IMPROVED SIGNAL-TO-NOISE WIDEBAND ACOUSTIC/ULTRASONIC CONTACT DISPLACEMENT SENSORS FOR WOOD AND POLYMERS

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ABSTRACT

Research leading to a significant improvement in the signal-to-noise sensitivity of wideband acoustic/ultrasonic contact displacement sensors for wood and polymers is described. Design principles for such high-sensitivity sensors are reviewed. Comparisons of response between ceramic and polymer piezoelectric elements are made on low modulus specimens. A new, practical high-sensitivity sensor is characterized and its signal-to-noise sensitivity is compared to that of an existing commercial wideband displacement sensor. The comparisons were made for polymer, maple, and redwood samples. Optimization of the piezoelectric element in the new sensor is considered. The typical increased sensitivity of the new sensor is about 30 dB over the existing commercial sensor.

Key words: Wideband sensor, high-sensitivity sensor, displacement sensor, sensor design for wood.

INTRODUCTION

The application of some acoustic/ultrasonics nondestructive evaluation (NDE) techniques has typically been practiced with relatively narrow band approaches. For example, typical accelerometers rarely have a useable bandwidth of more than 10 kHz, and resonant acoustic emission (AE) sensors typically have a peak sensitivity range of a few tens of kilohertz. Ultrasonics (UT) sensors (pulsers and receivers), although they are typically wideband, are sometimes used with a tone-burst type pulse. In recent years, the availability of multichannel transient waveform recording systems with high digitization rates (5 Msamples/s or more), wide dynamic range (10 bits or more), and deep memories (8,000 to more than 1,000,000 points) combined with signal processing software has opened the way to the use of wideband acoustic/ultrasonic NDE approaches. Just as the advent of "wideband recorded music" (i.e., high-fidelity music) made a dramatic impact on the ability of the listener to distinguish various aspects of recorded music, wideband acoustic/ultrasonic NDE techniques have the potential to impact the ability to make NDE-based distinctions between different test samples of a particular material. To exploit this potential fully requires understanding of wave propagation in finite samples, appropriate wideband sensors, and wideband sources. For the application of these wideband techniques to wood and polymers, it is especially important that wideband sensors with excellent signal-to-noise sensitivity be available. This requirement arises from the fact that these materials experience relatively high rates of frequency-based material attenuation. Also, due to this material attenuation, it is important that this sensitivity extend to lower frequencies where the material-based attenuation is not as severe.

The objectives of this paper are to first review some key principles of the design of high-sensitivity wideband piezoelectric displacement sensors in the approximate frequency range of 20 kHz to 1 MHz for low modulus specimens such as wood or polymers. Next, current background research results on development of a high-sensitivity sensor are presented. Finally, the paper presents a sensitivity characterization of a current best design of

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such a contact sensor. It should be noted that this research excludes the normal range of accelerometers (up to about 10 kHz), but that a number of the principles of high-sensitivity design carry over to high sensitivity accelerometers.

DISCUSSION OF DESIGN PRINCIPLES

Fundamental to the development of a high-sensitivity sensor is the need for consideration of both the response sensitivity and the electronic noise (e.g., thermal electronic noise). In the case of a wideband sensor, these two factors are taken into account by comparing the response-to-noise (i.e., signal-to-noise) as a function of frequency for candidate sensor designs. Also of fundamental importance is the need to consider both the sensor and the preamplifier as an inherent combination. This requirement arises from the fact that the piezoelectric sensor element and the associated electronics (in particular the input capacitance and electrical noise characteristics of the first transistor) interact with each other with respect to both the noise and response sensitivity. One previous publication (Tyree and Sperry 1989) compared acoustic emission sensors for wood, but the authors failed to characterize response and noise as a function of frequency.

Table 1 (see references after items 1–8 in this table) provides a list of key design requirements for practical, high-sensitivity, wideband, piezoelectric, displacement sensor designs in the frequency range from 20 kHz to 1 MHz. Wood and polymer samples present a key challenge to such sensor design in that typical wideband sensor elements have been made with ceramics that have material moduli on the order of 40 to 100 GPa, while wood moduli vary from about 10 GPa (parallel to grain) to 1 GPa (perpendicular to grain), and polymer moduli are on the order of 1 to 5 GPa. Thus item 7 in Table 1, which requires a sensor element much less stiff than the specimen material "below" it, is not easy to satisfy. On this point, it is helpful to summarize briefly current background research that has been carried out to examine whether a polymer piezoelectric sensor would result in a higher sensitivity wideband sensor.

TABLE 1. *Design attributes of practical, high-sensitivity piezoelectric displacement sensor/preamplifiers in the frequency range of 20 kHz to 1 MHz for wood or polymer specimens.*

1. A piezoelectric contact sensor can provide the best sensitivity (Boltz and Fortunko 1995).
2. The sensor aperture must be smaller than the expected wavelength (Scruby 1984). Wavelength = (Sound velocity at a certain frequency)/(frequency).
3. The first transistor must have low input capacitance, low current electrical noise and low voltage noise (Fortunko et al. 1992).
4. The sensor element (piezoelectric) must have high capacitance relative to parasitic capacitance (Fortunko et al. 1992).
5. In the case of sensor elements with marginal capacitance (relative to cable capacitance and transistor input capacitance), the first transistor should be physically located at the sensor element to reduce parasitic capacitance (Fortunko et al. 1992; Shiwa et al. 1993).
6. An out-of-plane displacement sensor must have a combination of sensor spring constant and backing mass that results in a sensor resonance frequency below the use range (Fortunko et al. 1992).
7. Both an in-plane and an out-of-plane sensor should have a sensor element spring stiffness well below that of the specimen material "below" it (Eitzen and Breckenridge 1987).
8. The sensor should be designed to minimize acoustic resonances (Scruby 1984; Proctor 1982).
9. The sensor should be shielded from electromagnetic interference.
10. The sensor should be protected from mechanical damage.
11. The sensor should not require the specimen to be an electrical conductor for use on non-conductor specimens.

BACKGROUND RESEARCH

Since polyvinylidene fluoride (PVDF) has a modulus about one order of magnitude less than a typical piezoceramic, early research examined a commercial PVDF sensor with two folded layers of 28-μm film. This sensor was applied as an in-plane sensor. In both its standard size (13.5 mm × 26.2 mm) and a modified small aperture size (5.6 mm × 6.2 mm), its output was some 50 dB less than a refer-

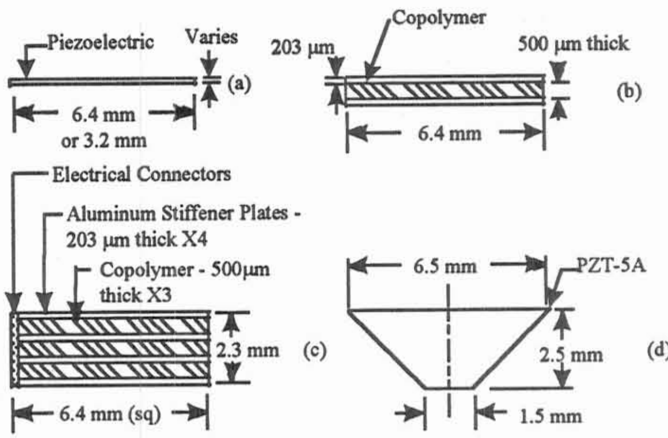

FIG. 1. Geometry of piezoelectric sensing elements: a) Electroded film (PVDF, or copolymer); b) Stiffened single layer copolymer; c) Stiffened triple stack copolymer (layers connected in parallel electrically); d) Electroded conical PZT element.

ence out-of-plane piezoceramic sensor on an aluminum plate (Hamstad 1994). Since finite element modeling of wave propagation due to the wideband pencil-lead-break source indicated the in-plane displacements were at most only 6 dB down from the out-of-plane displacements, in-plane sensors were dropped from future consideration (Hamstad 1994).

Since this early study indicated that polymer piezoelectrics provided much better response in an out-of-plane rather than in-plane mode, a second study examined mass-backed out-of-plane piezopolymeric sensor elements relative to a conical piezoceramic sensor element (Hamstad 1995). This study utilized a

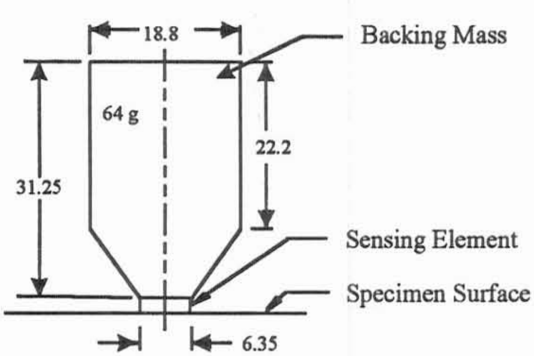

FIG. 2. Typical assembly of sensor system tested with tapered backing-mass design. All dimensions given in mm.

large (1.2-m × 1.5-m × 9.5-mm) polymethyl methacrylate polymer (PMMA) plate (modulus about 3.4 GPa) and a large (1.2-m × 1.5-m × 3.6-mm) aluminum alloy plate (modulus about 72 GPa). The large plates resulted in transient wave propagation without early reflections from the plate edges. Figures 1 and 2 show the sensor element designs and the backing mass configuration. To provide a calibrated absolute reference, the response of the experimental sensors was compared relative to the National Institute of Standards and Technology Standard Reference Material (NIST/SRM) lead zirconate titanate (PZT) conical sensor/preamplifier. This reference sensor (mass-backed, 609 g) has a flat frequency response and linear phase response from about 20 kHz to better than 1 MHz on steel. The response sensitivity is 177 v per μm of out-of-plane displacement. The NIST/SRM sensor has a conical element with an aperture of about 1.5-mm diameter and capacitance estimated to be approximately 20–25 pF. The closely coupled voltage preamplifier has a gain of −6 dB when its output is terminated as specified in 50 Ω. It also has a "band-dip" filter centered around 450 kHz, which results in an additional −3 dB to flatten a slight resonance that appears to originate from the 2.5-mm height of the truncated cone. This pre-

TABLE 2. *Key properties of piezoelectric materials.*

Material	Density 10^3Kg/m^3	Relative Dielectric Constant	Piezoelectric Stress Constant (In-Plane), g_{31}, 10^{-3}Vm/N	Piezoelectric Stress Constant (Out-of-Plane) g_{33}, 10^{-3}Vm/N	Modulus 10^9N/m^2
PZT-5A*	7.50	1,725	−11.4	25.0	63
			(Morgan Matroc 1991)		
PVDF+	1.8	12	216	−339	3
Copolymer+	1.9	8.3	?	−250	
	(Ikeda 1990)				4
PZT-5* (Alternate)	7.45	2,750	?	20.9	?

* Staveley Sensors, Inc.; East Hartford, CT.
\+ AMP Incorporated; Valley Forge, PA.

amplifier has flat frequency response from about 300 Hz (−3 dB down) to well above one megahertz. The input capacitance is limited (due to the lack of a connection cable) to approximately 15–20 pF (input capacitance ≈ 10–15 pF, and connectors ≈ 5 pF). Physically the electrical connections to the sensor are made through a thin rod (from the preamplifier) that bears on the brass backing mass of the sensor and through the test sample to the aluminum case of the preamplifier. On lower modulus materials, the NIST/SRM still has a flat response; but the output is reduced due to the stiffness of the piezoceramic relative to the specimen material (Hamstad 1994).

The key properties of the piezoelectric materials of the experimental sensors are given in Table 2 (Morgan Matroc 1991; Ikeda 1990). Both PVDF and the copolymer (P(VDF-TrFE)) were included in configurations summarized in Table 3. The preamplifier for the experimental sensors uses a low current-noise junction field effect transistor (FET) and bias resistor in an aluminum case that again fits over the mass-backed sensor. The FET (2 SK 932) and bias resistor are connected to a commercial unit (Fuji Ceramics, Model A1002). The concept was adapted from Shiwa et al. (1993). This preamplifier is also flat with a gain of about 8.5 dB (Cal Mode) from about 8 kHz (−3 dB down point) to well above a megahertz. The input capacitance seen by the sensor is estimated to be 15–20 pF. All experiments were carried out by applying out-of-plane, 0.3-mm diameter, 2H pencil-lead-breaks to the same surface of the plate on which the sensors were mounted. The sensors were located at a distance of 0.254 m from the source. Since the polymer plate does not conduct electricity, small pieces of copper foil (approximately 6 mm × 50 mm × 13 μm thick) were placed under the sensors and run along the polymer plate to the preamplifier case. This technique provided the connection

TABLE 3. *Summary of polymer sensor test configurations.*

Configuration (Dia mm)	Element material	Nominal thickness, μm	Number of layers	Electrodes	Backing mass, g	Pre-amp	Calculated total capacitance, pF	Spring stiffness 10^8N/m
Single Layer (6.4)	PVDF	28	1	*	64	FET	120	35
Single Layer (6.4)	PVDF	110	1	*	64	FET	30.6	8.8
Single Layer (6.4)	Copolymer	500	1	*	64	FET	4.3	3
Single Layer (3.2)	Copolymer	500	1	*	64	FET	1.1	0.6
Stiffened Triple Layer (6.4)	Copolymer	500	3-copolymer 4-stiffeners	***	64	FET	12.9	0.9
Conical Aperture (1.5)	PZT 5A	2,500	1	+	64	FET	20–25	1.3

\+ Nickel 12.7 μm nominal.
* Thick Ag Ink 5–7 μm nominal.
*** Aluminum Alloy 203 μm thick nominal.

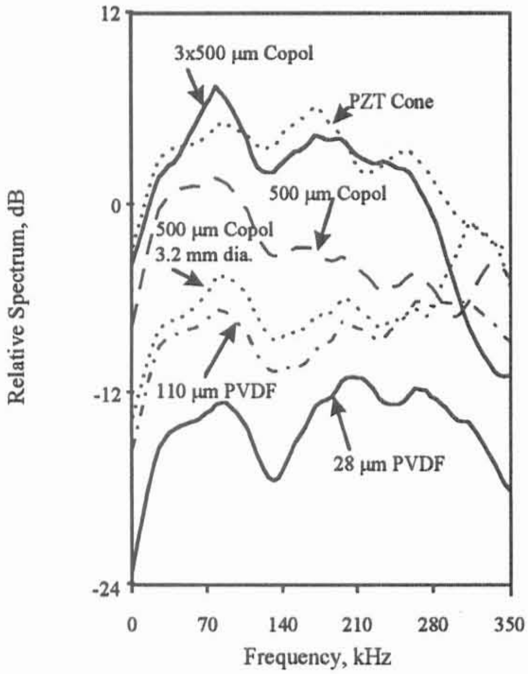

FIG. 3. Spectral response relative to NIST/SRM on polymer plate. Spectrums moderately smoothed for clarity. All polymer sensors about 6.4-mm diameter, except as indicated. Pencil-lead-break source.

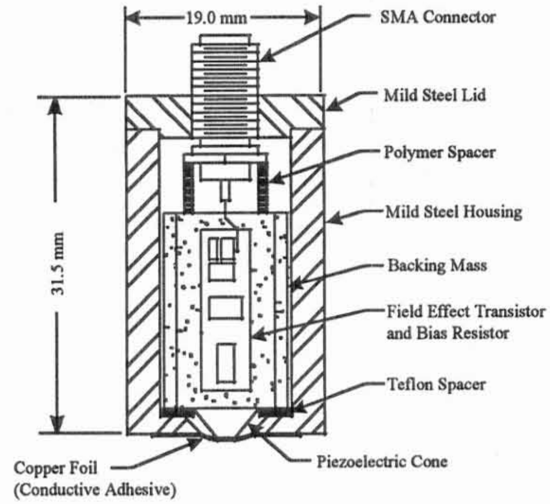

FIG. 4. Schematic drawing of practical wideband high-sensitivity sensor developed at NIST-Boulder.

of one electrode of each sensor to the preamplifier. Physically the other electrode was connected to the preamplifier by a thin metal rod that bears on the brass backing mass of the piezoelectric sensor. For the copper foil, viscous couplant (Apiezon M) was used on both sides of the foil in the sensor region to acoustically couple the foil to both the piezoelectrode and the polymer plate. The brass backing (64 g) was coupled to the piezoelectric polymers by the viscous grease as well. Figure 2 shows the dimensions of this brass backing and typical "sensor" geometry. The surface of the brass coupled to the sensor element had been ground flat with a smooth surface finish. All waveforms were recorded with a 12 bit digital recorder operating at either 5 or 10 Msamples/s.

Under these experimental conditions on the aluminum plate, it was determined that the best polymer sensors had approximately flat frequency response from about 40 kHz up to 1 MHz and were some 12 dB less in response sensitivity than the PZT cone (Hamstad 1995). But on the polymer plate, the best polymer sensor (a 3-× 500-µm stack of copolymer) had nominally the same response sensitivity as the PZT cone. These latter results are shown in Figure 3. Due to the effects of material attenuation, the response spectrums are shown only up to 350 kHz. Above about 280 kHz the original Fast-Fourier-Transforms (FFT) are not valid since the dynamic range of the waveform recorder is exceeded.

PRACTICAL SENSOR DESIGN

Since the best piezopolymeric sensor had no more response sensitivity (on the low modulus polymer specimen) than the PZT cone, and since the construction of a practical sensor (rather than the experimental sensor configuration) with the PZT cone was considerably easier than with a polymer piezoelectric, the next step in the research was to characterize and use a practical conical PZT sensor developed at NIST (Boulder, CO) (Hamstad and Fortunko 1995). This sensor meets most of the criteria of Table 1 with the exception of the relative spring stiffness of the sensor element to a wood or polymer sample. Figure 4 shows a schematic sketch of this sensor, and Fig. 5

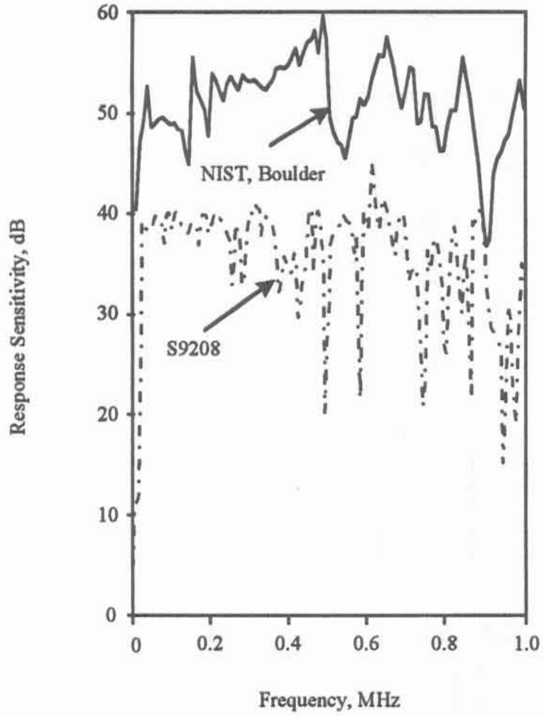

FIG. 5. Response sensitivity of new wideband sensor on steel (from NIST—Gaithersburg) and also commercial wideband sensor (S 9208) under similar conditions. Results shown at 0 dB gain of preamplifier and dB reference 1 v per μm displacement.

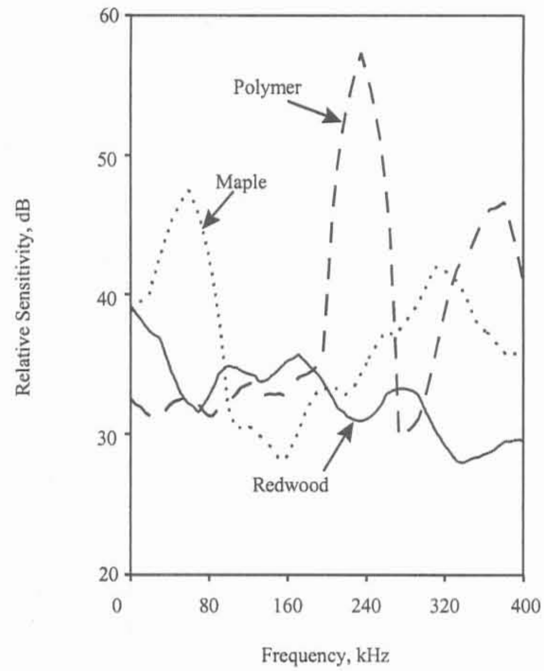

FIG. 6. Signal-to-noise sensitivity of new wideband sensor/preamplifier relative to commercial wideband sensor/preamplifier. On polymer plate specimen, maple plate, and redwood bar. Results at 0 dB gain and noise for sensors coupled to air. Pencil-lead-break source. Spectrums moderately smoothed for clarity.

shows the flatness of the sensor as determined on the large steel block at NIST, Gaithersburg, MD. This calibration was done with the closely coupled low noise FET (referred to above) used in the complete package. Prior to plotting in Fig. 5, the preamplifier gain of 8.5 dB was subtracted out. Hence, this figure shows the response sensitivity for 0 dB gain. The phase response (not shown) was determined during the calibration to be approximately linear out to about 900 kHz.

SIGNAL-TO-NOISE SENSITIVITY VERSUS COMMERCIAL SENSOR

The signal-to-noise sensitivity of the new sensor/preamplifier combination was compared in three cases of low modulus specimens with that of a commercially available wideband sensor/preamplifier. The commercial sensor is also a "flat" wideband sensor with its response sensitivity also shown in Fig. 5. Its phase response is not provided by the manufacturer. This calibration curve (Physical Acoustics Corp. 1995) was obtained on a large steel block similar to that at NIST/Gaithersburg. The comparisons were made on the polymer plate (described above), a maple veneer plate (dimensions 914 mm × 914 mm × 3.3 mm) and a redwood bar (34 mm square and a length of 3.046 m). The procedure in each case was to record the response waveforms for pencil-lead-breaks (with the sensors coupled to the specimens) and the electrical noise waveforms (with the sensor faces coupled to air). All the waveforms were corrected to 0 dB gain, and then the FFTs were calculated. The FFTs were averaged for at least five waveforms in each case.

Figure 6 shows the relative signal-to-noise responses of the new NIST/Boulder sensor relative to the commercially available sensor obtained using its associated commercial preamplifier (modified according to the manufacturer's directions to obtain wideband amplification). The relative sensitivity curve was obtained for the polymer plate with an out-of-plane leadbreak source at 0.254 m from the sensors. Figure 6 also shows the same relative signal-to-noise sensitivity on the maple plate for an out-of-plane leadbreak source at 0.254 m from the sensors. The propagation direction was at 45° to the longitudinal direction. To keep the Apiezon M couplant from soaking into the porous wood, approximately 90-μm-thick transfer tape was applied to the wood at the sensor location prior to applying the couplant. In addition Fig. 6 shows the same relative signal-to-noise sensitivity for a leadbreak applied to the center of one end of the redwood bar with the sensors located at the center of the other end of the bar. Again the transfer tape was used to prevent the couplant from soaking into the wood. The lengths of the response waveforms used to calculate the FFTs for Fig. 6 were 150 μs (polymer), 460 μs (maple), and 1.4 ms (redwood). Due to the dynamic range limitations, the approximate upper frequency of valid results in Fig. 6 is 420 kHz (polymer), 160 kHz (maple), and 60 kHz (redwood).

OPTIMIZATION OF CONICAL ELEMENT

Since the conical element resulted in the best practical sensor, the possibility of optimizing the conical element was examined for specimens with low modulus. The current element in the practical sensor is PZT-5A with an aperture of 1.5-mm diameter. Using the polymer plate and the previously described configuration (see Fig. 2), a series of cones with changes in the aperture diameter were tested. The diameters examined included 0.25, 0.5, 1.0, 1.5, 2.0, 3.5, and 4.0 mm. Smaller diameters reduce the element spring stiffness. In addition, a 1.5-mm aperture PZT 5 cone with an alternative ceramic formulation was tested. This material was chosen because of its higher dielectric constant (see Table 2), which could be expected to translate into a higher capacitance sensor element. Figure 7 shows the relative response sensitivities on the polymer plate of some of the different aperture cones of PZT-5A (relative to the NIST/SRM). Figure 8 shows the same relative response of the alternate PZT 5 and PZT-5A both for a 1.5-mm aperture on the polymer plate.

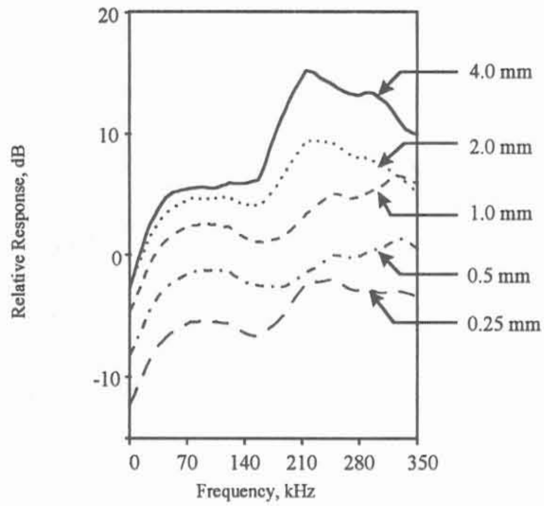

FIG. 7. Response sensitivity relative to NIST/SRM as a function of PZT-5A conical element aperture diameter. On polymer plate specimen all at 0 dB gain. Lead-break source. Curves significantly smoothed for clarity.

DISCUSSION OF RESULTS

Experimental results to date indicate that both a conical piezoceramic-based sensor and a piezoelectric polymeric-based sensor have approximately the same response sensitivity on a low modulus polymer specimen. Since the conical (NIST/SRM) absolute reference standard with its piezoelectric ceramic element has been found to have a response sensitivity that was about 20 dB down from the actual polymer surface displacements (Hamstad 1994), the expectation was that response sensitivity could be improved with a better design utilizing a polymer element. From a mechanics perspective, the key to increasing the response sensitivity (to the point where the sen-

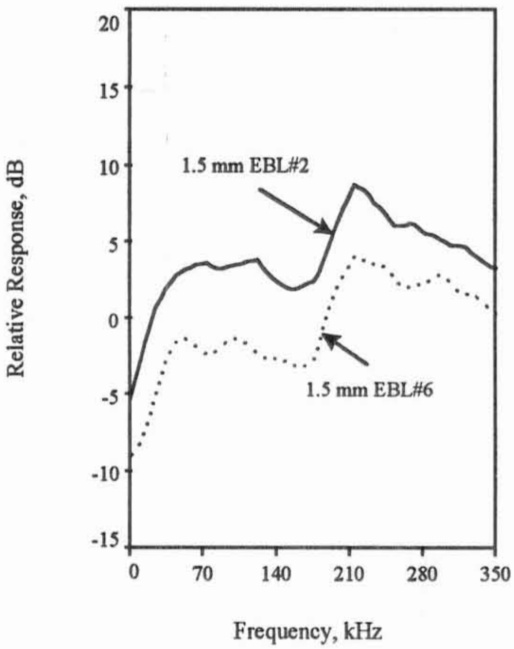

FIG. 8. Response sensitivity of higher (EBL #6) versus lower dielectric constant PZT 5 cones on polymer plate. Relative to NIST/SRM. Both at 0 dB gain. Lead-break source. Spectrums moderately smoothed for clarity.

sor element thickness is changed by the same value as the out-of-plane displacement acoustic wave) requires a significant reduction (at least one order of magnitude in the case of the conical element; see Hamstad 1995) in the spring stiffness of the sensor element. The piezoelectric polymer stack partially accomplishes this since its spring stiffness is better matched to the specimen material than the piezoceramic (Hamstad 1995). Experimentally this improvement in stiffness matching did not result in a higher response sensor. The reason for this result is that at the same time the capacitance of the sensor element must not be reduced too much or else the electrical output will be reduced when the parasitic capacitance begins to approach or exceed the sensor capacitance. Since mechanical sensor stiffness and sensor capacitance both decrease with reduced sensor diameter and increased sensor thickness, a stiffness reduction for a polymeric piezoelectric was not compatible with maintaining the electrical response.

Additional experiments with a copolymer stack with an even lower spring stiffness due to a 3.2-mm diameter instead of a 6.4-mm diameter verified the loss in sensor element capacitance more than offset the decrease in element spring stiffness. Thus all sensor designs of the current type require a compromise with currently available piezoelectric polymer materials. If a low modulus polymeric piezoelectric with a much higher dielectric constant could be developed, then it might be possible to optimize (decrease the diameter and increase the thickness) the geometry of the polymeric sensor to increase the response sensitivity. Hence, currently the conical PZT 5A element provides the best alternative for a high response sensitivity wideband sensor due to its relative ease of construction.

The newly developed practical wideband sensor (Hamstad and Fortunko 1995) does offer significant advantages over a commercial wideband sensor on low modulus materials such as wood and polymers. The comparison of Fig. 5 shows that the new sensor is at least as flat as the commercial sensor when its response is calibrated on a large steel block. And, further, its response sensitivity is about 10 dB higher. When the sensitivity (signal-to-noise ratio) of the new sensor is compared to the commercial wideband sensor on low modulus specimens, the new sensor exhibits a substantial sensitivity advantage. Figure 6 shows that the advantage averages about 30 dB on the PMMA polymer plate, the maple plate, and the redwood bar. Closer examination of the relative noise of the two sensor/preamplifier combinations reveals that a significant part (10 to 20 dB) of the sensitivity increase can be traced to lower electronic background noise of the new sensor/preamplifier. Figure 9, which compares the electronic noise of the two sensor systems, shows that this noise reduction is concentrated at the lower frequencies that are most relevant to materials with significant material attenuation at higher frequencies.

Possible optimization of the response of the new sensor for use on low modulus materials

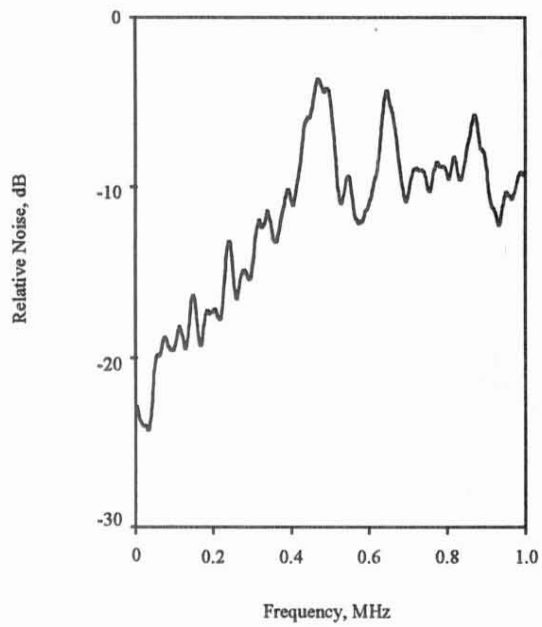

FIG. 9. Noise coupled to air of new sensor/preamplifier relative to commercial sensor/preamplifier. Both at 0 dB gain. Spectrum slightly smoothed.

was examined by changing the diameter of the aperture of the cone. Figure 7 shows that some increase in response sensitivity on a polymer specimen is possible as the aperture diameter is increased, but the flatness of the sensor is compromised by a resonance centered about 210 kHz with the larger aperture diameters. An additional attempt to optimize the response of the conical element by choosing a PZT 5 material with a higher dielectric constant did not produce an improvement. Figure 8 shows a decrease in response sensitivity of about 5 dB for an increase in the dielectric constant of about 60%. It is not clear why the response sensitivity dropped as the 60% increase in sensor element capacitance (assuming capacitance proportional to dielectric constant) should have more than offset the small 16% decrease in the out-of-plane piezoelectric stress constant.

CONCLUSIONS

A series of research efforts has examined the optimization of the sensitivity (signal-to-noise ratio) of wideband acoustic/ultrasonic contact displacement sensors for low modulus specimen materials such as wood and polymers. It was found that conflicts between mechanical and electrical design optimization prevent attaining a better response sensor using available piezoelectric polymer sensor elements as compared to a conical piezoelectric ceramic element. In spite of the lack of optimization of the polymeric piezoelectric sensor, it was found that a newly developed practical version of a mass-backed conical PZT-5A sensor element combined with a low noise closely coupled field-effect-transistor results in significant sensitivity increases over an existing commercial wideband sensor/preamplifier on low modulus samples of wood and polymers. This new sensor will enable development of wideband acoustic/ultrasonic NDE techniques.

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