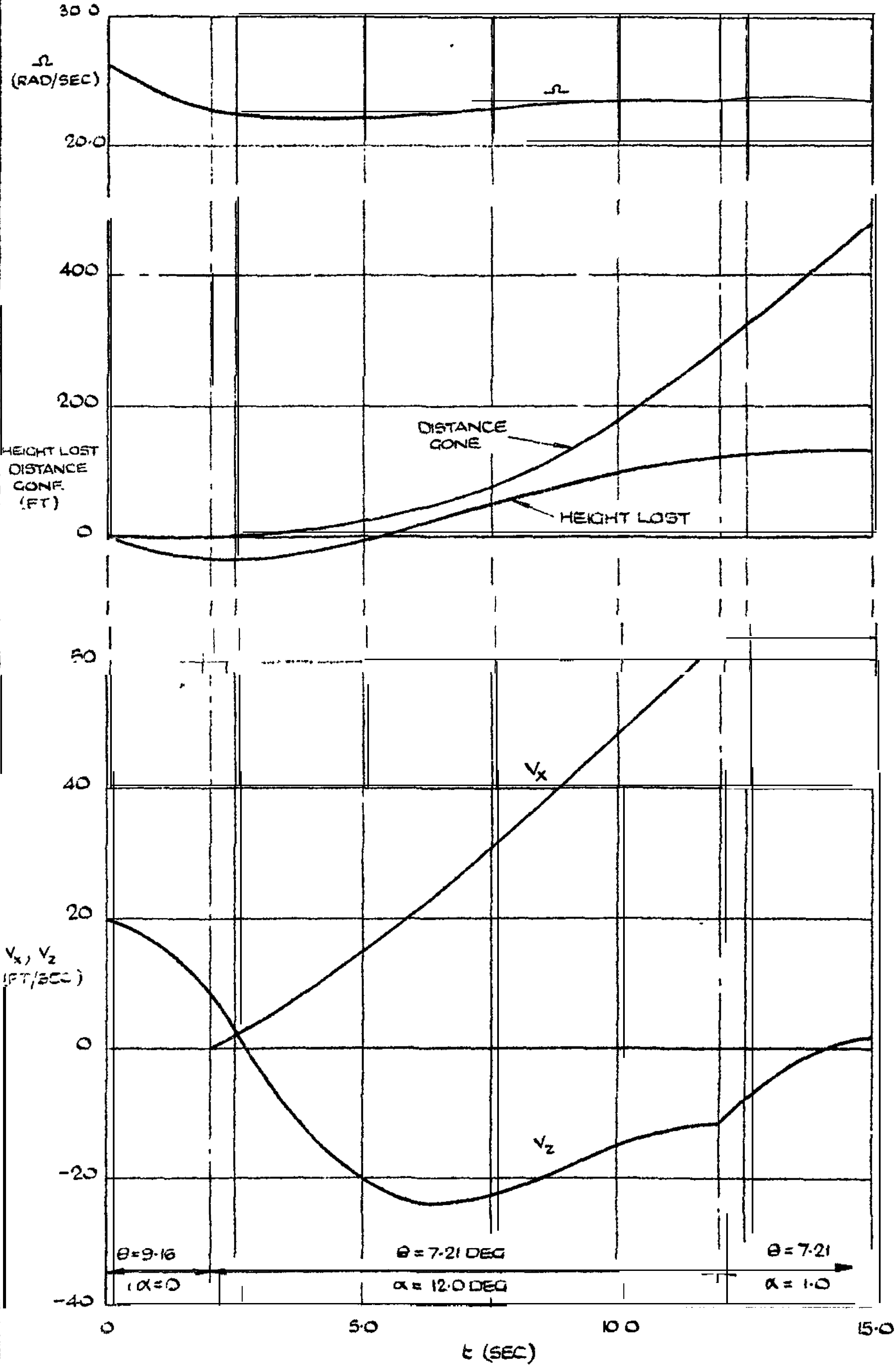
FIG.4.



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PERFORMANCE DURING TRANSITION TO CLIMBAWAY FOLLOWING FAILURE OF ONE ENGINE IN FULL POWER VERTICAL TAKE-OFF.

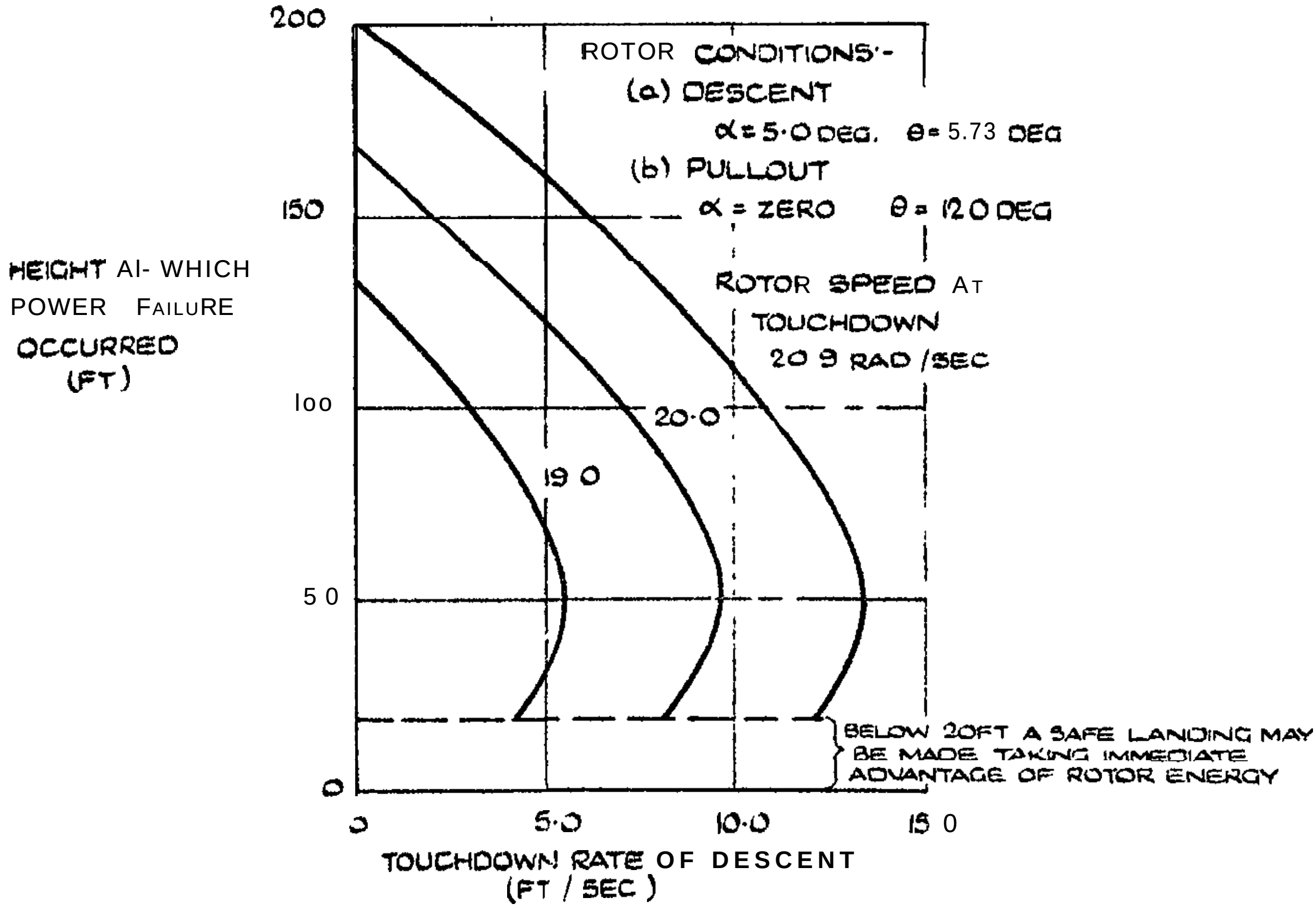

FIG 5 VARIATION OF TOUCHDOWN RATE OF DESCENT WITH HEIGHT AT WHICH POWER FAILURE OCCURRED DURING VERTICAL TAKE-OFF AT 1190 FT/MIN

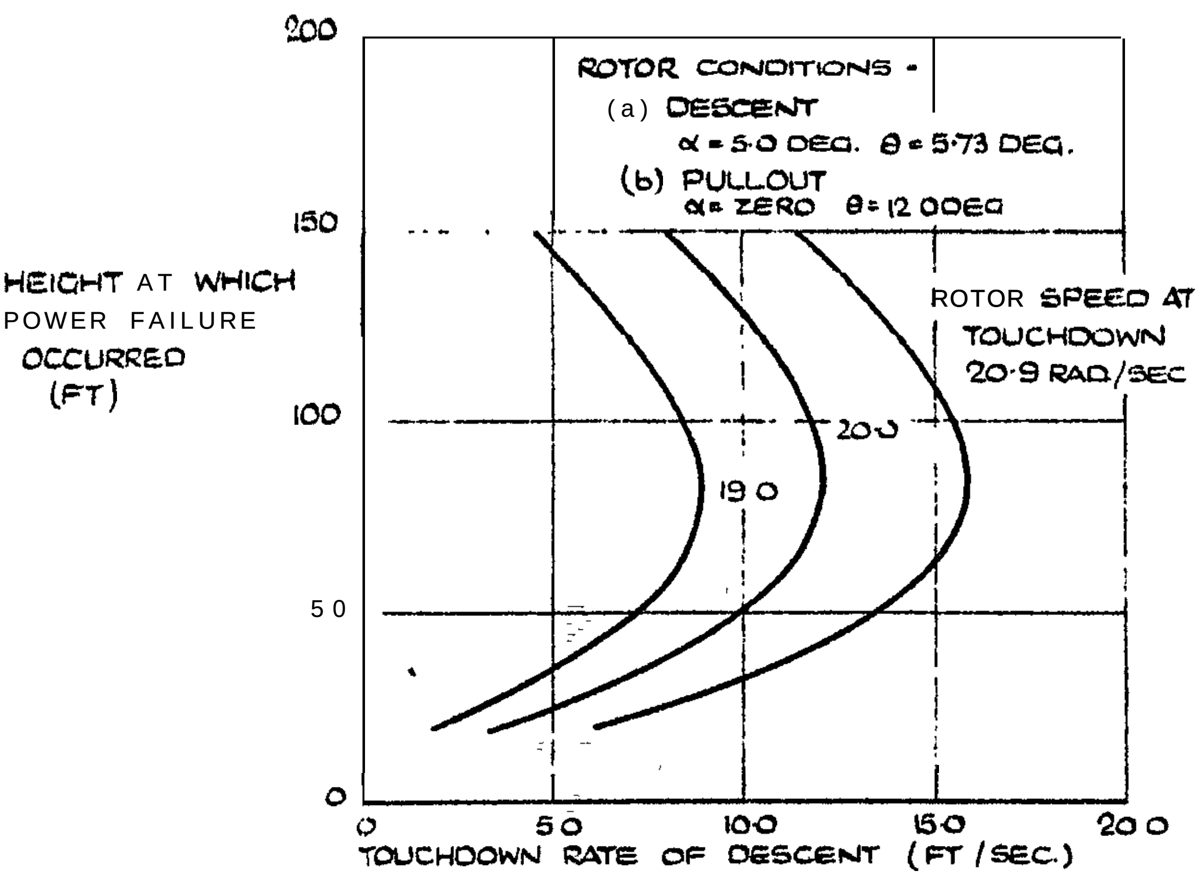

FIG 6 VARIATION OF TOUCHDOWN RATE OF DESCENT WITH HEIGHT AT WHICH POWER FAILURE OCCURRED DURING VERTICAL LANDING AT 300 FT/MIN

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