A New Tail Rotor for the S-61

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ABSTRACT

The development of a new tail rotor by Carson Helicopters for the S-61 is described. Criteria for new composite tail rotor blades, which were designed as a replacement for the current metal blades, included improved hover and low speed efficiency, and increased maximum thrust. Also, the characteristics of this new composite blade should be such that no changes in the aircraft would be required to use the new blades in place of the current metal blades. Test results are presented and experience with three prototypes is described.

INTRODUCTION

Carson's composite main rotor blades have produced significant improvements in the performance of the S-61, especially at high altitude [1]. An engine up-grade from the current CT58-140-1, 2 engines to the more powerful T58-GE-16 engines is scheduled for flight test this fall [2]. This installation will take advantage of the excellent high altitude performance of the main rotor. To benefit fully from these modifications, Carson has been developing new tail rotor blades for the aircraft to improve the trim and maneuvering in various flight conditions and to expand the high altitude envelope.

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Reference 2 discusses the importance of an increased thrust capability for the tail rotor to take full advantage of the increased power available at altitude with a new engine. This is illustrated in Figure 1, from [2]. This figure also illustrates the estimated lift gain in hover from increased tail rotor efficiency.

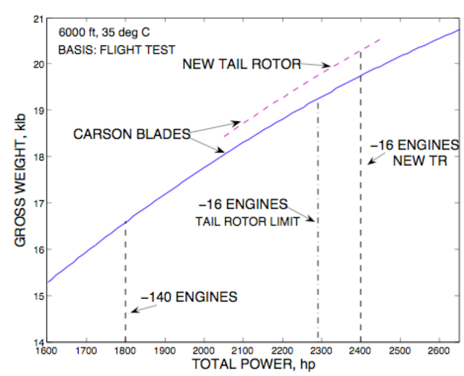

Figure 1: Influence of New Tail Rotor on Hover Lift with -16 Engines

Westland has noted the limitations of the current tail rotor on the Sea King [3,4] and has developed two alternatives designed to increase the maximum thrust available. The base line tail rotor has five rectangular planform blades, a symmetrical airfoil (NACA 0012), and no twist. One alternative adds a sixth blade, and the second uses a new composite blade with the same planform and a cambered airfoil section (RAE 9670 [7]) to increase the maximum thrust. The cambered airfoil improves the performance of the tail rotor at high thrust levels [3]. The first solution requires changes to the yaw control system as well as a new tail rotor hub. The second approach requires the addition of preponderance weights in the control system to reduce the large control moments generated by the pitching moment characteristic of the airfoil. The blade with the cambered section is also untwisted and consequently has a similar efficiency to the baseline [3] up to nominal hover trim. Above this thrust level, the cambered section shows a significant improvement. Similar results regarding efficiency are shown in [10] where the cambered section shows no improvement in efficiency until stall is encountered on the symmetrical section.

Carson's new design had the dual objectives of improving the efficiency of the tail rotor over the operating range and also increasing the maximum thrust available. Flight test results [3,4] show that at takeoff power, the current tail rotor is using 14-15% of the total power with a figure of merit of 0.55. Aerodynamic design studies conducted by Carson Helicopters showed that a new tail rotor design for the S-61 described below, offered the potential of a significant improvement in efficiency [1], with the estimated increase in the figure of merit, the power saving at takeoff power is about 85 HP, corresponding to more than 400 lbs of additional lift. The low speed flight envelope would be expanded in presence of cross winds and at high altitude [3]. As a result of these estimates, Carson decided to proceed with the development of a new tail rotor blade with advanced aerodynamic design.

In addition, a second equally important objective was to develop a new tail rotor that would not require any other changes to the helicopter. That is, as is the case for the Carson composite main rotor, the current tail rotor blades could be replaced by the new design with no other changes to the aircraft.

DISCUSSION

Blade Aerodynamics

As noted in Reference 3, an untwisted blade has a lift coefficient peak near the tip, with tip stall limiting the maximum thrust coefficient.

Figure 2 is similar to one in [3] showing the lift coefficient distribution along an untwisted blade at a C_T =.019. Also shown are the stall characteristics of the 0012 airfoil in the vicinity of the tip (C_l=0.82) for a tip Mach number of 0.64 (NR=103%), showing that tip stall is incipient at this C_T.

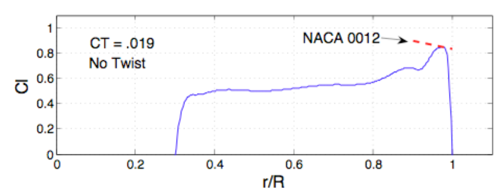

Figure 2: Spanwise lift coefficient distribution for the untwisted blade, C_T =.019.

This distribution can be compared to Figure 3 showing the predicted C_l distribution for a blade with 8 degrees of twist (washout).

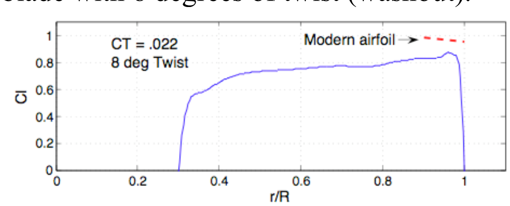

Figure 3: Spanwise lift coefficient distribution for the blade with 8 degrees twist, C_T =.022.

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Now the same peak lift coefficient corresponds to a C_T =.022, a 16% increase. In addition, using a modern airfoil section at the tip, the stall lift coefficient is increased to a C_l =0.95 as shown in the figure, so there is still a stall margin existing. Considering these results, the new design shows a potential for about a 35% increase in maximum thrust before encountering stall compared to the baseline metal blade.

The airfoil section is varied over the blade span using a suitable combination from [5,6]. Initial Carson prototypes also had a swept tip, however retaining the rectangular planform eliminated this contribution to the blade pitching moment. The blade radius and chord are the same as the current blade.

Blade Inertia and Stiffness

To meet the second objective of interchangeability, the blade planform is not altered (although early investigations included a swept tip) and the mass distribution and stiffness distribution of the new design must match the current metal blade as closely as possible. This is considered the best approach to minimizing the possibility of unexpected vibratory or stability problems with a new tail rotor design.

Critical blade frequencies in this regard include the first chordwise mode (the tail rotor does not have lag hinges). The tail rotor operates in the vertical plane and gravitational excitation can produce high oscillatory spindle loads if the in-plane frequency is not sufficiently far removed from one per rev, as this mode is lightly damped. In addition flap-lag instabilities ("buzz") must be avoided [3, 8]. A second frequency of concern is the second flapwise mode that is likely to be close to 3 per rev at high blade pitch angles [8,9].

The blade pitching moments must be maintained at a low value similar to those of the current blade otherwise, modifications to the yaw control system will be required. Airfoils with low pitching moments are used. In addition, the inertial properties of the blade must be carefully controlled as they are the dominant source of the control loads if the airfoil pitching moments are small. The existing yaw control system of the S-61 is designed so that if blade pitching moments are much larger that those of the current metal blades, the added load increase feeds into the cable system to the rudder pedals, and considerable lost motion will occur due to cable stretch as well as an increase in pedal force.

DESIGN STUDIES

First Prototype (Mod A 1997)

The first prototype used advanced airfoil sections [5, 6], and 12 degrees of linear twist and a swept tip. Without the availability of a ground test rig, Carson went directly to an instrumented flight test program with the composite tail rotor blades installed on an S-61.

The flight program was abbreviated because of high steady control loads and high in-plane oscillatory spindle loads. The short flight program did demonstrate a significant improvement in aerodynamic efficiency. However, the high steady control loads produced considerable lost motion (about 4 degrees of blade pitch) in the control system. The high spindle loads were an additional cause for concern and so the flight program was curtailed after two flights.

Since further experimental data were desired to pinpoint the precise source of these problems, Carson constructed a ground test stand. An extensive ground-based investigation of this new composite tail rotor blade was carried out and the results compared to the metal blade.

It was concluded from these tests that following design problems existed:

1. The mass distribution of the composite blade was not well matched to the metal blade. The spanwise cg of the blade was further outboard on the new composite blade compared to the metal blade and the outboard mass reduced the chordwise frequency below that of the metal blade. This combination along with low damping in this mode produced significant amplification of the composite blade in-plane bending response due to gravity and consequently high oscillatory spindle loads.

2. The chordwise mass distribution of the new blade did not match the metal blade closely, leading to increased steady control loads and consequently lost motion in the yaw control system.

3. Mold contour errors distorted the airfoil and increased the aerodynamic pitching moment. The swept tip was also a significant contributor to the blade pitching moment. The contribution of the tip was evaluated experimentally by fairing out the tip sweep.

In preparation for a revised tail rotor blade design, it was considered desirable to conduct additional tests on an aircraft with metal blades. Ground tests with metal blades on an S-61 aircraft were conducted to provide additional dynamic data on metal blade characteristics in preparation for a second prototype design. By operating over a wide range of rotor speeds (50% NR to 110%NR) the integral frequency crossings of various modes can be used to assist in estimating the blade frequencies at operating speed. As noted it [8], in calculating blade frequencies, it is difficult to determine the effective bearing stiffness at the root. The metal blades were designed with a section that can be changed if redesign is necessary [8]. Also, the stiffness of the bolted connection of the composite blade to the sleeve is difficult to estimate.

Second prototype (Mod B 2003-2005)

After some elapsed time during which Carson concentrating on developing and testing a new main rotor, a second prototype was constructed. This blade was fabricated following Carson recommended design changes in the blade mass and stiffness characteristics to obtain a better match of the metal blade. Also the blade sleeve was redesigned to increase the spacing of the bolts that attach the blade to the sleeve from 1.5 to 2 inches. It was considered that some of the in-plane frequency reduction noted with the first prototype could be due to this attachment.

Carson conducted extensive ground tests on the thrust stand with the Mod B blade.

This design appeared to have satisfactory characteristics from the ground test results. However, a detailed investigation showed that favorable control loads were achieved by locating the blade chordwise outboard cg far aft of the blade one-quarter chord. This leads to a significant reduction in the steady control load, as described below, but is considered to be an undesirable design feature which is likely lead to blade dynamic problems [8]. The spanwise cg and stiffness characteristics of this second prototype were a better match of the metal blade, in contrast to the chordwise cg position.

Because of the critical importance of the chordwise cg position [8], representing a poor match to the metal blade, Carson decided not to proceed with development of the Mod B design. A subsequent investigation showed that material fabrication errors were responsible for the far aft cg location.

Third prototype (Mod C 2006-2007)

For the Mod C blade, Carson decided upon a more conservative approach to the aerodynamic design by reducing blade twist to 8 degrees from 12 degrees and by eliminating the swept tip. It was estimated that these geometric changes would cause only a small reduction in tail rotor efficiency in the static case.

The Mod C blades have successfully passed fatigue testing and final ground and flight testing is expected to be in progress by the time of the conference.

ANALYSIS

Steady Control loads

An analytical expression for the pitching moment at the blade root due to the inertial properties of the blade and root fittings can be expressed as follows:

$$M_\Theta = \Omega^2 [(I_{zz} - I_{yy}) \sin(2 (\Theta_{B75} + i_p))/2 + I_{xz} \sin \beta_o \cos(\Theta_{B75} + i_p)] \qquad (1)$$

The x-axis extends spanwise along the blade 0.25 chord line and the y-axis points upward and z-axis points aft. The x, z system rotates with the true blade pitch at 0.75R (Θ_{B75}) . Note that θ_{B75} is not the input pitch because of the use of a δ_3 hinge. i_p is the inclination of the principal axis relative to the blade section at 0.75R, and β_o is the blade coning angle. The first term will always be negative ($I_{zz} < I_{yy}$), corresponding to a nose down blade moment. The second term, the product of inertia in the span-chord plane is usually positive to reduce the nose down contribution of the first term. The terms are often of equal importance. It is also necessary to account for all hinged mass contributions to these inertia terms, not only the blades. This formula predicts a fairly non-linear dependence on blade angle in large part to the variation of coning angle with blade angle.

The inertial properties of importance (I_{zz} , I_{yy} , I_{xz}) are not readily measured. I_{zz} and I_{yy} must be determined with accuracy since their difference is the order of $(c/R)^2$ I_{yy}. The first term in equation (1) is often referred to as the "tennis racquet" effect or propeller moment. The second term in equation (1) may be either sign depending upon the chordwise distribution of mass along the blade span. A forward chordwise cg near the tip tends to contribute a nose down moment (I_{xz} is negative) and conversely an aft cg near the tip contributes a nose up moment (I_{xz} is positive). The root fittings as well as the blade contribute to the result.

EXPERIMENTAL RESULTS

The inertial characteristics of the blades in part were deduced from the ground whirl testing. This is a good way of experimentally verify these quantities.

Steady blade pitching moments are compared to those of the metal blade for the first (Mod A) and third (Mod C) prototypes.

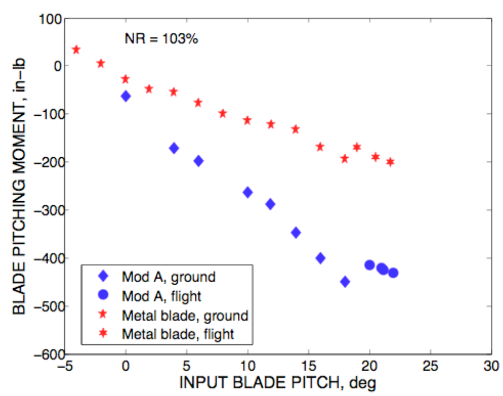

Figure 4: Comparison of the blade pitching moment of a metal blade and the 1st prototype composite blade, Mod A.

Figure 4 shows metal blade results both from two test ground tests as well as measurements on the aircraft compared to results from the first prototype showing the very large blade moments on the first prototype. This increase obtained for the first prototype resulted in high pedal forces. (They are about equal to zero for the baseline tail rotor) Three factors were responsible for the large moments, the swept tip, a difference in blade inertial properties, and a contour error in the mold fabrication. Fairing out the tip sweep and measuring the change in blade moment verified the magnitude of the swept tip contribution.

The second prototype is not discussed, as its characteristics were not satisfactory due in large part to fabrication errors.

The third prototype was extensively ground tested. This blade had a reduced linear twist and a rectangular planform. Figure 5 compares the measured blade moment for the third prototype (Mod C) composite blade with metal blade results. These results show that the moment characteristics of the Mod C composite blade are quite satisfactory.

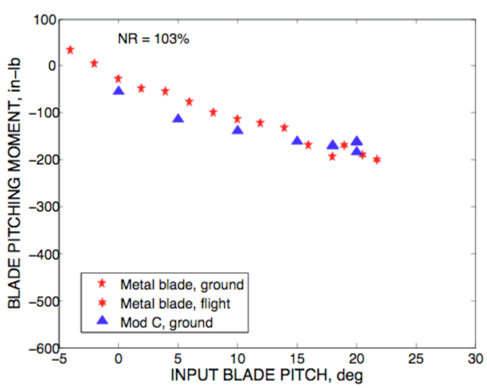

Figure 5: Comparison of blade pitching moment of a metal blade and the 3rd prototype composite blade, Mod C.

Blade Frequencies

Spectral amplitudes read from the flapwise and chordwise strain gages on the blade and spindle can be used to aid in determining the important blade natural frequencies. By operating the tail rotor on the aircraft and on the ground test stand over a wide range of rotor speeds (50%Nr to 110%NR), the spectral amplitude variations clearly identify when the frequency of a blade mode is equal to an integral multiple of the rotor speed.

The first in-plane mode can readily be detected by its crossing the of the 2 per rev line in the vicinity of 75% of normal rotor speed. A second critical mode, the second flapwise mode crossing at 3p is also readily detected by this approach. Then, the Southwell coefficients for the modes can be used to extrapolate the frequencies to operating rotor speed.

By conducting experiments on the aircraft as well as on the ground stand and comparing results, it is possible to observe that other modes associated with coupling to the airframe are not present and that the blade frequencies are unchanged, indicating that the tail rotor dynamics can be considered essentially a single blade problem [8].

CONCLUSIONS

1. A new tail rotor blade for the S-61 has been designed and ground tested.

2. The new blade will improve the low speed controllability and high altitude trim capabilities by increasing the maximum tail rotor thrust available at lower power.

3. Ground tests indicated directly a significant power saving in hover. At the same blade pitch, it was possible to run the new blades at significantly higher rotor speeds than the metal blades.

4. The new blade is a direct replacement for the current blade, and no changes to the aircraft will be required to install and use the new blades.

REFERENCES

1. Curtiss, H.C., Carson, F., Neve, A. The S61/Sea King with Carson Composite Blades, paper presented at the 34th European

Rotorcraft Forum, September 16-18, 2008, Liverpool, UK

2. Curtiss, H.C. , Carson, F., The S-61: The Next 50 Years, paper presented at the American Helicopter Society 66rd Annual Forum and Technology Display, May 11-13, 2010, Phoenix, AZ

3. Cook, C.V., A Review of Tail Rotor Design and Performance, Vertica, Vol 2, 1978

4. Cook, C.V. Flight Evaluation of a Highly Cambered Tail Rotor, paper presented at the 2nd European Rotorcraft and Powered Lift Forum, September 1976, Bückeburg, Germany

5. Noonan, K.W., Aerodynamic Characteristics of Two Rotorcraft Airfoils Designed for Application to the Inboard Region of a Main Rotor Blade, NASA TP 3009, July 1990

6. Bingham, G.J., Noonan, K., Two-Dimensional Characteristics of Three Rotorcraft Airfoils at Mach Numbers From 0.35 to 0.90, NASA TP 2000, 1982

7. Wilby, P.G., The Aerodynamic Characteristics of Some New RAE Blade Sections, and Their Potential Influence on Rotor Performance, Vertica, Vol 4, 1980

8. Carlson, R., Discussion of the Paper "Tail Rotor Design, Part II-Structural Dynamics", presented at the 25th Annual National Forum, May 14-16, 1969, Washington, DC

9. Hansford, R., Comparison of Predicted and Experimental Rotor Loads to Evaluate Flap-Lag Coupling with Pitch, Journal of the American Helicopter Society, Vol 24, No 4, October 1979

10. Robinson, F., Large Increase Obtained in Tail Rotor Thrust, Journal of the American Helicopter Society, 1971