PERFORMANCE OF A SIKORSKY S-61 WITH A NEW MAIN ROTOR

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Abstract

New composite main rotor blades for the Sikorsky S-61 have been designed, constructed and flight tested. Design criteria are described and the geometry of the new blade is shown. Results of an extensive flight test program conducted to obtain a Supplementary Type Certificate from the FAA for these blades are presented. The flight test program included an investigation of the performance and stability and control characteristics, and measurement of the structural loads. The flight test program was conducted with the aircraft as currently equipped with metal blades and the aircraft with new composite blades, so that direct load comparisons could be made. The flight test data show that the new blades provide a considerable increase in the hover lift capability and a significant improvement in level flight performance. Critical oscillatory control loads with the new blades are shown to have amplitudes lower than those of the aircraft with metal blades and the vibration characteristics of the aircraft are not appreciably changed by the new blades. Pilot comments indicate that the handling characteristics of the aircraft are improved with the new blades.

Introduction

About 10 years ago, Carson Helicopters conducted a study to investigate the performance gains that might be expected if new main rotor blades were designed for the Sikorsky S-61 helicopter. This new design would take advantage of the advances in airfoil development, modeling capability, and materials that have taken place since the Sikorsky S-61 was designed c. 1957. Carson Helicopters uses Sikorsky S-61 helicopters for a variety of tasks including heavy lift , logging, and fire fighting. and so emphasis in this blade design study was placed on gains in hover performance. Investigation of blade geometry including new airfoils, variations in twist and tip shape were undertaken using the EHPIC code of Continuum Dynamics, Inc (1, 2). In addition to a gain in the hover efficiency, it was equally important that a new rotor blade design should not produce an increase in the oscillatory loads experienced by the helicopter and its components in flight that would result in a reduction in component lifetime or a limitation in the flight envelope. A conservative approach was taken. The mass, mass distribution and stiffness characteristics of the new blade design were selected to match the metal blade characteristics as closely as possible. Matching the metal blade dynamic characteristics should minimize changes in the dynamic loading. Such an approach was considered desirable due to experience with replacement blades for another helicopter (3), and pessimistic estimates regarding the possibility of achieving this latter goal in the literature (4). The results of the design study indicated that a considerable increase in hover lift capability (1800 lbs.) could be expected. With this favorable conclusion, Carson made the decision to proceed with the development program. Critical components of the aircraft were identified, and the test helicopter was instrumented to measure the impressed loads in various locations. The blades of new design were constructed of composite materials. A full-scale thrust stand was not available, so the test program proceeded directly to flight. First, the metal blade tests were flown and then repeated with the composite blades. The flight test program was planned to obtain the necessary data required for a Supplementary Type Certificate from the FAA. It was completed in February 2002 (160 flight hours have been accumulated with the composite blades). These tests were conducted at the Carson facility in Perkasie, Pa and certain high altitude tests were performed at Leadville, Co. The tests included measurement of structural loads, performance and stability and control characteristics, evaluation of the height-velocity envelope and the ground resonance characteristics of the aircraft with composite blades. Some of the significant results of this program relating to the performance characteristics and structural loads are examined in this paper. The new design blades produced no changes in the height-velocity boundaries or the ground resonance characteristics of the aircraft, and so these topics are not discussed further.

Discussion

Design Studies

Aerodynamic design studies were undertaken, constrained by the mass and stiffness constraints mentioned above. To minimize possible effects of the new blades on the aircraft components it was desirable to maintain the same chord as the metal blade. In addition, as part of this study, aerodynamic investigations indicated that with the existing aircraft transmission torque limit there would be no advantage to a main rotor solidity change except at high altitude. The performance improvements that would be gained by use of modern airfoils were examined along with alterations in blade twist and tip shape. These studies using the EHPIC code concluded that the best airfoils available would be the RC series of airfoils, developed by the U.S. Army, AVRADCOM R and T Laboratories, Langley Research Center, for helicopter main rotor blades (5, 6). The RC(4) -10 (10 percent thickness) section was chosen for the inboard portion of the blade and the RC(3)-10, a section with less camber than the RC(4)-10, was used outboard. It was found that the flapwise stiffness required to match the metal blade could not be obtained with a 10 percent section, and that it would be necessary to use a 12 percent section, the same as the metal blade, over some part of the span. Experimental data were not available for a 12 percent RC(4) section and so the characteristics of a 12 percent thick RC(4) series airfoil were predicted using a CFD code at Princeton University. The airfoil studies concluded that the aerodynamic characteristics of an RC(4)-12 section would be satisfactory inboard. As a result, the RC(4)-12 section extends from the blade root to about 70 percent radius, where a transition to an RC(4)-10 starts, and then to an RC(3)-10 at the tip. The effect of twist was examined and the computational studies indicated that a significant gain in figure of merit would be obtained with a linear twist of 12 degrees, a four degree increase over the metal blade. Different tip configurations were examined and a tapered, 30 degree swept tip extending over the last five percent radius was chosen as the best combination to provide increased efficiency without large steady state control system loads.. The predicted figure of merit for the final design is nearly 0.79 at the nominal operating thrust coefficient corresponding to an 1800 lb. increase in lift**.** Figure 1 shows the geometry of the blade, selected for fabrication from composite materials. The metal blade geometry is also shown. The trailing edge tab on the composite blade was added after initial flight tests for reasons described below. While these design studies focussed on hover, the computational results also indicated that there would be modest improvements in the translational flight performance.

After the composite blades were fabricated, their properties were measured and compared to the metal blades before run-up. The first mass moment of the composite blades differs by less than 1 percent from the metal blades. Consequently, the centrifugal force produced by the new blades is essentially the same as that of the metal blades. The static droop of the flight set of composite blades was measured and found to vary less than 0.5 inch over the five blades while it varied as much as 2.5 inches for five metal blades. Thus, because of this variation among the metal blades, a precise comparison of the static droop is not possible, although the droop is quite similar for both sets of blades.

Since Carson Helicopters could not locate a full-scale thrust stand to be used for initial run-up of the new blades before flight, they were mounted directly on the instrumented test aircraft (an S-61R) and flown without ground test. The natural frequencies of the new rotor blades mounted on the aircraft were determined by measurement of the amplitude spectra of the blade bending strains over wide range of rotor speeds . Harmonic crossings of the blade frequencies can be determined from the amplitude and the blade natural frequencies at operating RPM estimated. Flapwise and chordwise frequencies were determined by this approach. The torsion frequency was estimated from the transient response of the blade in the flight regime where retreating blade stall is present. The composite blade frequencies estimated from these data were compared to calculated values for the metal blade. The metal blade frequencies were calculated based on measured physical characteristics. The composite blade first chordwise frequency is closer to four per rev than that of the metal blade. It was difficult to match the chordwise frequencies of the metal blade because the metal blade has a segmented trailing edge, with pockets that do not contribute to the chordwise stiffness. The flapwise frequencies were quite closely matched. The measured torsion frequency for the composite blade is 7.66 per rev, somewhat higher that the value (6.60p) indicated for the metal blade by Beno (7). It is considered that this high torsion frequency is a significant contributor to the very favorable vibration characteristics of the new blades. No problems were found or indicated by measurements upon ground run-up on the test aircraft, so flight tests began with hover at light gross weight, and careful monitoring of loads as the weight, airspeed, and altitude were increased.

Flight Test Program

The test aircraft was instrumented to measure aircraft accelerations at various locations, control positions, rotor blade flap and lag angles, main rotor shaft strains, various critical components in the rotating and stationary parts of the control system, and in the tail rotor. For the composite blade, bending and torsion moments were measured at various spanwise locations as indicated by the design study. Total axial strain at the trailing edge was measured at four spanwise locations. These loads as well as other aircraft operating parameters were measured in a total of 48 different steady state and transient maneuvers for the aircraft equipped with metal blades and the new composite blades. Tests were conducted at four gross weights, two cg positions, the fore and aft limits. In the steady maneuvers, two rotor speeds were examined. A total of fifty data channels were generally used, and the sample rate was 500hz with the data typically filtered at 50 hz. Generally in the steady flight maneuvers, 15 seconds of data were collected at each flight condition. In maneuvers as much as 30 seconds of data was often found necessary to obtain a clear entry into and exit from the maneuvers. Initial flight tests with the composite blades showed relatively high values of the steady loads in the rotating (pitch control rod) and consequently in the stationary (the right lateral servo) control system, particularly near hover. As a consequence, a fixed trailing edge tab of 0.2R with 6 degrees of upward deflection was added to the blade. The effectiveness of the tab is presented in Figure 2 where it is shown that the tab produced a significant reduction in the steady load in the pitch change rod especially at low speeds. A corresponding reduction in steady load occurs in the components of the stationary control system. The tab did not produce a measurable change in rotor performance.

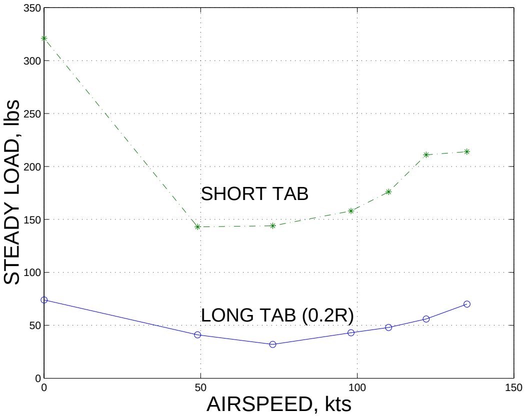

Figure 2: Tab effect on steady pitch rod load.

Performance

Hover flight tests demonstrated that the aircraft with new composite blades achieved its design objective by lifting 2000 lbs. more than with the metal blades, out of ground effect, at the same torque.

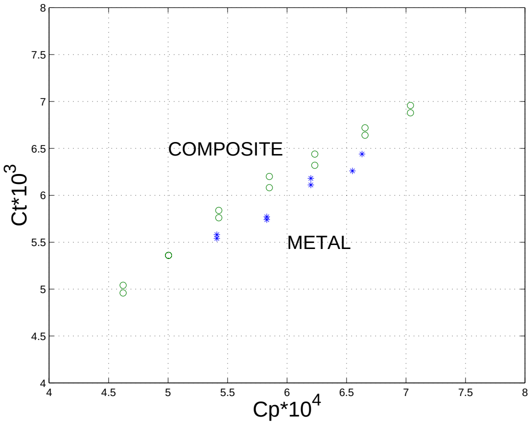

Figure 3: Power coefficient vs thrust coefficient in tethered hover.

This increase corresponds closely to the 1800 lbs.(main rotor figure of merit = 0.79) predicted by the EHPIC code. Figure 3 presents performance data at a height of 100 ft.

Although there is considerable scatter in composite blade measurements, it can be seen that the new blades are clearly superior to the metal blades. Level flight performance improvements are shown in Figure 4 at 20500 lbs. gross weight, 2000 ft. density altitude.

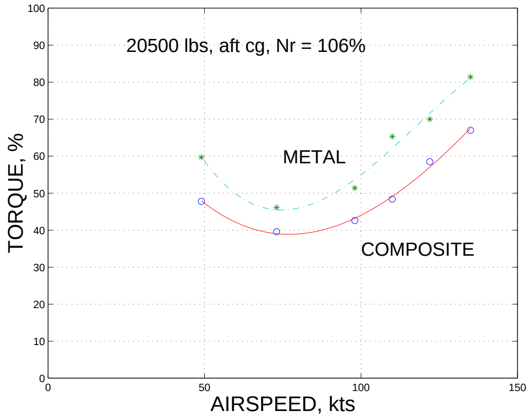

Figure 4: Level flight performance comparison.

The total engine torque required for level flight at different airspeeds for the aircraft with the metal blades is compared to that with the composite blades at a rotor speed of 215 rpm. The level flight performance is significantly improved by the composite blades. At 68 percent torque, 215 RPM, the airspeed of the aircraft with composite blades is about 17 kts faster than the metal bladed aircraft. This corresponds to a 15 percent increase in range. Thus, in addition to a gain in hover lifting capacity, the aircraft with composite blades shows a significant improvement in the range-payload characteristics. The climb performance of the aircraft is also improved as would be expected from the reduction in torque required for level flight shown in Figure 4 . Flight test results show about a 400 ft/min. increase in the rate of climb at altitudes of 6000 and 10000 ft at 20500 lbs gross weight.

Structural Loads

The structural load investigation comprised the most extensive part of the flight test program. Measurement of loads in critical components of the rotating and stationary control system were made in a large number of maneuvers for the aricraft equipped with metal and composite blades. Comparison of the oscillatory loads in these components with metal and composite blades was of primary importance, in order to evaluate possible effects on component lifetimes. Identical measurements were made for the aircraft with metal blades and composite blades. In addition, blade bending and torsion moments were measured for the new blades at various spanwise locations for comparison with design values and to provide loads for the composite blade fatigue ground test program. Typical results pertaining to the oscillatory loads in the blade pitch change rod and the right lateral servo are presented here. The lifetime of many of the control system components is based on the oscillatory loads in these two elements. Other control system component loads showed similar behavior to those discussed. The oscillatory load shown is one-half the largest measured peak to peak load change occurring within one rotor revolution over the complete fifteen seconds of data in each steady flight condition. The significance of the amplitude of the oscillatory load in the pitch change rod, for example, is that it is related to the endurance limit of a number of the components in the rotating control system. This is an oscillatory load of approximately 800 lbs. in this element. Figure 5 shows the pitch change rod oscillatory load comparison in steady flight at various airspeeds at 203 rpm (Nr of 100 percent).

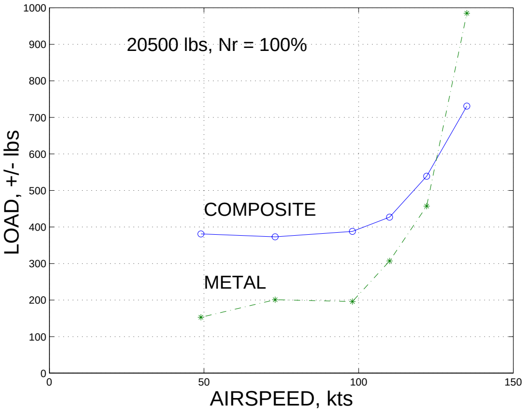

Figure 5: Comparison of oscillatory load in pitch change rod.

It can be seen that the oscillatory load with composite blades is higher than that experienced by the aircraft with metal blades in the region where the loads are well below the endurance limit. However, the oscillatory load in the pitch change rod, indicative of retreating blade stall, rises more steeply with airspeed for the metal blade aircraft, and increases to a higher critical value above 100 knots compared to the composite blade aircraft. Figure 6 shows a more dramatic improvement due to the new blade at increased rotor rpm (Nr of 106 percent).

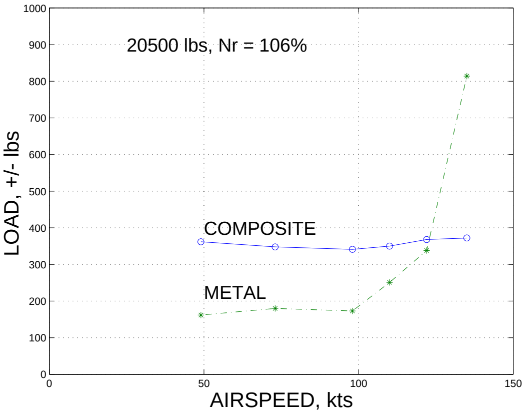

Figure 6: Comparison of oscillatory load in pitch change rod.

While the load characteristic with the metal blade is only slightly changed by a change in rotor speed, with the the composite blades there is no oscillatory control load increase up to 1.11Vne. Similar behavior is found in the oscillatory load in the stationary control system as would be expected. Figure 7 shows the oscillatory load in the right lateral servo at an Nr of 106 percent.

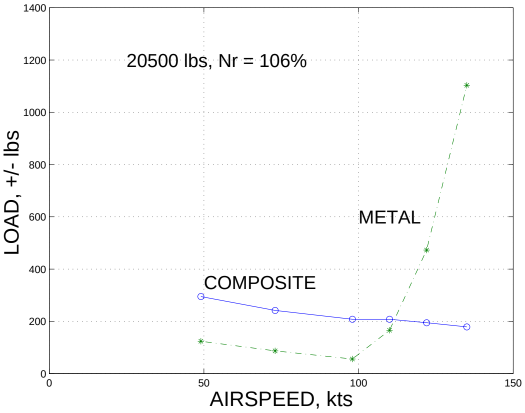

Figure 7: Comparison of oscillatory load in right lateral servo.

The difference in the maximum oscillatory load measured in turns and a pull-up is shown in Figure 8 for the right lateral servo

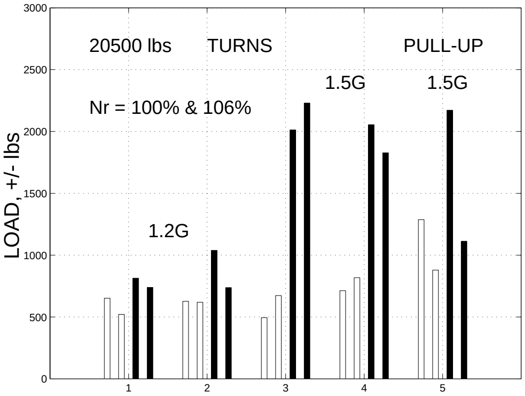

Figure 8: Comparison of oscillatory load in maneuvers in right lateral servo, composite(white), metal(black).

The maneuvers shown are all performed at Vne and consist of left and right turns at 1.2g and 1.5g and a symmetrical pull-up. The oscillatory loads produced in the right lateral servo by the metal blades are considerably higher than those for the composite blades in these maneuvers. It may be noted that the turns at 1.5g are performed at Vne and are maneuvers that are severe and well past the stall boundaries given for the aircraft (8). The pilot indicated that it was difficult just to achieve the required load factors (1.5g) in maneuvers with the metal blades, while there was little problem achieving the load factor with the composite blades. In these maneuvers, the stall boundary for the metal blade aircraft in a 1.5g turn at this gross weight and density altitude (6000 ft.) is exceeded by more than 20 kts(8). The 1.5g turns shown in this series of maneuvers were flown at 97 kts. At a higher airspeeds, the lower angular rate corresponding to the normal acceleration gives less load relief. In general, the pilots reported that it was considerably easier to perform all required maneuvers with the new blades. Also, there was very little evidence of the pitch-lag vibration that occurs with the metal blades in severe maneuvers.

Stability and Control

No apparent quantitative differences were noted in the measured longitudinal and lateral-directional static stability characteristics with the new blades. Both the Carson pilot, with extensive experience in the S-61, and the DER pilot reported that the aircraft equipped with composite blades demonstrated improved handling characteristics, especially near hover and in maneuvers. The aircraft was found to be easier to hover with the new blade design. In maneuvering flight the sense that the aircraft was near to the boundaries of the flight envelope was much less evident with the new blades. Little change in the measured vibration characteristics was noted with the new blades. Figure 9 shows that the aircraft experiences lower lateral vibrations in the cockpit at high gross weight at an Nr of 106 percent with the new blades.

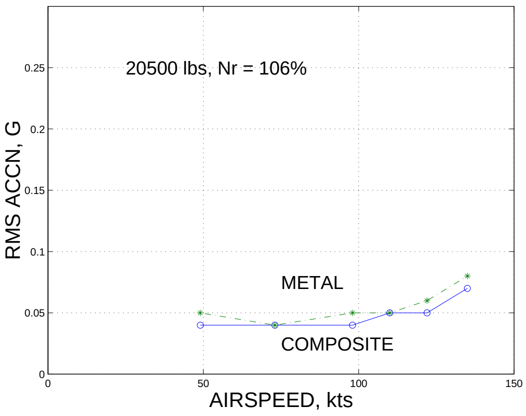

Figure 9: Comparison of RMS lateral acceleration on the cockpit floor.

Future Plans

The favorable results obtained during this flight test program lead to the next step, exploring the possibilities for envelope expansion. The advantages of a new tail rotor design have been explored analytically, and Carson Helicopters is proceeding with the development of new tail rotor blades. With the improved cruise performance, it also is of interest to investigate various avenues for aircraft drag reduction.

Conclusions

1. A new main rotor has been designed and developed for the Sikorsky S-61 helicopter that produces considerable improvement in hover and translational flight performance.
1 Oscillatory control system loads for the S-61 equipped with the new design composite blades are similar to those for the aircraft with metal blades in the intermediate speed range where the loads are not critical.
2 At high speeds and in maneuvers where oscillatory loads can affect component lifetimes, the loads are significantly lower for the aircraft with composite blades.
3 No change in component lifetimes, or modifications to the S-61 helicopter are required to use the new blades. Standard tools are used to replace the metal blades with composite blades.

Acknowledgement

Considerable assistance on this program was provided by Vic Shami of AvMod, Hurst, Tx

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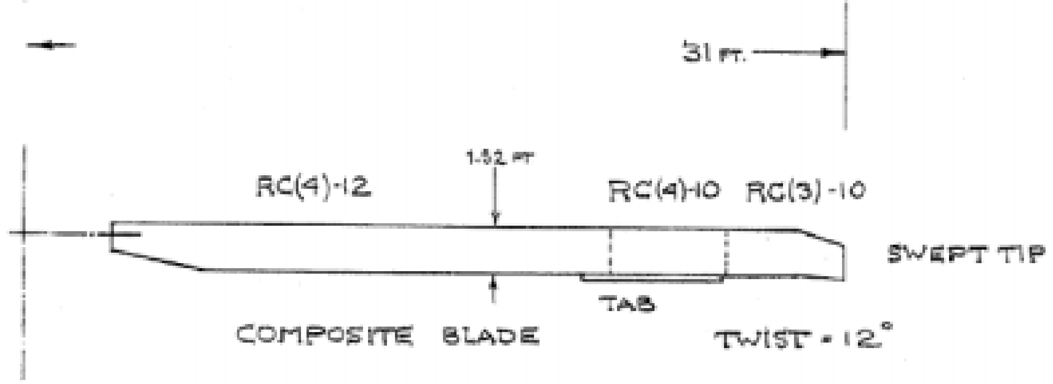

Figure 1: Comparison of blade geometry.