ABSTRACT. A spatially sparse array of conventional piezoelectric transducers is attached to a part surface to monitor its structural health. Artificial flaws are incrementally added to simulate damage progression. The structure is flooded with ultrasonic energy by transmitting on a single transducer, and waveforms are recorded from other transducers in the array. Simple waveform differencing techniques between pre-flaw baseline waveforms and post-flaw waveforms show promise for determining the state of damage progression in both concrete and aluminum samples.

INTRODUCTION

Structural health monitoring (SHM) is a field of growing importance. The goal of SHM is to detect defects that may be detrimental to the performance of a structure or lead to its failure while the structural assembly is still in service [1]. Most structural defects may be detected, located, and sized using conventional ultrasonic nondestructive evaluation (NDE) methods on individual structural components during manufacturing. However, these methods are often very difficult to apply to final assemblies.

In recent years there has been a preponderance of research activities in the area of ultrasonic guided waves for SHM and routine NDE of structures, but only a few successful commercial applications of the technology [2,3]. One factor limiting broader use of this method is that some knowledge of wave modes for the structure is required, either via a closed form solution or by numerical methods. This information is used to both design the inspection system and to interpret the inspection results [4,5]. Generally, the theory for wave propagation in shells and plates is well known, but difficult to apply to complicated structural shapes. For real world structures with variable boundary conditions, computation of the wave field from various stimuli is not practical.

This paper offers an alternative approach that can be applied to any structure. An array of piezoelectric transducers is attached to or embedded in a structure, where each transducer can be either a transmitter or a receiver of ultrasonic energy. The action of pulsing on one transducer "floods" the structure with ultrasonic energy, and responses are recorded from all other transducers in the array. Waveforms sets are compared from pre-flaw and post-flaw test conditions, and simple differencing methods are shown to be effective for tracking damage progression.
EXPERIMENTAL STUDY

For this study the technique is applied to two specimens, one of cast concrete and the other an aluminum "I" beam. The concrete specimen is expected to have a much stronger diffuse field component than the aluminum specimen, as the wave field in will be strongly scattered from the aggregates in the concrete. The aluminum specimen is expected to have a much stronger guided wave field due to the "I" geometry of the specimen. An array of three transducers is shown attached to the concrete sample in Figure 1, and the aluminum "I" beam specimen in Figure 2.

Transducers were constructed using longitudinally polarized, 2.25 MHz PZT disks, 12.5 mm diameter, and were attached to the samples using cyanoacrylate adhesive. A conventional ultrasonic pulser receiver was used for transducer excitation and waveform amplification. Waveforms were digitized with a sampling rate of 50 MHz at a resolution of 8 bits, and averaged over 50 waveforms.

FIGURE 1. Concrete block, 250mm x 63mm x 63mm. FIGURE 2. Aluminum "I" beam, 1.8 meters long.

FIGURE 3. Comparison of time - frequency spectrograms for aluminum and concrete specimens.
Typical spectrograms are shown in Figure 3 for both specimens studied. Note the higher frequency components clearly visible on the spectrogram from the aluminum specimen. For times later than 1000 microseconds, all frequency components above 0.3 MHz are filtered out by the concrete specimen, whereas the aluminum specimen still has a substantial amount of energy as high as 1 MHz.

Flaws placed in the specimens consisted of progressively enlarged holes and notches. Differencing analysis routines were applied to pre-flaw and post-flaw waveforms using steps depicted in Figure 4. First, waveforms are simply subtracted to obtain a "difference" waveform. Next, the square of this differenced waveform is computed numerically. Lastly, the voltage squared waveform is integrated to obtain an accumulated energy distribution over the recorded time interval. These energy accumulation curves are compared for various flaw conditions. The baseline condition consists of three waveforms recorded before a new flaw series was placed in a specimen; i.e. transmit on 1 and receive on 2, transmit on 2 and receive on 3, and transmit on 2 and receive on 3. Any other transmit receive combinations are redundant for an array of three transducers due to reciprocity.

**Concrete Specimen Results**

Waveforms were recorded for three test conditions for the concrete specimen: (a) baseline prior to drilling hole, (b) after drilling a 10 mm diameter x 20 mm depth hole, and (c) after enlarging the hole depth to 40 mm. The location of the hole is visible in Figure 1 near the lower right corner of the block.

Waveforms for transmit on 1 and receive on 2 are compared in Figure 5 for this baseline and these two flaw conditions. Cursory examination shows the differences between these three waveforms are very slight. Before 400 microseconds it is difficult to see any difference in the waveforms, and past this time only minor differences are visible.

![FIGURE 4.](image_url) Analysis method used to compute differences between pre-flaw and post-flaw recorded waveforms; (a) typical differenced waveform, (b) square of differenced waveform, and (c) waveform integrated to show accumulated energy.
FIGURE 5. Baseline and post-flaw waveforms for concrete specimen for transmitting on transducer 1 and receiving on transducer 2; (a) baseline waveform, (b) waveform recorded after drilling 10mm diameter by 20mm deep hole, and (c) waveform recorded after enlarging hole depth to 40mm.

Accumulated energy curves are shown in Figures 6 and 7 for the concrete specimen. The 50% energy accumulation point is not reached until about 500 microseconds, and the differenced waveforms continue to accumulate energy until about 2500 microseconds. For reference, a travel time of 2500 microseconds corresponds to S wave and L wave travel distances in concrete of about 6 meters and 10 meters, respectively. Since the block length is 250 mm, the wave field is active for approximately 24 to 40 block path lengths. This suggests that the major contribution to the wave field is the various wave modes "bouncing" around in the specimen.

FIGURE 6. Accumulated energy curves from concrete specimen for two 10mm diameter hole depths: 20mm and 40mm. These plots show the early time record from 0 to 500 microseconds for (a) transmit on 1 and receive on 2, (b) transmit on 1 and receive on 3, and (c) transmit on 2 and receive on 3.
First arrival of energy on the differenced waveforms gives an approximate distance from the transducers to the hole (Figure 6). Even though the exact wave mode is not known because of the complicated wave field, it is expected that the arrival time will increase with increasing path distance. Here, path distance is measured from the sending transducer to the flaw and back to the receiving transducer. Note in Figure 6 that the longest arrival time is for sending on transducer 1 and receiving on transducer 3, and this is also the greatest path length.

Maximum level of the accumulated energy curves increase with increasing hole depth. Qualitatively, the relative energy received is most likely due to where the defect is with respect to the aperture of the sound field from the sending transducer, the scattering efficiency from the defect to the receiving transducer, and the overall path length. The highest energy level is for the transducer pair 2 and 3. This is the second shortest path length, and almost directly at the center of the aperture for transducer 3.

**Aluminum Specimen Results**

A series of holes and notches were machined in the aluminum beam as illustrated in Figure 8. Baseline waveforms were recorded prior to machining each of the four holes, and before machining each of three notches. All flaws were enlarged in the steps shown in Figure 8, and post-flaw waveforms were recorded after each machining step. The analysis baseline was updated as holes and notches were progressively added to the specimen. Results for only two of flaws are shown here, hole H1 and notch N1, as these results are typical for all the flaws.

Accumulated energy curves are shown in Figure 9 for hole H1. The first arrival is consistent with the total distance that the waves travel from the sending transducer to hole H1, and back to the receiving transducer. This path length is about 1 meter for transducer pair 1 and 2, and the arrival time is about 325 microseconds for this path (Figure 9a). For transducer pair 1 and 3, the total path length is about 700 mm, and arrival time is about 220 microseconds, and for 2 and 3, path length is about 400 mm and arrival time is about 125
microseconds. From these results, the average velocity is approximately 3.2 mm/µsec for the lead edge of disturbances from the hole. This value is consistent with shear and Rayleigh velocities in aluminum.

**FIGURE 8.** Transducer and flaw placement for aluminum "I" beam specimen.

**FIGURE 9.** Accumulated energy curves for hole H1 after it was progressively enlarged in diameter for the aluminum specimen for (a) transmit on 1 and receive on 2, (b) transmit on 1 and receive on 3, and (c) transmit on 2 and receive on 3.
The accumulated energy, at the end of the 4000 microsecond recording interval, increases almost linearly with increasing hole diameter (Figure 9). Further, the highest relative levels are for transmitting on 2 and receiving on 3, which is the closest transducer pair to hole H1. Next, is for transducers 1 and 3, which is next closest, and the lowest levels are for transducers 1 and 2, which are separated from H1 by the greatest distance.

Accumulated energy curves are shown in Figure 10 for notch N1, and the first arrival on these curves is consistent with the distance that the waves travel from the sending transducer to the defect, and back to the receiving transducer, as was also the case for hole H1. The total path length is about 380 mm from transducer 1, to the notch N1, and back to transducer 2. The arrival time for this path is about 120 microseconds (Figure 10a). For transducer pair 1 and 3, the path length is about 650 mm, and arrival time is about 225 microseconds (Figure 10b). For pair 2 and 3, path length is about 350 mm and arrival time is about 110 microseconds (Figure 10c). From these results, the average velocity is approximately 3.1 mm/µsec for the lead edge of disturbances from the notch N1. As was the case for hole H1, this velocity value is consistent with shear and Rayleigh velocities in aluminum.

As was the case for hole H1, increases in relative energy are again approximately linear with increasing flaw size for notch N1. Energy was received for a slightly longer time from the notches compared to the holes, as the upper energy levels have not quite reached a constant value at 4000 microseconds. This is expected since the notches are planar flaws oriented perpendicular to the direction of propagation.

**FIGURE 10.** Accumulated energy curves for notch N1 after it was progressively enlarged in length for the aluminum specimen for (a) transmit on 1 and receive on 2, (b) transmit on 1 and receive on 3, and (c) transmit on 2 and receive on 3.
RELATED STUDIES

Waveform differencing is not always as straightforward as presented here. Changing environmental conditions, such as surface contact and temperature differences, can change a baseline waveform and make simple waveform differencing ineffective. A continuation of this work has extended this study to include environmental effects. Another paper by the authors presents results for separating environmental effects and flaw conditions into separate recognizable classes using feature based neural network analysis methods [6].

CONCLUSIONS

A sparse array of ultrasonic transducers shows promise for structural health monitoring applications for both aluminum and concrete specimens. Waveform differences were computed between pre-flaw and post-flaw conditions, and processed to obtain accumulated energy curves. These curves are useful for determining the lead edge of the disturbance arrival from the flaws, and arrival times are consistent with the total path length from the transmitter to the flaw and back to the receiver. For the aluminum beam, this leading edge propagates at approximately the Rayleigh wave velocity.

The asymptotic upper level of the accumulated energy curves increased with increasing defect size for both the concrete specimen and the aluminum beam. Further, the separation between the curves was approximately linear with diameter for the holes, and linear with total flaw area for the notches.

REFERENCES