Inspection of helicopter rotor blades with the help of guided waves and "turning modes": Experimental and finite element analysis

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Abstract
Modern helicopter rotor blades constructed of composite materials offer significant inspection challenges, particularly at inner structures, where geometry and differing material properties and anisotropy make placement of the probing energy difficult. This paper presents an application of Lamb waves to these structures, where mode conversion occurs at internal geometric discontinuities. These additional modes were found to successfully propagate to the targeted regions inside the rotor and back out, allowing evaluation of the structure. A finite element model was developed to simulate wave propagation and mode conversion in the structure and aid in identifying the signals received in the laboratory experiment. A good correlation between numerical and experimental results was observed.

Keywords
blades, composite materials, finite element analysis, helicopters, inspection, rotors, nondestructive evaluation, QNDE, Aerospace Engineering

Disciplines
Aerospace Engineering | Materials Science and Engineering | Structures and Materials

Comments
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INSPECTION OF HELICOPTER ROTOR BLADES WITH THE HELP OF GUIDED WAVES AND “TURNING MODES”: EXPERIMENTAL AND FINITE ELEMENT ANALYSIS

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ABSTRACT. Modern helicopter rotor blades constructed of composite materials offer significant inspection challenges, particularly at inner structures, where geometry and differing material properties and anisotropy make placement of the probing energy difficult. This paper presents an application of Lamb waves to these structures, where mode conversion occurs at internal geometric discontinuities. These additional modes were found to successfully propagate to the targeted regions inside the rotor and back out, allowing evaluation of the structure. A finite element model was developed to simulate wave propagation and mode conversion in the structure and aid in identifying the signals received in the laboratory experiment. A good correlation between numerical and experimental results was observed.

Keywords: Nondestructive, Ultrasonic, Lamb Waves, Helicopter Rotors, Composite Laminates, Finite Element

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INTRODUCTION

Helicopter rotor blades are highly complex structures, constructed of composite materials and designed to operate in harsh environments and withstand severe vibratory loading. The continued exposure to severe load spectrums induces damage in the rotor blade, and continuous periodic inspections are required to ensure continued availability of the rotorcraft and its safe operation. However, inspection of these structures is not a trivial matter, with the complexity of design and myriad of materials used. Although several studies have examined the ability of structural health monitoring (SHM) methods for detecting and characterizing damage with continued flight cycles [1-3], traditional nondestructive testing (NDT) modalities such as ultrasonic testing, bond testing and the simple tap test remain useful and in use. These traditional NDT methods will remain essential tools for establishing the continued safety of helicopter at operational facilities, but will also continue to provide information and guidance at maintenance, repair and overhaul (MRO) facilities. Here, these traditional NDT modalities pinpoint damage sights that guide repair operations, so to minimize the removal of undamaged components and materials, and also ensure repairs are effective.
In all rotor designs, the rotor spar is the primary load bearing component. Therefore, the condition of the spar and any components attached to or bearing upon it must be known to ensure continued safe operations. In previous work, the authors have evaluated the condition of other parts of the main rotor, such as the trailing edge core and skin using tap test, air coupled UT (ACUT) and bond testing. However, the condition of the spar is difficult to gauge in areas where it is not in intimate contact (bonded) with the skin, namely the curved leading and trailing edges. Examples in Fig. 1 show two conditions that had been difficult to evaluate; the trailing edge side of the spar where it is bonded to the core, bottom left, and the leading edge/nose region with cracking in the nose starting at the spar, bottom right. Both contact UT probes and ACUT were employed to interrogate these areas, with little success.

Recently, ACUT was again evaluated, this time using Lamb waves instead of longitudinal waves. With the ACUT probes oriented at an angle to the rotor surface, lamb modes are easily generated and propagate reasonably well in the part. Here we report experimental and finite element modeling results that demonstrate a significant utility in the use of ACUT/lamb waves for the inspection of spars and other internal elements of rotor blades.

INITIAL LABORATORY TESTS

In the re-evaluation of the spar using lamb modes and ACUT, a simple UT flaw detector was used to drive the probes in a pitch/catch configuration, with the addition of a 40dB pre-amplifier on the receiver side (the pre-amp is significantly lower with respect to noise than the internal amp in the flaw detector). The setup, shown in Fig. 2, made use of Lamb waves, shown in in the figure diagram, generated in the skin/spar bond region, which converted into additional Lamb modes at the geometry transition (where the skin and spar separate), some of which traveled around the trailing edge side of the spar. After traveling around the trailing edge side of the spar, the Lamb modes then mode converted again at the second geometry transition, coupled into the bonded skin/spar region on the opposite side, where leakage was then detected by the receiver. The received signal A-scan trace is

![Diagram of rotor design and challenging spar inspections.](image)

FIGURE 1. Example of rotor design and challenging spar inspections.
shown at the bottom of Fig. 2. As can be seen, there are several modes present. These initial lab results demonstrated that Lamb waves could propagate in this complicated structure and should be brought to bear on the spar/rotor inspection issues. The ACUT probes and flaw detector instrumentation presented several advantages: very consistent coupling on the curved rotor geometry, easy setup (a relatively broad range of probe angles generated lamb modes), and a “system” particularly well suited for field/depot inspection. In order to evaluate whether the assembled components and method would be of value, the modes types available needed to be identified, so as to choose the mode most likely to interact and allow identification/characterization of the damage types found in rotors.

FINITE ELEMENT MODELING

A model/simulation of a generic rotor with skin, spar and core similar to the laboratory sample was developed using ANSYS, with the intent to determine what modes were generated and help in differentiating the different modes in the experiment. The model, shown in Fig. 3, was of the center-rear portion of the rotor, with a section of bonded skin/spar on each side and skin/core sandwich region below. The generic material properties are also shown in the Fig. 3.

The excitation pulse was a standard seven cycle tone burst with a Hanning window. Excitation frequency was chosen as 200 Khz. For the materials properties, skin and spar dimensions used in the model, the dispersion curve plot in Fig. 4 shows that two modes should be available in the frequency range used in the experiments (gray band), fundamental anti-symmetric mode ($A_0$) and fundamental symmetric mode ($S_0$). Figure 5 shows diagrammatically two modeling/simulation and experiment configurations. The upper probes above the skin/spar geometry transitions and their propagation path, solid lines, are referred to as “direct”, where the excitation was applied in the bonded skin/spar region, with modes propagating toward the first geometry transition, around the back of the
Skin/Spar – CFRP
\( E_x: 10.3e9, \ E_y: 10.3e9, \ E_z: 181e9 \)
\( \nu_{xy}: 0.34, \ \nu_{yz}: 0.0159, \ \nu_{xz}: 0.0159 \)
\( G_{xy}: 3.84e9, \ G_{xz}: 7.17e9, \ G_{yz}: 7.17e9 \)
Density: 1580 Kg/m³

Core - Foam:
Elastic modulus: 1.3 MPa
Poisson’s ratio: 0.3
Density: 40 Kg/m³

**FIGURE 3.** ANSYS model of center/rear portion of rotor and materials properties used.

**FIGURE 4.** Dispersion curve for rotor skin/spar and frequency-thickness region, grey band, applying to experimental work and simulation.

...spar to the bonded skin/spar on the opposite side. The probes below of the geometry transitions and their propagation path, the dashed lines, are referred to as “turning”, where the propagation path involved a reversal of direction as described by [4]. It was thought that turning modes might have applications in evaluating disbonds in the skin/spar at the geometry transition as described in [4], and so were evaluated in the simulations...
RESULTS: COMPARISON OF MODEL AND EXPERIMENT

The generic model and simulation of the “direct” path is shown in Fig. 6, upper left, where an excitation point (transmitter) is shown as a black arrow and three measurement positions (receivers) are shown as gray arrows, marked 1-3. The results of simulations are shown for each of the marked “receiver” locations, 1-3, with the Lamb modes present identified. For example, in simulation 1, upper right, the gray circle indicates the measurement (receiver) location, with the A-scan trace showing the original mode generated, $A_0$, propagating forward, with trailing waves that have reflected off the geometry transition, propagating backward. Note that each time a mode passes through or is reflected from a geometry transition, a pair of modes result. For example, in simulation 1, the original $A_0$ mode interacts with the geometry transition, resulting in a reflected $A_0$ and $S_0$ and a transmitted $A_0$ and $S_0$. The notation shown in Fig. 6 represents the modes present: initially only an $A_0$, then an $A_0$ and $S_0$ from the original $A_0$, labeled $A_0A_0$ and $A_0S_0$ (the first mode indicates the source, with the last, bold type face mode indicating current mode). Similarly, in simulation 2, when the modes present in the curved arc of the spar trailing edge interacts with the second transition, the $A_0A_0$ produces $A_0A_0S_0$ and $A_0A_0A_0$, and the $A_0S_0$ produces an $A_0S_0A_0$ and $A_0S_0S_0$. The superscript R indicated modes reflected from the geometry transitions. In the A-scans from simulations 2 and 3, the upper traces represent the out-of-plane component, the lower traces show both out-of-plane and in-plane components (note that $S_0$ modes contain mostly in-plane component).

Figure 7 is a comparison of simulation 3 and experiment, and demonstrates a very good match between the two. Note that the order of mode arrivals is consistent between experiment and simulation, and the lower right trace, with the trace voltage axis magnified, shows the earliest arriving $A_0S_0S_0$ mode, which will always have small amplitudes because it is primarily in-plane displacements. Nominal mode amplitudes are also consistent between simulation and experiment.
FIGURE 6. "Direct" path propagation simulation results, with fixed transmitter location (black arrow, upper left) and three receiver locations (dark grey arrows).

FIGURE 7. Comparison of simulation 3 and experiment, showing consistent mode content, arrival order, and nominal amplitudes.
A similar simulation was made for comparison to the “turning” path experiment, where a transmitter signal was impinged on the trailing edge skin/core region, with three receiver location simulations similar to the “direct” path simulation. For brevity, only simulation 3 is shown here, with experimental results included, in Fig. 8. Note that the mode arrival order is again consistent between simulation and experiment as well as the nominal amplitude of the modes. Also note that as the position of the receiver is below the 2nd geometric transition, two turning modes result, as indicated by the double “T” superscripts.

The turning mode experiments and simulations were undertaken because of the utility demonstrated in [4], where turning modes were employed to evaluate disbonds of “T” stiffeners bonded to solid laminates, a geometry similar to that found in the rotor blades here. At the geometry transitions in the rotors, where the outer skin and spar separate, a disbonds at this location could be characterized by a simple time-of-flight measurement. For example, with a disbonds at the second geometry transition in our model (also called a corner delamination), the propagation path of the pair of modes, $A_0A_0^T$ and $A_0S_0^T$, traveling around the trailing edge side of the spar would be increased by the presence of a disbonds, resulting in a time delay at the receiving probe located at the simulation 3 position. A simulation was performed on this condition and did reveal a time-of-flight delay as shown in Fig. 9. A time-of-flight shift as observed in Fig. 9 shows that the method has the capability to detect and characterize corner delaminations, although, this has to be experimentally verified.

![Comparison of “turning” modes path simulation 3 and experiment, showing consistent mode content, arrival order, and nominal amplitudes.](image-url)
CONCLUSION AND FUTURE WORK

The modeling/simulation effort of this work significantly helped in identifying the modes present, and the quality of the match between simulation and experiment was surprising for such a simple model. The ability to identify which modes are present in the experiment will allow the concentration to be directed toward those modes expected to interact most favorably with specific damage or defect types. Experiment and modeling will next concentrate the propagation of modes around the interior of the leading edge of the spar, in an effort to enable detection of cracking in the nose of the rotor. Additional samples containing disbonds between the skin and spar near the geometric transitions will be needed to be either found or fabricated, so to evaluate the use of turning modes in the measurement of the extent of disbonded regions and compare to the model/simulation results presented here.

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