CHARACTERIZATION OF CRACKS IN THICK PLATES BY LAMB WAVE DIFFRACTION STUDIES

Josef Paffenholz and Ivan C. Getting

Cooperative Institute for Research in Enviromental Sciences (CIRES)
Campus Box 449
University of Colorado
Boulder, CO 80309

Hartmut A. Spetzler

Cooperative Institute for Research in Enviromental Sciences (CIRES)
Campus Box 449
Geological Science Department
Campus Box 250
University of Colorado
Boulder, CO 80309

INTRODUCTION

The object of the work is a combined theroretical and experimental study of diffraction of Lamb waves by two- and three-dimensional cracks in a plate. An important motivation for this project is the desire to develop a technique capable of detecting and characterizing cracks in weldments in plates. We want to analyze the dependence of the scattered signals on the dimension, angle of inclination and depth of burial of the crack. The basic measurement techniques requires the accurate determination of minute normal surface displacements at ultrasonic frequencies. Such measurements have recently been made possible by the development in our laboratory of a new surface displacement capacitive tranducer [1]. The measured displacements will be compared with the theoretical predictions.

EXPERIMENT

Configuration

The first generation of measurements is being made on a 2 dimensional model. The specimen is a glass piece of 6.35 mm thickness, 25.4 mm height, and 2286 mm length. The signal in the specimen is generated by a steeel ball bearing with a diameter of 1.59 mm diameter being dropped from a height of 165 mm onto the smallest dimension edge of the specimen. Normal displacements are measured along the impacted surface of the specimen at various locations. For these idealized tests the specimen is mechanically decoupled from its supports and from the receiver transducer housing. This provides isolation from floor vibrations and prevents loss of the signal into the support structure.

Aluminium-coated coverslides of 0.18 mm thickness are glued on the plate to provide electrically conductive and smooth surfaces required by our capacitive transducer.
The receiver output is recorded on a 20 MHz digital oscilloscope with pretriggering capability and can be transferred to a computer for analysis.

Capacitive Transducer

The principle of our capacitance transducer is simple. The grounded conducting sample surface constitutes one electrode of a capacitor and the capacitance probe the other. A surface displacement changes the gap between the sample and the capacitance probe. The resulting change in capacitance constitutes the signal. A detailed description of the instrument is given in [1].

There are several advantages of the capacitive transducer compared with the registration of ultrasonic waves via piezoelectric transducers:

1.) The transducer is noncontacting and does not interfere with the displacements of the free surface of the sample.

2.) This eliminates problems with the reproducibility of the transducer-sample contact as found with piezoelectric transducers.

3.) Because the transducer has no mechanical resonances and the detection circuits are suitably broad-band the response function is flat over a wide frequency range.

4.) Due to the small probe diameter of 0.3 mm the transducer acts as a true point receiver over the entire frequency spectrum of interest. Thus problems with incoherent arrival of energy, which occur with larger sensing areas are avoided. In it's present configuration, it measures only that component of the surface displacement that is perpendicular to the surface.

5.) The transducer lends itself well to absolute calibration by virtue of its being a noncontacting, point receiver with flat response.

The absolute calibration of this instrument has been determined by laser interferometric methods over the frequency range from 20 kHz to 1MHz. The resolution is 10^{-11} m, the sensitivity is 160 mV/nm. The response function is flat to +/- 3 dB.

Results

First results for the crack free plate are shown in Fig. 1. Two traces were noisy and therefore ommitted. Different phases which characterize the onset of different plate modes are recognizable as well as the reflections from the left and right edge of the sample.
With the experience gained from this simple case, we will proceed with the introduction of cracks.

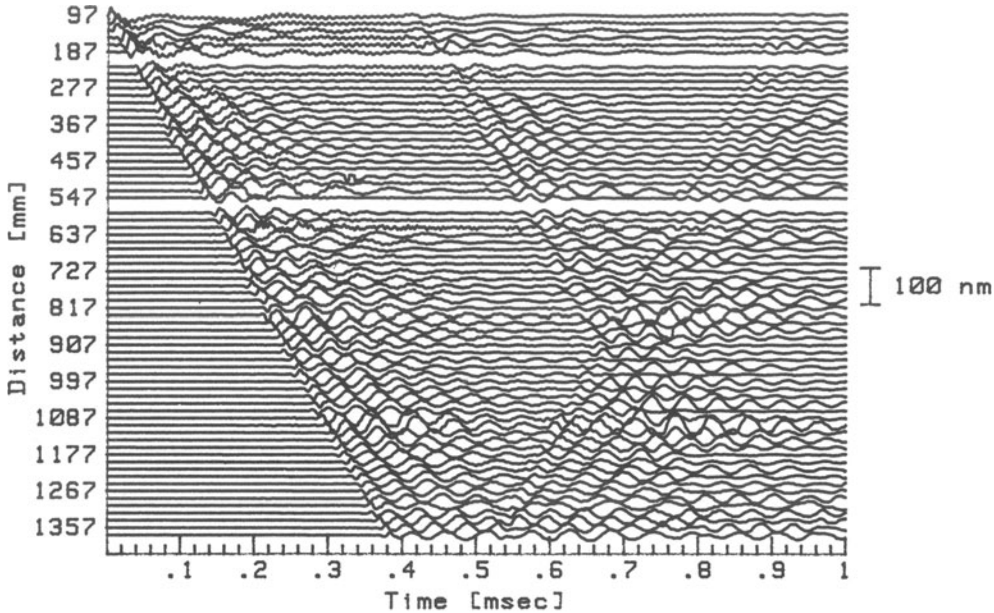

Fig. 1. Normal surface displacements as a function of time measured at various distances from the source. The complexity of the signals increases with increasing distance from the source due to onset of different plate modes. The velocity calculated from the arrival times is 3.38 mm/ μ sec.

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THE USE OF ULTRASONIC HARMONIC GENERATION TO DETERMINE CRACK OPENING CONDITIONS IN COMPACT TENSION SPECIMENS

William T. Yost, Min Namkung, and S.G.Allison

NASA-Langley Research Center
Mail Stop 231
Hampton, VA 23665-5225

INTRODUCTION

In 1971, Elber reported the discovery of a crack closure phenomenon that occurs with fatigue. He noted that closure of the crack planes near the crack tip can occur while the applied stress is still tensile [1]. The existence of a closure stress opens the way of defining an effective stress intensity factor, K_{eff}, given by

$$K_{eff} = (\sigma - \sigma_{closure})(\pi a)^{1/2}$$

where σ is the applied tensile stress, $\sigma_{closure}$ is the crack closure stress, and a is the crack half length. The stress intensity factor is useful in correlating fatigue crack propagation data, especially after overloads [2]. The precision of K_{eff} depends upon how well one can determine $\sigma_{closure}$. However it is difficult to experimentally determine $\sigma_{closure}$, since conventional crack opening determination is imprecise. The purpose of this paper is to present an ultrasonic technique that shows promise as a means to accurately determine when the crack is open.

SOME OF THE PRESENT TECHNIQUES TO MEASURE CRACK OPENING LOAD

The compact tension specimen is shown schematically in Fig. 1. It is loaded using clevis grips placed in a load frame. An extensometer is placed across the mouth of the specimen. Tension is applied cyclically between a maximum and a minimum value. As this is done, the crack initiates at the notch, and propagates into the specimen. The crack growth rate depends upon the parameters established for the loading cycle, the material properties of the specimen, and environmental factors as well as test sample geometry.

As a cycle of specimen loading begins, the applied load is measured with a load cell. The displacement across the mouth is measured with the extensometer. One can, in theory, plot the load vs. displacement, and determine the crack opening load by determining the point where the load vs displacement takes on a constant slope for the higher value loads. However, such a plot is not very sensitive to crack opening vs load, so other data analysis techniques are preferred. We will briefly present two of these, which are currently in use. (The authors are indebted to Dr. J. Newman and E. Phillips of NASA-Langley Research Center for their helpful discussions about these techniques). In both of the techniques presented here, one first loads the specimen to maximum and then decreases the load. During the part of the cycle where the load is decreased from maximum, one determines a straight line fit from the values measured while unloading from maximum. We call this the "upper data".

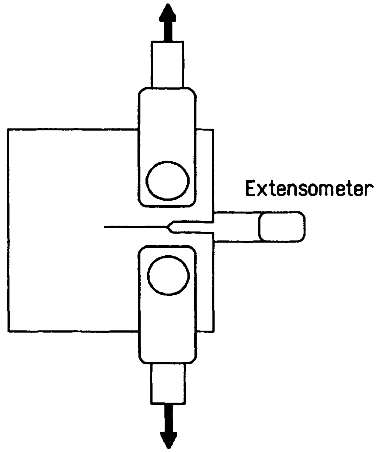

Fig. 1 Compact Tension Specimen

The "Load-Reduced Displacement" method for data analysis is shown in Fig. 2. One defines "reduced displacement as the difference between the straight line fit of the upper data and the measured displacement. This is shown in Fig. 2a. Next, one plots the load vs the reduced displacement, which is shown in Fig. 2b. The crack opening load is determined as the point where the curve goes vertical, as marked with the arrow.

The "Load-Slope Change" method for data analysis is shown in Fig. 3. In this method, one determines a series of slopes during the unloading portion of the cycle, as shown in Fig. 3a. By plotting Load vs. slope increase (the difference between the reference slope measured at the top, and the slopes along the rest of the curve) as in Fig. 3b , one can determine the crack opening load by marking the load where the slope increase first deviates from zero. This is marked with an arrow.

We illustrate the "Load-Slope Change" method with measurements that we took on a compact tension specimen used in this study. The specimen is machined from Al 2219-T851 material. The maximum and minimum loads are 4000 lbs and 400 lbs. Fig. 4 is a plot of the Load vs Slope Increase data. One can observe that the data clearly exhibit the effects of noise in the measurement system. It is difficult to precisely determine where the load-slope increase plot is tangent to the vertical axis. The problem of noise causes substantial uncertainty in the determination of the crack opening load.

USING HARMONIC GENERATION TO DETERMINE CRACK OPENING

The use of ultrasonic harmonic generation to measure lattice anharmonicity is well documented in the literature [3,4,5]. Also, Hikata and Elbaum have studied the effects of dislocation motion on harmonic generation [6,7]. Buck et. al. [8] have used harmonic generation by surface waves to look at fatigue states in aluminum. Richardson [9] has described the generation of harmonics at the interface of unbonded surfaces. While all effects mentioned above apply to this problem, we use the fact that as a crack in a compact tension specimen is opened, harmonics are generated at the (unbonded) surfaces of the crack interface.

The equipment diagram sketch is shown in Fig. 5. A 5 Mhz tone burst is generated by the function generator (a Hewlett-Packard #3314A), is power-boosted by an amplifier (an ENI A-150), and is converted into an acoustic wave by the 5 MHz undamped transducer (a lithium niobate compressional transducer). After the wave traverses the sample, it is received by the 10 MHz transducer (a lithium niobate 10 MHz undamped compressional transducer), where the ultrasonic wave is converted into an electrical signal. The output signal is amplified and detected by a receiver (ICOM IC-R71A). A 40 dB attenuator is placed in the path when receiving the fundamental signal. The receiver is tuned to the appropriate frequency, and its detected output is measured with an oscilloscope (Tektronix 2445), which is triggered from the function generator and delayed to compensate for the traversal time of the ultrasonic signal through the sample.

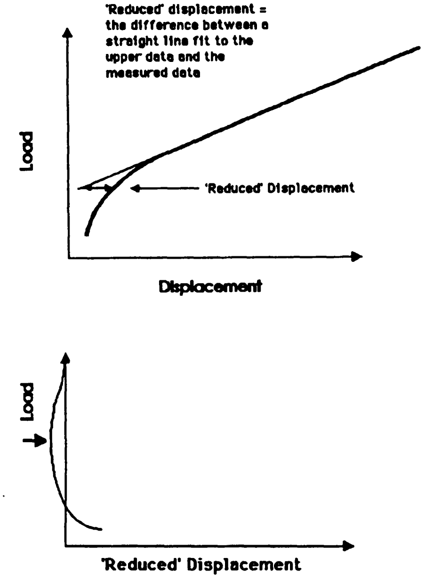

Fig 2. Load-Reduced Displacement Method to Determine Crack Opening Load

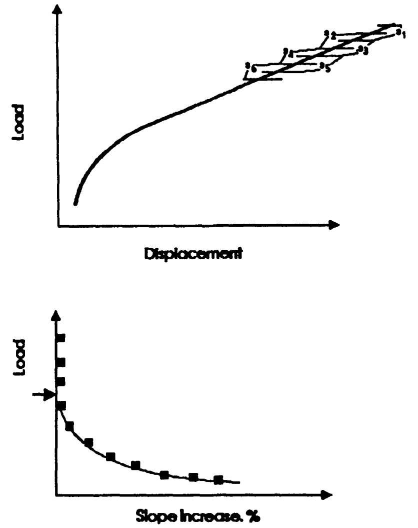

Fig. 3. Load-Slope Change Method to Determine Crack Opening Load

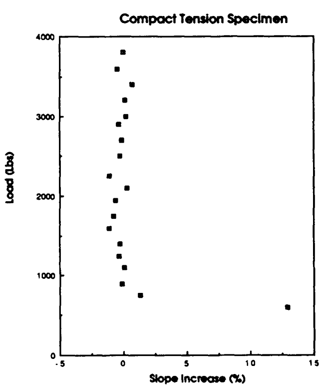

Fig.4 Load Vs. Slope Increase

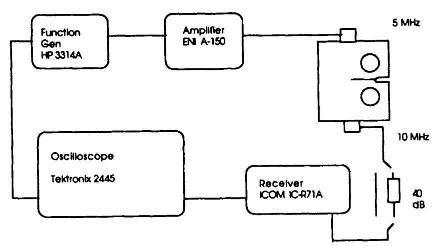

Fig. 5 Equipment Diagram

Using the above arrangement, we measured both fundamental and the harmonic output from the 10 MHz transducer in a specimen of AL 2219-T851 (1 in thick by 7.5 in. length x 7.19 in. high) that had been previously cracked. The measurement sets were taken as follows: (1) near one end of the sample in a region away from the crack to determine the response of the measurement system and the material; (2) over the cracked region to determine the characteristics of ultrasound propagation across the crack; and (3) over the cracked region during the loading cycle to determine any difference in harmonic generation content during the loading cycle. Before the measurements under load were taken, we cyclically loaded the specimen from 400 to 4000 lbs in tension, until the crack propagated an additional 0.275 in. to a total crack length of 2.9 in. The transducers (5 MHz and 10 MHz) were mounted in aluminum housings, and placed on the compact tension specimen and axially aligned, as shown in Fig. 6. For (2) and (3) the axial line of the transducer pair approximately intersected the crack tip.

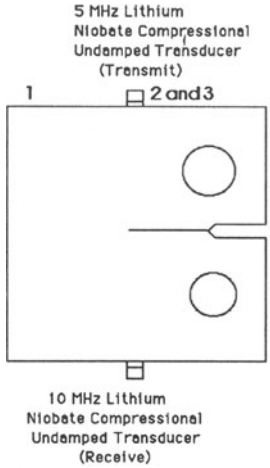

Fig. 6 Transducer Placements

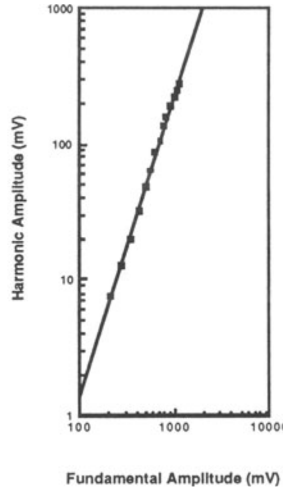

Fig. 7 Harmonic Amplitude Vs Fundamental Amplitude

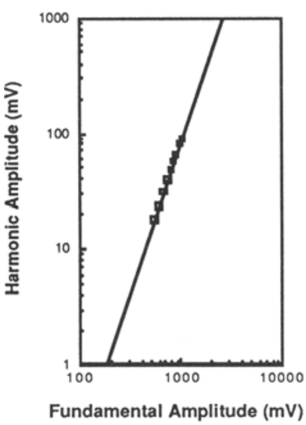

Fig. 8 Harmonic Amplitude Vs Fundamental Amplitude

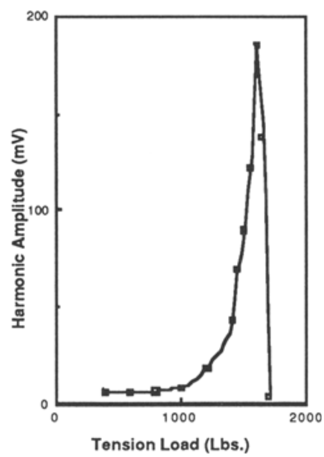

Fig. 9 Harmonic Amplitude Vs Load

Fig. 7 is a log plot of harmonic amplitude vs fundamental amplitude where the wave is propagated through material far from the crack. Fig. 8 is a log plot of harmonic amplitude vs fundamental amplitude when the ultrasonic wave is propagated across the crack without any load applied. In comparison of the two graphs, we notice that the slopes are slightly different, and that the harmonic output is diminished in the case of propagation through the crack. The increase in slope for the propagation through the crack can be explained by the fact that some additional harmonic generation could occur at the crack (most probably around the asperities).

The specimen was placed under load. The harmonic output from the receive transducer was measured and plotted as a function of load. The received fundamental amplitude was held constant during the measurements. The results are shown in Fig. 9. We notice that the maximum harmonic output occurs at a load of 1550 lbs, and abruptly drops to its premaximum level at a load of 1600 lbs. This value is in agreement with theoretical calculations using finite element analysis.

CONCLUSIONS

It appears that ultrasonic harmonic generation can be a useful tool in the monitoring of crack opening dynamics in compact tension specimens. The value obtained in this case was in agreement with the value predicted by theory. Moreover, this technique seems to be immune to the noise problems that plague other techniques.

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