NINTH EUROPEAN ROTORCRAFT FORUM

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AUTOROTATION - THEORY AND PRACTICE

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ABSTRACT

For the safe operation of any helicopter it is important to know the combinations of height and speed at which an engine failure may result in a landing which is outside the limits of the aircraft.

The theoretical interdependencies of the helicopter's dynamic and aerodynamic parameters are analysed in order to recommend an ideal solution for autorotative flight. This is followed by a review of the practical techniques and procedures which are taught to student helicopter test pilots at Boscombe Down in order for them to investigate safely the autorotative performance of a single engined helicopter and to use the incremental approach in the preparation of an 'avoid curve' diagram to predict the unsafe combinations of height and speed. The margins allowed for error are, inevitably, small and the test pilot must be made fully aware of the need to allow for a variation of skill level between individual helicopter pilots and for their need to be given prompt warning cues in order to take the correct recovery actions within the limited safe time available.

INTRODUCTION

1. The training of helicopter test pilots is a complex and demanding task which is described in detail at Reference 1 and outlines the methods used at the Empire Test Pilots' School in the United Kingdom. This paper concentrates on one aspect of the training received by student test pilots, that of autorotation and engine-off flight.

2. The aim of test pilot training is to develop the specialist skills of a pilot with above average flying ability, to enable him to make critical and accurate observations while engaged in a demanding flying task. He must learn not to compensate for the deficiencies of his aircraft, to establish limits of aircraft use to which other pilots will operate, and to communicate his findings accurately.

3. One of the most demanding and potentially dangerous areas of helicopter testing is that of autorotation and engine-off flight. The margins for error are small. Close supervision of the students and attention to the flight safety implications are inherent in the ETPS approach to this high-risk training situation. This paper reviews and analyses the theoretical aspects of autorotational flight, then goes on to give an insight into the practical techniques and procedures which are taught to student helicopter test pilots at ETPS in order for them to investigate safely the autorotative performance of a helicopter.

4. The aircraft of the ETPS fleet comprise:

   a. Aerospatiale Gazelle Mk 3

   b. Westland Scout

   c. Westland Wessex Mk 5

   d. Westland Navy Lynx HAS Mk 2

   e. Sikorsky Sea King Mk 1

The aircraft used for autorotative studies are the Gazelle, Scout and Wessex.

AUTOROTATION

5. The early part of the ETPS rotary wing course covers the flight testing procedures used to investigate the handling qualities of helicopters during flight throughout the power-on flight envelope, including take-off, landing and low speed manoeuvres. The final area of the envelope requiring investigation is the power-off condition. This involves understanding the theoretical background to the exercise and assessing the helicopter in entry to autorotation, descent, recovery from autorotation and the subsequent landings. Operation in these regimes may result from power plant or transmission failure, or be initiated by the pilot for operational or training reasons.

THEORETICAL CONSIDERATIONS

6. Student test pilots are introduced to the subject of autorotation in their ground school studies. Before the students come to this subject area, they will have spent many hours learning mathematics, aerodynamics, gas properties, mechanics, aero engines, helicopter rotor performance, rotor dynamics and non-dimensional performance analysis. This principle of theory before practice is fundamental to the training methods used at the Empire Test Pilots' School. The following paragraphs are from their theoretical studies of autorotation which are designed to provide a sound basis for their understanding of the background to the flying exercises.

BLADE ELEMENT MODES

7. It is first necessary to appreciate the difference between autorotation and windmilling although the terms differ only in degree.

a. Windmilling. In the windmilling condition, the blades or blade elements are set at a pitch angle which will produce a torque force in the direction of rotation, regardless of the size of the thrust produced.

b. Autorotation. In the autorotative condition, the blades or blade elements are set at a pitch angle which will produce the maximum thrust, but the torque force is zero.

8. In order to produce an autorotative or windmilling mode of working, the direction of the resultant relative airflow must be from below the plane of rotation in order to generate a lift force (L) which has a forward horizontal component. This requires that the helicopter must be descending relative to the air. Figure 1 shows this situation.

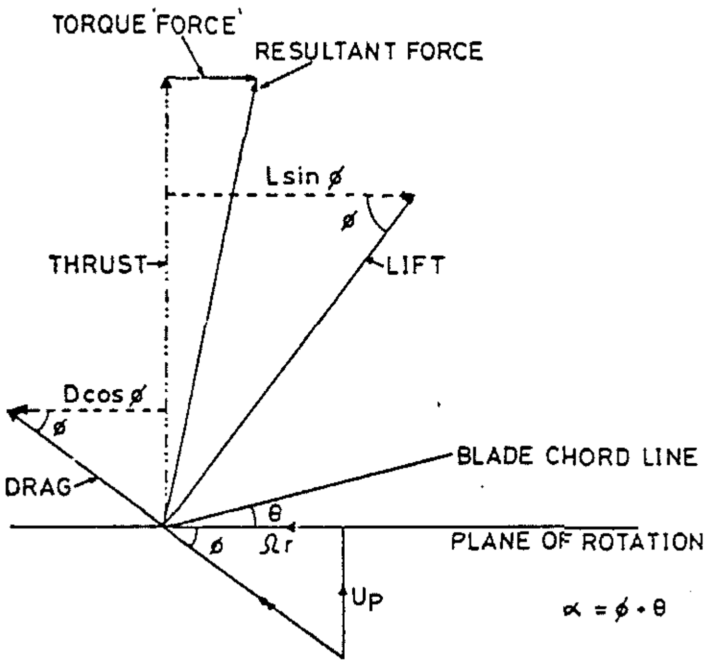

Figure 1
Forces Acting on a Blade Element - Windmilling Condition

9 The lift and drag forces acting on the element produce a resultant which comprises a thrust component perpendicular to the plane of rotation and a torque "force" acting in the direction of rotation of the blade. In the absence of friction, the blade element will be just autorotating when the forward component of the lift balances the backward component of the drag to give a zero torque "force" as shown in Figure 2.

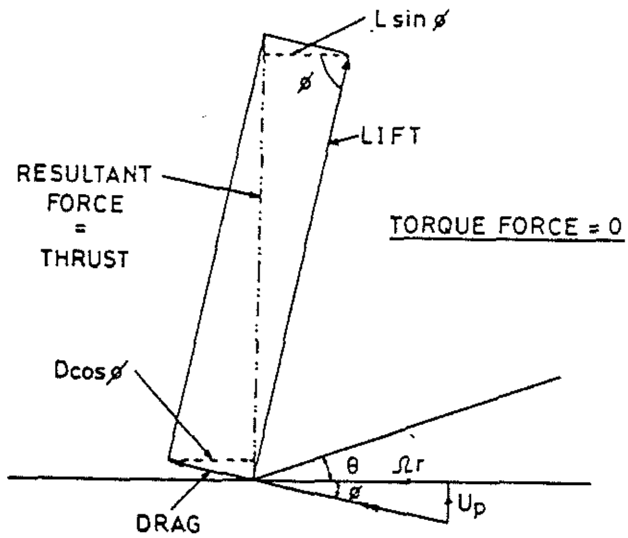

Figure 2
Blade Element - Autorotative Condition

10. To produce a positive torque force, the inflow angle ϕ must be greater than the value that produces the autorotative condition. However the value must not be too great or the blade element will stall.

11. If we now consider a complete blade, untwisted so that θ, the pitch angle, is constant, we find that the elements of the blade are operating at different angles of attack as shown in Fig 3 for vertical autorotation. The magnitudes of the angle of attack depend on the value of ΩR. It is therefore possible for only a limited range of blade elements to produce a torque force which assists rotation; others may be stalled and some may be operating at too low a value of ϕ.

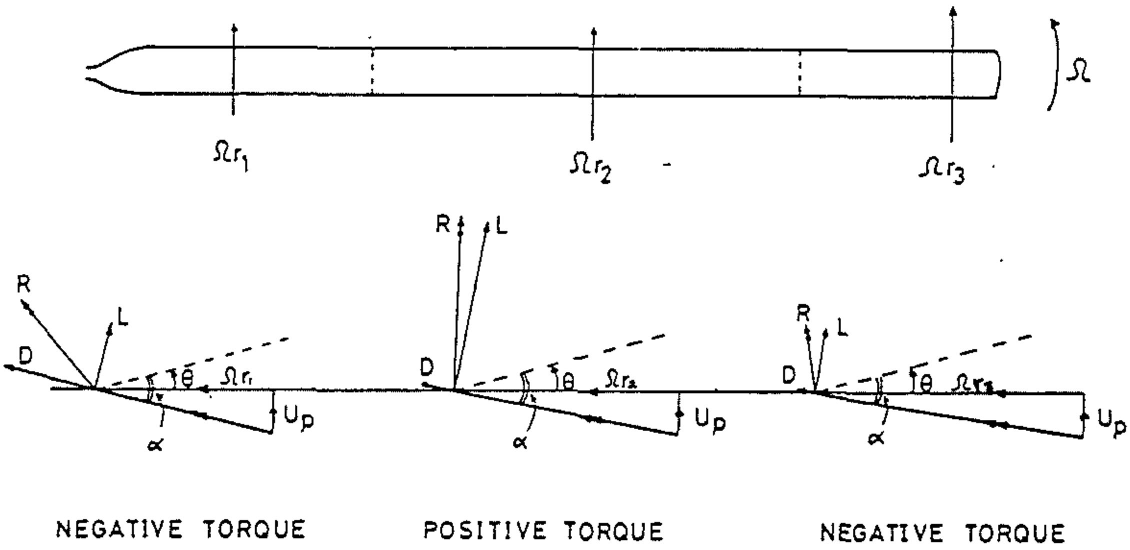

Figure 3
Variation of Element Operating Conditions with Radial Position

Near the root, the angle of attack is too great and the elements are stalled resulting in a drag torque "force". Near the tip, the angle of attack is too low, again producing a torque "force" opposing rotation. It is only in the centre of the blade that the elements are operating so as to produce "positive" torque "forces" and for autorotation of the whole rotor the windmilling elements must produce sufficient torque to overcome the retarding torques from the remaining elements, the frictional losses in the transmission/gearbox, and the torque required by the tail rotor. The situation is further complicated in forward flight due to the asymmetry of the resultant airflow.

AUTOROTATIVE PERFORMANCE

12. Using blade element theory and the appropriate induced velocity relationships, the rate of descent under autorotative conditions can be calculated. In forward flight, with power available, the power required is given by:

$$P = WV_c + Tv + \tfrac{1}{8}\rho c b \Omega^3 R^4 \; (1 + 3\mu^2)\; C_D + D_p V \qquad (1)$$

In autorotative forward flight the power available is zero; the last three terms on the right of equation (1) must be positive, since they represent power used (ie induced, profile and parasite power respectively); thus V_c must be negative. The rate of descent is then given by:

$$V_d = -V_c = \frac{1}{W}\left[Tv + \tfrac{1}{8}\rho c b \Omega^3 R^4 \; (1 + 3\mu^2)\; C_D + D_p V \right] \qquad (2)$$

Figure 4 shows the variation of rate of descent with changing forward speed for the Wessex 2 at two weights and corresponding RRPM.

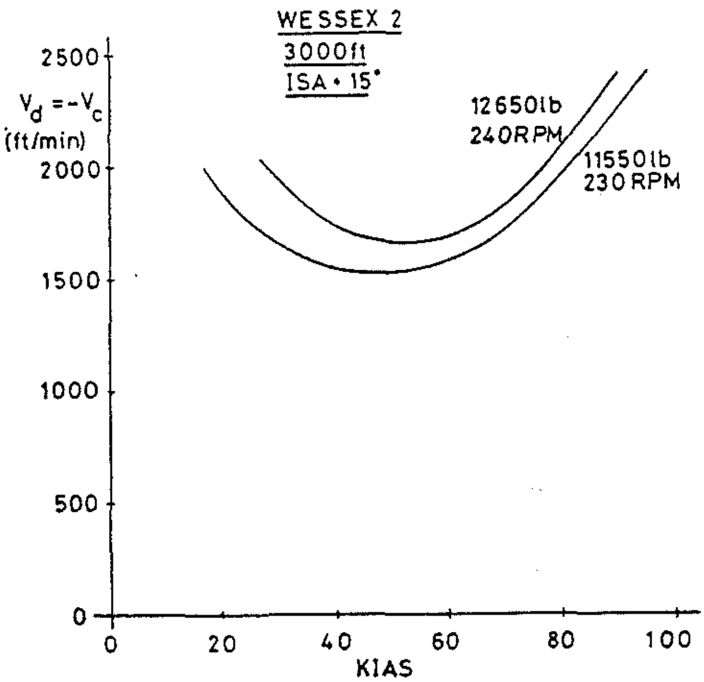

Figure 4
Descent Performance - Wessex 2

13. A simple theoretical analysis in Reference 2 shows that the vertical rate of descent is proportional to the square root of the disc loading (thrust/rotor disc area) and is inversely proportional to the square root of the air density. An increase in solidity (relative blade area) results in a decrease in the rate of descent.

14. Equation (2) indicates that to reduce the rate of descent, the profile power should be minimised by operating at minimum RRPM. This is true as long as the thrust to offset the weight is maintained. In practice, little advantage is gained by operating at the lowest possible RRPM and the highest (relative) pitch angles. The RRPM should therefore be maintained to provide energy for the flare manoeuvre. This requirement does not however affect the need for both the blade profile drag coefficient and the fuselage drag to be kept as low as possible.

FLIGHT AFTER TOTAL ENGINE FAILURE

15. Following a total power failure there are three main cases to be considered:

a. Vertical flight near the ground.

b. Vertical flight away from the ground.

c. Forward flight.

VERTICAL FLIGHT NEAR THE GROUND

16. If power failure occurs near the ground in vertical flight, the pilot has sufficient time to make any major control changes except for rapidly raising the collective lever. Hence, the helicopter drops back to the ground, the rate of descent being restricted by the utilisation of some of the kinetic energy stored in the rotor. The maximum safe height from which a landing can be made is therefore determined mainly by the energy absorbing properties of the undercarriage.

VERTICAL FLIGHT AWAY FROM THE GROUND

17. If engine failure occurs in vertical flight when well clear of the ground, the pilot is assumed to reduce the collective pitch in an attempt to maintain the rotor speed and to use cyclic to gain forward speed at the expense of initially increasing the rate of descent. He then makes a flare out and landing in which the rotor energy is used to reduce the rate of descent and forward speed to a value which can be tolerated by the undercarriage. Figure 5 shows the typical variation of collective pitch (θ), RRPM (Ω) and the rate of climb ($-V_c$) during the recovery from an engine failure situation whilst in the hover well clear of the ground.

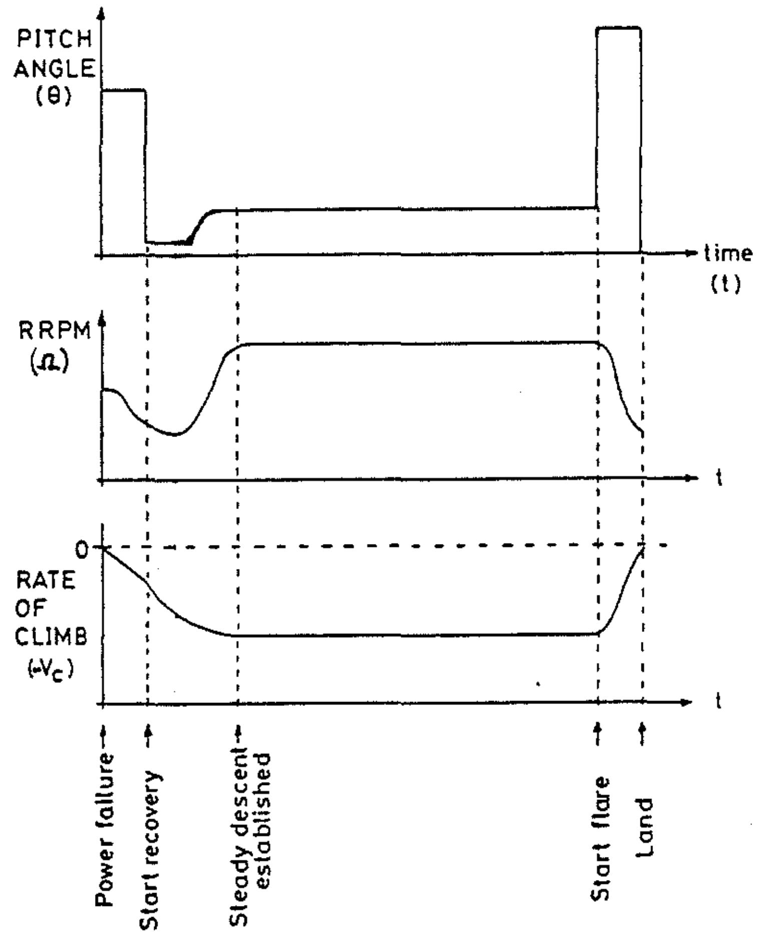

Figure 5
Recovery After Engine Failure When Well Clear of the Ground

18. In Figure 5, we can see the time taken for the pilot to react to the power loss. It is typically of the order of 0.75s. During this time the RRPM decays and the rate of descent of the helicopter starts to build up. After this reaction time it is assumed that the pilot reduces collective pitch to a minimum. The RRPM then starts to build up, whilst the rate of descent increases. The pilot is then assumed to raise the collective pitch slightly to give a constant RRPM and a steady rate of descent. Immediately prior to touchdown, the pilot flares the aircraft to increase RRPM, reduce groundspeed and rate of descent then finally raises the collective pitch to cushion the impact. The thrust produced by the rotor will have increased as the RRPM finally decays and the helicopter's rate of descent will have been reduced - to allow the helicopter to land at a rate of descent below the design maximum rate of descent for the undercarriage.

19. The speed to which the RRPM decays whilst the pilot is appreciating and reacting to the power loss is critical. If the RRPM decays too much, the rotor decelerates and it becomes impossible to recover the helicopter. Reference 3 specifies that the time delay available to the pilot before the RRPM decays to a dangerously low value should be 2 seconds or greater. This minimum rotor speed is difficult to determine theoretically, but a feel for the problem can be obtained if it is assumed that the minimum allowable rotor speed (Ω_{min}) corresponds to the maximum mean lift coefficient achievable by the rotor ($C_{L_{MAX}}$). If the thrust is assumed to be constant throughout the delay period, and C_{L_r} is the mean lift coefficient corresponding to the rotor speed (Ω_o) at power failure, then it can be shown that the allowable time delay t is given by:

$$t = \frac{\pi I_R V_T^2 w}{WP} \left(\sqrt{\frac{C_{L_{MAX}}}{C_{L_r}}} - 1 \right) \qquad (3)$$

Thus the allowable time delay is seen to increase with:

a. Increased disc loading (w).

b. Increased tip speed (V_T).

c. Increased rotor inertia (I_R).

d. Decreased mean lift coefficient (C_{L_r}).

20. A conflict then arises as a high disc loading requires a low rotor radius; a high inertia requires a large rotor radius and a high disc loading and tip speed means that the hover power required under normal conditions will be high. A compromise must then be reached that will give both a satisfactory time delay and a reasonable hover power requirement. A further problem arises when the power-off rate of descent is considered. To obtain low rates of descent the disc loading and tip speed should be a minimum.

21. Finally, in the flare the rotor kinetic energy must be converted into thrust to decrease the rate of descent and groundspeed. The most convenient criterion for comparison of the flare capability is the ratio of the rotor kinetic energy to the gross weight ie:

$$\frac{KE}{W} = \frac{I_R\,\Omega^2}{2W} = \frac{I_R}{2W}\left(\frac{V_T}{R}\right)^2 \qquad (4)$$

Equation (4) shows that if for powered flight considerations the tip speed must be kept low, then rotor inertia must be drastically increased to maintain the kinetic energy. For a given blade design, inertia may be increased by adding tip weights until a structural or dynamic limit is reached. Also, it is quite common to autorotate at a rotor speed higher than that for powered flight. This, however, has the disadvantage of increasing the rate of descent in autorotation. Given a choice, the rotor should be optimised for the role of the helicopter and given good flare characteristics as the effectiveness of the flare can be crucial to the safe completion of the autorotational landing.

FORWARD FLIGHT

22. In forward flight the pilot can utilise his forward speed to improve the gliding angle, or initially gain height or maintain rotor speed. However, it should be possible in the flare to reduce the forward speed to a minimum appropriate to the available landing area, although at very low RRPM, loss of tail rotor authority may become a major factor.

THE AVOID CURVE

23. There are combinations of height and forward speed that may cause uncontrolled landings in the case of total engine failure. These combinations of height and forward speed should thus be avoided during normal operation of the helicopter. An "avoid" curve for a typical helicopter is shown in Figure 6.

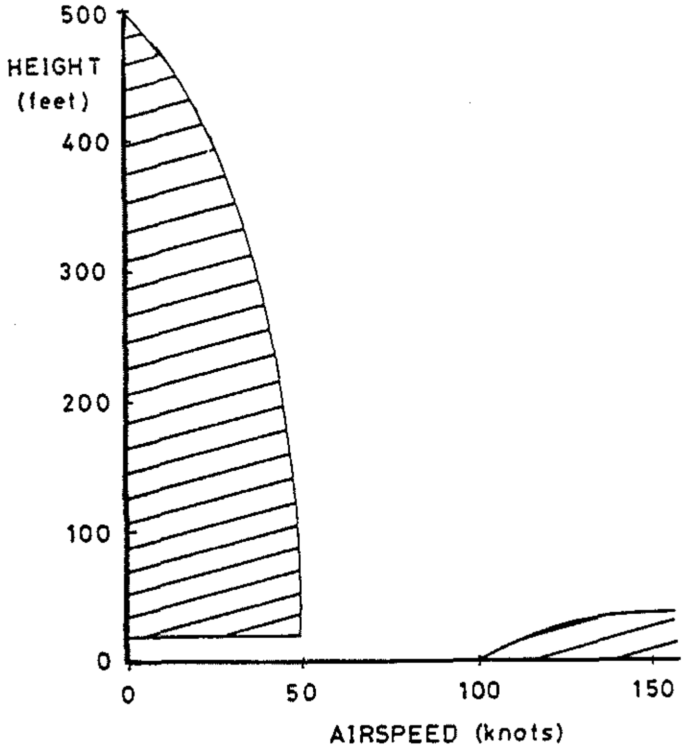

Figure 6
Typical Avoid Curve

THE PRACTICAL TEST EXERICSE

24. Before the student commences the flying exercise he is given a series of detailed briefings covering all practical aspects of the planning and execution of the test exercise. The tests are arranged so that both the operational and emergency aspects of autorotative flight are covered concurrently. The 4 hours solo flying time and 2 hours dual demonstration flights allocated for the exercise permit only a basic examination of the aircraft's characteristics at a representative but limited number of points throughout the flight envelope. Extracts from these briefings and the conduct of the flying exercise are covered in the remainder of this paper.

AIMS AND REQUIREMENTS

25. The aims of these tests are to determine whether the handling qualities of a helicopter during autorotative flight and engine-off landings are safe and compatible with its intended roles; to recommend any modifications which would improve its qualities; and/or to recommend any special techniques, limitations, and warnings that would be beneficial to the operational user. The handling qualities that the helicopter should exhibit during these tests are set out in Reference 3.

GENERAL TEST CONSIDERATIONS

FLYING PRACTICE

26. It is necessary during this exercise to use techniques which leave little or no margin for errors. In the interests of flight safety, a test pilot should ensure that he is in regular practice at autorotations and engine-off landings. At ETPS most students lack experience in this area and are thus gradually exposed to the more demanding landings before this exercise is flown.

AIRCRAFT ROLES

27. Throughout the evaluation, the student should bear in mind the role of the aircraft as he assesses its handling characteristics. For example:

a. Army reconnaissance helicopters should possess handling qualities which will permit the pilot to enter a fast descent quickly and recover to level flight rapidly at very low level. This implies that the trim and attitude changes in such manoeuvres should be small and the engine response good.

b. Helicopters designed for the basic training role should possess good handling qualities during transition to and from autorotation.

CONDITIONS RELEVANT TO THE TEST

AIRCRAFT LIMITATIONS

28. At a test establishment the test pilot would have a design certificate containing all the relevant limitations of the aircraft; these limitations would have evolved from manufacturers' tests, and must be observed. For the ETPS exercise the limitations set out in the Aircrew Manual and ETPS Orders are regarded as a substitute for the Design Certificate. An example of these limitations for the Wessex Mk 5 are as follows:

Max Rotor Speed with turbine engaged (transient)	258
Min Rotor Speed with turbine engaged (transient)	205
Max Rotor Speed in autorotation (sustained)	245
Max Rotor Speed in autorotation (transient)	258
Min Rotor Speed in autorotation (sustained)	205
Min Rotor Speed in autorotation (transient)	190
Max 'run on' ground speed for engine-off landings (estimated)	30 kts
Min altitude for initial rotor decay tests	5000 ft

NOTES: 1. Transients must not exceed 10 seconds duration.

2. For the 'lever delay' and 'low autorotative RPM' tests at ETPS, the minimum RRPM of 190 is not to be used for longer than 10 seconds.

SYSTEMS FAILURE

29. Depending on the systems fitted to the test aircraft, it may be necessary to carry out some tests with manual or partially powered flying controls, and possibly without the assistance of autostabilisation and stick trim. For example, some helicopters have engine-driven hydraulic pumps; if the engine fails the flying controls revert to manual and so it would be necessary to make some of the tests in manual control.

INSTRUMENTATION

30. Although standard cockpit instrumentation and control position indicators are adequate for a number of tests, trace recording facilities are essential for the engine-off landings and lever delays to ensure safety and to provide the maximum amount of data from each manoeuvre. The following parameters are recorded:

a. Rotor speed.

b. Throttle position, fuel flow, compressor speed/engine speed, torque/boost.

c. Collective pitch.

d. Cyclic stick position (longitudinal and lateral).

e. Yaw pedal position.

f. Fuselage attitude (pitch and roll).

g. IAS.

h. Pressure altitude.

i. Rad alt height.

j. Time.

FLIGHT SAFETY

31. Due to the high risk nature of this exercise, initial tests should always be made under the most favourable conditions, then extreme conditions should be approached incrementally. There are two phases of this exercise which should be approached with extreme caution. Statistics show that accidents are more likely to occur during lever delay tests and engine-off landings than at any other time. Therefore the following points are emphasised at ETPS:

a. The implications of making various control movements under blade/jack stall conditions should be clearly understood.

b. Control movements should be kept to a minimum at low RRPM.

c. The tests are flown only in favourable weather conditions over an area where a successful engine-off landing could be made in the event of an engine malfunction.

d. Parachutes should be worn for these tests.

THE ETPS TEST EXERCISE

INITIAL TESTS

32. Initially, slow and then rapid entries into autorotation are made in level and climbing flight at minimum power speed followed by a recovery to powered flight. These entry tests are then expanded to include representative airspeeds from zero to the maximum. The rapid entry tests indicate the likely aircraft characteristics during a rapid collective lever reduction after a sudden engine failure. The following data should be obtained during these entries:

a. Any tendency of the rotor speed to exceed its limiting values and the corrective movements of the collective pitch required to control RRPM.

b. Any requirements for large cyclic or pedal movements to retain control of the aircraft, and the adequacy of control ranges.

c. Any other undesirable features such as large attitude changes, vibration, engine control problems or difficulties arising from loss of power controls.

d. The ease with which the helicopter can be entered into autorotation. Factors affecting opinion on this are:

(1) Control Positions. Frequency and magnitude of control movements (pilot workload) required during entry (including 'uncontrollable' attitude and heading changes). Adequacy of control ranges.

(2) Aircraft Response to Controls. Effectiveness of controls. Unusual lags, rates, accelerations, displacements of the aircraft following control displacement.

(3) Control Forces. Unusual forces; ease of trimming.

e. Changes in indicated airspeed.

f. Vibration levels.

g. Engine/rotor performance and handling; throttle/lever co-ordination.

h. Comments pertinent to the role; for example, adequacy of downwards field of view.

MANOEUVRES IN AUTOROTATION

33. The helicopter is now flown in straight and manoeuvring autorotative flight at various airspeeds throughout the flight envelope. The student should observe all the parameters mentioned previously during the entry phase but particular emphasis should be placed on evaluating the ease with which forced landing manoeuvres can be flown and rotor speed contained within limits. For example, does a poor field of view from the cockpit hinder the pilot in positioning the aircraft for a forced landing?; is pilot workload excessive which might distract his attention from the essential task of completing the landing safely?

LOW ROTOR SPEED TESTS

34. One of the most important areas to investigate is the aircraft's handling qualities at the minimum autorotative rotor speed. This limit, specified by the manufacturer, is approached incrementally as serious handling problems may be encountered prematurely. The student must ensure that the rotor speed is never allowed to go below the minimum value, while concentrating on the following points:

a. Adequacy of cyclic and yaw control ranges.

b. Control response.

c. Any indications of 'blade stall', such as vibration/jack stall.

d. Height lost to recover RRPM to the normal value.

e. Effect of a gentle flare on rate of recovery of RRPM and overall height lost.

RECOVERIES TO POWERED FLIGHT

35. Following each autorotative descent recoveries to powered flight are initiated using selected angles of flare. The purpose of these tests is two-fold; recoveries from operational type autorotative manoeuvres must be investigated and aircraft behaviour during representative manoeuvres that will be used for the eventual power-off landing should be assessed. These tests also provide valuable information such as approximate height lost during recovery and the effectiveness of various flare techniques in arresting the downward and forward motion of the helicopter.

POWER-OFF LANDINGS

36. Depending on the results of these early tests, a programme of low-level recoveries, culminating in power-off landings, can be planned. Initially a series of autorotative approaches from a constant start height should be made, each terminating in a recovery to powered flight. The first is carried out at the speed for minimum rate of descent and at the recommended optimum rotor speed. Subsequent approaches are then made at airspeeds and rotor speeds to cover the permissible ranges with a view to determining the effects of these parameters on the range. The airspeed and rotor speed should be returned to the optimum in the final stages of the descent so that a safe engine re-engagement can be made. These tests then concentrate on recoveries using various flare techniques ranging from full flare to constant attitude at air-speeds, rotor speeds and flare initiation heights bracketing what is felt to be the optimum for a power-off landing. The following data is obtained:

a. Effect of airspeed and rotor speed on range.

b. Ease with which normal IAS and rotor speed can be regained from abnormal conditions (eg maximum IAS, minimum RRPM) to set the aircraft up for execution of an engine-off landing.

c. Effect of small changes in IAS, RRPM, and height on the anticipated conditions for an engine-off landing.

d. Any difficulties experienced with field of view that may cause problems with height judgement during the landing.

37. After thorough analysis of all the earlier data the student should now be confident to carry out his very first solo power-off landing at the optimum conditions followed by a series of further landings, varying the parameters in a similar way and if possible, touchdown ground speeds. Ideally, the engine should be throttled to an idling RPM which will give a zero power contribution throughout the sequence, but it may be necessary to stop the engine; at least one landing during the ETPS exercise is completed with the engine shut down. Special note should be made of:

a. Rotor speed throughout the manoeuvre. For example, before and after any flare and at touchdown.

b. Length of ground run resulting from various touchdown speeds in various wind speeds. Undercarriage behaviour. Effectiveness of brakes, wheel locks. Tendency to wheel shimmy.

c. Attitude changes.

LEVER DELAYS

38. Subject to the autorotational entry tests being satisfactory, the effect on rotor speed and general aircraft behaviour of delaying the reduction of collective pitch following a sudden loss of engine power is investigated. Starting at minimum power airspeed in level flight at a safe height and following a careful briefing and count down, the throttle is closed rapidly. A slight delay is then observed allowing the rotor speed to decay to a preselected value, well above the minimum power-off RRPM, at which point the collective lever is rapidly lowered fully. The minimum transient rotor speed is then noted and the time taken for the RRPM to recover to normal is measured. The size of the rotor speed underswing is then calculated. The delay time is then increased incrementally until either the minimum RRPM is reached during the underswing, or a handling problem is encountered, or the collective delay time of 2 seconds is achieved. This is a very demanding and critical exercise for the student and it is essential that he monitors the underswing very carefully as it may change markedly with increasing delay time. It is most important that the engine failure cues are fully assessed and the student is expected to report whether the combination of achievable lever delay and engine failure cues are compatible with the aircraft's role.

AVOID CURVE

39. A project pilot should have a detailed knowledge of the following before 'avoid area' tests are commenced:

a. The power-off handling qualities of the aircraft.

b. The maximum safe delay times that can be attained between closing the throttle and lowering the lever throughout the flight envelope, especially at high power settings.

c. The height lost, if any, between power failure and achieving acceptable stabilised conditions from which a power-off landing may be made. This height loss should be known for all conditions within the flight envelope.

d. The maximum acceptable vertical and horizontal velocities at touchdown.

Due to the time available, and the ETPS students' relative inexperience and the critical nature of avoid curve testing this exercise is flown as a dual demonstration flight with the student "flight proving" the already cleared avoid curve as shown at Figure 7 by evaluating the test points in order.

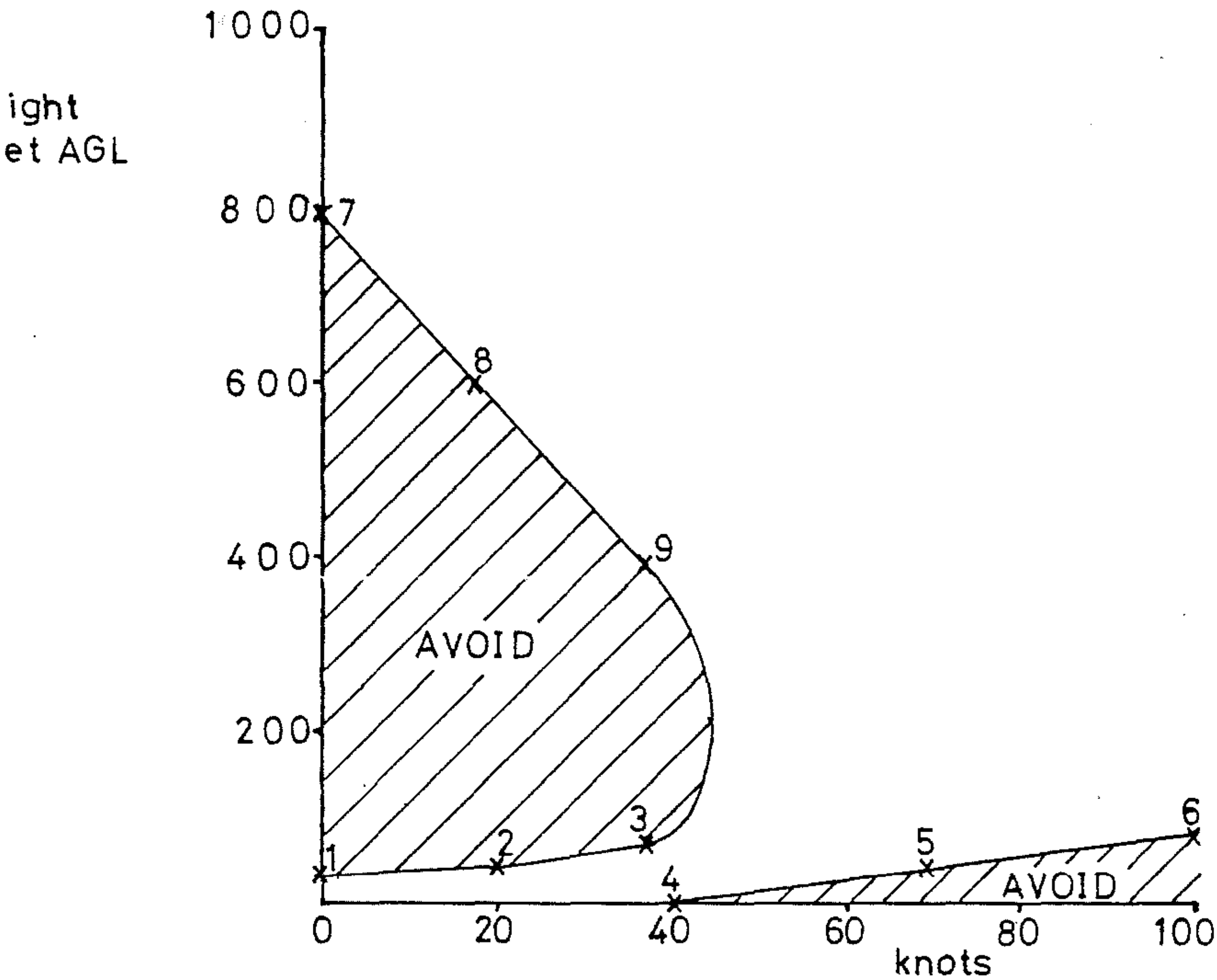

Figure 7
Planning the Avoid Curve Test Points

40. Positions 1, 2, 3 and 4 can be easily determined as they are merely a function of rotor inertia and performance during decay, combined with undercarriage/airframe strength and behaviour during run on. All the remaining positions (5-9) are a function of the height loss while achieving suitable autorotative conditions after a representative delay between power failure and lowering the lever. Positions 5 and 6 demand 'quick-stop type' manoeuvres; positions 7-9 require various degrees of acceleration before suitable autorotative conditions prevail. Obviously, all these positions are approached in stages; for instance the 38 kts position 3 would probably be assessed initially from approximately 10 ft AGL; position 7 might be approached from zero speed and 1200 ft AGL. This exacting exercise is found difficult and

traumatic by most students who are called upon to use their flying skills to the limit whilst attempting to observe accurately and draw meaningful conclusions.

CONCLUSION

41. The culmination of the autorotational exercise, as in all exercises at ETPS is for the student to produce a detailed written report which should analyse and highlight any deficiencies in aircraft handling requiring operational limitations to be imposed. After marking of his report and subsequent discussions with staff tutors, the student will have completed the most demanding 4 hours of test flying out of his course total of over 100 test flying hours. The experience, skill levels and ability to communicate effectively which the ETPS test pilot graduate will have obtained in this area and the other areas of helicopter testing provide him with the means to carry out his future tasks successfully with safety, professionalism and efficiency.

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SYMBOLOGY AND ABBREVIATIONS (in order of use)

ETPS	Empire Test Pilots' School
L	Lift on blade element
D	Drag on blade element
R	Resultant force on blade element
Ω, RRPM	Rotor rotational speed
Up	Component of relative airflow perpendicular to plane of rotation of blade element.
θ	Angle of pitch of blade element (collective pitch)
ϕ	Inflow angle at blade element
α	Angle of attack of blade element
r, r_1, r_2, r_3	Radii of blade elements
P	Power required in forward flight
V_c	Rate of climb
V_d	Rate of descent
W	Weight of helicopter
T	Thrust produced by rotor
v	Induced velocity at rotor
ρ	Air density
c	Blade chord
b	Number of blades
R	Rotor radius
μ	Advance ratio
C_D	Blade profile drag coefficient
D_p	Fuselage profile drag
V	Resultant velocity of helicopter
KIAS	Knots indicated airspeed
$C_{L_{MAX}}$	Maximum mean rotor lift coefficient
C_{L_r}	Mean rotor lift coefficient at power failure

Ω_o	Rotor speed at power failure
t	Time delay
w	Disc loading
V_T	Rotor tip speed
I_R	Rotor polar moment of inertia
KE	Rotor kinetic energy
IAS	Indicated airspeed
AGL	Above ground level