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A THEORETICAL STUDY OF THE EFFECT OF BLADE ICE ACCRETION ON THE POWER-OFF LANDING CAPABILITY OF A WESSEX HELICOPTER

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1 INTRODUCTION

The freedom to fly helicopters in known or forecast icing conditions is now being sought by military and civil operators. This requirement has come about because the exploitation of North Sea Oil needs the commercial operator to provide all the year round support, while the services need to fly in all weather conditions for maximum effectiveness. The aircraft currently used, however, have unprotected blades, and although a full anti-icing treatment is feasible, the cost of retrofitting the equipment, and its effect on the aircraft performance rule this out. A cheaper system involving partial de-icing by electrical, chemical or mechanical means has not yet proved entirely satisfactory, so the possibility of obtaining a limited clearance with unprotected blades is being investigated.

The task of giving a clearance is the responsibility of the CAA for civil aircraft, and A & AEE, Boscombe Down for military aircraft. Each helicopter has to be treated on its own merits, and flight trials are normally made in natural icing to provide the necessary evidence to the certifying authority. This technique has proved successful for the British Airways S-61 helicopters, which are now cleared to fly in light icing[1], and the Westland Lynx. A & AEE have also been carrying out a more fundamental investigation of helicopter icing[2], and have also experimented with various de-icing systems. Much of this work has been made with a Wessex helicopter fitted with specially developed instrumentation, and these tests have shown that the Wessex is not very tolerant of icing. Large and rapid torque rises have been experienced on some occasions which caused concern for the safety of the crew should a total power failure occur. The calculations described in this paper were an attempt to provide A & AEE with some indication of the maximum torque rise that could safely be tolerated in forward flight before the autorotational performance of the aircraft became seriously degraded, and it became impossible to make a power-off landing. The work is fully described in Ref 3 and only a few of the results are presented here.

A brief summary of some of the results from the flight tests is presented in section 2, and section 3 describes the degraded aerofoil characteristics used to represent the ice in the calculations. The effect of ice on the calculated torque required in steady forward flight is outlined in section 4. Section 5 considers the aircraft performance following total power failure, and attempts to relate the performance losses with the excess torque in forward flight.

2 A BRIEF SUMMARY OF THE FLIGHT TRIALS

2.1 Forward flight performance

The flight trials made by A & AEE with the Wessex in natural icing have shown large variations in performance losses, but the interpretation of the results is difficult because of the lack of suitable instrumentation to measure the icing environment. A simple accretion device, known as the hot rod, is normally used to measure the liquid water content of the cloud, but this becomes saturated at temperatures just below zero. Thus occasionally large torque rises have occurred with only frosting of the hot rod, and conversely, a large amount of ice has accreted on the hot rod with little or no effect on the performance of the aircraft.

A majority of the flights show a similar pattern of events, with the torque increasing within a few minutes of entering the cloud, and then stabilising as continuous accretion and shedding on the blades occurs. The hot rod during this stable state generally accretes ice at a constant rate. The latter part of a prolonged flight of this type is shown in Fig 1. The aircraft was flying at about 90 knots at 3000 feet with an outside air temperature of -3.5°C. The estimated liquid water content of the cloud was 0.6 g/m^3 representing light icing. The torque increase was between 500 and 600 lb ft, an increase of about 30% relative to the clean aircraft. Limited manoeuvres were possible; an acceleration to 100 knots at 53 minutes, and a gentle climb initiated at 55 minutes. This is clearly a tolerable situation although the reduction in range due to the increased fuel consumption may not always be acceptable.

The second example from the flight tests, Fig 2, shows a more extreme encounter, and was the sort of event that caused concern for the safety of the aircraft and crew. The flight was made at 5000 feet in this case with a similar outside air temperature to the previous example, but the estimated liquid water content was 1.3 g/m^3, indicative of severe icing. The pilot had to make a large application of collective pitch to maintain speed and altitude, while the torque showed no sign of stabilising and was increasing at 100% per minute. The very high starload readings also suggest that blade stall was occurring.

A summary of the torque increases measured with the Wessex during the 1973/4 winter trials are shown as functions of altitude and airspeed in Fig 3. The speed shown in this figure is the difference between the maximum allowed speed, V_{max} , which depends on the weight and altitude, and the aircraft speed, thus an increase in speed is represented by a decrease in the velocity difference. Most of the large torque rises occurred at the higher altitudes and near the recommended speed limit of V_{max} -15 knots , suggesting that blade stall is partly responsible. There are, however, some notable exceptions; a torque increase of between 700 and 900 lb ft, for example, was recorded at an altitude of only 2300 feet.

2.2 Performance in autorotation

The autorotational performance of a helicopter is of vital importance in icing because of the greatly increased risk of engine failure due to the ingestion of ice or slush. The ability of the aircraft to autorotate is checked regularly during the flight tests but the changes in performance have varied widely, and it has not been possible to correlate the loss in rotor speed, or the increase in rate of descent with the excess torque carried when the power was cut. The rotor head camera has since shown that ice is frequently shed from the rotor on entry into autorotation or during the descent through warmer air, but this does not always happen as the following two examples will illustrate.

The excess torque at the moment the throttle was closed was 60% in both cases. The ambient temperature was -5°C in the first example, and the rotor head camera showed ice extending to the blade tip. The loss in rotor speed during the autorotational descent was only 4 rpm, and when steady power-on flight was re-established two minutes later, the torque increase was only 10% with ice on the inboard portion of the blades to 20% radius. The second example was with an outside air temperature of -6°C. The aircraft would not autorotate with the collective pitch at its normal temperature setting, and required 10% of the full aircraft power to maintain the rotor speed above the minimum permitted level.

3 DEGRADED AEROFOIL CHARACTERISTICS

The aerofoil characteristics used to represent the ice form an essential part of the calculations, but the available experimental data is sparse. The data used in the calculations were based on some early NACA tests made in the Lewis Icing tunnel on a NACA 0011 section[4]. The chord length of the model was over 7 feet so the rate of ice accretion is not comparable with that on the blades of the Wessex, which have a chord length of 1.367 feet. Fig 4 shows one of the results from the icing tunnel tests with the aerofoil angle of attack at 2.3°. The liquid water content of the stream was 0.5 g/m^3, and the air temperature was -3.9°C. The drag increase exceeded 250% with a loss of lift approaching 15%, and even greater degradations were recorded when the liquid water content of the air stream was increased. These tests, however, covered only a limited range of parameters, and the reduction in the maximum lift coefficient of the aerofoil was not defined.

The degraded aerofoil characteristics used in the calculations were obtained by modifying the clean aerofoil data. Two factors, Δa and ΔC_{D_0}, representing the change in the aerofoil lift curve slope and zero lift drag, were applied to the clean aerofoil data in the following way,

$$C_{L_{\text{iced}}} = C_{L_{\text{clean}}} (1 + \Delta a) = \alpha a(1 + \Delta a)$$

$$C_{D_{\text{iced}}} = C_{D_{\text{clean}}} (1 + \Delta C_{D_0})$$

where $C_{D_{\text{clean}}}$ is the drag coefficient of the clean aerofoil at the unfactored lift coefficient, α is the angle of attack, and a is the clean aerofoil lift curve slope. This relatively simple approach was necessary because the large number of calculations required in the investigation meant that only a linearised method could be used, thus precluding a more detailed representation of the aerofoil characteristics.

The calculations were normally made with three sets of aerofoil characteristics, chosen to represent light and severe icing, with an intermediate case which allowed the effect of independently changing the lift and drag characteristics to be studied. The values of Δa and ΔC_{D_0} used were; $\Delta a = -10\%$ with $\Delta C_{D_0} = 100\%$ to represent light icing; $\Delta a = -25\%$ with $\Delta C_{D_0} = 200\%$ to represent severe icing; and the intermediate case used $\Delta a = -25\%$ with $\Delta C_{D_0} = 100\%$. The increase in drag refers only to the zero lift value and much greater increases than the nominal 100% and 200% are produced at other lift coefficients. This is clearly shown by the lift-drag polars of the clean aerofoil, and two of the degraded aerofoils in Fig 5.

The ice could be represented over all or part of the blade span, and some later calculations were made with ice extending to the tip but with the magnitude of the degradations varying in the spanwise direction. The second set of results is not discussed in this paper but full details are contained in Ref 3.

4 CALCULATED TORQUE INCREASE IN FORWARD FLIGHT

The torque required in steady forward flight was computed with a well proven method, modified to accept the degraded aerofoil characteristics over all or part of the span. Calculations were made for a range of aircraft speed from 50 to 100 knots, at altitudes of 3000 feet and 5000 feet, and with the spanwise extent of ice varying from the root cut out to the tip. The full set of results is presented and discussed in Ref 3, and only the results relevant to the autorotational performance study are included here. Fig 6 shows the excess torque calculated using the three sets of degraded aerofoil characteristics for an aircraft speed of 90 knots at 3000 feet altitude. The separate effect of independently changing the two parameters describing the degraded aerofoil characteristics can be clearly seen in this figure.

The effect of increasing the spanwise extent of ice is to transfer the load to the clean portion of the blade until the tip eventually stalls. Fig 7 shows the lift coefficient distribution on the retreating blade ($\psi = 270^\circ$) with ice to 80% radius compared to the clean blade. The higher drag associated with the increased lift coefficient near the tip can make a significant contribution to the excess torque especially with large reduction in lift curve slope. This can be seen in Fig 6 by comparing the two curves with the same increase in zero lift drag.

5 THE AIRCRAFT PERFORMANCE FOLLOWING TOTAL POWER FAILURE

The calculation of the aircraft behaviour following total power failure simulates the complete manoeuvre from the moment of engine failure, through the steady descent to the landing flare. The method developed uses a simple time integration of the aircraft equations of motion with a simultaneous solution of the rotor forces. Linearised aerodynamics are again used making the method compatible with the forward flight calculation.

The parts of the calculation requiring changes to the aircraft flight path are controlled by specifying the disc incidence and collective pitch using, whenever possible, the current values of altitude, speed and rate of descent so that the computer program is self contained and needs the minimum of external guidance. The method used to 'fly' the aircraft in each phase of the manoeuvre is briefly described in the following sections with the results.

5.1 Entry into autorotation

The entry into autorotation is one of the critical phases of the manoeuvre requiring prompt action by the pilot to prevent the rotor speed decaying to less than the minimum allowed. The initial rate of rotor speed decay depends on the rotor torque at the moment of engine failure, thus pilot intervention becomes more urgent as the excess torque increases.

The engine failures simulated in the calculations have all been made at an initial flight speed of 90 knots, which is about the maximum flown in the icing trials and therefore represents the worst possible condition. A typical calculation for the clean aircraft with an all up weight of 13200 lbs is shown in Fig 8. An application of cyclic pitch is made immediately to tilt the disc back and reduce the speed to about 60 knots for the steady descent. This tilt back also helps to reduce the loss of rotor speed. The magnitude of the cyclic input depends on the difference between the current speed and the minimum power speed and gives typically an 11° nose up attitude after 1.5 seconds. The nose up attitude is then reduced to about 5° until the speed approaches that required for the steady descent. The deceleration from 90 knots to 60 knots takes about 15 seconds.

The collective pitch is lowered after a specified time delay, and at a specified rate to the minimum setting. These variables being adjusted to maintain the rotor speed above the transient minimum. This therefore gives an indication of the maximum time that the pilot has to react. The collective pitch in the example, Fig 8, was lowered after a delay of one second at a rate of $12^\circ/s$, to 8.5°, which gave a minimum rotor speed of 199.4 rpm, well above the transient minimum speed of 190 rpm.

The calculations with ice on the blades were made with the normal minimum collective setting of 8.5° and sometimes at a lower setting which was necessary to give the clean aircraft rotor speed in the steady descent. The time delay was varied to maintain the rotor speed above the minimum level, and Fig 9 shows the maximum delay plotted against the excess torque at the initial flight conditions, viz 90 knots at 3000 feet altitude. A maximum time delay of 1 second was used and this is seen to be adequate for a torque increase of less than 300 lb ft. The minimum rotor speed attained varies according to the time delay and the limit line shown in Fig 9 divides the cases in which the rotor speed decayed below the transient minimum, and those cases where the speed remained above. The limit line is quite well defined even though three sets of degraded aerofoil characteristics were used, and the same torque increase could be produced with a different radial extent of ice. Thus the problem of entering autorotation is largely dependent on the excess torque carried at the moment of engine failure and is not affected by the way in which the torque is produced. The provision of a reduced minimum collective pitch setting, however, is also essential in the more extreme cases. Fig 10 shows the entry into autorotation for an airfraft with ice on the blades to 85% radius, with $\Delta a = -25\%$ and $\Delta C_{D_0} = 200\%$.

The excess torque in this case was 65% and the aircraft would not autorotate at the normal collective setting, a reduction of 2° being necessary. This example corresponds quite closely to the second of the flight examples mentioned in section 2.2.

5.2 The steady descent

The effect of ice on the blades in the steady autorotative descent is to decrease the rotor speed and increase the rate of descent compared to the clean aircraft with the same collective pitch setting. The rotor speed can be restored to its normal level by reducing the collective pitch but the rate of descent will be further increased. The calculations were therefore made at two collective settings, the first corresponding to the normal aircraft minimum setting, so the degraded performance shows up as a loss of rotor speed and an increase in rate of descent, and then with the collective pitch reduced to restore the rotor speed to the clean aircraft level, so the loss in performance appears solely as an increase in rate of descent. The second set of results also shows the magnitude of the collective pitch reduction needed to be sure of providing an acceptable rotor speed.

The rotor speed and rate of descent as the radial extent of ice is increased for the three sets of degraded aerofoil characteristics are shown in Fig 11. The calculations were made for a collective pitch setting of 8.5°, corresponding to the normal setting for the standard aircraft. Increasing the loss of lift curve slope from 10% to 25% while keeping the drag increase at 100% leads to a smaller loss of rotor speed, presumably because the lower lift coefficients on the iced portion of the blade appears similar to a lower collective setting. The rate of descent, however, is higher. The high drag increase of 200% gives very large losses in autorotational performance, and the curve has not been continued with ice extending to more than 80% span because the aircraft would not autorotate with this collective setting.

The second set of results, shown in Fig 12, were made with the collective pitch adjusted to give the clean aircraft rotor speed, and have been plotted against the excess torque carried at the moment of engine failure. Similar trends to those shown in Fig 11 are evident with a smaller reduction in collective required when the lift curve slope is reduced for the same drag increase. This figure also shows that the minimum collective setting needs to be reduced by about 2° to provide an adequate safety margin with regard to rotor speed, although the rate of descent may exceed

3000 ft/min in the worst case. The results shown in Fig 12 suggest that there is no obvious correlation between the change in the autorotational performance and the excess torque in power-on flight, even though only three sets of degraded aerofoil characteristics have been used. This is presumably because of the very different load distributions on the blades in power-on and power-off flight. Therefore any safety limits for the flight tests which take into account the autorotational performance of the aircraft must be based on the difficulty of entering autorotation, or in the worst case, on the ability to make a engine-off landing.

5.3 Power-off landings

An engine-off landing is a finely judged manoeuvre involving exchanges of kinetic, potential and rotor energy. The aim is to land the aircraft in a suitable attitude with horizontal and vertical velocity components that are sufficiently low to avoid damaging the aircraft and its occupants.

The method devised, which is fully described in Ref 3, uses the current values of altitude, forward speed, and rate of descent to calculate the disc incidence and vertical acceleration in much the same way as a pilot would use his instruments and visual references to determine the control inputs. Five other variables are also needed to control and vary the landing technique.

The flare is initiated when a prescribed altitude, h_f , is reached. A linear tilt back to a specified disc incidence, α_f , is then made in 3 seconds. During this period the rate of descent and forward speed decrease, and the rotor speed increases due to the additional upflow of air through the disc. The second phase of the manoeuvre lasts until an altitude h_h is reached, h_h being another of the controlling variables. The pitch attitude is kept fairly high during this phase to maintain the longitudinal deceleration, and the rate of descent usuallly decreases further, depending on the variation of disc incidence. The rate of descent is then allowed to increase in a controlled manner until the final collective pull up is made. The disc incidence is reduced as the altitude passes through h_h , to prepare the aircraft for a touch down in a near horizontal attitude, and the final collective pull up is made when another specified altitude, h_p is reached.

The landings had to be made within a number of constraints, some imposed by airframe limitations, and some for operational reasons. Thus the vertical velocity on touch down had to be less than 8 ft/s, the maximum rotor speed was limited to 258 rpm, and the aircraft pitch attitude had to be kept below 30° nose up. Fortunately run on landings at up to 20 knots were specified corresponding to a 10 knot ground speed into a 10 knot wind. The difficulty of making a successful landing was further complicated since the maximum collective pitch available for the final collective pull up was less than for the standard aircraft. This was because the collective pitch travel was limited, and the minimum setting had been reduced to provide an adequate safety margin in the steady descent.

An initial series of calculations was made with the clean aircraft using a systematic variation of the main parameters to see if any particular landing technique consistently gave successful landings. The flares were initiated at altitudes ranging from 117 feet to 143 feet with different initial conditions and the other parameters varied accordingly, but the Wessex has quite a satisfactory engine-off landing performance and no overall trend of how best to perform the manoeuvre could be discerned. One of the landings from this series is shown in Fig 13. The rate of descent was 1846 ft/min when the flare was initiated and the rotor speed 236 rpm. The touch down was fairly hard at 6.5 ft/s, mainly because of the limited collective pitch, but the forward speed was satisfactory, and both the pitch attitude and maximum rotor speed were held within the limits.

The calculations with ice on the blades were made for a range of aircraft weight, and at each weight the amount of ice was increased until it became quite clear that a successful landing was impossible. The ice increases the difficulty of making a landing because the initial rate of descent is higher giving less time to perform the manoeuvre, with possibly a reduced rotor speed giving less energy to exchange. The landings therefore become progressively more difficult as the extent of ice or the degradations to the aerofoil characteristics are increased, and only a small amount of ice can have a significant effect. The most severe conditions for which a successful landing was made had ice extending to 60% of the blade span with $\Delta a = -25\%$ and $\Delta C_{D_0} = 200\%$. The initial rate of descent, Fig 14, was 2500 ft/min with the rotor speed at about the clean aircraft level. The flare had to be initiated at 172 feet to allow sufficient time to reduce the forward speed without exceeding the 30° nose up attitude.

The excess torque at the moment of engine failure for which successful landings were made is shown in Fig 15 for a range of aircraft weight. The excess torque clearly provides a good indication of the ability to survive a total power failure though the allowable torque increase is not very large and decreases rapidly at higher weights. Higher torque increases than those shown could be tolerated but only if there was a high probability of ice shedding during the descent through warmer air.

6 CONCLUSIONS

The work described in this note summarises the results from a more thorough investigation of the performance of a Wessex helicopter in icing conditions. The aim of the work was to provide A & AEE with some information on the safe levels of torque increase that could be tolerated in steady forward flight while retaining the ability to survive a total power failure.

The calculations have shown that the difficulty of entering autorotation can be correlated with the excess torque in steady power-on flight, but the change in the autorotational performance in the steady descent follows no simple rule because of the different nature of the loads on the blade. The minimum collective pitch setting also needs to be reduced by about 2° to ensure that the aircraft will autorotate, and to provide an adequate rotor speed during the descent. This reduction in the minimum collective setting however, increases the difficulty of making a power-off landing because the range of collective pitch travel is limited. The ability to make a successful engine-off landing depends strongly on the weight of the aircraft, but the calculations show that the excess torque can be used to define safe operating limits.

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4. D.T. Bowden, effect of pneumatic de-icers and ice formation on aerodynamic characteristics of an aerofoil, NACA TN 3564, February 1956.

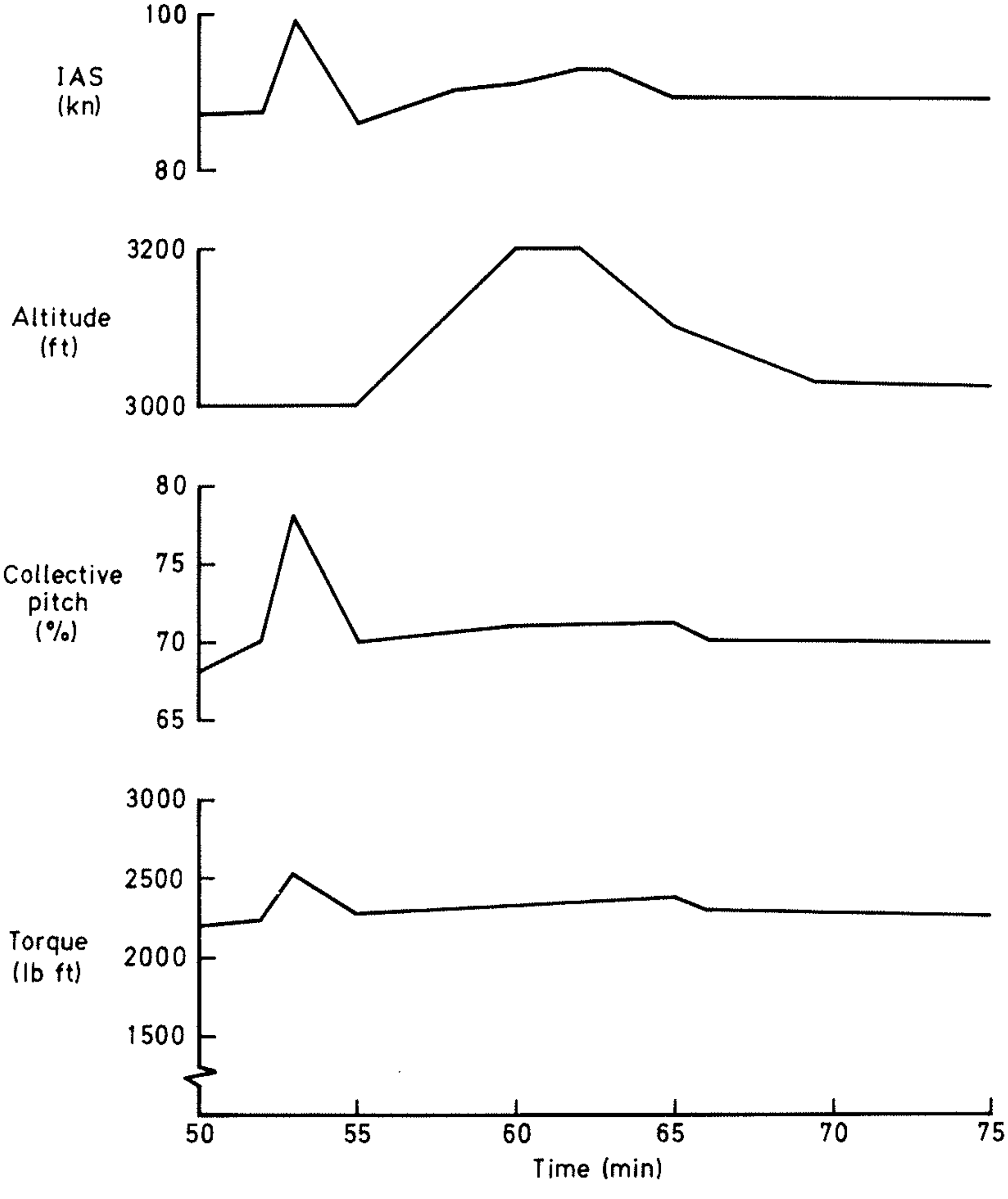

Fig 1 Flight in light icing; OAT = −3.5°C, estimated liquid water content 0.6 g/m^3

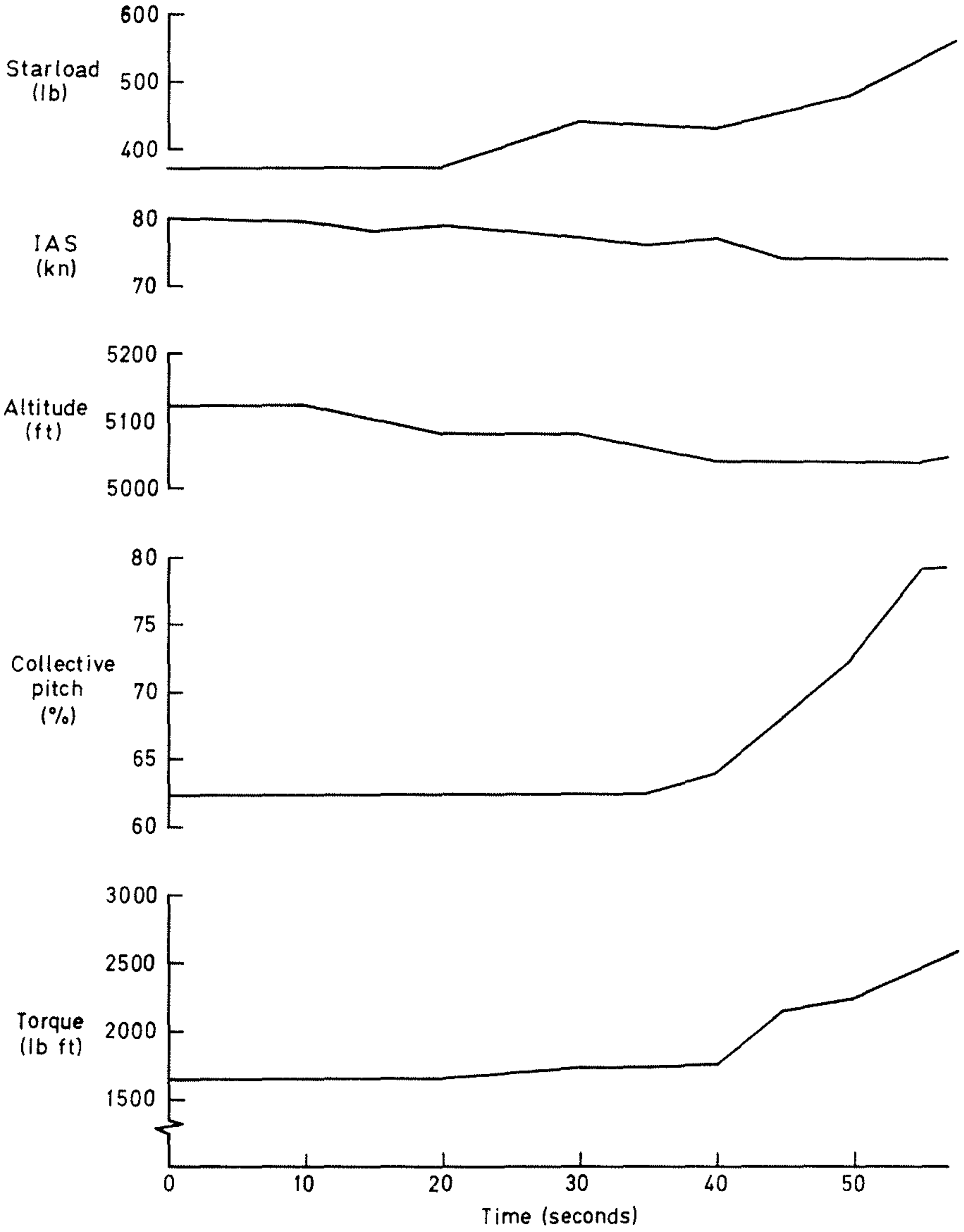

Fig 2 Flight in severe icing; OAT = -3.5°C, estimated liquid water content 1.3 g/m^3

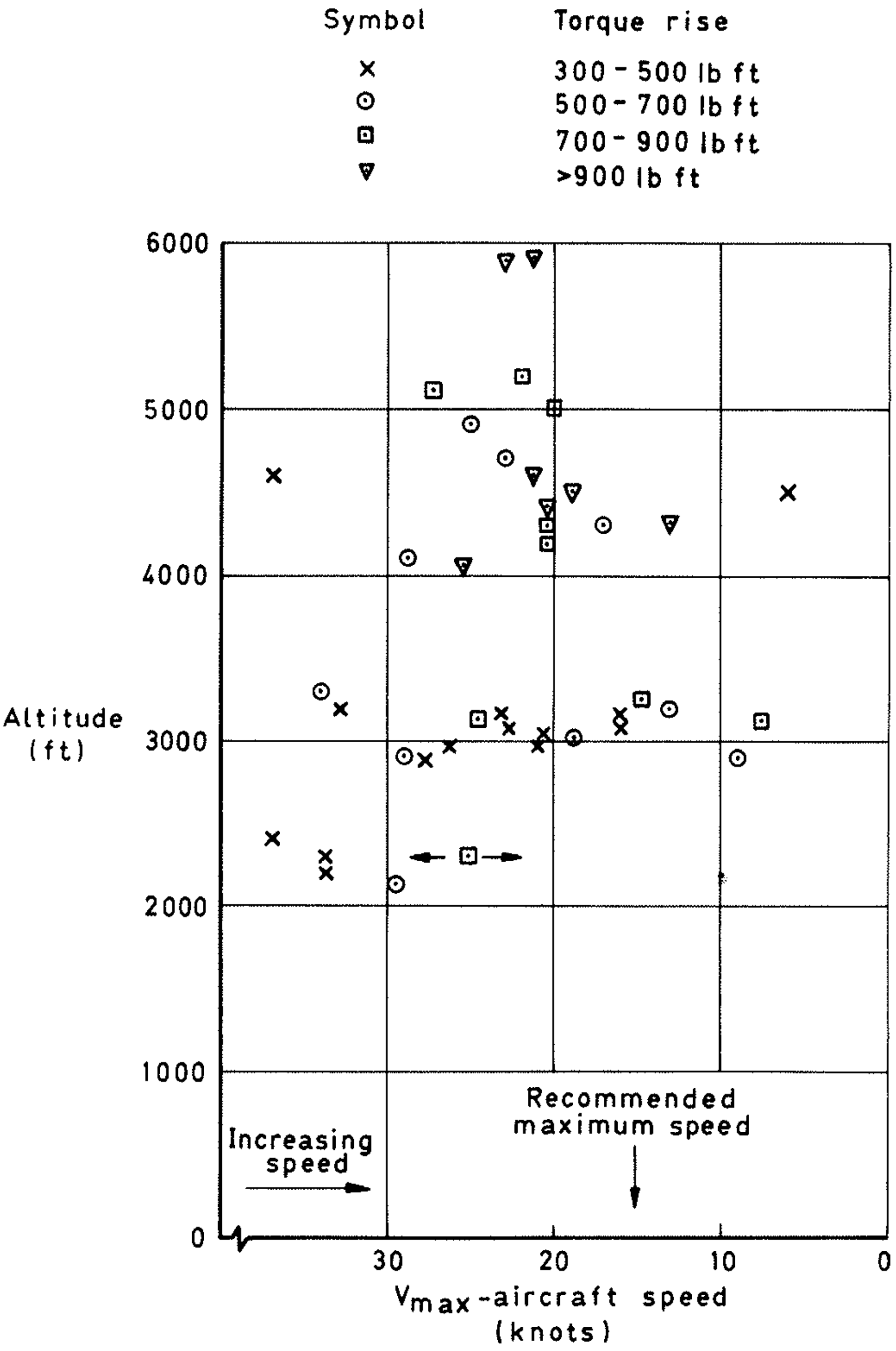

Fig. 3 Flight conditions and torque increases measured during the 1973/4 trials

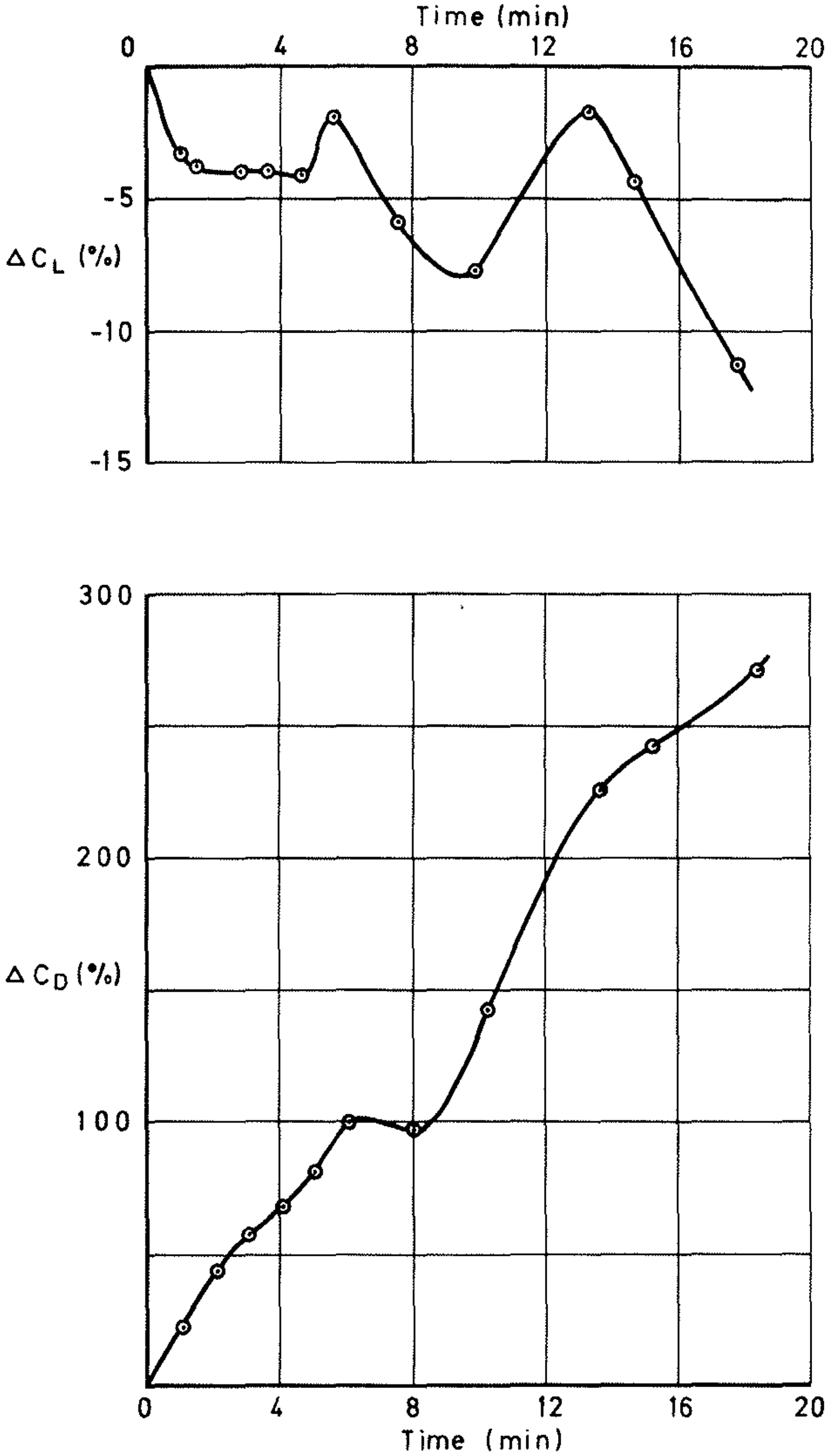

Fig 4 Measured drag increase and lift decrease for NACA 0011 aerofoil in an icing tunnel, $\alpha=2.3^\circ$, LWC=0.5 g/m^3, T=-3.9°C

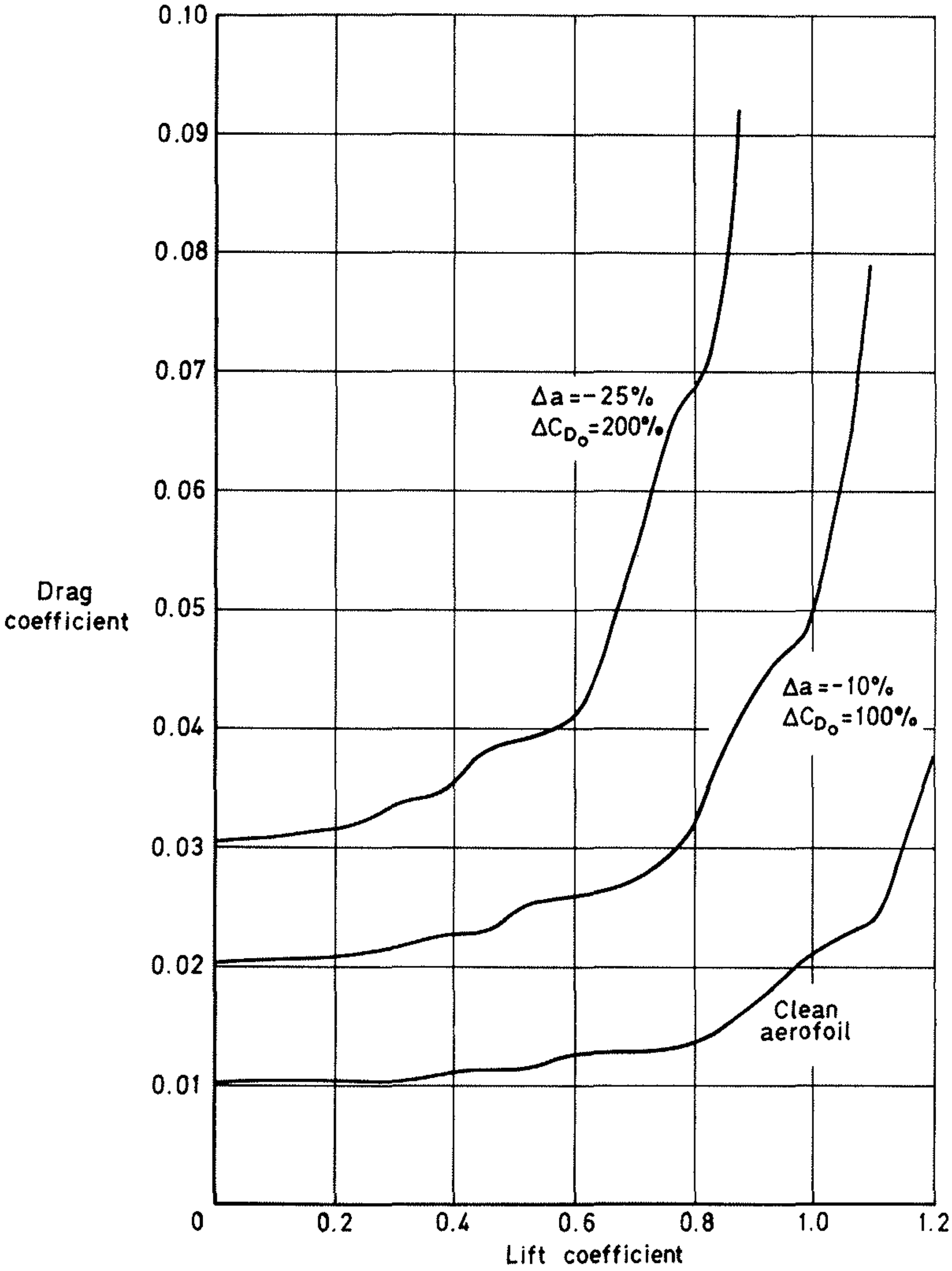

Fig 5 Clean aerofoil and two degraded aerofoil lift-drag polars

AUW 13200 lb
90 knots 3000ft altitude

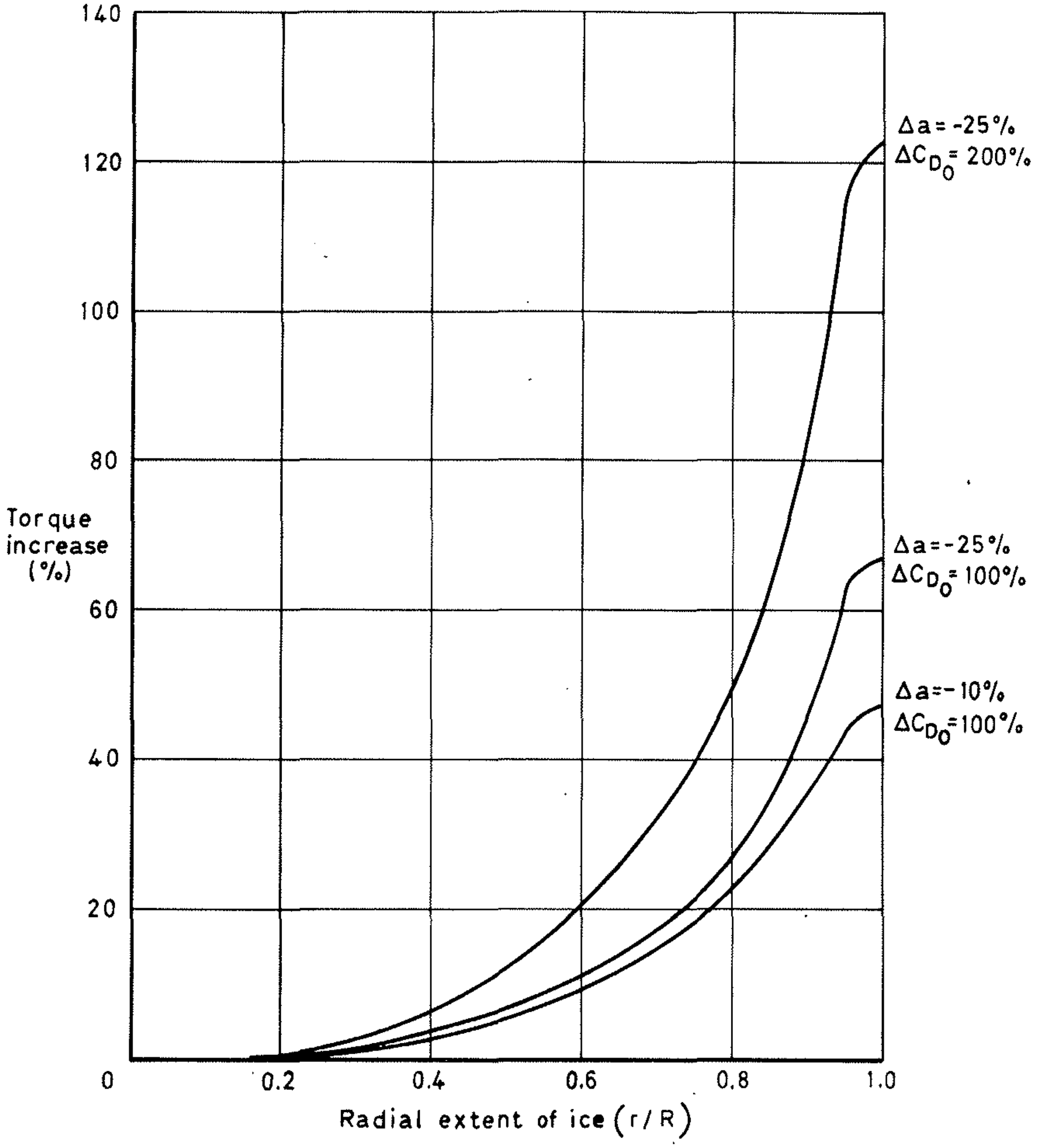

Fig 6 Calculated effect of the spanwise extent of ice on the aircraft torque

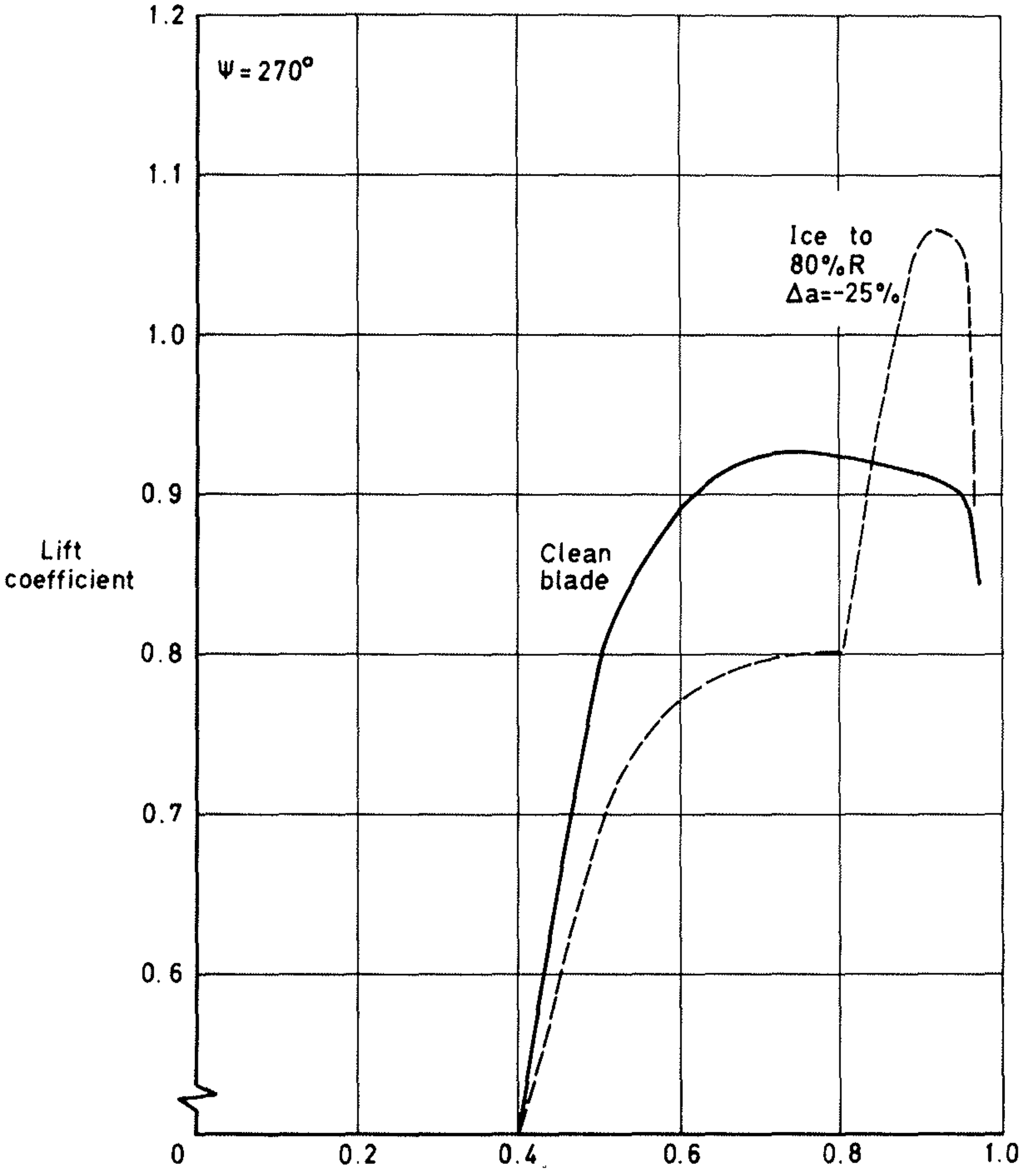

Fig.7 Retreating blade lift coefficient distribution for clean blade and with ice to 80% radius; 90 knots 3000 ft altitude

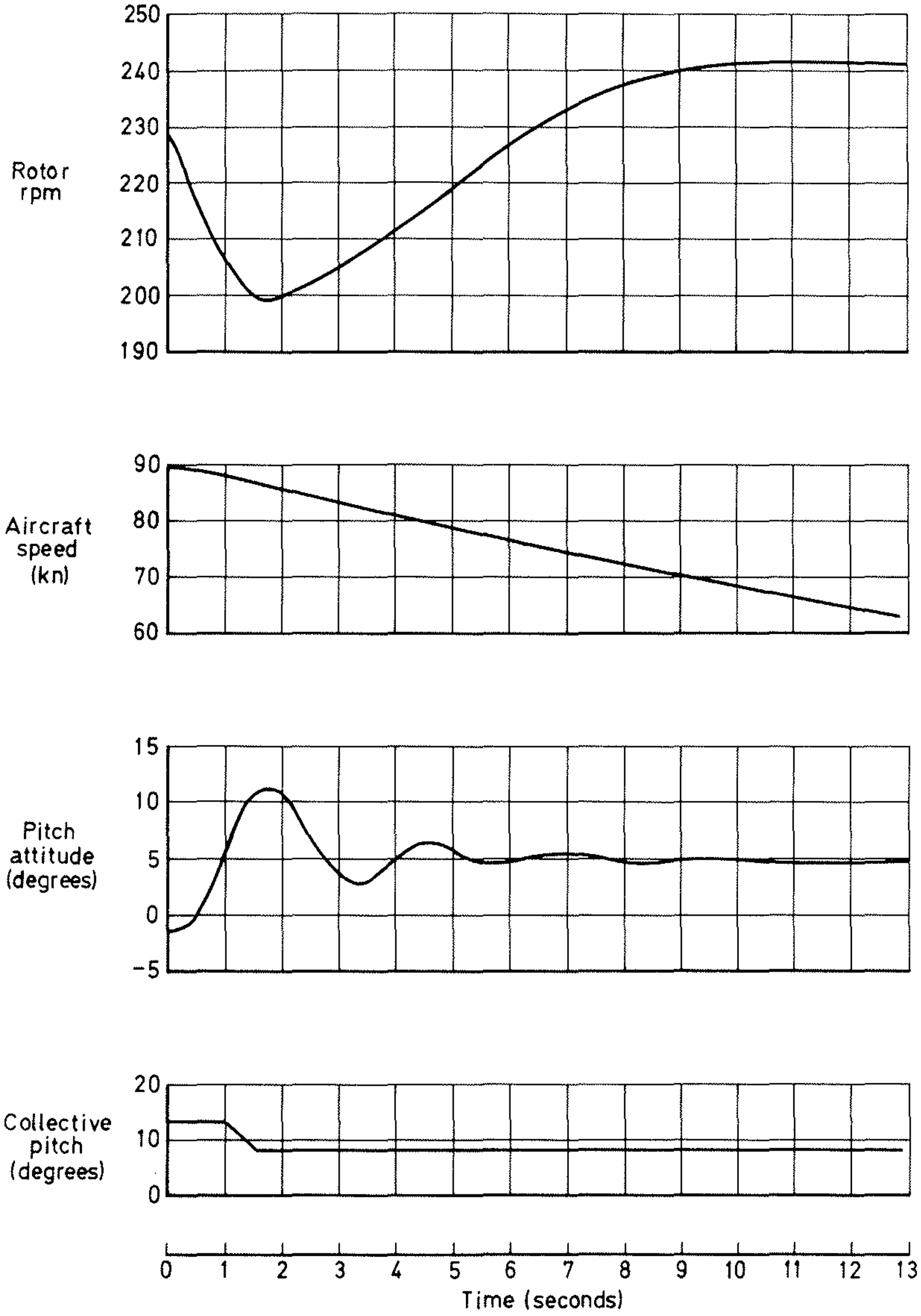

Fig 8 Calculated entry into autorotation for a clean aircraft; initial altitude 3000ft, AUW 13200lb

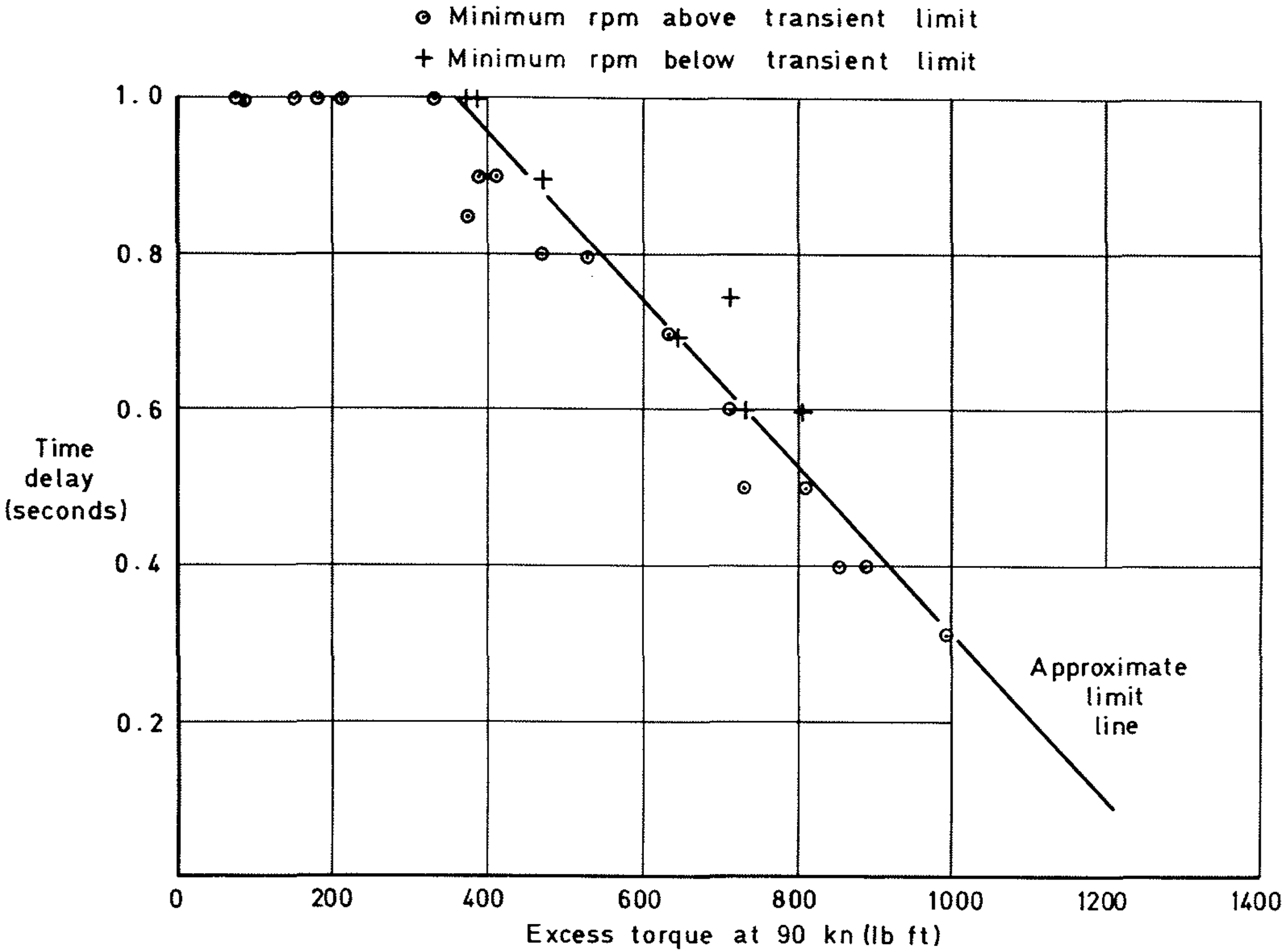

Fig 9 Correlation of the time delay before reducing collective pitch and the excess torque at the moment of engine failure: Aircraft weight 13200 lb

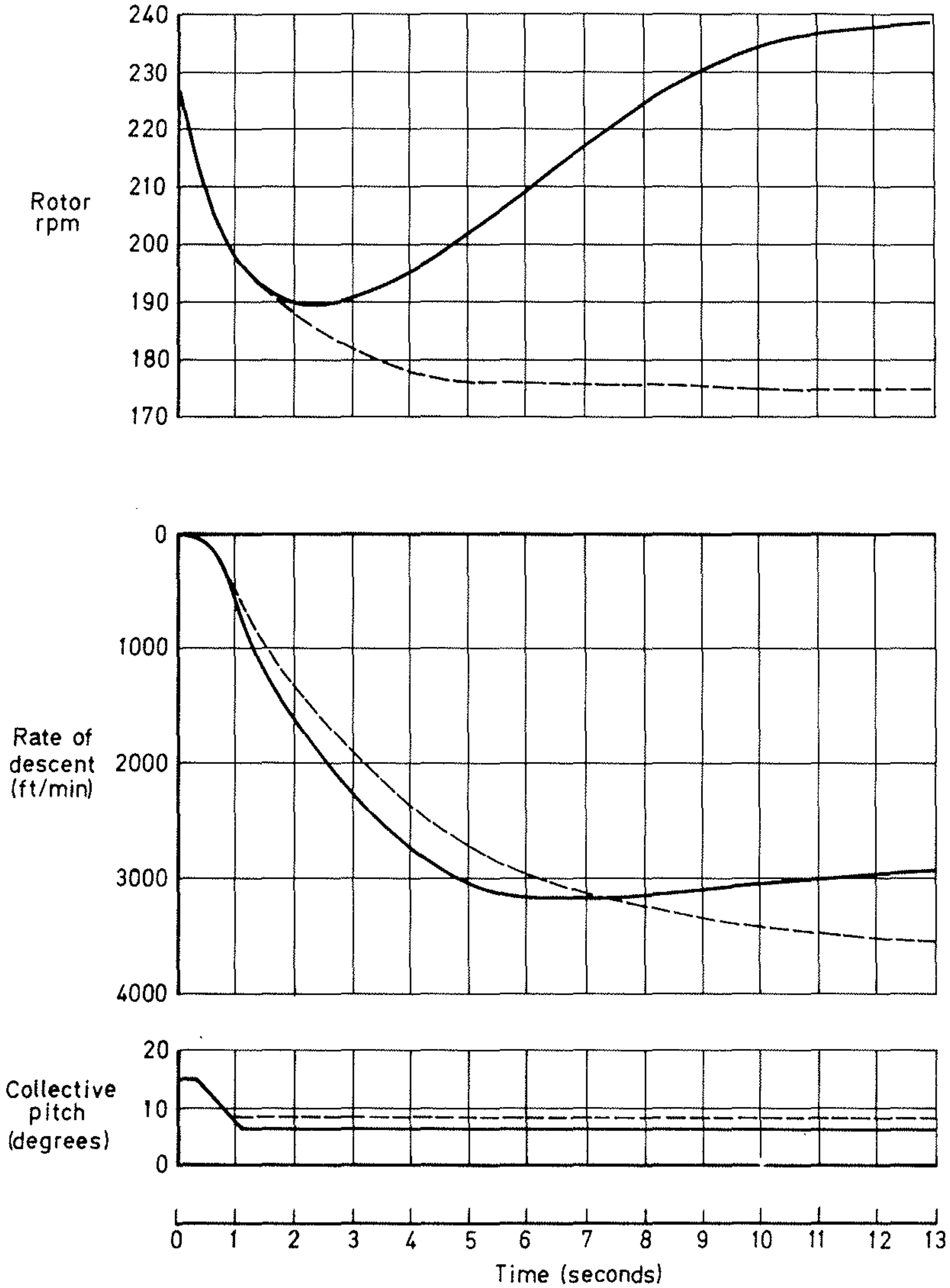

Fig 10 Comparison of the entry into autorotation with two minimum collective pitch settings, $\Delta C_{D_0}=200\%$ $\Delta a=-25\%$, ice to 85% span

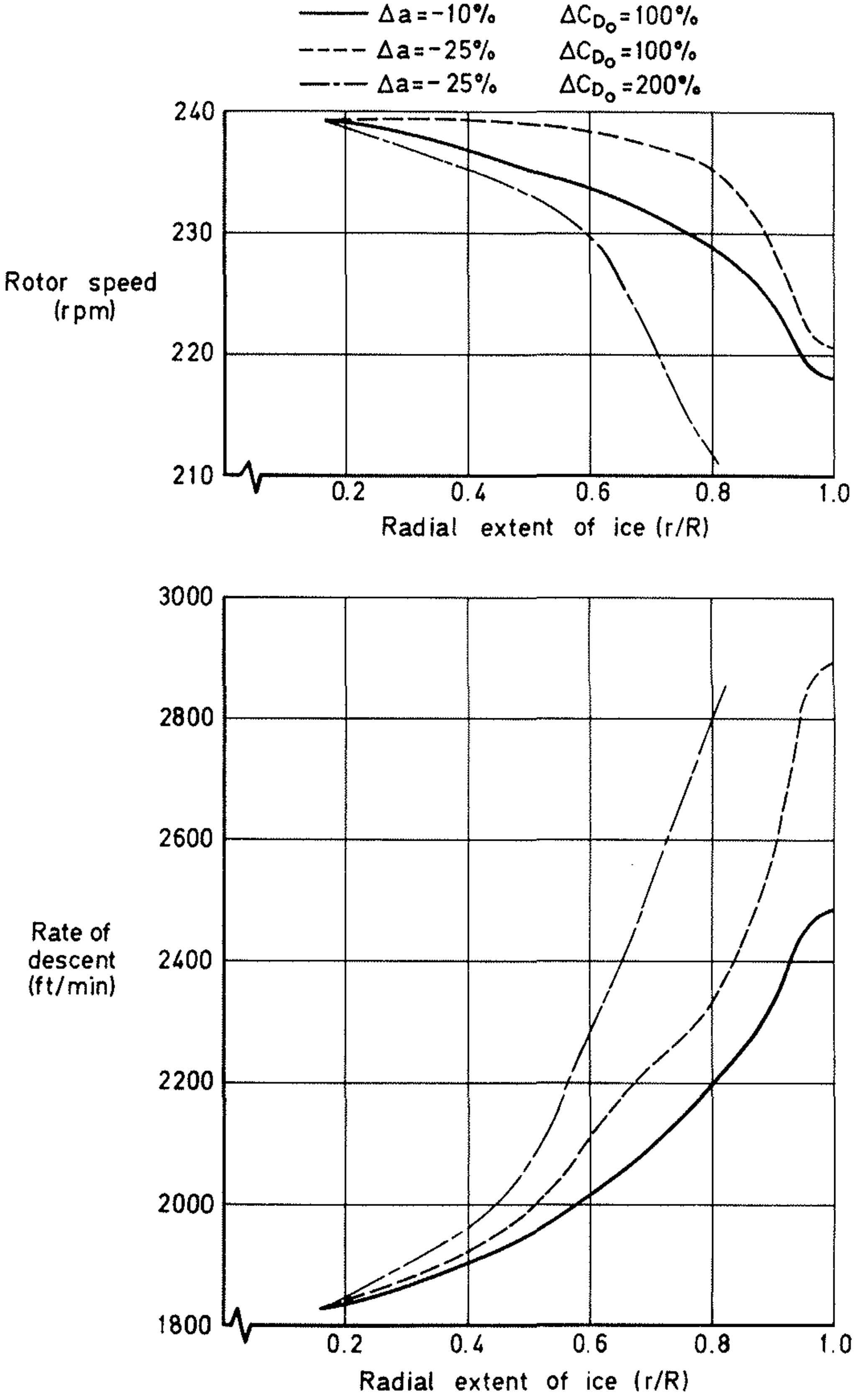

Fig 11 Calculated effect of the spanwise extent of ice on the steady autorotational characteristics at 60kn; collective pitch 8.5°

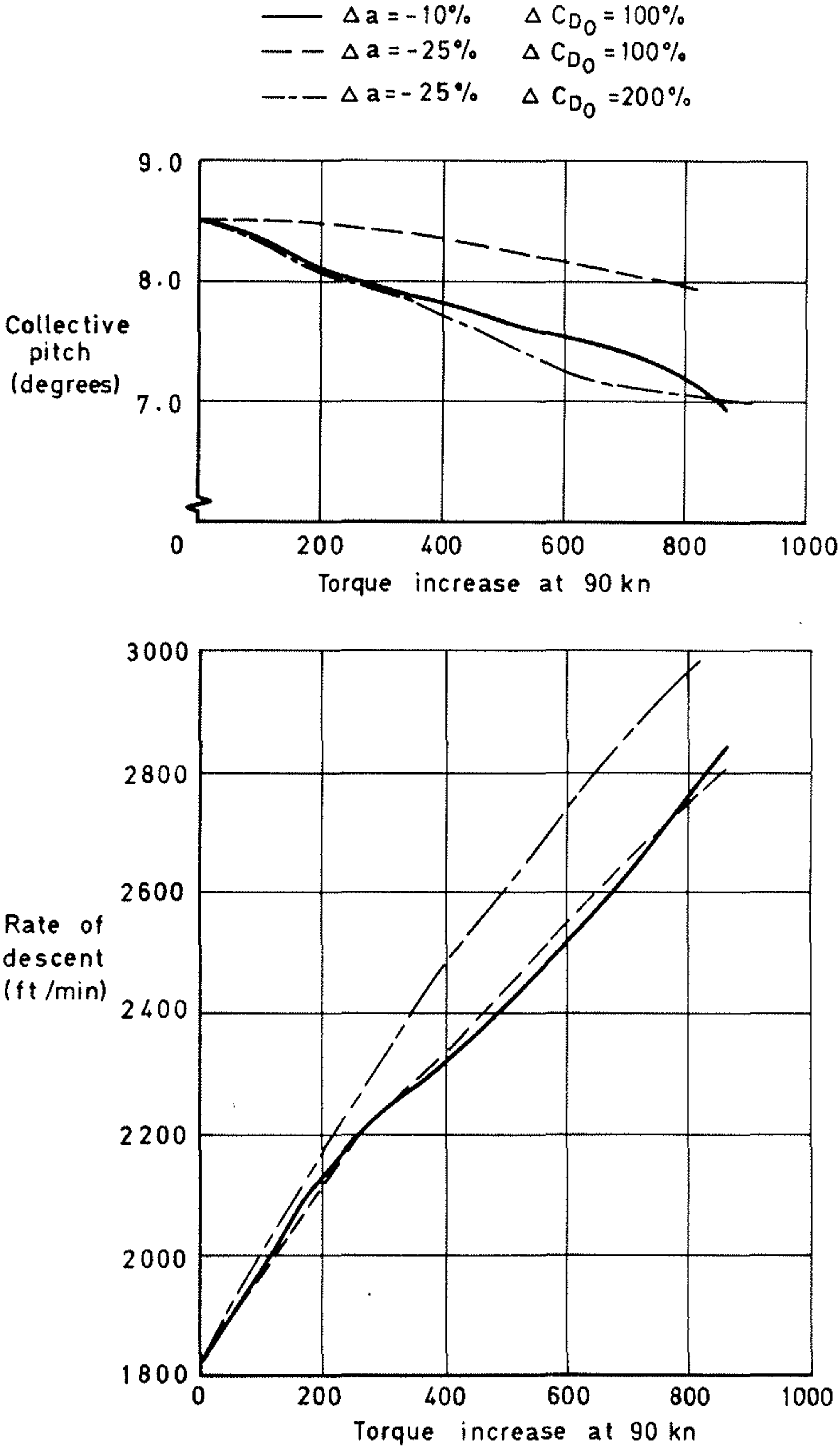

Fig 12 Collective pitch and rate of descent for clean aircraft rotor speed v excess torque in power on flight at 90 kn

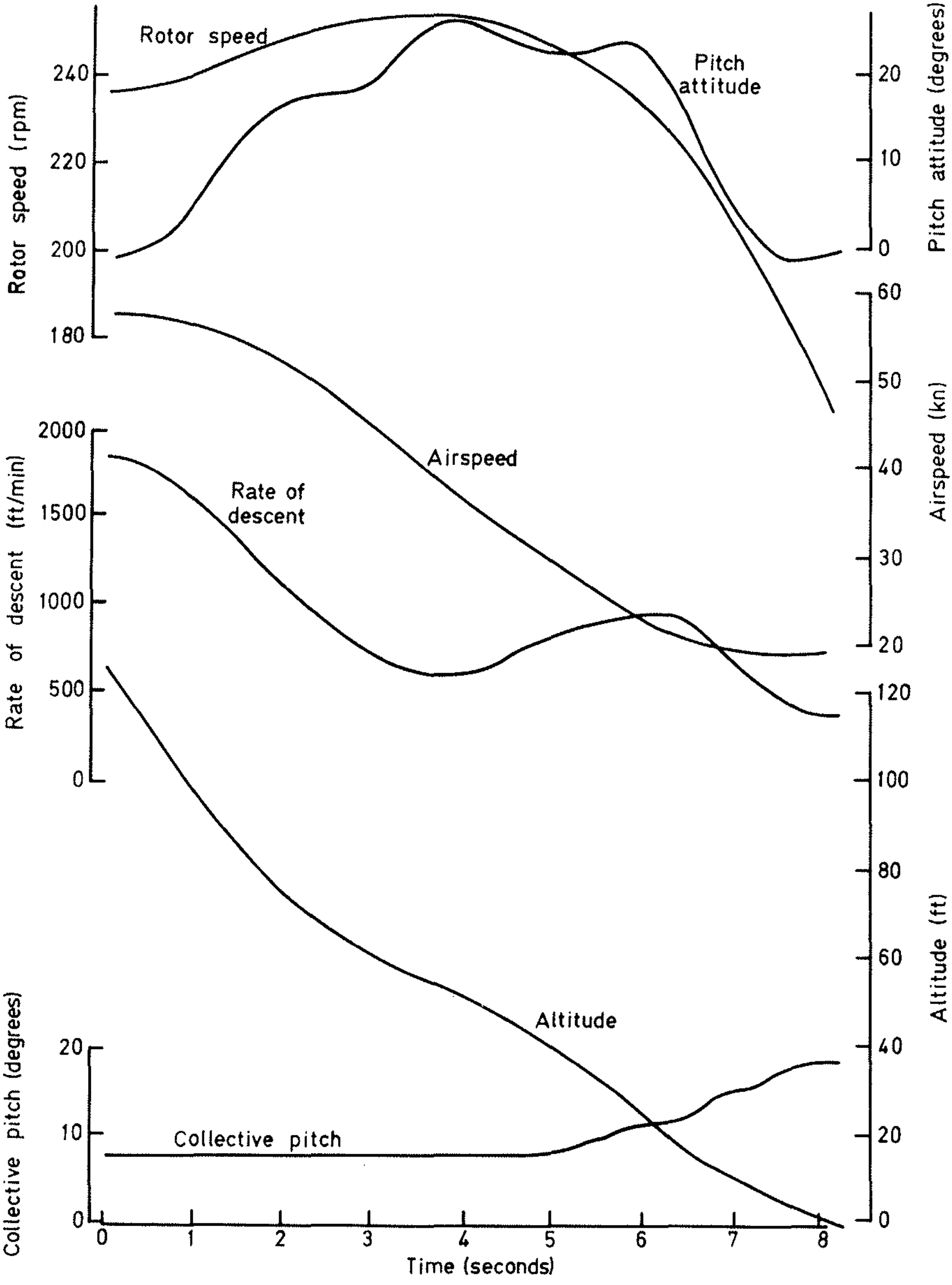

Fig 13 Calculated clean aircraft engine-off landing, all up weight 12500 lb

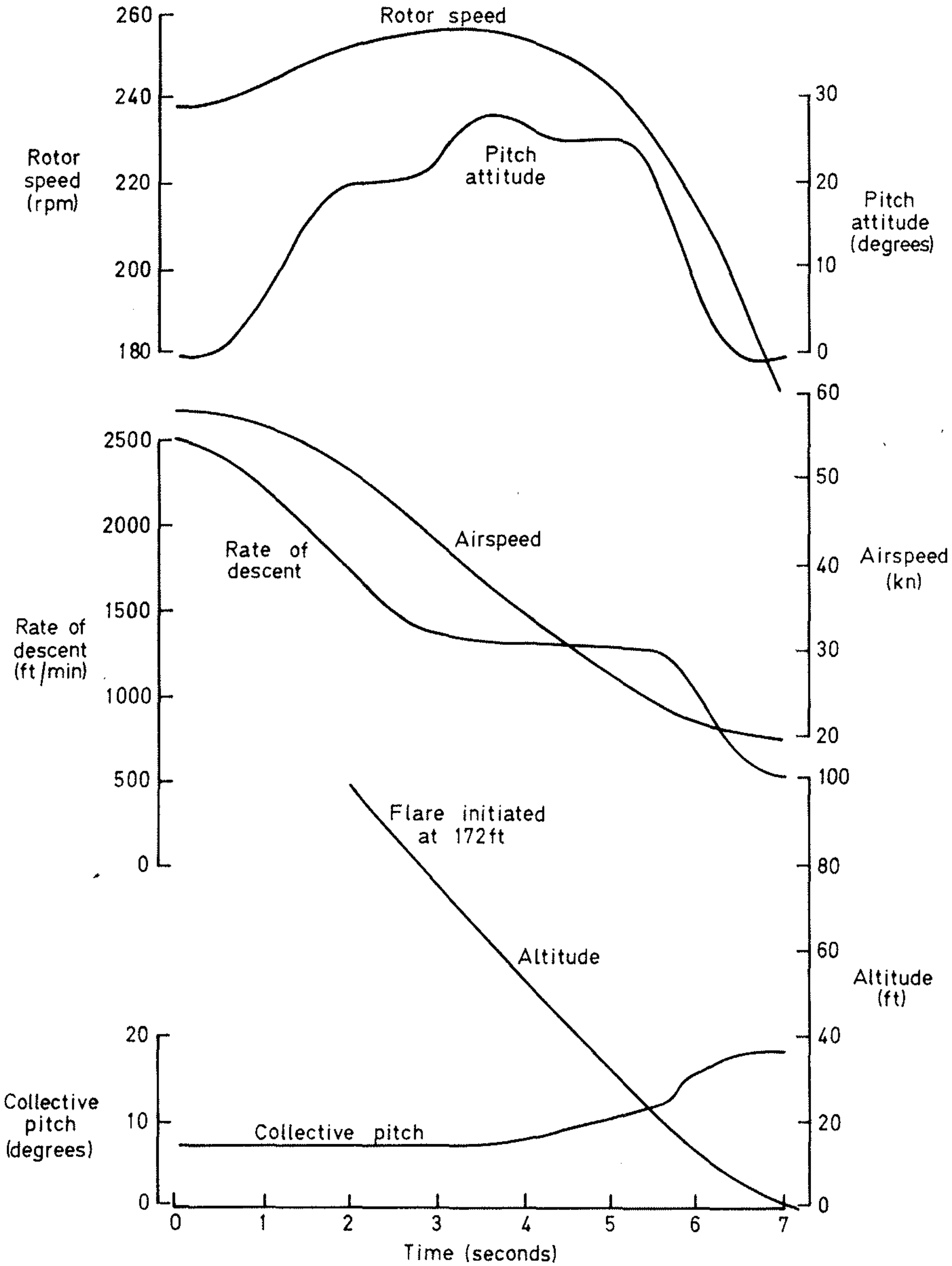

Fig 14 Calculated engine-off landing with ice to 60% of the blade span, $\Delta a = -25\%$, $\Delta C_{D_0} = 200\%$, aircraft weight 12500 lbs

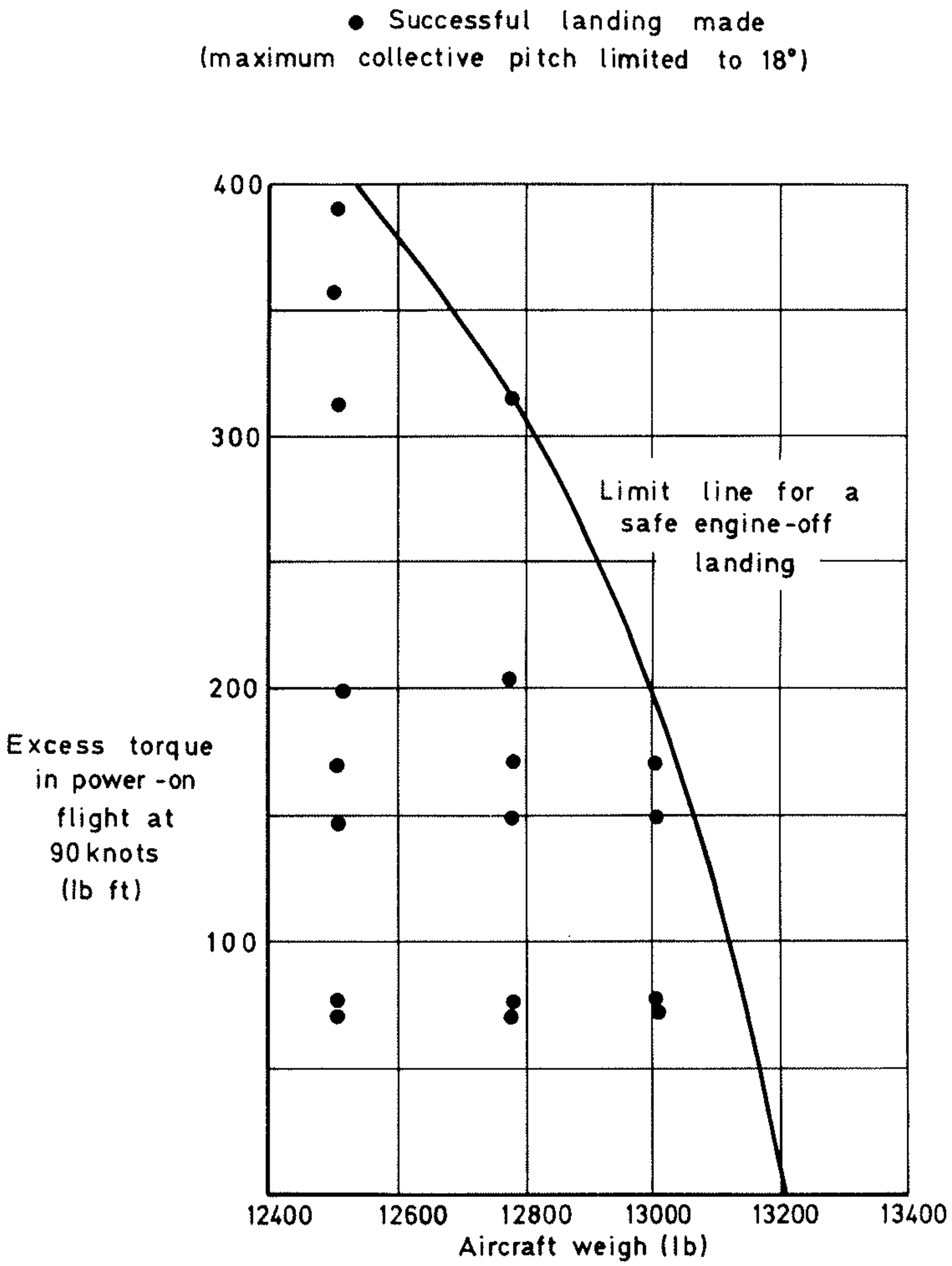

Fig 15 Calculated excess torque in power-on flight for which a safe engine-off landing is possible