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ACOUSTIC EMISSION AS A NDE TECHNIQUE FOR DETERMINING COMPOSITE --ETC(U)
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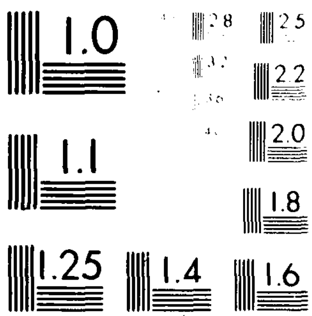

MICROCOPY RESOLUTION TEST CHART

ACOUSTIC EMISSION AS A NDE TECHNIQUE FOR DETERMINING COMPOSITE ROTOR BLADE RELIABILITY

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I. INTRODUCTION

Fiber-reinforced composite rotor blades are being introduced into the Army inventory to replace conventional metal blades. An all-composite blade offers the advantages of lower cost, increased aerodynamic performance, improved ballistic tolerance and a greatly increased service life.

Nondestructive evaluation of these structures is extremely important, as they are susceptible to fabrication errors, service damage and environmental degradation. Due to the complex design and fabrication of these blades, adequate nondestructive evaluation (NDE) techniques have not been developed.

This paper will discuss the progress made in an ongoing program to investigate the use of acoustic emission (AE) to determine the structural integrity of a composite main rotor blade. The blade is constructed primarily of S glass/epoxy and aramid/epoxy. Figure 1 shows the blade structure, which is composed of a multiple-cell filament-wound spar, an aramid trailing edge and a filament-wound blade skin supported by an aramid fiber paper honeycomb core. The design and manufacture of these blades have been presented elsewhere (1). A total of four blades are being tested, two blades with known areas of delamination and two blades without these defects.

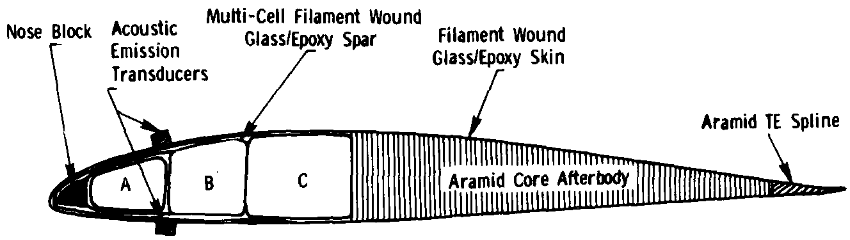

Figure 1. BLADE CROSS SECTION SHOWING PLACEMENT OF TRANSDUCERS

The Applied Technology Laboratory (ATL) at Ft. Eustis and the Army Materials and Mechanics Research Center (AMMRC) are presently investigating the propagation characteristics of flaws in this rotor blade. An AE proof test, a novel NDE technique, is being used to monitor flaw initiation and growth in the blades as a result of fatigue testing. The acoustic emission results will be correlated with mechanical property and other NDE data (ultrasonic, thermography, and radiography) and used to determine the structural integrity of the rotor blade. It is expected that these techniques will be readily adaptable to new product certification and in-service inspection of nonmetallic rotor blades.

II. EXPERIMENTAL

The blades are being fatigue tested by the Structures Laboratory of ATL in a 200K-2-108 fatigue test machine. The blade is mounted in the machine at the tip using a doubler arrangement (shown in Figure 2) and at the root end through an adapter to a hub yoke. The fatigue loading spectrum of alternating flap, chord and torsion bending moments used is representative of actual flight loads (2). A steady axial load is applied through the centrifugal force (Cf) loading system. This tensile load approximates the centrifugal force exerted on the blade during flight. Test frequency is approximately 13 Hz. Flight spectrum loading continues for 28 million cycles, which is equivalent to 1440 hours (4 years) of flight time. If no void growth occurs after 28 million cycles of spectrum loading, the fatigue loads will be increased. AE proof tests will occur prior to the spectrum loading, at 10 and 20 million cycles and at the completion of the first phase of testing (28 million cycles). AE proof tests will be performed more frequently during the higher amplitude loading. Thermographic analysis of heat patterns generated during spectral loading are being performed at periodic intervals by Virginia Polytechnic Institute and State University (VPI) under contract DAAG29-76-D-0100. Ultrasonic, X-ray and borescope inspections are also being conducted by personnel at ATL.

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Figure 2. TIP END CONFIGURATION (SHOWN DURING FLAPWISE BENDING PROOF TEST)

III. ACOUSTIC EMISSION

A. Theory

Research on acoustic emission (AE) from reinforced plastics began in the aerospace industry in the early 1960's. The most significant observation was that the AE count activity began at a repeatable load and increased as the sample was stressed to failure. Since then, the study of acoustic emission has accelerated along with the expanded use of reinforced plastics in structural applications. In the mid 1970's two more basic observations were made: the first related the amplitude of the AE event to the actual failure mechanism (3), and the second documented a deviation from the well-known Kaiser effect (4).

Recently, several application areas have emerged which utilize the ability of AE to assess the structural integrity of reinforced plastic components. In the chemical industry AE has been used to certify hundreds of new and in-service reinforced plastic storage tanks (5,6). The test procedure is presently being modified to include pressure piping and pressure vessels. Numerous

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aerial manlift device (cherry picker) booms have been examined (7). The booms, used primarily by utility companies, were a major inspection problem. AE has proven to be a reliable and cost-effective solution to this safety problem. The automotive industry is investigating AE as a quality assurance tool for the growing number of reinforced plastic automotive components (8,9).

When a material is significantly stressed, it emits mechanical stress waves. These stress waves are known as acoustic emissions. The observed acoustic emission event (Figure 3) from a reinforced plastic material under stress can be described as an exponentially decaying sinusoid. Though various characteristics of the event can be measured, the number of events, amplitude of the event, number of counts (threshold crossings) and rms measurements are particularly significant.

As a reinforced plastic material is loaded to failure, the event characteristics change significantly. The AE during low stress levels are low amplitude signals, and are usually related to cracking of the matrix material or delamination. At higher stress levels higher amplitude signals are observed, which have been associated with fiber failure. Amplitude results are usually displayed in a histogram fashion (Figure 4), known as an amplitude distribution. On the X-axis is the amplitude in decibels (dB) (relative to 1 μV at output of preamp), and on the Y-axis is the number of events. Figure 4 depicts the triple-peaked amplitude distribution first reported by Wadin (3). Though this has not been fully explored, it is widely accepted that each amplitude cluster is associated with a specific failure mechanism. In this example the lowest amplitude events are the result of matrix crazing. The intermediate amplitude cluster is due to delamination and the highest amplitude events are the result of fiber fracture.

The acoustic emission count activity (Figure 5) also provides a characteristic curve as composite samples are loaded to failure. Counts begin at 25 to 50 percent of the failure load. There is very little variation in the onset of emission or in the shape of the "knee" during tests of identical samples.

The Kaiser effect is the "absence of acoustic emission activity until previously applied stress levels are exceeded." The phenomenon can be observed in reinforced plastics at low load levels. At high loads, repeated stress to the same level will result in additional emission. As illustrated in Figure 5 the deviation from the Kaiser effect can be quantified and is often referred to as the Felicity ratio. It is widely believed that the Felicity ratio is a measure of the amount of previous damage to the material.

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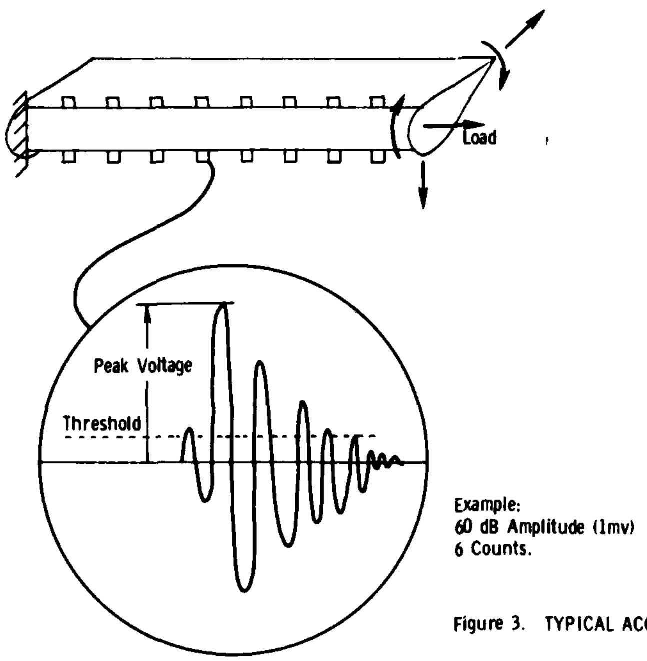

Figure 3. TYPICAL ACOUSTIC EMISSION EVENT

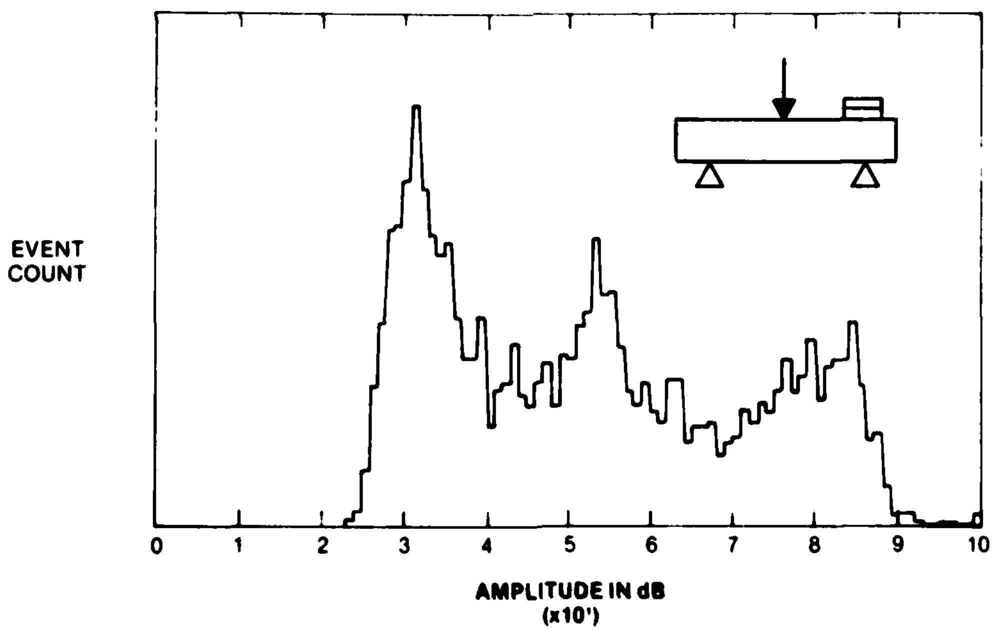

Figure 4. AMPLITUDE DISTRIBUTION (AFTER WADIN, REF. 3)

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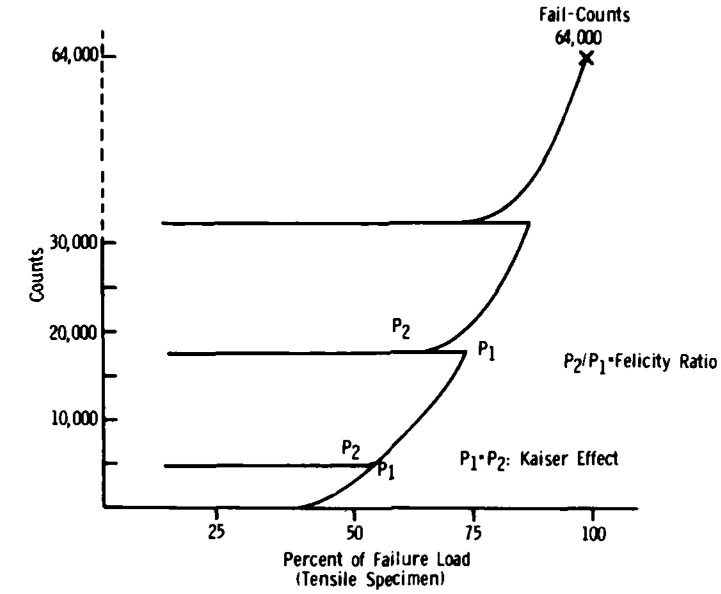

Figure 5. AE COUNT ACTIVITY (AFTER FOWLER, REF. 5)

In order to study the degradation of a material due to cyclic loading an acoustic emission proof test can be used. If a material is loaded to a proof load and this load is in the region where the Kaiser effect applies, we can reload to this level and no emission will occur. Also, no emission will be heard during a hold period. However, as fatigue damage starts to occur, an increase in AE activity will be evident during each proof load, and emission will occur during hold periods. This change in the AE behavior can be used as a measure of the residual strength and of the remaining fatigue life.

As the acoustic emission stress wave travels through a material it loses energy by attenuation and dispersion. Figure 6 illustrates attentuation along the length of an actual rotor blade. An electronic device was used to simulate AE events at various distances from a sensor. In one case (lower curve) the simulator was set to output a small signal similar to that of matrix crazing, and in the second case (upper curve) the signal was similar that of fiber fracture. Naturally, the larger signal can be detected over a greater distance.

We can take advantage of the fact that AE signals travel only short distances in composite materials. As illustrated in Figure 7 an event of 60 dB (matrix crazing) would be detected by

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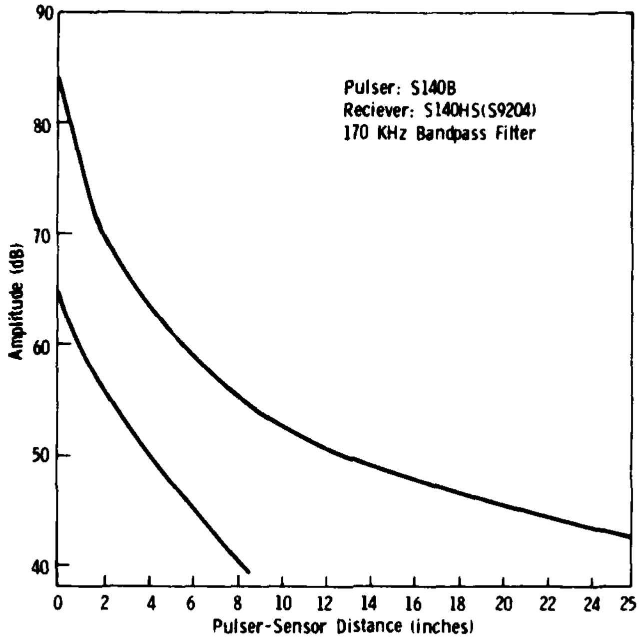

Figure 6. ATTENUATION PLOT

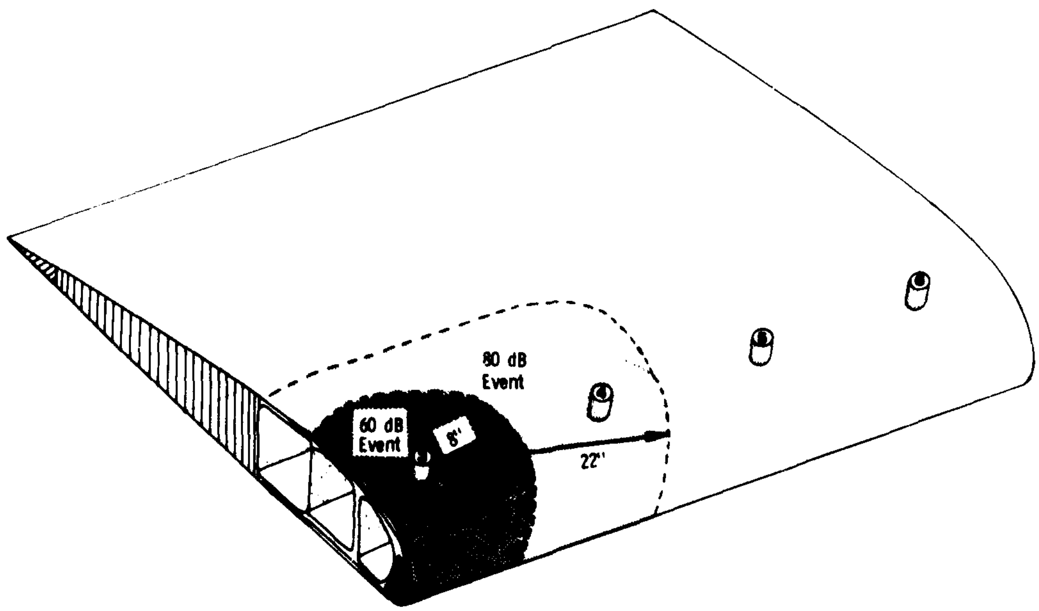

Figure 7 ZONE LOCATION

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sensor number 3 only if it occurred within the dashed line marked 60 dB event. There is no possibility that a 60 dB event occurring close to sensor number 3 could be detected at sensor number 5. Thus, an operator noting activity from only sensor number 3 would be aware that the source is close by. However, a large event, of perhaps 80 dB (fiber fracture), will travel a much greater distance, and several sensors would be affected. An operator noting several simultaneously active sensors could assume that a large event had occurred in the center of the group. To further simplify the location of large events an electronic gate can be used. The gate allows only the first sensor hit to record the event. The philosophy of locating events in this manner is known as zone location.

B. Procedure

The acoustic emission system used to monitor the rotor blade proof loads is illustrated in Figure 8. It is an 8-channel, mixer-based, noncomputerized unit manufactured by Dunegan/Endevco Corporation. The system accepts signals into eight independent

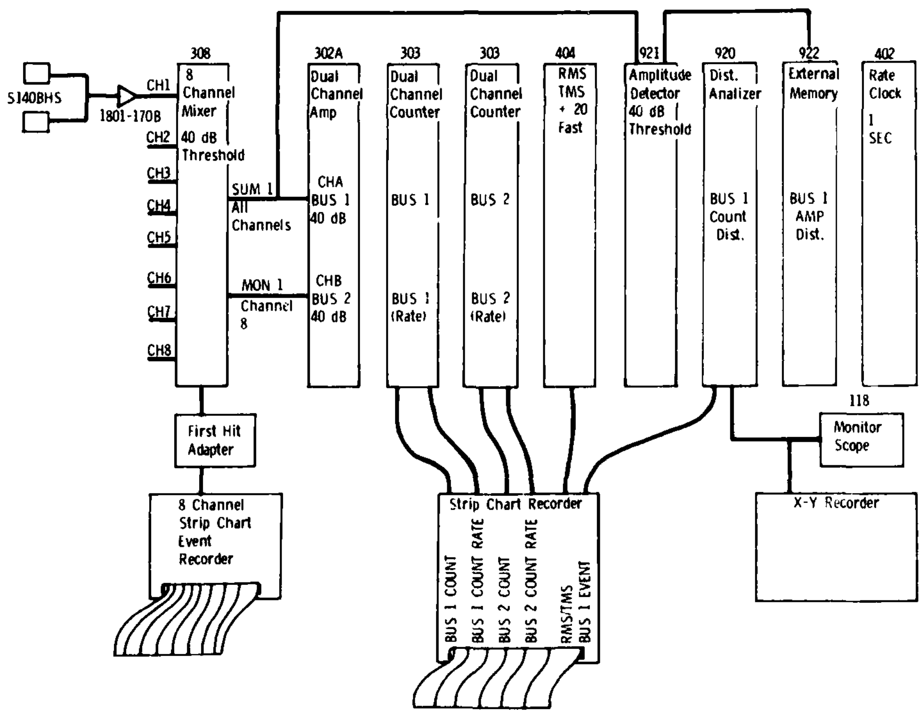

Figure 8 MODULAR DIAGRAM OF ACOUSTIC EMISSION APPARATUS

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channels. Each channel consists of two sensors teed into one pre-amplifier. Four output devices are utilized: an 8-channel event recorder indicating which sensors are closest to the source, a 6-pen strip chart recorder indicating count, event and rms data, a real-time monitor oscilloscope displaying count and amplitude distributions, and an X-Y recorder to plot the count and amplitude distributions. The equipment is shown in Figure 9.

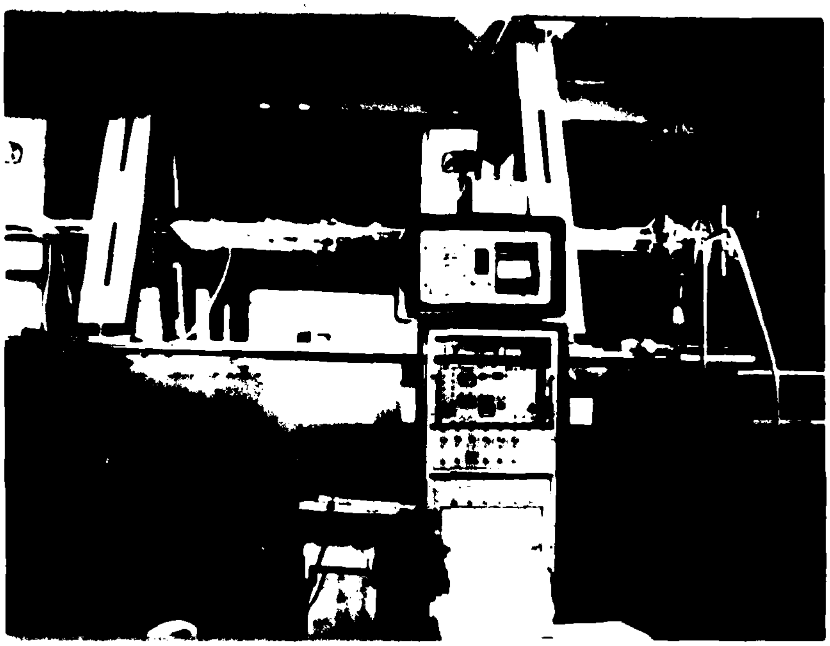

Figure 9. ACOUSTIC EMISSION EQUIPMENT

Dunegan/Endevco S140B/HS (S9204) transducers were selected for this test because of their high sensitivity and good frequency response at 100 to 120 kHz. Prior to attaching the transducer, the blade was lightly sanded and cleaned with acetone. The transducers were then mounted on the blade with silicone rubber adhesive (GE RTV 102). Figure 10 shows the spanwise transducer location and spacing (approximately 14.5 inches apart). The chordwise transducer location is at the junction between cells A and B as shown in Figure 1. This spacing will pick up a 60 dB event at a distance of 8 inches, and an 80 dB event at a distance of 22 inches (see Figure 7). The operation of each sensor is checked at the beginning of each test with a hand-held pulser.

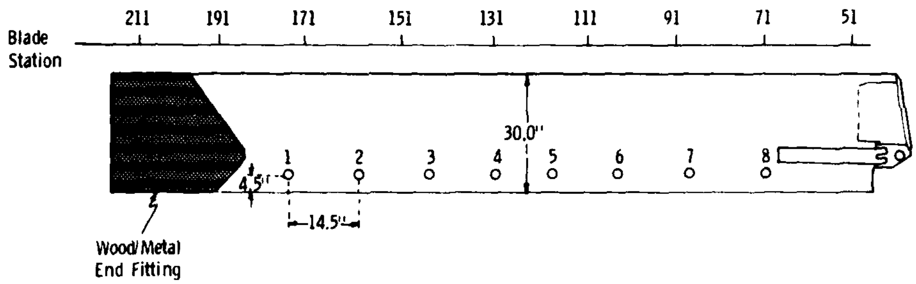

Figure 10. AE TRANSDUCER LOCATION

The blade is proof tested in increments to a load approximately 10 percent higher than the load achieved during spectrum loading. The blade is proofed separately in each loading mode in the following order:

a. Flapwise bending
b. Chordwise bending
c. Cf (tension)
d. Torsion
   minimum Cf
   varying Cf

C. Results and Discussion

The acoustic emission tests have been only partially completed, but some of the preliminary results are presented here. The initial (prior to spectrum loading) proof loads resulted in negligible acoustic emission in bending (chordwise and flapwise) and torsion, but a large activity in the Cf loading. During the Cf loading, 21,273 counts and 1481 events were accumulated, with amplitudes primarily in the 40 to 70 dB range. The second proof load, applied at approximately 10 million cycles, again resulted in very little emission in all modes except the Cf loads. The Cf load resulted in emission from sensor pairs 5 and 8. A total of 752 counts and 144 events were measured, and the amplitudes ranged from 40 to 60 db. The AE was primarily coming from the area of sensor pair 5 (station 115) with sensor pair 8 (root end) one quarter as active. Figure 11 shows the data points obtained, as well as the projected AE results based on the periodic overload technique. As fatigue damage occurs, the ultimate strength of

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the composite structures will decrease. When this value decreases to approximately twice the proof stress, an upswing in the event curve is anticipated.

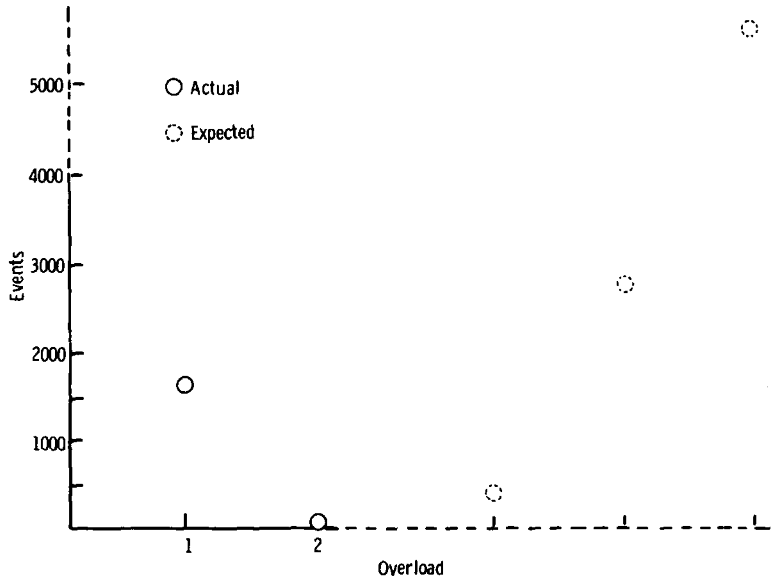

Figure 11. DETECTED EVENTS PER OVERLOAD

The acoustic emission results have been as expected--an initially "noisy" proof load, and a second, much quieter, proof load. The amplitudes resulting from both tests were in the range expected from matrix crazing and delamination. There is also the possibility that some of the emission is due to rubbing of surfaces in the delaminated areas. Upon examination of the pulse-echo ultrasonic results, it was seen that the area near sensor pair 5 was the site of a large delamination. This indicates that the instrumentation could be picking up some growth in the delaminated area. Pulse-echo ultrasonic examination subsequent to the second proof test (10 million cycles) showed no measurable change in void dimensions, leading to the conclusion that the AE resulted from either very small void growth or rubbing of the void surfaces or a combination of the two. However, the amplitudes of the emissions were low enough to conclude that no significant damage occurred during either the fatigue loading or the proof tests.

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IV. OTHER NDE TECHNIQUES

A. Thermography

There is preliminary evidence that "trouble spots" can be located during cyclic testing by a nondestructive technique called vibrothermography, originated in 1974 by Reifsnider (10), et al. Vibrothermography uses a real-time heat imaging device such as a video-thermographic camera to observe the heat patterns generated by hysteresis dissipation during cyclic excitation of the specimen under test. The heat patterns generated in this way are directly related through their intensity and distribution to the mechanical response of the test piece and to the collective effect of any and all defects which disrupt the integrity of the material and thereby disrupt the internal distributions of stress. Figure 12 shows such a heat pattern which was observed during spectral loading of the subject rotor blade after about 4.7 million cycles. The image of the blade extends from the bottom left to the top right of the figure; other details in the figure are background images. Just to the lower left of center in the figure

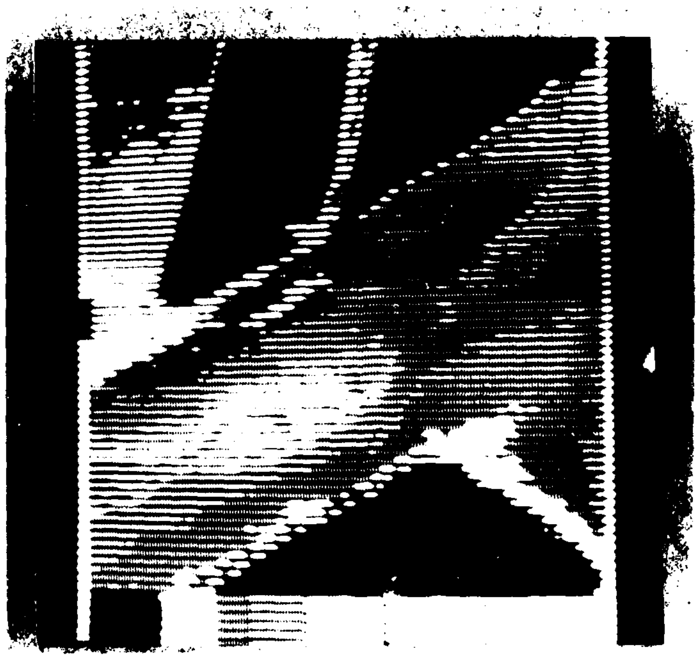

Figure 12. HEAT PATTERN GENERATED DURING FATIGUE TEST

there is a distinct contour pattern which was formed by different shades of color in the display of the thermographic camera. Each of these is an isotherm separated by $0.5^{\circ}C$. Another contour pattern, somewhat less distinct, is visible in the top right corner of the figure. These two "hot spots" showed an elevation of from 2 to $2.5^{\circ}C$ in temperature compared to the remainder of the blade which was essentially uniform in temperature. The pattern was distinct, unchanged in pattern when observed from day to day, and reproducible in the sense that when cyclic loading ceased, it faded out slowly but reappeared upon the resumption of cyclic excitation. These indications are very promising, and they support earlier findings which suggest that vibrothermography may be an excellent quantitative method for locating, characterizing, and understanding defect development and growth during the cyclic loading of composite laminates and structuies (11).

B. Ultrasonic Inspection

A pulse-echo ultrasonic technique to monitor defect growth during the test was developed and is being used throughout the program. The initial test, which covered the entire spar, nose cap, and trailing edge surfaces, was found to be in good agreement with the original C-scan results. Nine specific areas are being monitored by the periodic tests. A complete pulse-echo ultrasonic test, similar to the one run prior to the initiation of the fatigue test program was run at 10 million cycles. There was no measureable change in the flaw size during any of these ultrasonic tests. This is in agreement with the other results, which indicate very little fatigue damage to the blade.

C. X-Radiography and Borescope Inspection

The test blade was X-rayed prior to the start of the fatigue test. Initial radiographic analysis of the nose cap showed random minor separation in the unidirectional fibers. The blade trailing edge radiographs showed areas of varying density which have been attributed to resin content variations.

The internal condition of individual spar tubes is monitored by using a borescope. Initial inspection detected damage in the middle spar tube between stations 150 and 165. The damage, which was probably caused by withdrawal of the mandrel, extended from the tube floor forward to the wall and continued to the tube ceiling. Photographs were taken of the area to document this condition and provide data for reference purposes. Inspection of the spar tubes after 10 million cycles showed some additional tearing away of the loose fibers with some now extending to the aft wall of the tube.

V. SUMMARY

This paper has been a presentation of progress made in a continuing project to evaluate the usefulness of several NDE techniques for monitoring flaw initiation and growth in composite helicopter rotor blades.

The acoustic emission results indicate minor fatigue damage, and lead us to believe that it is possible to project an AE failure curve based on the emissions from periodic proof overloads. The vibrothermography results suggest that it may be an excellent method for locating, characterizing, and understanding defect development and growth during cyclic loading of composite structures. Preliminary indications suggest that these two novel and complementary NDE techniques can be used to determine problem areas, and these areas can be further investigated using conventional NDE techniques.

The AE technique could have wide application in new product certification and in-service inspection of composite rotor blades. The blades could actually be proof loaded while in the field, and the acoustic emission results would give an accurate estimate of the remaining service life. This technique could be adapted to determine the structural integrity of many composite structures.

ACKNOWLEDGMENTS

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