SECOND EUROPEAN ROTORCRAFT AND POWERED LIFT AIRCRAFT FORUM

Paper No. 24

FLIGHT EVALUATION OF A HIGHLY CAMBERED TAIL ROTOR

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September 20 - 22, 1976

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1. Summary

A flight evaluation of a highly cambered tail rotor blade has demonstrated improvements in low speed handling qualities and performance when compared with the performance of a standard symmetrical section blade. In hover and low speed flight thrust increases of 35% before the onset of stall were being observed.

2. Introduction

The tail rotor of a conventional single main rotor helicopter provides the moment necessary to react the main rotor torque, plus a means of controlling the aircraft in yaw.

The maximum demands on the tail rotor occur in low speed flight when the main rotor power consumption is high and manoeuvres are performed which require an additional thrust increment to that required to counter the torque. The manoeuvres that are most demanding are yaw rotations in the same direction as the main rotor rotation and sideways flights in the direction of the tail rotor thrust (see figure 1). Aircraft yaw accelerations during these manoeuvres are, of course, additional demands.

The additional thrust required to perform these manoeuvres is typically the same as that required to balance the torque. An aircraft designed to have high 'agility' would require a greater proportion of available thrust for manoeuvres.

3. Discussion

The limitations on the available tail rotor thrust in low speed flight are usually due to the blade stall, restrictions on pitch range and torque limitations, or combinations of them. Most conventional tail rotors operate beyond the onset of blade stall during the more severe manoeuvres, which aggravate any restrictions on torque or pitch range. However, because tail rotor blades are normally untwisted, the onset of stall is not an indication of the maximum thrust available, rather an indication of a change in the thrust-pitch and thrust power curves. A typical relationship between thrust and power for a tail rotor and fin combination in hover is shown in figure 2. The graph also shows the growth of the control loads, which is a good indicator of the onset of blade stall. Blade stall on a highly loaded and untwisted blade originates from the tip and moves inboard as pitch is increased. Thus the design criteria for a tail rotor aerofoil section is concerned with maximum lift coefficients at Mach numbers corresponding to the tip region of the blade in low speed or hovering flight; unlike the main rotor where it is normally the retreating blade stall and advancing tip Mach number under high speed cruise conditions that determine the desirable characteristics for the aerofoil.

On the basis of the requirement to maximise the lift coefficient in the Mach number region 0.5 to 0.6 without adversely affecting the maximum Mach number at zero lift, the RAE developed a cambered aerofoil which exhibited a 35% improvement in lift over NACA 0012 in the critical Mach number region. Figure 3 compares the separation boundary of the cambered section with that of the conventional symmetrical NACA 0012. Figure 4 shows the difference between the aerofoil pitching moment of the cambered and NACA 0012 sections at a typical lift coefficient of 0.6. A large amount of camber, with the resultant high pitching moments was considered acceptable because of the high torsional stiffness of the low aspect ratio blades and the strong control system.

4. Flight Trials

In order to evaluate the low speed handling qualities and performance improvements offered by this new section a set of blades was manufactured and test flown on a Westland Sea King (see fig.5). The blades were of the same overall dimensions, weight and dynamic characteristics as the standard symmetrical blades; with the exception of the chordwise balance which was brought forward by 1% of the chord to maintain flutter stability margins.

The major part of the flight programme concentrated on the low speed performance and handling where the improvements over an aircraft fitted with the standard rotor were immediately obvious. The Mk.1 Sea King has an operational restriction, like many aircraft, on take-off and landing at high a.u.w.'s in winds from the right. This restriction was effectively removed by the improved tail rotor. Figure 6 shows the low speed flight envelopes for aircraft fitted with the standard and cambered tail rotor blades. The 'boundary' lines indicate the a.u.w. - altitude combinations above which the pilot might experience an inability to maintain heading in wind conditions in excess of 10 kts from the right. As the aircraft has a maximum take-off weight of 20,500lb at S.L., I.S.A. conditions the cambered blade effectively removed this landing and take-off restriction. In addition to the enlargement of the flight envelope the pilots noted that the total power requirements in the right sideways flight manoeuvres were reduced by comparison with the standard rotor.

Although the low speed handling qualities were improved by substantial margins, the results do not necessarily indicate the magnitude of the increase in thrust before the onset of stall. Because it was not possible to measure the thrust directly, the comparison between standard blade and the cambered blade rotor was made on measurements of main rotor torque (being proportional to the tail rotor and fin thrust), tail rotor power and control loads in hover. Using this information it was possible to construct the thrust-power relationship for the <u>standard</u> tail rotor/fin combination to values above stall in the hover condition. (This was possible because of the installation of the uprated engines and gearbox in the experimental aircraft). The <u>cambered</u> tail rotor installation stall point could not be reached in hover because of power and a.u.w. limitations on the aircraft. A procedure was therefore adopted using steady low speed sideways velocities, which required a substantial increase in thrust*, to determine the performance limits

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* The large increase in tail rotor thrust required with operation into the right sideways flight condition is believed to be due to the forces produced by the main rotor wake flow over the tail boom.

of the cambered tail rotor. The procedure was to establish a precise hover condition and record main rotor torque and tail rotor coning angle, then proceeding into a steady right sideways flight to measure the change in coning angle and hence estimate the change in thrust of the tail rotor. The change in thrust was estimated on the basis of measured relationship of thrust to coning angle. Theoretical analysis showed that sideways speeds (tail rotor axial velocities) of up to 10kts would produce thrust-power relationships that were indistinguishable from those in hover. In addition, the effect on the thrust at which stall occurs would be unaffected by small axial velocities on a rotor where the induced velocity is in excess of 100ft/sec. It was therefore considered acceptable to compare the cambered tail rotor results with the standard rotor measurements obtained in hover. The resulting tail rotor/fin combination thrust-power relationships for the cambered and standard blades are shown in figures 7 and 8. Also shown on these graphs are the relationships between control load and tail rotor power (or thrust). These measured loads show clearly the point at which the onset of stall occurs by the sharp increase in the vibratory loads in the control spider arm.

On the basis of a comparison of the thrust at which the onset of stall occurs the cambered blades produce nearly 50% more thrust before stall than the standard blade. It should be noted, however, that the standard blade had an external (to profile) erosion protection strip fitted and the cambered blade did not. From measured wind tunnel data of the effect of an external erosion shield on the two dimensional aerofoil characteristics, at typical tip Mach numbers, it is estimated that the cambered blades are giving approximately 35% improvement in thrust by comparison with a standard blade with a NACA 0012 section (without an external erosion shield).

High steady aerodynamic pitching moments generated by the blade made it necessary to install a spring in the control circuit so that in the event of a hydraulics failure the pilot would not experience an excessively large pedal force. The predicted control system forces are shown in figure 9 as a function of tail rotor pitch. Also shown is the standard rotor control load which is normally reacted by a spring for the same reason. The 'band' illustrated for the cambered blade section indicates the variation in control forces over the speed range of 0 to 140kts. The flight investigation showed that there was no difficulty in flying in manual or when performing a simulated hydraulic failure. The spring was fitted in parallel with the control rod at the rear of the tail rotor gearbox.

The forward flight investigated covered speeds up to V_{NE} + 10% (140kts), maximum power climbs and manoeuvres up to V_{NO}. As expected the steady loads in the control system were higher than those of the standard rotor, (see figure 10), otherwise the performance and handling in forward flight was indistinguishable from that of the standard rotor. Although higher vibratory control loads were expected there was no evidence that they were any higher than those associated with the standard tail rotor. No limitations to the performance of either the standard or cambered blades were observed up to the maximum forward speed of the aircraft (V_{NE} + 10%).

5. Conclusions

A tail rotor employing blades with cambered section designed to give high lift at hovering tip Mach numbers has been shown to give large improvements in the low speed handling envelope, particularly in operations with winds from the right.

A quantitative assessment of the increase in thrust achieved before stall, by comparison with a standard NACA 0012 section blade, indicates that the theoretically estimated 35% increase in thrust is being achieved in the complex flow conditions of the tail rotor.

6. Acknowledgements

The author wishes to acknowledge the assistance of his colleagues during the tests and in the analysis of the results, which were carried out under contract to the Ministry of Defence (Procurement Executive).

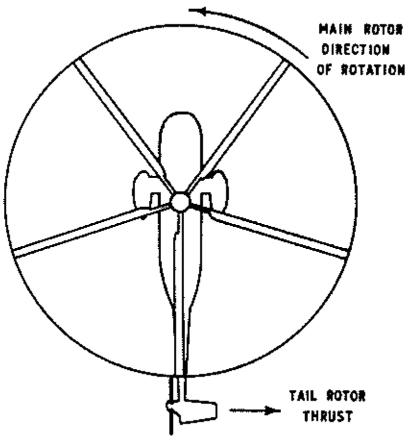

FIG. 1 PLAN OF A TYPICAL HELICOPTER

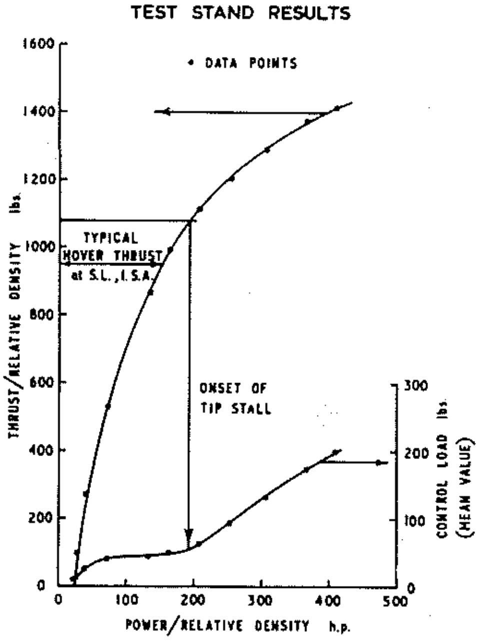

FIG. 2 WESSEX TAIL ROTOR PERFORMANCE

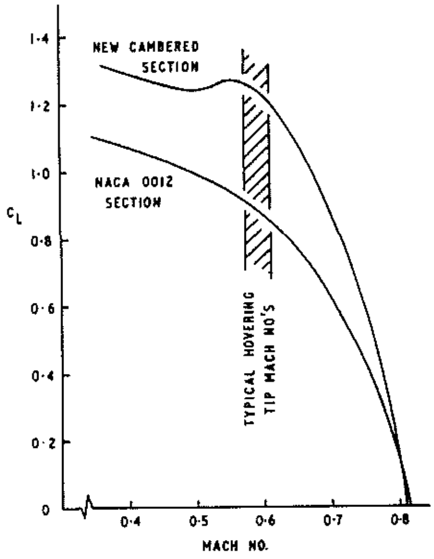

FIG. 3 AEROFOIL SECTION SEPARATION BOUNDARIES

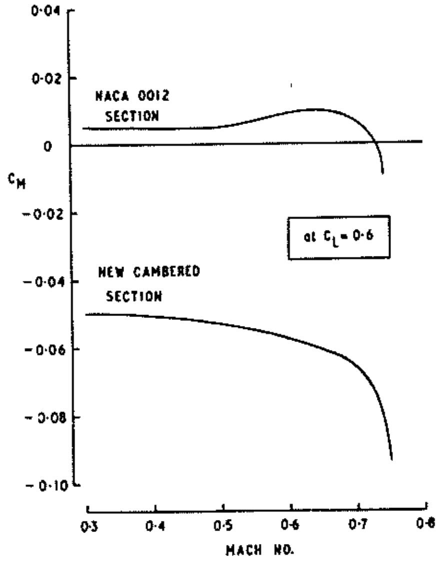

FIG. 4 AEROFOIL PITCHING MOMENT CHARACTERISTICS

FIG. 5. SEA KING WITH CAMBERED TAIL ROTOR

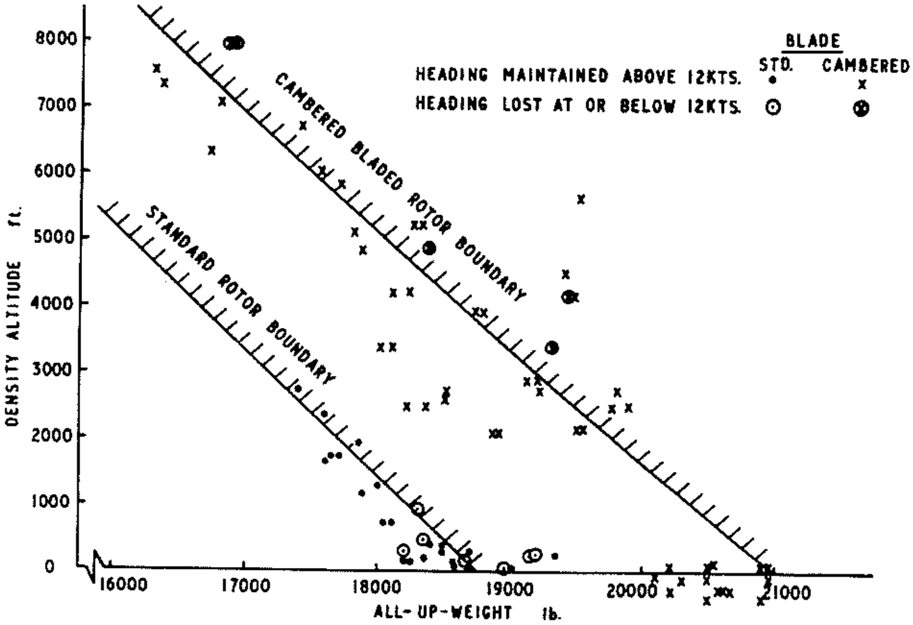

FIG. 6 LOW SPEED FLIGHT ENVELOPE LIMITATIONS
10 KT STARBOARD FLIGHT LIMIT

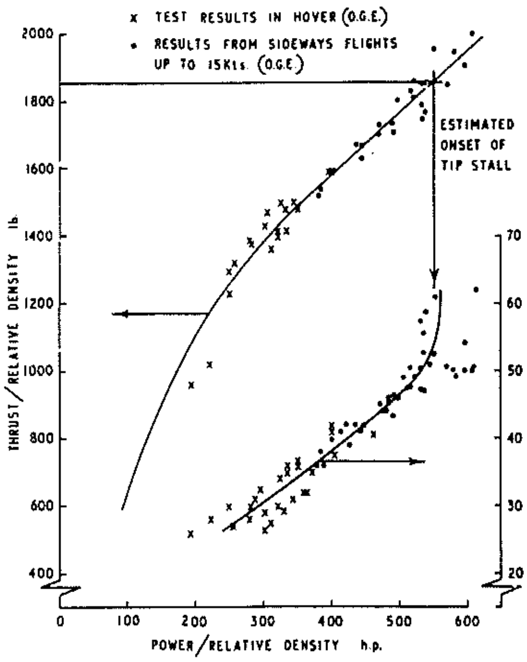

FIG. 7 CAMBERED BLADE PERFORMANCE IN LOW SPEED FLIGHT

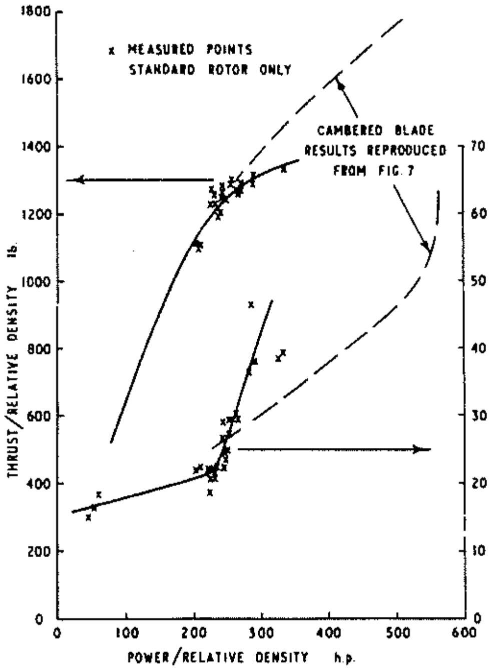

FIG. 8 STANDARD BLADE PERFORMANCE IN HOVER, O.G.E.

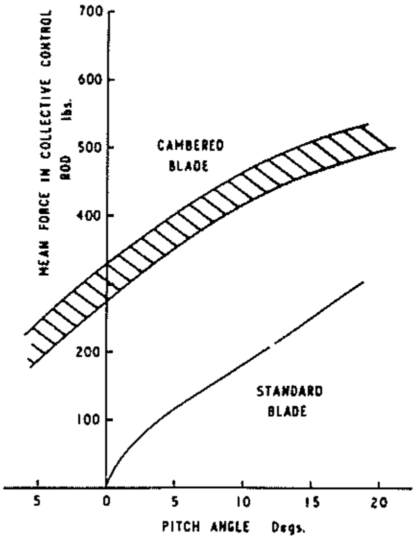

FIG. 9 ESTIMATED STEADY CONTROL LOADS

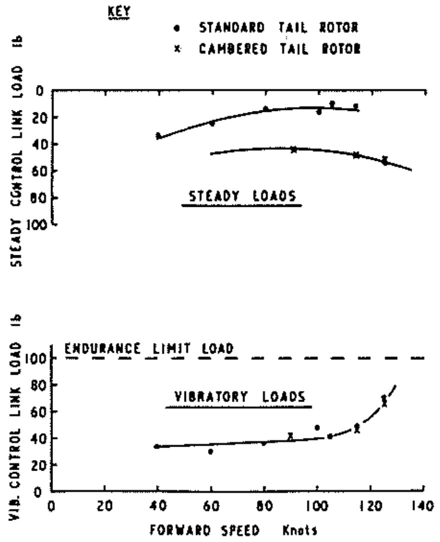

FIG. 10 CONTROL LOADS