A Wire-Guided Transducer for Acoustic Emission Sensing

Ian T. Neill[a], I. J. Oppenheim[a*], D. W. Greve[b]
[a] Dept. of Civil and Environmental Engineering, Carnegie Mellon University, Pittsburgh, PA 15213
[b] Dept. of Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh, PA 15213

ABSTRACT

A novel transducer for active or passive sensing has been developed and tested experimentally. It features a steel wire acting as a wave guide between a piezoceramic element and the structure under test. Some advantages of the wire-guided transducer include its applicability to structures operating at high temperature, which otherwise preclude the surface mounting of piezoceramics, its small contact area to the structure, which enables several such transducers to be deployed in an arc around a known crack location as an acoustic emission sensor array, and its low cost and ease of installation. Another potential advantage is simplified signal processing for source localization, which is developed in this paper and evaluated experimentally.

The various steel wires used in our experiments to date are less than 1 mm in diameter and between 10 cm and 100 cm in length. The wire guides have been studied with active excitation under a pulse excitation as used in ultrasonic testing, at a relatively high frequency such as 1 MHz, and in the frequency range of 100 kHz to 500 kHz which is often of interest for Lamb wave generation in thin plates or for acoustic emission sensing. Our tests confirm that the wire acts as a cylindrical rod in which the fastest wave is the lowest longitudinal mode, displaying a sharp arrival, and in which the lowest flexural mode and lowest torsional mode are also excited; we report excellent agreement between measured and predicted wave speeds, as expected.

We show experimental results in which a group of wire-guided transducers permit the localization of an impact on a thin plate and discuss the automation of this task for use in the field. We also show the ability of the wire-guided transducer to detect acoustic emission events simulated physically by pencil lead breaks.

Keywords: Acoustic emission, high temperature sensing, impact localization, waveguide.

1. INTRODUCTION

For high temperature sensing, much work has been performed in the development of a waveguide for use as a buffer between an ultrasonic transducer and a test structure [1], [2]. For flow measurement, Lynnworth *et al.* have given particular attention to the development of waveguide techniques for measuring flow of hot fluids [3]. Those authors summarize examples of waveguides used to isolate a transducer from a specimen or fluid, citing [4] prior work on thick rods (both smooth and threaded), clad rods, thin rods (both smooth and threaded), hollow tubes, spiraled sheets, and thin blades, and then describe the development of a bundle of slender metal rods. Lynnworth has authored or co-authored over 200 publications and is responsible for a major body of work on the topic of ultrasonic waveguides. Other recent research in the development of waveguides has highlighted the use of cylindrical rods in waveguide applications [5]. In our work here, we look to employ waveguide techniques to address issues of space and temperature that currently affect the ability to mount ultrasonic sensors in important inspection areas on both vehicles and civil structures.

Due to the relatively low Curie temperature of the piezoceramic material lead-zirconate-titanate (PZT), most common PZT transducers cannot be surface mounted to structures operating at high temperatures. Furthermore, the use of a commercial transducer in non-destructive evaluation and monitoring may require the use of a prohibitively large waveguide. For the inspection of cooling pipes at power plants, this problem is of particular importance. In situations

---

[*] Contact author: ijo@cmu.edu; 412-268-2950; Carnegie Mellon University, Department of Civil and Environmental Engineering, Pittsburgh, PA, 15213.

Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2007,
edited by Masayoshi Tomizuka, Chung-Bang Yun, Victor Giurgiutiu, Proc. of SPIE Vol. 6529,
652913, (2007) · 0277-786X/07/$18 · doi: 10.1117/12.715358

where space is a limiting factor, such as the leading edge of the wing of the space shuttle, a small and unobtrusive sensor device is needed to perform effective and reliable ultrasonic testing of the structure. In recent work by Lee and Tsuda [6], those authors present the concept of a fiber-guided transducer for use as both an active and passive sensor in pitch-catch or pulse-echo mode. Their device uses fiber-optic fiber as a waveguide to acoustically couple a piezoceramic wafer to a test structure. In this paper, we build on the concepts of Lee and Tsuda, and on the considerable amount of work performed earlier in the investigation of ultrasonic waveguides, to propose a novel wire-guided transducer for use in impact and acoustic emission detection. The wire-guided transducer uses a steel wire to acoustically couple a piezoceramic wafer to a test structure, allowing for application on high temperature structures through remote location of the piezoelectric element and implementation in hard-to-reach areas through a reduction of the required contact surface area. Experimental results showing the utility of this device as an impact and acoustic emission detector and locator are described.

2. EXPERIMENTAL BEHAVIOR OF STEEL WIRE WAVEGUIDE

Ultrasonic waveguides are often used in the practical application of piezoelectric transducers, and we began our study with an experimental investigation of a thin steel wire in that role. Laboratory experiments were performed to determine the wave modes generated in the wire and confirm the expectation that the wire will act as a cylinder or rod. In their work examining fiber-optic fiber as an acoustic waveguide, Lee and Tsuda used a fiber-optic fiber to transmit ultrasonic waves between two piezoelectric transducers in pitch-catch mode [7]. A similar experiment is performed here. Two wafer-type lead-zirconate-titanate (PZT) piezoceramic transducers of dimension 10 mm x 12 mm x 0.5 mm were acoustically coupled to the ends of a steel wire of diameter 0.74 mm and 90 cm length. A 5-cycle windowed sinusoid was used to drive the actuating transducer and the signal transients at the sensing transducer were recorded for a number of different center frequency values for the driving signal. Signal generation and data acquisition used a National Instruments PCI-6110 with an output resistance of 50 ohms. This procedure was repeated following the addition of a mechanical damping material to the underside of each transducer. The damping material used in this case was a tungsten-epoxy composite material 4mm thick and applied to the PZT wafer in two strips using thin cyanoacrylate adhesive. Figures 1 and 2 compare the damped and undamped cases for a characteristic signal transient, for a center frequency of 200 kHz.

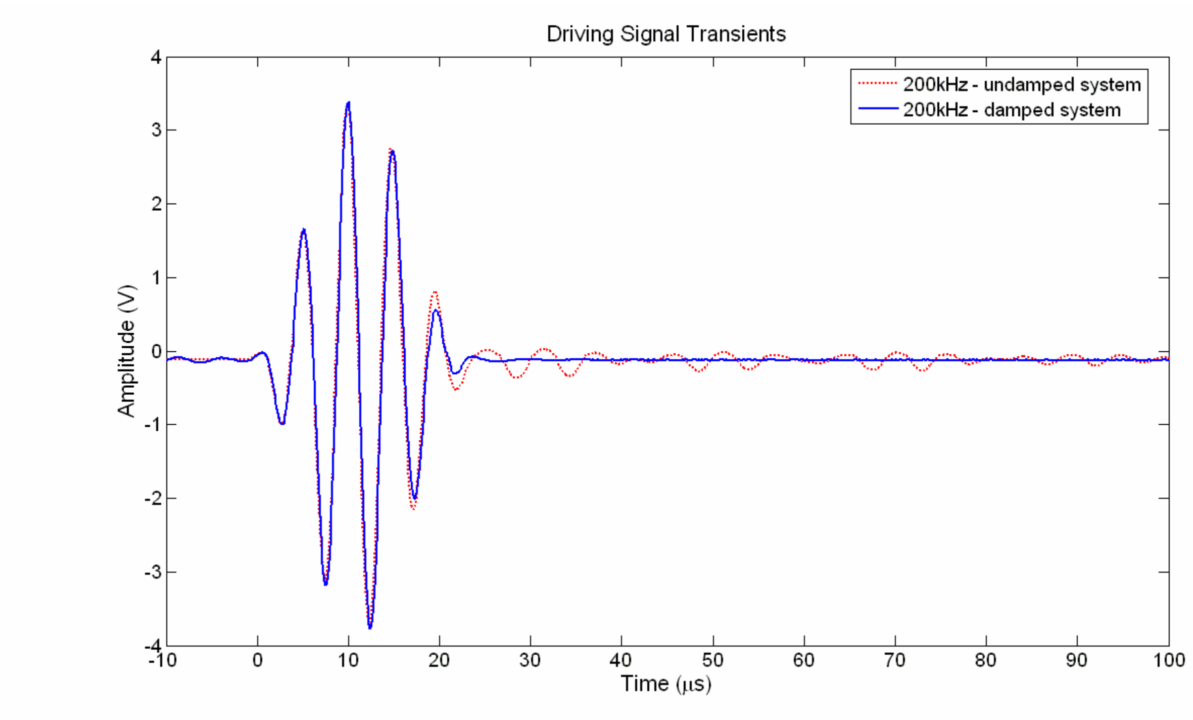

Figure 1. Signal at the actuating transducer in both the damped and undamped cases; 200 kHz center frequency.

Figure 1 records the driving signals at the actuating transducer, which in the undamped case shows a clear elongation of the driving signal associated with unwanted response of the transducer following the five-cycle driving period. Figure 2 records the signals arriving at the sensing transducer, which in the undamped case shows an unwanted response due to "ringing," which is not indicative of the intended five-cycle pulse traveling in the wire waveguide. In contrast, the damped system displays the clear arrival of the intended five-cycle pulses, one at approximately 180 μs and another at approximately 280 μs, but at significantly lower amplitude than the undamped system. Due to the clarity of the arrival locations observed in the damped system, we proceed using the damped case in our further treatment of this experiment.

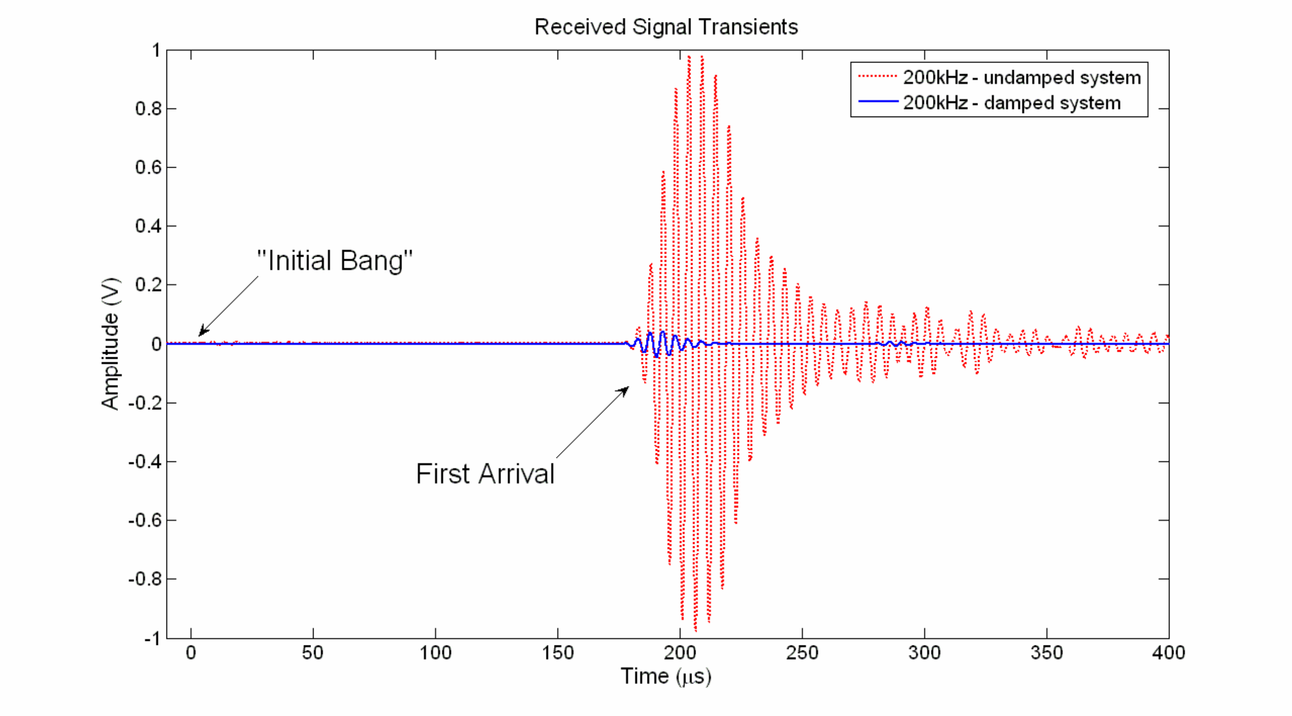

Figure 2. Transient signals recorded at the sensing transducer. In the undamped system, signals received after the initial arrival do not all correspond to reflections along the length of the waveguide.

Figure 3 shows the signal at the sensing transducer, over a time extending to 700 μs, for pulse center frequencies between 100 kHz and 700 Khz. Referring to the 200 kHz signal transient in figure 3, four clear arrivals are detected at the sensing transducer over a period of 700 μs. Examining the nature of the distinct arrivals over a range of frequencies allows us to determine the different wave modes present in the waveguide. The theoretical velocity of a longitudinal wave propagating in a thin steel rod is 5.06 km/s and is non-dispersive over the range of frequencies examined here [8] for a wire with a diameter of 0.74 mm. This behavior shows good agreement with the non-dispersive arrival occurring at 180 μs in figure 3. From the velocity of this wave mode and the length of the steel wire waveguide, we are further able to conclude that the non-dispersive arrival occurring at 520 μs corresponds to a travel distance of three wire lengths and is therefore due to reflections from the end of the 90 cm steel wire.

Because the actuating PZT transducer is not mounted symmetrically on the wire, we expect to observe a flexural wave propagating along the length of the wire. According to theory, for a wire with a diameter of 0.74 mm, the lowest flexural wave mode is dispersive over the range of frequencies from 100 kHz to 700 kHz. In our experiments, we observe a signal arrival that increases in velocity as the center frequency of the driving signal is increased. This arrival occurs at 600 μs for an excitation signal center frequency of 100 kHz and moves to 330 μs at 700 kHz. Comparing the velocity of this signal with the theoretical value for the $n=1$ flexural mode, we are able to conclude that it corresponds to the lowest flexural mode in a thin rod.

The signal arriving at 280 μs does not correspond to a reflection of the longitudinal mode along the length of the wire. Furthermore, the velocity of this arrival at low frequencies is too great to correspond to the lowest flexural mode, and because it is non-dispersive, it cannot be associated with a higher energy flexural mode. However, the lowest torsional mode in a rod of circular cross-section is non-dispersive and propagates at the transverse (shear) wave velocity, c_2, which is given [8] as 3.16 km/s. This theoretical value corresponds well with the observed behavior of the arrival at 280 μs and we conclude that this signal indicates the presence of a torsional mode in the wire waveguide.

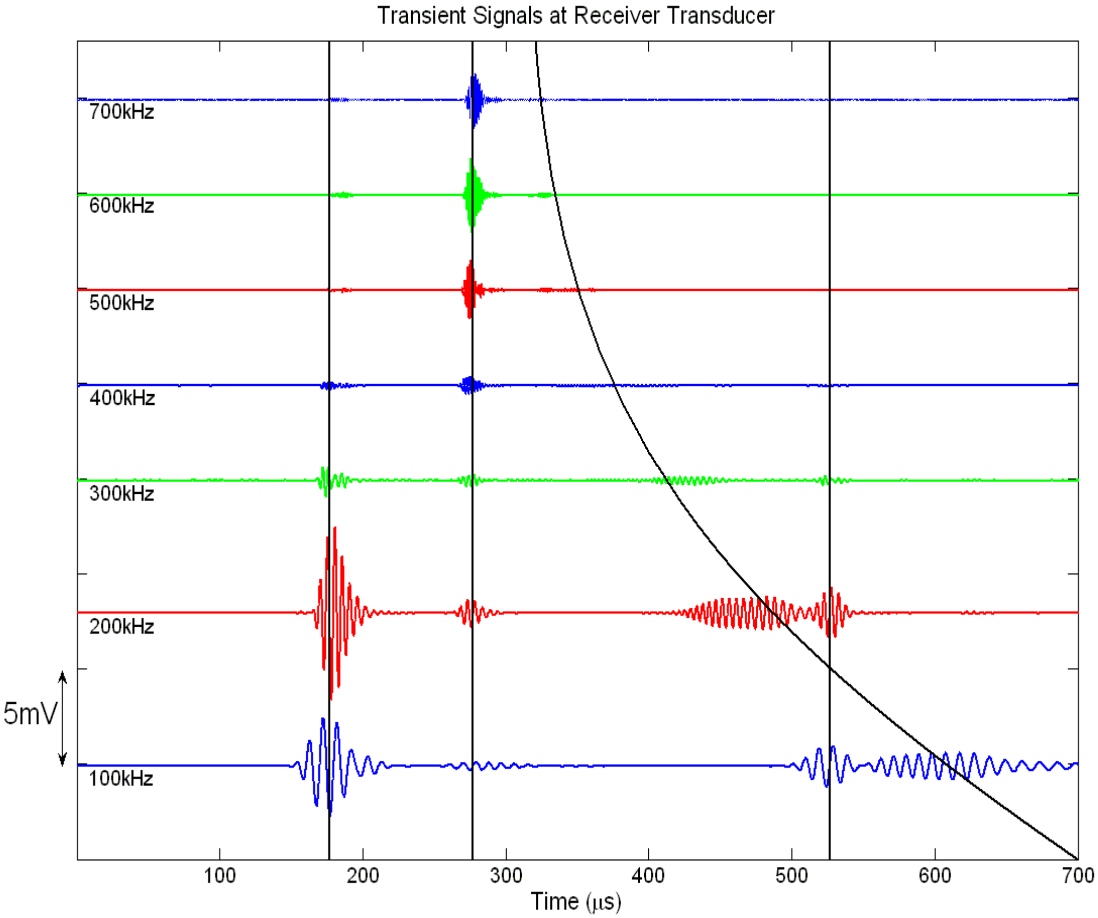

Figure 3. Transient signals recorded at the sensing transducer under mechanical damping of both the actuating and sensing transducers.

With the addition of the torsional mode to the more common longitudinal and flexural modes, our experiments show the presence of three distinct wave modes in a thin steel-wire waveguide. Figure 4 shows the experimental results plotted as group velocity dispersion curves.

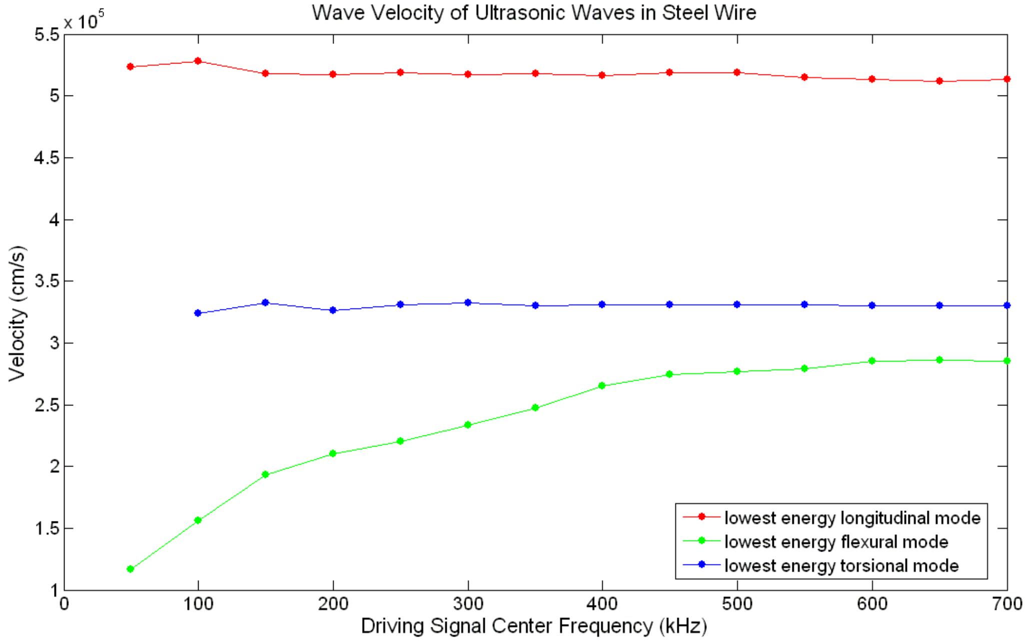

Figure 4. Group velocity dispersion curves, as determined experimentally, for three modes in the wire waveguide.

3. IMPACT DETECTION AND LOCALIZATION

Using an array of multiple wire-guided transducers, it will be possible to detect an impact to a structural member and determine its location. This is similar to an approach previously reported [9] in which PZT transducers were directly attached to the structure. In our experiments, three wire-guided transducers were arranged in a triangular array on a square aluminum plate with overall dimensions 122 cm x 122 cm x 1.6 mm. Choosing one corner of the plate to be the origin, the (x, y) coordinates of the three transducers are (x_0, y_0) = (20 cm, 25 cm), (x_1, y_1) = (61 cm, 96 cm), and (x_2, y_2) = (102 cm, 25 cm). The distance between each pair of transducers was approximately 40 cm. The size of the PZT wafer used here is the same as described in the previous pitch-catch experiment, and the length and diameter of wire used as a waveguide were chosen to be 19 cm and 0.41 mm, respectively. To increase the durability of the transducer device, and to provide a reproducible means of contact with the test structure, a brass tab of dimensions 12.7 mm x 6.4 mm x 1.6 mm was soldered to the free end of the steel wire. Figure 5 shows the completed device before contact to the plate.

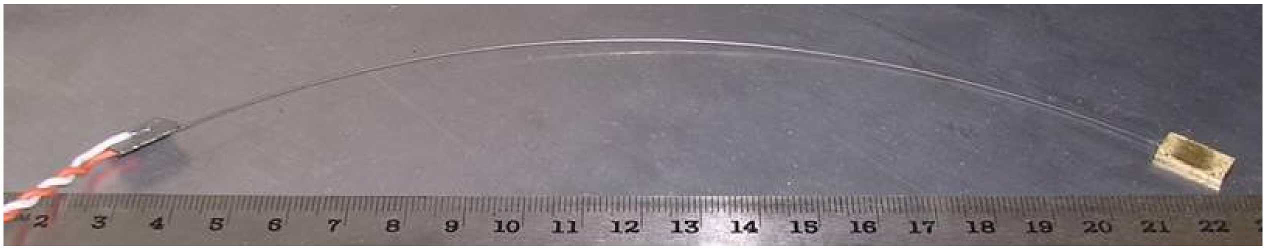

Figure 5. Wire-guided transducer used in impact detection and localization studies, 0.41 mm diameter. The steel wire is soldered to a small brass tab and is acoustically coupled to the PZT wafer using thin cyanoacrylate adhesive. The brass solid is contacted to the test structure using the same adhesive.

Impacts to the aluminum plate were created using ball bearings dropped from a height of 25 cm at a number of different locations on the plate. For every impact, the signal transient at each transducer was recorded and the time difference of arrival was manually determined for each pair of sensors, as shown in figure 6. This data was collected and analyzed using programs written in LABVIEW. The velocity associated with first arrival of the impact signal was experimentally determined to be c = 5.6 km/s. The time-difference of arrival between each pair of sensors, the coordinates of the sensors, and the coordinates of the impact are related to one another in a set of non-linear equations generated by the following relationship:

$$\Delta t_{ij} = \frac{\sqrt{(x_{impact} - x_i)^2 + (y_{impact} - y_i)^2} - \sqrt{(x_{impact} - x_j)^2 + (y_{impact} - y_j)^2}}{v}$$

In the resulting set of equations, Δt_{ij} is the time-difference of arrival observed between sensors (i) and (j), v is the experimentally determined velocity of the fastest wave mode, (x_i, y_i) is the coordinate location of sensor (i), and (x_{impact}, y_{impact}) is the desired coordinate location of the impact. A computational program written in LABVIEW was used to solve the above non-linear system of equations for the impact coordinates, (x_{impact}, y_{impact}). Table 1 compares the known coordinates of impact locations with the coordinates obtained experimentally, and shows the average error of the method to be on the order of 1 cm.

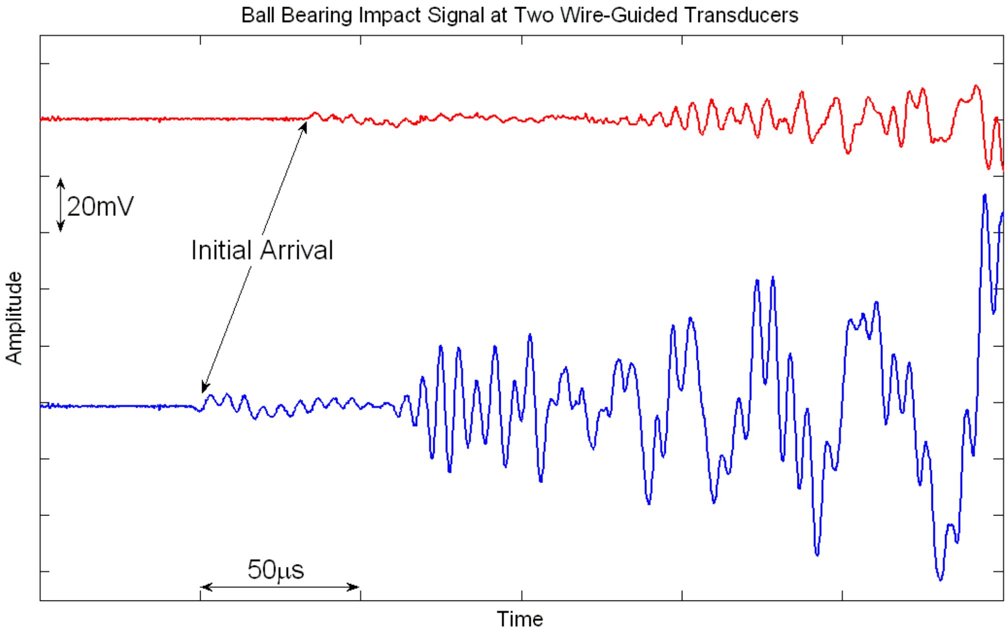

Figure 6. Time difference in arrival of the fastest mode propagating in the aluminum plate is used as the time-difference of arrival for impact localization.

Table 1. Comparison of known impact coordinates with experimentally determined impact coordinates; experimental results are an average of three trials.

Known coordinates of impact (cm)	Experimentally determined coordinates (cm)	Error (cm)
(61, 48)	(61, 47)	1
(40, 47)	(40, 46)	1
(40, 75)	(39, 76)	1
(71, 75)	(70, 76)	1
(92, 35)	(93, 34)	1

In our experiments to localize impact, the arrival time of the fastest wave mode was most precisely determined by visual inspection. Automation of this task can be performed using a straightforward approach in LABVIEW or other analysis software. For our purposes, an automated arrival-detection program was created in LABVIEW and a number of ball bearing impacts were performed at different locations. In most cases, the algorithm was both accurate and efficient. However, the possibility of large noise peaks occurring in the signal will complicate the process and can lead to the misinterpretation of data during the automated signal processing task.

4. DETECTION OF SIMULATED ACOUSTIC EMISSION EVENTS

To show the utility of the wire-guided transducer in acoustic emission detection, acoustic emission events were simulated physically using pencil lead breaks. This experiment was conducted using the same wire-guided transducers and aluminum plate used in the impact localization experiments. A pencil-lead 0.5 mm in diameter and 1cm in length was broken at a distance of 20 cm from the contact of the waveguide with the test structure. Figure 7 shows a simulated AE event as recorded by the wire-guided transducer.

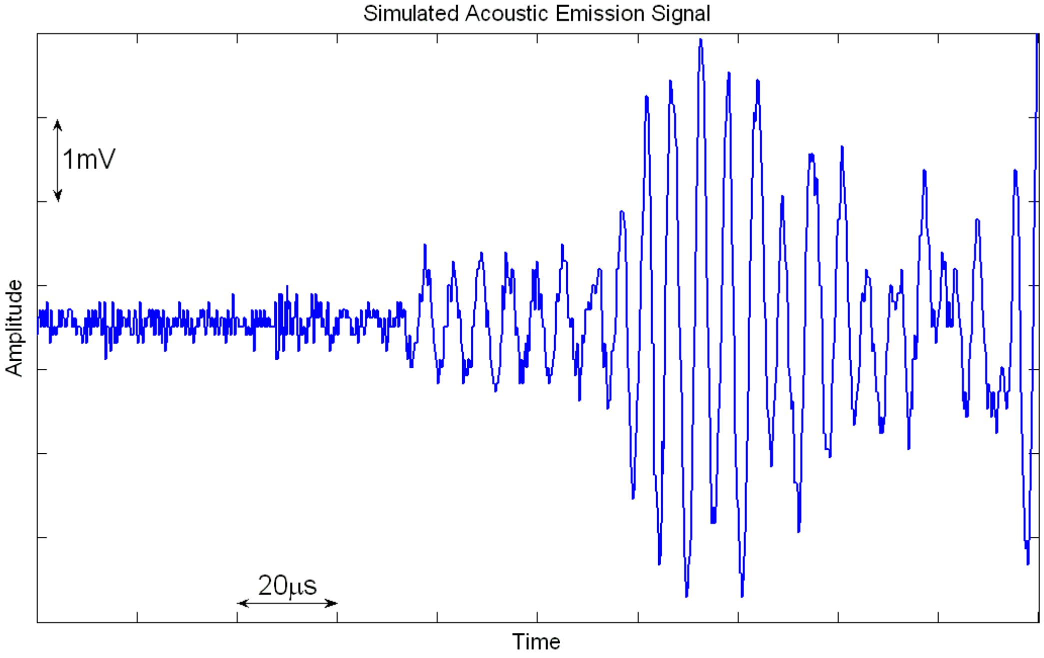

Figure 7. Signal produced by a pencil-lead break 20 cm from the contact position of a wire-guided transducer.

The low signal-to-noise ratio of these events makes accurate localization difficult at long distances. However, the ability of a number of wire-guided transducers to form an array over a small area provides a potential advantage for monitoring at-risk areas in structures.

5. CONCLUSIONS

The ability to monitor acoustic emission events using wire-guided transducers would allow for effective detection of structural flaws in structures operating at high temperature, which is difficult to do using current sensor technology, or in locations that are spatially constrained. In this paper, we have presented a low-cost wire-guided transducer for application in high temperature and in space constrained environments. The wire-guided transducer allows for the remote location of a piezoelectric transducer, and multiple transducers can be easily arranged in an array for source localization. The use of a thin steel wire as a waveguide has been examined, and was found to behave like a thin cylindrical rod with the propagation of three independent wave modes as predicted for the center frequencies that were examined. We have studied, preliminarily, the ability of this device to serve as an impact detector and localizer on a thin metal plate, and as an acoustic emission sensor.

ACKNOWLEDGEMENTS

The authors wish to acknowledge support from the National Science Foundation under grant CMS-0329880. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. The authors are very thankful to an anonymous reviewer whose suggestions greatly improved our final manuscript.

REFERENCES

1. L. C. Lynnworth, "Ultrasonic buffer/waveguide," U.S. Patent 6,047,602, Apr 11, 2000.
2. L. C. Lynnworth, "Marginally dispersive ultrasonic waveguides," U.S. Patent 5,159,838, Nov 3, 1992.
3. Lawrence Lynnworth, Yi Liu, and John Umina, "Extensional Bundle Waveguide Techniques for Measuring Flow of Hot Fluids," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control,* Vol. 42, No. 4, 538-544, 2005.
4. A. Brown and L. Lynnworth, "Ultrasonic flowmeters," in *Flow Measurement Practical Guides for Measurement and Control*. 2nd ed., D. W. Spitzer, Ed, Research Triangle Park, NC: Instrumentation, Systems, Automation Soc., 2001, Ch. 20, 517-575.
5. Hatano, Hajime, "Waveguide for Transmitting and Radiating High-Frequency, High-Power Ultrasound Using Higher Mode Vibrations of a Cylindrical Rod," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control,* Vol. 42, No. 4, 518-524, 2005.
6. Jung-Ryul Lee and Hiroshi Tsuda, "Investigation of a fibre wave piezoelectric transducer," *Meas. Sci. Technol*., Vol. 17, 2414-2420, 2006.
7. Jung-Ryul Lee and Hiroshi Tsuda, "Sensor application of fibre ultrasonic waveguide," *Meas. Sci. Technol*., Vol. 17, 645-652, 2006.
8. Graff, Karl F., *Wave Motion in Elastic Solids*, New York: Dover, 1975.
9. In-Gul Kim, Hong-Young Lee, and Jin-won Kim, "Impact Damage Detection in Composite Laminates Using PVDF and PZT Sensor Signals," *Jnl. Intelligent Material Systems and Structures*, Vol. 16, No. 11-12, 1007-1013, 2005.