APPLICATION OF A SELF-CALIBRATING ULTRASONIC TECHNIQUE TO THE
DETECTION OF FATIGUE CRACKS BY THE USE OF LAMB WAVES

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INTRODUCTION

The reliability of fatigue-crack detection plays an important role in the safety of aircraft structures. Improvements in this reliability can be achieved by making the inspection technique independent of the coupling of the sensor to the specimen. A self-calibrating technique previously developed by the authors [1] makes it possible to detect and quantitatively characterize defects in aircraft structures with greater reliability.

The detection of fatigue cracks emanating from rivet holes in aircraft skin requires an optimum spatial distribution of the applied ultrasonic signal. Selection of an appropriate mode of Lamb wave propagation can greatly improve the sensitivity and resolution of the testing system and makes it possible to detect cracks in different layers of a rivet joint.

In this paper the self-calibrating technique is applied to the detection of fatigue cracks in aircraft structures. Experimental results have been obtained for Lamb wave interference with fatigue cracks and EDM notches around rivet holes in different layers of a lap joint. The self-calibrating technique has also been tested on a bolted joint for crack detection in the second (bottom) layer. Discrete macrocracks simulated by EDM notches have been characterized in the second layer of a specimen that modeled a spar-cap/strap connection in the tail section of the DC-10.

MEASUREMENT OF \|R/T\| FOR CRACK CHARACTERIZATION

In principle, the crack size can be determined by an accurate measurement of either or both the reflection, R, and transmission, T, coefficients for an ultrasonic signal propagating across the area with the crack. Then the results have to be compared with theoretical results for R and/or T as functions of crack size or with measurements on specimen with flaws of known sizes.

Unfortunately, reflection and transmission coefficients are difficult to measure correctly, primarily because the coupling between the transducers and the specimen is unpredictable and very difficult to reproduce from one measurement to another. Since it is time consuming to calibrate the complete set-up for each measurement, a configuration of

transducers suitable for a self-calibrating measurement technique has been proposed by the authors [1]. This configuration of two transmitting-receiving transducers is shown in Fig. 1.

![Fig. 1. Transducer configuration for the measurement of |R/T|.](image)

Suppose transducer 1, placed normal to the crack direction, is fired first. Transducer 2, placed on the other side of the crack normal to its direction, receives the transmitted signal with voltage

\[ V_{12} = A_1 \cdot D_{10} \cdot T_c \cdot D_{02} \cdot S_2 \]  

where

- \( A_1 \) = response function of transducer 1, including the transmission from the transducer to the specimen,
- \( D_{10} \) = response function for transmission over the distance from 1 to 0, including attenuation and diffraction,
- \( T_c \) = transmission coefficient of the crack,
- \( S_2 \) = response function of transducer 2, including transmission from the specimen to the transducer,
- and \( D_{02} \) is defined analogously to \( D_{10} \).

Transducer 1 receives the reflected signal with voltage

\[ V_{11} = A_1 \cdot D_{10} \cdot R_c \cdot D_{01} \cdot S_1 \]  

where

- \( R_c \) = reflection coefficient of the crack,
- \( D_{01} \) = response function for transmission along the distance from 0 to 1 and \( S_1 \) is defined analogously to \( S_2 \).

Similar expressions are obtained when transducer 2 is fired. We have

\[ V_{21} = A_2 \cdot D_{20} \cdot T_c \cdot D_{01} \cdot S_1 \]  
\[ V_{22} = A_2 \cdot D_{20} \cdot R_c \cdot D_{02} \cdot S_2 \]

where \( A_2 \) and \( D_{20} \) are defined analogously to \( A_1 \) and \( D_{10} \), respectively.

Next we consider the ratio \( V_{11} \cdot V_{22}/V_{12} \cdot V_{21} \). It then easily follows that

\[ \frac{|R_c|}{|T_c|} = \left( \frac{V_{11} \cdot V_{22}}{V_{12} \cdot V_{21}} \right)^{1/2} \]
Thus, the ratio of $|R_c|$ and $|T_c|$ is obtained in terms of four measured voltages. Because no information about signal strength, coupling, distance or surface condition is required, the result given by Eq. (5) is self-calibrating.

EXPERIMENTAL CONFIGURATION

A schematic of the apparatus used in this experiment is shown in Fig. 2. A HP 3325B Function Generator produces a continuous sine wave signal in the frequency range from 1.5 to 6.5 MHz. This signal is applied to the Metrotek MG701 Gate which produces a tone-burst of the desired number of cycles with peak-to-peak voltage from 0.1 to 0.25 volts. The tone-burst is then amplified by a 50 dB power amplifier (ENI Radio Frequency 325LA) to a 30 to 75 volts peak-to-peak voltage. The amplified tone-burst is subsequently applied to an ultrasonic transducer. The transducer sends an ultrasonic signal towards the crack. The signal received by the receiving transducer is amplified by a 5662 Panametrics Preamp. The output signal is then digitized by an Oscilloscope (Tek 2465B) and the data is acquired by a personal computer.

To maintain exactly the same conditions of electrical signal generation and amplification, the two transducers are connected parallel. Since the measured voltage amplitudes for the transmitted signals, $V_{12}$ and $V_{21}$, are overlapping, the signals used in equation (5) are taken as half the total measured amplitude. To prevent overlap of the signals $V_{11}$ and $V_{22}$ the transducers should be installed at different distances from the crack.

RIVET JOINT WITH RADIAL EDGE CRACKS: TOP LAYER

The self-calibrating technique has first been applied to the quantitative characterization of radial edge cracks emanating from a rivet hole. Rivet holes were drilled in two aluminum 2024-T351 plates, each 1 mm thick, and radial EDM notches were cut on opposite sides of the hole in the top plate. The two plates were then joined with a countersunk rivet. The specimen is shown in Fig. 3. Three specimens with EDM notches of sizes 0.5 mm; 1.5 mm; and 3.3 mm were prepared. The technique has also been tested on...
aircraft panels with fatigue cracks of sizes 1.5mm; 2.75mm; and 4.4mm provided by the FAA Technical Center (Atlantic City).

Two ultrasonic transducers (Harisonic ABM 0504, 5Mhz) were used in conjunction with variable angle beam wedges (VABM-W04) for the selection of an appropriate mode of Lamb wave propagation. The angle for the highest sensitivity of the ultrasonic system was found to be about 58 degrees. The transducers were placed on the specimen at different positions with respect to the rivet hole. Fig. 4 shows waveforms acquired for ultrasonic wave propagation across the area with and without a flaw. Considerable variation of the amplitudes of reflected signals can be noted for the detection of the crack from opposite sides of the rivet hole. These signal variations were caused by different coupling of the transducers to the specimen surface. Signal amplitudes have been measured for Lamb wave propagation across the cracks and EDM notches, and $|R/T|$ ratios were calculated and plotted versus flaw lengths (Fig. 5). It can be seen from Fig. 5 that changes in the values of $|R/T|$ are consistent with the flaw length in contrast to the amplitudes of the reflected signals which are plotted for comparison.

SEALED RIVET JOINT WITH RADIAL EDGE CRACKS

The same ultrasonic transducers and wedges were also used for the detection of cracks in both layers of a rivet joint. The transducers were placed on a specimen with EDM notches 3.3mm long in the top and bottom layers, and with a 0.1mm thick layer of a silicon rubber sealant in between the 1mm thick aluminum 2024-T351 layers (Fig. 6). The angles of incidence as well as the frequency of generation of ultrasonic waves were adjusted to select a specific mode of Lamb wave propagation. Fig. 7 shows amplitudes of the signals reflected from the EDM notches at different angles and frequencies. As shown, an appropriate selection of the mode of Lamb waves makes it possible to distinguish cracks in the different layers.
Fig. 4. Waveforms for the detection of radial EDM notches emanating from a rivet hole.
Fig. 5. Characterization of fatigue cracks and EDM notches.

Fig. 6. Crack detection in a sealed rivet joint.

Fig. 7. Crack detection in the different layers of sealed rivet joint.
CRACK CHARACTERIZATION IN A DC-10 SPAR-CAP/STRAP CONNECTION

The self-calibrating technique has been tested to detect and characterize cracks in the form of EDM notches in a specimen that models a DC-10 tail connection. This specimen has been developed at Northwestern University in accordance with McDonnell Douglas CO. specifications for NDI of such structures. The specimen consists of a lower aluminum plate with four triangular EDM notches (0.05"x0.086"; 0.1"x0.173"; 0.15"x0.259"; and 0.2"x0.346") emanating from the bolt hole on the top and at the bottom of the plate. An upper aluminum plate and the lower plate have a 0.1mm layer of silicon rubber sealant in between and are connected with bolts. The ultrasonic transducers with variable angle beam wedges have been placed on the surface of the upper plate on opposite sides of the bolt (Fig. 8). First, the angles of incidence were selected for optimum detection of the EDM notches. A schematic of ultrasonic signal propagation is shown in Fig.9. Then the amplitudes of the reflected and the transmitted signals were measured and calculated values of $|R/T|$ were plotted versus the lengths of the EDM notches (Fig. 10). A curve for calculated areas of the EDM notches is also shown on the same plot for comparison.

![Fig. 8. Transducer configuration on DC-10 specimen.](image)

![Fig. 9. Schematic of ultrasonic wave propagation in the bolted-joint specimen.](image)
CONCLUSION

The sensitivity and resolution for the detection of cracks in rivet joints have been improved by using experimentally selected modes of Lamb wave propagation in the top and the bottom layer of the joint. Application of the self-calibrating technique made it possible to extend the method beyond the stage of crack detection towards crack characterization.

A method for the inspection of a bolted DC-10 spar-cap/strap connection using shear wave generation from the top layer of a sealed structure has been suggested. The self-calibrating technique has been successfully tested on a specimen that models the bolted joint.

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