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Notes on Helicopter Rotor Behaviour after Engine Failure in Hovering Flight

By

W. STEWART, B.Sc., and G. J. SISSINGH, Dr. Ing.

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COMMUNICATED BY THE PRINCIPAL DIRECTOR OF SCIENTIFIC RESEARCH (AIR), MINISTRY OF SUPPLY

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May, 1949

Summary.—Calculations have been made of the changes in rotor speed following engine failure on a typical helicopter in hovering flight. Various time functions for the collective pitch operation are considered. The results are in excellent agreement with the one recorded case of an actual power failure in hovering flight.

Rapid pilot action in reducing the collective pitch after engine failure is essential to prevent dangerously low rotational speed of the blades. The possibilities of automatic pitch reduction or of a power failure warning to the pilot are considered.

1. *Introduction.*—In helicopter design a free-wheel unit is incorporated between the engine and the rotor so that in the event of power failure the rotor is automatically free from any retarding influence of the engine. However, when the engine fails, the rotational speed of the blade will initially decrease, and subsequent auto-rotation is only possible when certain conditions of flow through the rotor disc, and of blade pitch setting have been established. For a helicopter at low forward speed, some loss of height in establishing these conditions is unavoidable.

From the point of view of airworthiness there are two features to be considered, first the loss of blade rotational speed and secondly the loss of height. Although these are interdependent, the rotor behaviour would appear to have a direct effect on the safety of the helicopter while the loss of height involved could be considered as a possible modification to the flight procedure, particularly in the take-off and landing technique. This report deals mainly with the loss of rotational speed.

Calculations have been made to evaluate the loss in blade rotational speed following engine failure in hovering flight. Various time functions for the collective pitch operation are considered to emphasise the importance of pilot reaction. The effect of variation in rotor moment of inertia is also considered. The numerical evaluations are based on Sikorsky S-51 data as representing a typical helicopter and the results are compared with an actual case of power failure in flight.

During a series of flight tests on a Sikorsky S-51 helicopter at the National Luchtvaartlaboratorium in Holland, actual power failure occurred while the helicopter was hovering at about 2,000 ft. An auto-observer was in use at the time of the incident and records of the subsequent helicopter and rotor behaviour and of the pilot's reactions and control movements were obtained. These records are of exceptional value as the engine failure occurred with no warning whatsoever, thus giving a pilot's reaction under true conditions. It should also be pointed out that considerable danger would be involved in attempting to simulate these conditions in flight.

* R.A.E. Tech. Note Aero. 1997, received 18th August, 1949.

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2. *Estimation of Rotor Speeds.*—The rotational deceleration of the rotor at any instant is given by

$$\dot{\Omega} = \frac{Q}{I} \qquad \ldots \qquad (1)$$

where Q is the instantaneous torque and I the moment of inertia of the rotor, together with the equivalent inertia of the tail rotor and rotating parts.

It is assumed that after engine failure in hovering flight the rotor remains at zero forward speed but that vertical velocity develops due to the loss in thrust. The vertical acceleration is given by

$$\frac{\dot{v}_a}{g} = \frac{W - T}{W} \qquad \ldots \qquad (2)$$

where W is the weight of the helicopter and T is the instantaneous thrust.

It is not possible to derive general expressions for thrust and torque in vertical descents and hence the calculations have to be made using 'step by step' methods. From flight tests in steady vertical descents[2] values of thrust and torque coefficient for a given pitch setting and corresponding rates of descent can be obtained. Also, for the static conditions, zero rate of descent, values of thrust and torque coefficient for any given pitch setting can be estimated accurately. Thus, for a given pitch setting two points for thrust coefficient and for corresponding torque coefficient are obtained at different rotor tip advance ratios ($v_a/\Omega R$). Assuming a linear variation in the thrust and torque conditions, it is then possible to cross-plot charts of thrust and torque coefficient in terms of pitch angle and rotor advance ratio. These charts were used to give the appropriate thrust and torque coefficients for the calculations.

Starting from the instant of power failure and using time intervals of $\frac{1}{4}$ sec, step by step calculations were made from equations (1) and (2) to obtain rotational speed of the rotor and the rate of descent of the helicopter as functions of time.

The numerical evaluations were based on the S-51 helicopter as this is representative of a typical rotor system and also to give a comparison with the actual flight incident. The relevant data are:—

Weight of helicopter	W = 4900 lb
Rotor diameter	48 ft
Rotor moment of inertia	I = 2000 lb ft sec^2.

The calculations have been made for four cases of the collective pitch-time function.

Case A.—The pitch is maintained at the hovering setting of 11 deg throughout.

Case B.—The pitch is constant at 11 deg for one second and is then reduced steadily to the normal auto-rotation value (4 deg) during the next second.

Case C.—The pitch is reduced steadily from the instant of engine failure from 11 deg to 4 deg in one second.

Case D.—This corresponds to the measurements following the actual case of power failure in flight. The pitch setting is maintained at 11 deg for one second and is then reduced to 2 deg during 2·4 sec.

In addition, calculations have been made to show the effect of moment of inertia of the rotor on decrease of rotor speed. Cases A and D above are used and an increase and a decrease of 50 per cent in moment of inertia are considered.

3. *Results.*—3.1. *General.*—The results of the calculations of rotor speed and associated rate of descent for the various collective pitch functions are given in Fig. 1 against time from the instant of engine failure. The rotor immediately begins to lose rotational speed. This loss of rotor speed leads to a decrease in thrust and the helicopter starts to descend. The rate of descent causes an increase in the incidence of the blade and at the same time introduces an inclination of the relative airflow at the blade resulting in a decrease of the retarding torque on the rotor. The above affords a general description of the rotor behaviour and each of the cases is now considered in detail.

3.2. *Case A.*—In this case, the pitch is maintained constant at 11 deg. The behaviour is as described above but due to the high pitch, the incidence reaches the stall limit quickly, the stalled area of the disc spreading from the centre outwards as the rate of descent increases. At about 2 sec the outer sections of the disc are becoming stalled and the resulting large increase in drag coefficient and decrease in lift coefficient lead to a much greater deceleration of the rotor.

With the pitch maintained at the 11-deg value, the rotor would come to rest in a very short time. In a matter of 2 sec the rotor conditions are serious; in 3 sec the rotational speed is dangerously low; in about 4 sec disaster would be almost inevitable. This case illustrates the absolute necessity for immediate pitch reduction after engine failure.

3.3. *Case B.*—The pitch is constant for the first second after engine failure and is then reduced to the auto-rotation pitch (4 deg) during the next second. This is very effective in preventing further loss of rotor speed and by the time the lowering of the pitch is completed, *i.e.*, at 2 sec, the rotor speed is almost steady. Thereafter, as the rate of descent increases the rotor regains its normal speed and steady auto-rotation develops.

It is felt that this pitch-time function gives safe rotor operating conditions. Nevertheless, it must be pointed out that for the S-51 helicopter a limitation is imposed giving a minimum permissible rotor speed corresponding to $(\Omega/\Omega_0) = 0 \cdot 88$ and this value is reached in $0 \cdot 5$ sec. This restriction is imposed by C.A.A. from considerations of retreating blade stalling in forward flight. It does not have any direct application to the transient conditions of the aspects now being considered. A much lower value would be acceptable but the magnitude of this safe value would be a function of the rotor parameters, particularly from the point of view of blade stalling.

3.4. *Case C.*—In this case the pitch is reduced steadily from the instant of engine failure to the auto-rotation value of 4 deg in one second. This would represent some form of automatic pitch-changing device, for example by suitable blade hinge arrangements; it could not possibly be obtained in a manual pitch-change layout.

This arrangement is very effective and limits the minimum rotor speed to $0 \cdot 82$ of its initial value. The greater rate of descent in the initial stages (due to the pitch reduction) should be noted. This will be dealt with in more detail in the discussion of automatic action.

3.4. *Case D.*—This case was calculated for comparison with the actual flight measurements. The agreement with the flight result is excellent and provides a verification of the method of estimation.

The shape of the rotor speed curve is similar to Case B above and the same comments are equally applicable.

3.5. *Effect of Moment of Inertia.*—The results of the calculations in Cases A and D with moments of inertia of 1,000 and 3,000 lb ft sec^2 are compared with the standard condition of 2,000 lb ft sec^2 in Fig. 2.

The initial rotor deceleration is inversely proportional to the moment of inertia. Thus, with lower inertia the blades reach the stalling conditions more quickly with the consequent further rapid loss of rotational speed. The absolute values of the time scale should be noted particularly. For the lower value of inertia, the serious stall conditions are reached in less than 2 sec and while this is greater than the pilot's reaction time in the case considered (D) the margin of safety is small. In the general case the reaction time may be slightly longer with consequent dangerous rotor conditions. In view of the small order of the times involved, the effect of increased rotor inertia in delaying the loss of rotational speed is very important.

4. *Influence of Pilot's Reaction Time.*—For a manually operated pitch system, the rate at which the rotor loses rotational speed following an engine failure at high pitch is so great that the pilot's reaction time is a vital factor in the safety of the helicopter. In the only case measured the pilot's reaction can be quoted as one second to start collective pitch action and 2·4 sec to lower the pitch.

The one second before moving the pitch lever is considered less than could be expected in the average case. Detection of engine failure in so short a time is difficult. The sound of the rotor and the transmission etc. which keep rotating when the engine has stopped, make it difficult to identify the failure by sound. The sudden swing directionally due to the release of the torque reaction can easily be confused with an air gust. Thus, in the actual case, the pilot's tail rotor corrective action was virtually instantaneous while he took one second before moving the pitch lever. Thus, in the average case to identify the engine failure and to take pitch reduction action, especially if the pilot's hand was not near the lever at the time, the delay could easily be of the order of 2 sec.

From the point of view of rate of pitch reduction, it is unreasonable to expect the pilot to do this very rapidly. Rapid decrease in pitch means loss of lift and also loss of control as the response due to tilting the disc by means of his control stick is a simple function of the thrust magnitude. Thus, the pilot will only reduce the pitch at a rate at which he still feels he has sufficient general control of the helicopter.

Thus, it could be expected that the general case of an engine failure might give a reaction time of about 2 sec before moving the control and a further 2 sec during which the pitch was being reduced to its auto-rotation value. The importance of rapid action after engine failure should be fully appreciated by all helicopter pilots.

5. *Automatic Pitch Change.*—The necessity for rapid pitch reduction after engine failure suggests the use of some automatic pitch-changing device. There are several ways in which the desired pitch conditions may be achieved but other operating conditions should not be overlooked.

The problem of engine failure at low altitude must be seriously considered. If automatic pitch reduction were made, the rate of descent would increase more rapidly than it would with no corrective action (*see* Fig. 1) and the helicopter would have a heavy landing. Thus at very low altitude the loss in rotor speed is not as important as the landing rate of descent.

If automatic pitch reduction is considered, some means of cutting out the automatic device for low altitude flying must be incorporated.

Alternatively, some form of power failure warning could be fitted. A number of simple solutions are available using the relative movement of the blade on the drag hinge or the separation of the engine and rotor speeds at the free-wheel unit. With this form of power failure warning to the pilot, this time to carry out appropriate action could be reduced to within safe limits of the rotor behaviour.

6. *Conclusions.*—6.1. Calculations of the rotor speed following an engine failure in hovering flight on a single-rotor helicopter have been made for various time functions of collective pitch operation. The effect of moment of inertia is also illustrated.

6.2. The results are in excellent agreement with the one recorded case of engine failure in flight.

6.3. The pilot's reaction time has an important influence on the rotor behaviour.

6.4. Automatic pitch reduction is desirable but safety in the low altitude case must be considered. As an alternative a power failure warning could be used.

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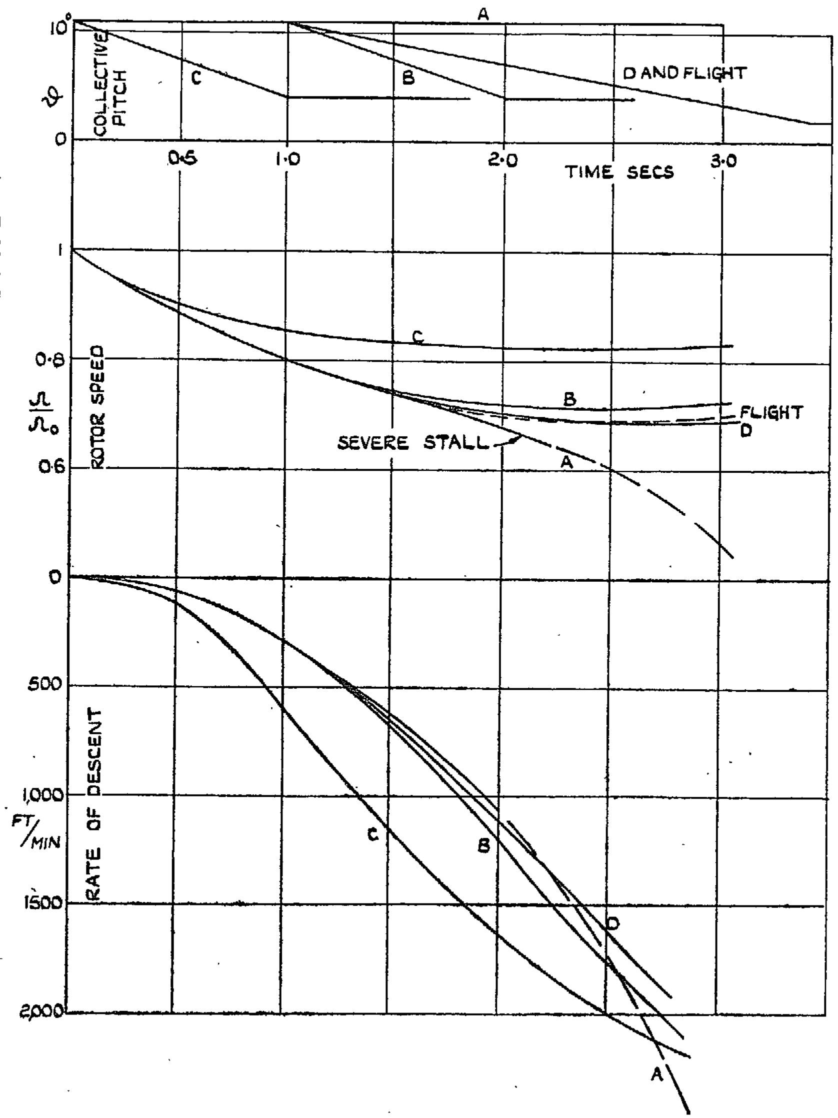

FIG. 1. Rotor behaviour after engine failure. S-51 helicopter.

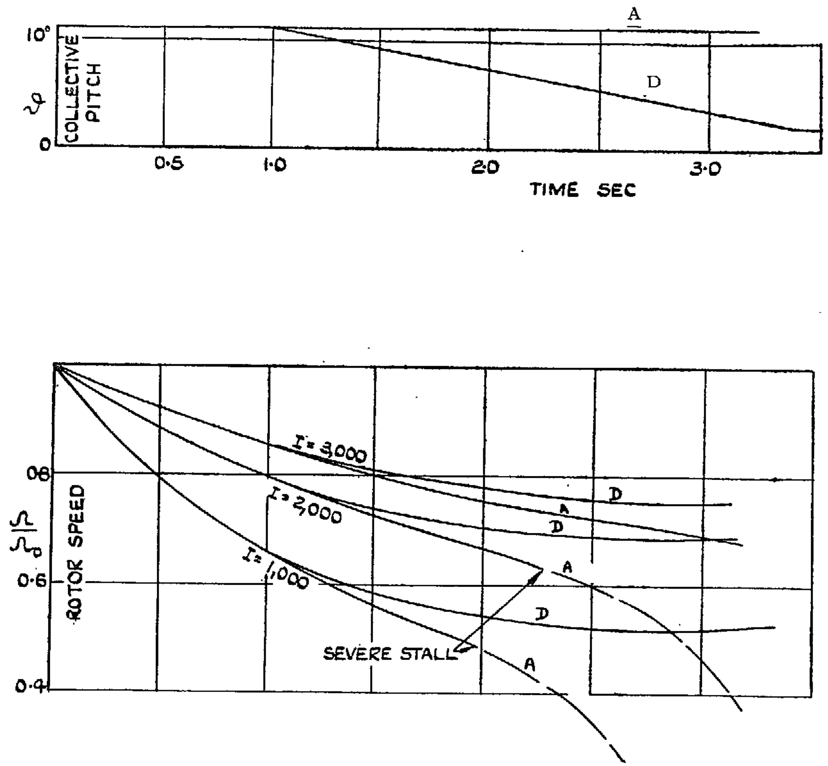

FIG. 2. Effect of moment of inertia on rotor speed after engine failure.

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