SELF-CALIBRATING ULTRASONIC METHODS FOR IN-SITU MONITORING OF FATIGUE CRACK PROGRESSION

J. E. Michaels[1], T. E. Michaels[1,2], B. Mi[1], A. C. Cobb[1] and D. M. Stobbe[2]

[1]School of Electrical and Computer Engineering, Georgia Institute of Technology,
Atlanta, GA 30332-0250
[2]G.W.Woodruff School of Mechanical Engineering, Georgia Institute of Technology,
Atlanta, GA 30332-0405

ABSTRACT. Ultrasonic sensors permanently affixed to aluminum coupons are used to monitor progression of damage during fatigue testing with the long term goal of structural health monitoring for diagnostics and prognostics. Necessary for success are proper design of the ultrasonic testing methods, robust transducer mounting techniques, and real-time signal processing for determining the state of the structure. It is also highly desirable for the overall system to be self-calibrating with built-in diagnostics in order to detect and compensate for sensor degradation or failure. Self-calibrating ultrasonic techniques are applied for monitoring of cracks initiating and propagating from the inaccessible inner diameters of rivet holes where the transducers are mounted on the accessible specimen surface. Angle beam ultrasonic methods are utilized that are suitable for detecting small defects in critical local regions of high stress. Results are presented for aluminum coupons subjected to low cycle fatigue and demonstrate ultrasonic tracking of crack growth.

INTRODUCTION

Techniques for in-situ monitoring of structural integrity are of considerable interest for critical aerospace and civil structures. Many methods have been proposed for structural health monitoring and can be grouped into two categories: global and local. A global test is one that is sensitive to a large area of the structure, whereas a local test is sensitive only to a specific localized region. Vibration modal analysis [1] [2], diffuse ultrasonic waves [3] and guided ultrasonic waves [4] are examples of global methods, whereas strain gages and conventional ultrasonic inspection techniques are examples of local methods.

The protocol for many critical components is to retire the component after its calculated service life is exceeded, which is usually overly conservative in that many good parts are prematurely retired. Condition based maintenance in which components are assessed and repaired or retired only when necessary is an alternative approach with the benefit of keeping good parts in service until their true useful life is over. For many structures the critical “hot spots” are known; that is, the high stress areas which are suspectable to cracking during cyclic fatigue loading. There are two distinct but complementary scenarios for assessing these critical areas of a structural component: (a) perform visual or other nondestructive inspections to certify the structure for continued service, or (b) use in-situ measurements to continually monitor these areas in order to reduce the need for periodic inspections or maintenance actions. This paper addresses the latter case in which in-situ measurements are made using permanently attached ultrasonic transducers in order to detect the initiation and growth of fatigue cracks during cyclic loading.

CP760, *Review of Quantitative Nondestructive Evaluation Vol. 24,* ed. by D. O. Thompson and D. E. Chimenti

The work presented here falls into the general framework of structural health monitoring using a sparse array of attached or embedded ultrasonic transducers [5]. The structure is interrogated by sending and receiving ultrasonic signals between all the respective transducer pairs. Recorded waveforms contain both coherent and diffuse portions where "coherent" refers to the early time, identifiable echoes, and "diffuse" refers to later time part of the signal in which specific echoes can no longer be identified. The coherent portion of the signal generally consists of the direct arrival and distinct reflections from boundaries, and the diffuse signal is formed after multiple reflections in the structure give the received signal an essentially random nature. The coherent portion of the waveform is sensitive to defects in the direct propagation path between the source and receiver, whereas the diffuse portion is sensitive to a larger, global area of the structure. Thus, structures may be interrogated globally by analyzing the diffuse portion of the waveforms [6], and locally by analyzing the coherent portion. For the work reported here, the transducers are positioned to aim the energy at an identified "hot spot" of the structure and are thus sensitive to small changes in the local material condition. The specific application is detection of crack initiation and growth near rivet holes in aluminum plate-like specimens. Other researchers have applied ultrasonic techniques for monitoring cracks growing from seeded defects during laboratory fatigue tests (e.g. [7]), but have not specifically considered their application to structural health monitoring.

MEASUREMENTS

Two pairs of miniature angle beam ultrasonic transducers (70° shear) were glued to fatigue specimens using high strength epoxy as illustrated in Figure 1. The specimen size was approximately 300 mm x 50 mm x 6 mm, and the material was 7075-T6 aluminum. One pair of transducers was used to monitor fatigue crack growth for each rivet hole. The basic idea is to monitor the through transmission signal from each transducer pair with the expectation that its amplitude will decrease as cracks grow out from the rivet hole perpendicular to the center of the ultrasonic beam path. However, any changes in the coupling of the transducers to the specimen or the degradation of the transducers themselves will also change the through transmission amplitude. Thus, pulse echo reflections from the holes are also monitored in order to detect changes in transducers or coupling.

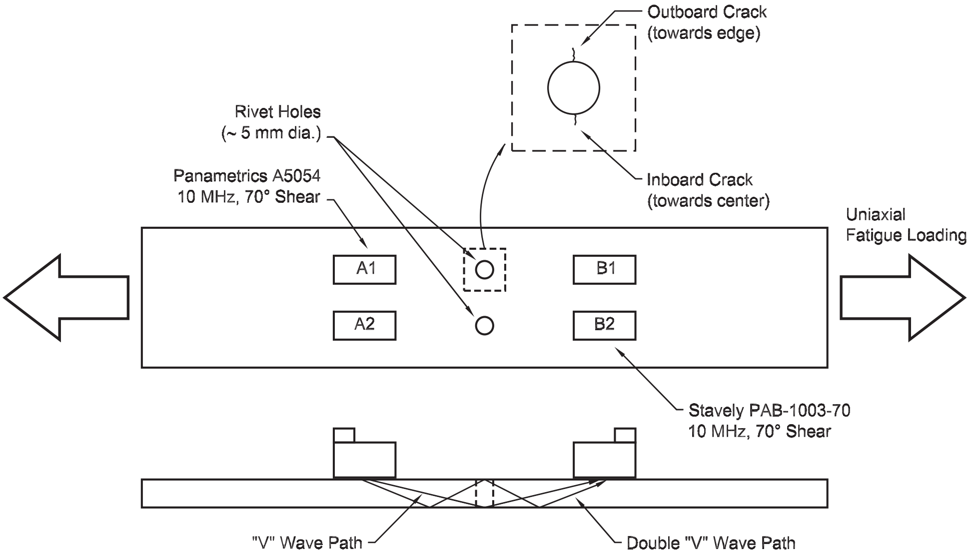

FIGURE 1. Ultrasonic transducer placement on fatigue specimen.

The through transmission beam path between each transducer pair is illustrated in Figure 1. Pulse echo and through transmission signal returns were optimized to determine the placement of individual transducers on the specimen. The transmit transducers were positioned to optimize pulse echo signal returns from the rivet holes; specifically, reflected signals from the half "V" and full "V" wave paths to and from the rivet hole were balanced, and typical signals are shown in Figure 2. Thus, the entire length of the rivet hole from the top to the bottom surface was flooded with ultrasonic energy for this transmit transducer position. As also illustrated in Figure 1, the receive transducers were positioned in the same manner but the through transmission signals were also observed to ensure that there were strong received signals from the undamaged specimen.

Results are reported here from a fatigue test on one specimen that was performed in blocks of 2640 load cycles each. After each block, the testing was halted and the following ultrasonic waveforms were recorded for both transducer pairs: (a) pulse echo from side A, (b) pulse echo from side B, and (c) through transmission from A to B. These measurements were made on both the unloaded specimen and the specimen under 5000 lbs. of axial load. Reported here are data from the hole with the larger cracks that caused the specimen to fail.

ANALYSIS METHODS

The basic premise behind using through transmission ultrasonic (TTU) signals as a metric for monitoring crack growth during fatiguing is that the TTU signal will decrease in amplitude as cracks form around the rivet holes. However, any changes in coupling efficiency of the transducers to the specimen or in the transducers themselves will also reduce the amplitude of the TTU signal. In the extreme case, if either the transducers or coupling fail completely, the through transmission signal would disappear, resulting in the incorrect interpretation of the presence of large cracks. However, since the cracks grow out from the sides of the hole away from the transducers, as shown in Figure 1, the pulse echo signals reflected from the holes are not affected by the cracks and are thus a monitor of the integrity of the transducers and coupling. In the case of only moderate degradation, the through transmission signals may still contain sufficient information to monitor crack growth provided that self-calibrating analysis methods are implemented to either compensate for or be independent of this degradation.

Two algorithms for self-calibration of the TTU results are considered. The first uses the energy of the half "V" pulse echo (PE) signals reflected from the front of the rivet holes to perform a correction; however, this algorithm requires recording the PE waveforms from each transducer in the TTU pair in addition to the TTU waveform. The second algorithm uses an energy ratio method formed by comparing TTU waveforms recorded first under no load and then under a static load, thus factoring out transducer and coupling variations.

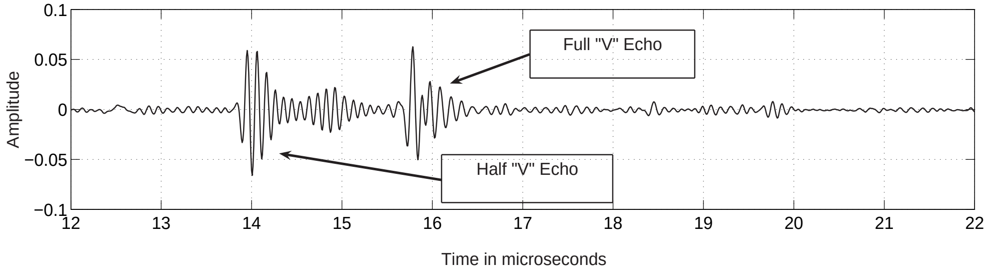

FIGURE 2. Typical pulse echo waveforms from rivet holes (70° refracted shear wave mode).

Corrected Relative Energy Method

The motivation for this self-calibration method is that changes in coupling efficiency will affect both the PE and TTU signals. The PE signals from each side of the hole are monitored and used to compensate the TTU signal. The term "relative" refers to the TTU energy being relative to that of the undamaged specimen, and "corrected" refers to the PE correction.

The PE waveforms were windowed as shown in Figure 3 to bracket the first echo return from the rivet hole. This window is early enough in time so that only the half "V" path pulse echo signal reflected from the bottom corner of the hole is in the window, and this reflection is completely unaffected by the cracks. Energy values were computed for PE waveforms from both transducers A and B as:

$$E_{PE_A} = \int_{T_A} [x_{PE_A}(t)]^2 dt \tag{1}$$

$$E_{PE_B} = \int_{T_B} [x_{PE_B}(t)]^2 dt \tag{2}$$

Next, TTU waveforms were windowed as illustrated in Figure 4 to select the largest peak which is the double "V" path arrival. The signal received in this time window showed good sensitivity to changes in the damage condition near the rivet holes. The TTU energy was computed as:

$$E_{TTU} = \int_{T_{AB}} [x_{TTU}(t)]^2 dt \tag{3}$$

The relative loss in energy during fatiguing is calculated by scaling the current energy by the initial energy prior to fatiguing:

$$\tilde{E}_{TTU} = \frac{E_{TTU}}{E_{TTU}^{initial}} = \text{relative energy} \tag{4}$$

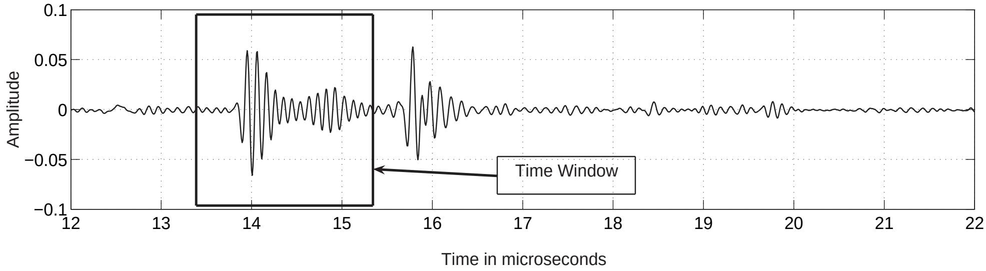

FIGURE 3. Time window for computing energy of pulse echo half "V" reflection.

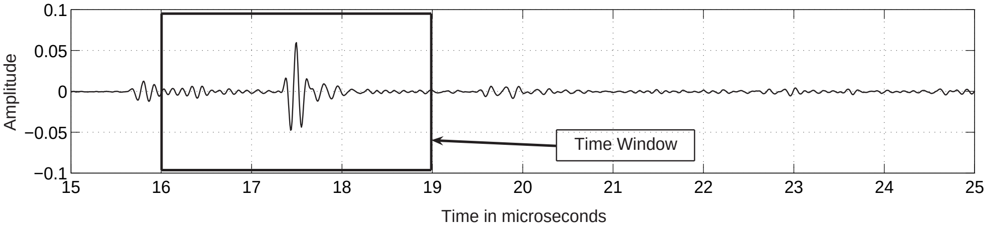

FIGURE 4. Time window for computing received energy of through transmission waveforms.

A similar relative energy calculation is made for the two PE signals. Finally, a corrected relative energy parameter is computed by correcting the relative TTU energy by both of the pulse echo relative energy values:

$$\hat{E}_{TTU} = \frac{\tilde{E}_{TTU}}{\sqrt{\tilde{E}_{PE_A}\tilde{E}_{PE_B}}} \tag{5}$$

Values computed using Equation 5 are henceforth referred to as the corrected relative energy.

Normalized Energy Ratio Method

The motivation behind the normalized energy ratio method described in this section is that a crack under sufficient axial load opens up and thus blocks a higher percentage of the TTU signal energy than does the same crack under no-load conditions. This behavior is evident from the TTU waveforms shown in Figure 5, which also shows the time windows used for the calculations below. The first step for this method is to calculate the TTU energies from the no-load and loaded conditions:

$$E_{NoLoad} = \int_{T_{AB}} \left[x_{NoLoad}(t)\right]^2 dt \tag{6}$$

$$E_{5000lbs} = \int_{T_{AB}} \left[x_{5000lbs}(t)\right]^2 dt \tag{7}$$

where E_{NoLoad} and $E_{5000lbs}$ are the TTU energies as per the designated applied load. The ratio of these energies is then calculated:

$$R_E = \frac{E_{5000lbs}}{E_{NoLoad}} \tag{8}$$

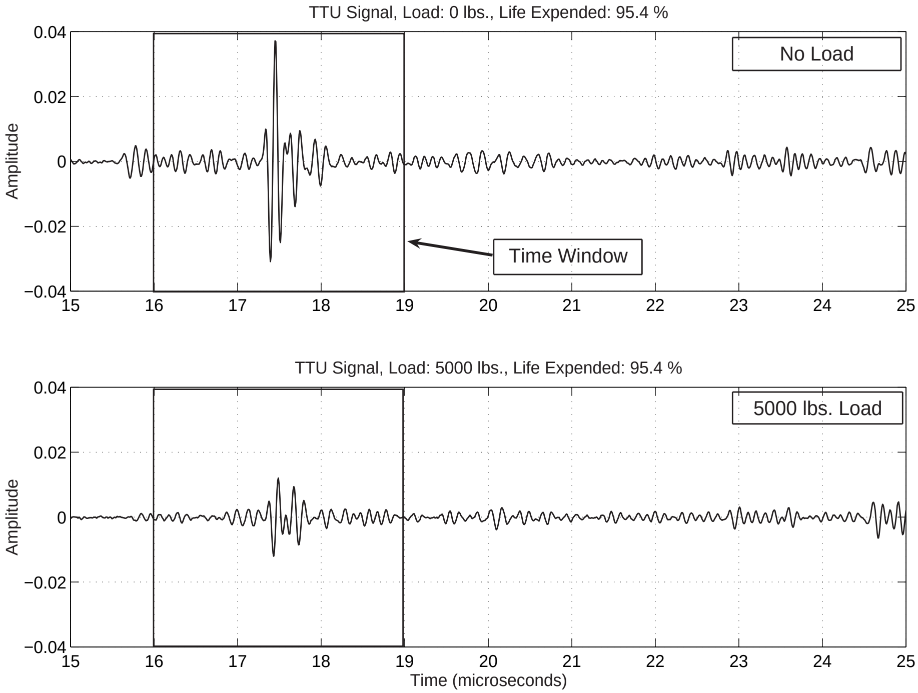

FIGURE 5. The effect of axial load on through transmission waveforms for specimens with rivet hole cracks.

This ratio is computed for the initial undamaged material state and after each block during the fatigue tests. These values are referred to as $R_E^{initial}$ and $R_E^{current}$, respectively, and were used to compute the final normalized energy ratio, $\hat{R}_E$:

$$\hat{R}_E = \frac{R_E^{current}}{R_E^{initial}} \tag{9}$$

Values computed using Equation 9 are henceforth referred to as the normalized energy ratio.

RESULTS

Loss of energy as measured by the relative energy calculated as per Equation 4 is plotted in Figure 6 vs. % life expended for two load conditions; i.e., no-load and 5000 lbs. These results were not corrected using the pulse echo energy values. The initial energy, $E_{TTU}^{initial}$, was computed from waveforms recorded before the start of the fatigue process, and represents an undamaged specimen condition. Note that the TTU relative energy curve measured at a load of 5000 lbs. begins to decrease when the cracks inside the rivet holes approach a surface length of approximately 0.01 inches, which is when they are just visible using a 10X magnifier. For the last 40% of the fatigue life, the drop is approximately linear and approaches a relative energy of zero at 100% of expended life. The no-load curve also exhibits a drop, but not until 80% of life expended. After 80% of life, the no-load and 5000 lb. load curves maintain a clear separation for the remainder of the specimen life. This difference in response between no-load and loaded crack conditions is consistent with the supposition that the opening of the crack under load blocks the TTU energy from propagating across the crack.

Corrected relative energy results are shown in Figure 7 that are calculated using Equation 5; i.e., with PE correction. The curves of Figure 7 are very similar to those for the case of no PE correction shown in Figure 6. Neither of the transducers nor their bonds degraded appreciably during these fatigue tests, and the PE signals are stable and of consistent energy.

The normalized energy ratio calculated using Equation 9 is shown in Figure 8 for the same data of Figures 6 and 7. The results from this energy ratio method are consistent with the relative energy method. The ratio is very close to unity prior to the onset of visible crack formation at approximately 55% of the expended life, and past this point the curve drops monotonically as specimen failure is

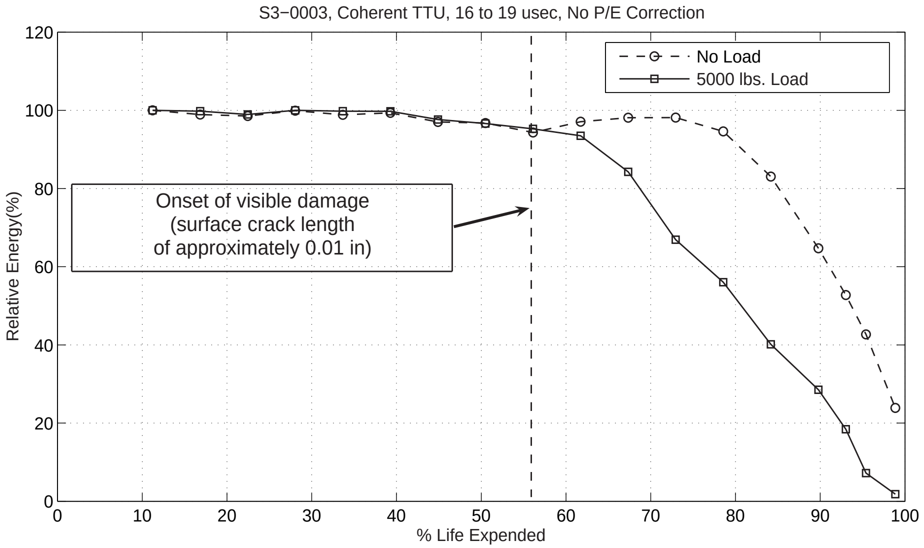

FIGURE 6. Loss of through transmission energy vs. expended life, no pulse echo correction.

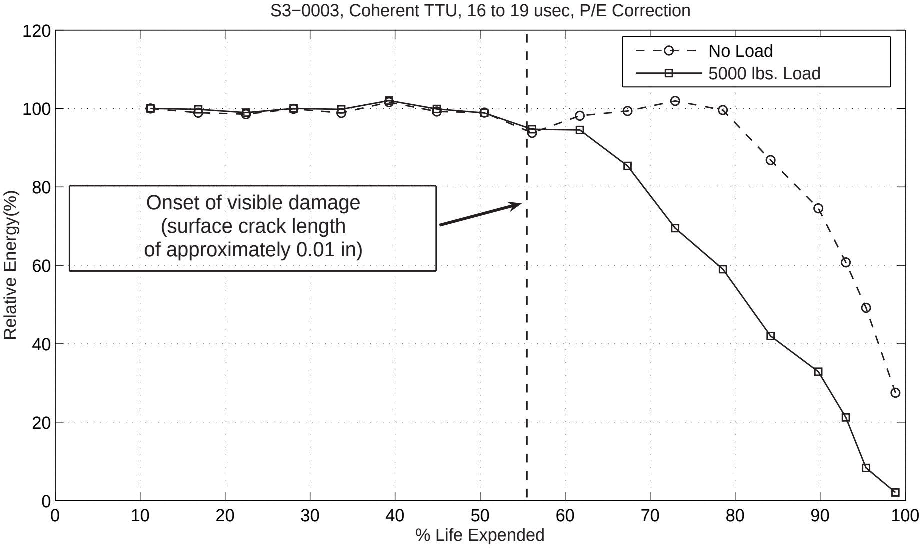

FIGURE 7. Loss of through transmission energy vs. expended life, with pulse echo correction.

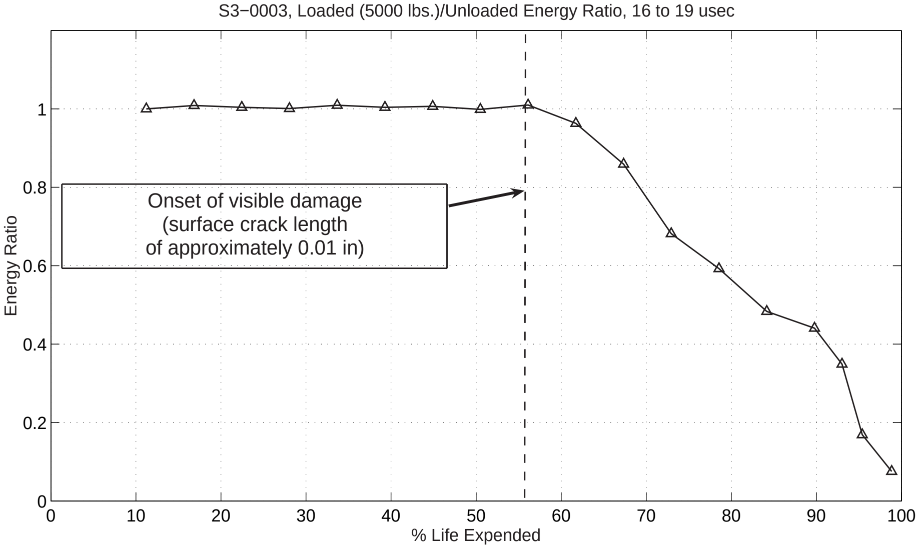

FIGURE 8. Normalized energy ratio vs. expended life.

approached. The energy ratio curve has more structure in the last 20% of specimen life, which may be due to actual changes in the crack growth rate.

SUMMARY AND CONCLUSIONS

1. Through transmission ultrasonic angle beam methods are a useful tool for monitoring the onset of crack initiation and subsequent crack growth originating from the inside of rivet holes in 7075-T6 aluminum specimens during cyclic fatigue.
2. A self-calibrating method based upon using the pulse echo signals from the rivet holes to compensate the through transmission signals was successfully implemented. Its effectiveness

is dependent upon the pulse echo signals not being affected by the crack, and this method is expected to be successful in compensating for moderate transducer or coupling degradation.

3. A second self-calibrating method was implemented by forming a ratio of loaded to unloaded through transmission energy followed by normalization to the undamaged condition. The effectiveness of this normalized energy ratio is based upon the opening of the crack under load. This inherently self-calibrating method is thought to be the better choice of the two for structural health monitoring because it provides a more direct measure of the interaction of the ultrasonic signal with the crack.

4. Future work is needed to quantitatively evaluate the efficacy of these self-calibrating methods and to determine the maximum transducer and coupling degradation that can be tolerated; a series of tests incorporating artificially introduced coupling variations is recommended.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of the Defense Advanced Research Projects Agency (DARPA), Defense Sciences Office, “Structural Integrity Prognosis System” Program, contract No. HR0011-04-0003 to Northrop Grumman Corporation, Integrated Systems.

REFERENCES

1. D. J. Inman, *Engineering Vibration*. Englewood Cliffs, New Jersey: Prentice Hall, 1994.
2. K. E.-A. Van Den Abeele, A. Sutin, J. Carmeliet, and P. A. Johnson, “Micro-damage diagnostics using nonlinear elastic wave spectroscopy,” *NDT&E International*, vol. 34, pp. 239–248, 2001.
3. J. E. Michaels and T. E. Michaels, “Ultrasonic signal processing for structural health monitoring,” in *Review of Progress in Quantitative Nondestructive Evaluation* (D. O. Thompson and D. E. Chimenti, eds.), vol. 23B, (New York), pp. 1476–1483, American Institute of Physics, 2004.
4. P. Cawley, M. J. S. Lowe, D. N. Alleyne, B. Pavlakovic, and P. Wilcox, “Practical long range guided wave testing: applications to pipes and rails,” *Materials Evaluation*, vol. 61, pp. 66–74, 2003.
5. T. E. Michaels and J. E. Michaels, “Sparse ultrasonic transducer array for structural health monitoring,” in *Review of Progress in Quantitative Nondestructive Evaluation* (D. O. Thompson and D. E. Chimenti, eds.), vol. 23B, (New York), pp. 1468–1475, American Institute of Physics, 2004.
6. J. E. Michaels, A. C. Cobb, and T. E. Michaels, “A comparison of feature-based classifiers for ultrasonic structural health monitoring,” in *Proceedings of SPIE Conference on Health Monitoring and Smart Nondestructive Evaluation of Structural and Biological Systems III* (T. Kundu, ed.), vol. 5394, pp. 363–374, 2004.
7. J.-Y. Kim and S. I. Rokhlin, “Surface acoustic wave modulation on a partially closed fatigue crack,” *Journal of the Acoustical Society of America*, vol. 115, no. 5, pp. 1961–1972, 2004.