DETERMINATION OF THE ABSOLUTE SENSITIVITY LIMIT OF A PIEZOELECTRIC DISPLACEMENT TRANSDUCER

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INTRODUCTION

Many ultrasonic techniques, such as conventional acoustic emission [1], waveform-based acoustic emission [2] and ultrasonic testing of high-stiffness reinforcing fibers [3], require highly sensitive, broadband, displacement transducers. Optical probes, such as interferometers, offer both large dynamic range and a very wide bandwidth, but do not exhibit the sensitivity needed for such applications [4, 5]. Piezoelectrics, on the other hand, have approximately 40 dB higher sensitivity than optical probes and can be designed to exhibit an acceptably wide bandwidth [6, 7]. In our applications we typically use transducers that exhibit flat frequency response from 10 kHz to 1 MHz on metals. This paper details a procedure by which the noise floor of one of our "HFHS", piezoelectric transducers can be measured and compared to a model.

The principle of our modeling and experimental approach is illustrated in Figure 1. Here, for clarity, we consider only two primary noise sources: $\delta_{NS}$, the thermal displacement noise level and $V_{NA}$, the electronic noise associated with the preamplifier electronics. In Figure 1, $\delta_{SS}$ denotes the displacement amplitude of an incident ultrasonic signal, $R$ is the transducer responsivity defined as the ratio of output voltage to input displacement, $G$ is the amplifier voltage gain and the voltage output of the preamplifier, $V_{OUT}$, is given by

\[ V_{OUT} = \delta_{SS} + \delta_{NS} \]

Figure 1. Simplified Noise Model Configuration.
\[ V_{OUT} = G \sqrt{\left( \delta_{SS} R \right)^2 + \left( \delta_{NS} R \right)^2 + \left( V_{NA} \right)^2}. \]  

From Eq. (1) we can find the minimum detectable surface displacement, \( \delta_{SS} \),

\[ \delta_{SS} \approx \sqrt{\frac{\delta_{NS}^2}{R^2} + \left( \frac{V_{NA}}{R} \right)^2}. \]  

It is evident from Eq. (2) that in order to minimize \( \delta_{SS} \) it is necessary to maximize the responsivity, \( R \), of the transducer and minimize \( V_{NA} \). \( V_{NA} \), however, is typically fixed. In the case of a low-noise field-effect transistor (FET) system, \( V_{NA} \) is typically 1 to 2 nV/\sqrt{Hz}. \( \delta_{NS} \) is a physical property of the substrate and can be estimated using the fluctuation dissipation theorem [8] as shown in reference [4]. For our purposes it is convenient to put Eq. (2) in the form:

\[ \delta_{SS}^2 = \frac{\left( \delta_{NS} R \right)^2 + \left( V_{NA} \right)^2}{R^2}. \]  

To estimate a typical \( \delta_{NS} \), we can use expressions for the half-space, mechanical impedance from Greenspan [9], and the impedance, \( \Delta \rho v_E \), for a rod geometry, where \( v_E \) is the extensional wave velocity. These impedances can be used in conjunction with the fluctuation dissipation theorem to calculate the thermal displacement noise level. In the limit \( kT \gg h\nu \), the root-mean-square (RMS), time dependent displacement fluctuation of a surface area on a specimen with a given mechanical impedance, \( Z \), is approximately

\[ \langle \delta_{\text{min}}(f) \rangle \approx \frac{1}{\pi f} \sqrt{\frac{kT \Delta f}{\text{Re}[Z]}} \]  

where \( \Delta f \) is bandwidth, \( k \) is Boltzmann’s constant, \( T \) is temperature in kelvin, \( f \) is the mean frequency and \( Z \) is the complex mechanical impedance. Here \( Z \equiv F/v \), where \( F \) is the applied harmonic force and \( v \) is the resultant phase velocity.

Optical interferometers used to sense surface displacements generally do not have sensitivities near the thermal displacement noise level [10, 11]. In Figure 2 we compare the sensitivity limits of a practical Michelson interferometer with the thermal displacement noise levels in an aluminum half-space and rod. We assume a 1 mm diameter contact area, a temperature of 296 K, a 7 mW, 632.8 nm laser and a polarized-optics interferometer [12]. In this paper we demonstrate how to measure the practical sensitivity of our transducers in the region bounded by the limit of an interferometer and the thermal displacement noise level of an aluminum half-space in the frequency region from 100 kHz to 1 MHz.
EXPERIMENTAL PROCEDURE AND CONFIGURATION

To experimentally determine the sensitivity limit of a piezoelectric, surface-displacement transducer we use a procedure analogous to that described by Motchenbacher and Fitchen [13] for determining the noise-equivalent-power of photodetectors. In our case we use Eq. (3). The experimental procedure and associated apparatus are illustrated in Figs. 3 and 4. Specifically, we use a variable amplitude piezoelectric source in conjunction with a Michelson interferometer to determine the responsivity, $R$. We also measure the total noise of the system at the output of the amplifier and calculate the noise bandwidth. $R$ corresponds to the denominator, and the total noise corresponds to the numerator in Eq. (3).

The sample used for the sensitivity measurements is a 7075 (T-6) aluminum half-cylinder with a diameter of 609.8 mm and a thickness of 177.8 mm. A conical-type transducer ("HFNP" in Figure 4) is used to generate surface acoustic waves (SAWs). The transducer under test (HFHS) is situated 95.25 mm from the HFNP transmitting transducer on the surface of the sample and the optical beam probe is incident equidistant on the opposite side. We drive the HFNP transducer with a narrow-band, electrical signal. The SAWs generated by the HFNP are then detected simultaneously by the interferometer and the HFHS transducer. At specific frequencies the transmitting transducer is driven at different voltage levels. At each level, the displacement is measured using the Michelson interferometer and the output voltage (p-p) of the receiver transducer is also recorded. The signal and noise RMS values are determined using appropriate "crest" factors [13] to account for the spectral characteristics of the SAW signal and noise forms.

Figure 2. Displacement vs. frequency region of interest.
Figure 3. Response sensitivity determination.

Figure 4. Measurement configuration.
MODELLING

Figure 5. illustrates the piezoelectric preamplifier configuration used in our studies. The conical piezoelectric element is mechanically coupled to the specimen and a large mechanical backing. It is also electrically loaded by the bias resistor and the input impedance of the preamplifier. The dotted components in Figure 5 denote the input electrical characteristics of the first stage of the preamplifier. $C_m$ is the Miller capacitance (3 pF), $C_{in}$ is the input capacitance (~10 pF), $R_{in}$ is the input resistance and $R_B$ is the gate self-biasing resistor (3.3 MΩ). Our model is considerably more sophisticated than in Figure 1. Specifically, we take into account the electrical noise caused by the preamplifier and bias resistor and the mechanical noise caused by dissipation in the piezoelectric, backing mass and specimen. Our computer model also includes the effects of electrical loading of the piezoelectric element by the preamplifier and the mechanical loading by the backing and the specimen. A block diagram of our complete computer noise model is shown in Figure 6.

Figure 5. Receiver configuration

Figure 6. Block diagram of computer transducer signal and noise model.
RESULTS

Figure 7 shows the minimum detectable displacement of the piezoelectric transducer as measured using the set-up of Figure 4. Also shown in Figure 7 are the thermal displacement noise level for an aluminum half-space and the limit calculated using the computer noise model of Figure 6. The measured sensitivity of the transducer is within 6 to 10 dB of the thermal displacement noise and only a few dB above the model results. Specifically, using this transducer we can achieve a sensitivity of $5 \times 10^{-17} \text{m}/\sqrt{\text{Hz}}$ on an aluminum substrate. We attribute the discrepancy between the model results and the measured values to the model’s current inability to account for the displacement division caused by the adhesive copper layer between the piezoelectric and the specimen.

These results were acquired using an interferometer which exhibits several undesirable characteristics. The HeNe laser used in the interferometer is both low-power (7 mW) and noisy (3% fluctuation on the power supply). The detector arrangement was only minimally shielded, and the robustness of the stabilization electronics was minimal. An improved optical system would provide a much greater range of operation in both displacement and frequency.

Figure 7. Interferometer, transducer model, thermal limit and measurement results.
DISCUSSION

We have described a process by which a sensitive, piezoelectric, surface-displacement transducer can be characterized using a less-sensitive, interferometric system. We have accounted for and modelled the noise sources which affect such a transducer. We have also demonstrated that a conical-type transducer has sensitivity approaching the thermal displacement noise level of an aluminum substrate. In order to extend this work to materials such as polymers and composites we are currently building an infra-red (1.064 μm), diode-pumped, laser interferometer which has increased power (200 mW) and less noise (0.1%) than the HeNe laser (7 mW, 3%) used in this work. Using an infrared laser will also allow us to apply this technique to materials with lower visible-light reflectivity and provide increased dynamic range. Finally, we have adopted a stabilization system with much greater damping range (4 μm, as opposed to 1.25 μm used in this work). These enhancements will be instrumental in extending these techniques to the characterization of surface displacement transducers for use on polymers and composite materials.

REFERENCES