ABSOLUTE SENSITIVITY OF AIR, LIGHT AND DIRECT-COUPLED WIDEBAND ACOUSTIC EMISSION TRANSDUCERS

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INTRODUCTION

Previous work has compared the relative performance of various wide-band ultrasonic transducers used as receivers [1]. Studies have also been made comparing the merits of various optical sensors [2] and evaluating their applicability to acoustic emission (AE) [3]. In this paper, the calculated and measured sensitivities of such transducers are compared with the sensitivity of transducers capable of detecting low amplitude AE events in steels [4, 5]. While optical sensors appear to provide many practical advantages over contact sensors, particularly at very low frequencies, it is found that they cannot meet the sensitivity requirements for wide-band AE detection in metals. Furthermore, it is found that a new transducer, recently developed at NIST, has sufficient sensitivity for such applications. In particular, this high-fidelity, high-sensitivity (HFHS) sensor is found to exhibit sensitivity which approaches the "thermal rattle" limit in aluminum within 10 dB over the 250 kHz to 1 MHz region. Also, it is shown that the new transducer's noise floor is well below both the necessary sensitivity level to monitor AE in metals and the sensitivity limits of both optical and airborne-sound transducers. Furthermore, its performance is in good agreement with the computer model used in its design.

ACOUSTIC EMISSION DETECTION REQUIREMENTS

Scruby, Wadley and Simmons [4, 5] have shown that a transducer with a sensitivity of 10^{-16} $m/\sqrt{Hz}$ is capable of detecting low amplitude AE events in metals. Since we are interested in waveform-based AE applications, which require very high-fidelity, a flat frequency response from 20 kHz to 1.2 MHz is necessary. In order to avoid loading the sample surface, a noncontacting method would be desirable. Furthermore, the transducer must be single-mode; it must measure either displacement or velocity in the specified frequency region. Finally, the transducer should be able to operate on materials exhibiting a wide range of material mechanical impedances as defined by Greenspan [6]. The mechanical impedance approaches the Aρc limit at high frequencies. Here A is the contact area, ρ is the density and c is the elastic wave velocity.

In this paper, we consider optical interferometers, optical knife-edge detectors, optical heterodyne sensors, air-coupled capacitive transducers, and a new, direct-coupled, conical-type piezoelectric transducer recently designed at NIST. In order to determine which transducer would best meet our needs, we have made a careful review of the literature to determine the absolute sensitivity limits of the noncontact transducers and used a computer model of the new HFHS transducer. We also verified the performance of the HFHS sensor using a Michelson interferometer.

THERMAL LIMITS

The mean square of the displacement of the atoms in a cubic lattice can be calculated following either the classical approach of Debye [7] and Waller [8] or a rigorous quantum mechanical derivation first given by Ott [9]. This thermal limit, the square root of which is included in Fig. 1, is [10]

$$\langle u_\infty{}^2 \rangle = \left(\frac{\hbar}{2M}\right)\frac{1}{3N}\sum_{\mathbf{k}_j}\frac{1}{\omega_j(\mathbf{k})}\coth\left(\frac{\hbar\omega_j(\mathbf{k})}{2k_BT}\right). \tag{1}$$

If the sum over **k** is replaced with integrals restricted to a corresponding real-space area on a half-space and only surface-normal phonon components are considered then the root-mean-square (RMS) fluctuation reduces to an expression [11] which is identical to a specialization of the Fluctuation Dissipation Theorem first obtained by Callen and Welton [12]. In the limit $kT>>h\nu$, the RMS time displacement fluctuation of a surface area on a solid, isotropic, half-space is approximately

$$\langle \delta_{min}(f) \rangle \cong \frac{1}{\pi f}\sqrt{\frac{kT\Delta f}{Re[Z(f)]}}, \tag{2}$$

where Δf is bandwidth, k is Boltzmann's constant, T is temperature in Kelvin, f is the frequency of the vibration and Z is the complex mechanical impedance defined as

$$Z \equiv F/\mathrm{v}, \tag{3}$$

where F is the applied force and v is the resultant surface velocity. Using Eq.(2) and Greenspan's [6] expression for the complex mechanical impedance Z the thermal fluctuation limit is calculated as a function of frequency for a 1 mm diameter circular area on aluminum with a 1 Hz bandwidth. The results are included in Figs. 1 and 4.

SENSITIVITY LIMITS: NONCONTACT TRANSDUCERS

In this study several types of noncontacting transducers are considered. For noncontacting transducer types we determine the sensitivity using published expressions and experimental results [3, 13, 14, 15].

For air-coupled transducers, we use the expression of Tarnow [13]. Tarnow shows that the sensitivity-limiting factors for an air-coupled, capacitive transducer are the membrane volume and the gas constants. Specifically, the minimum detectable displacement is

$$\langle \delta(f) \rangle = \frac{1}{2\pi f \rho c Re[Z(f)]} \sqrt{\gamma k T \frac{P}{V}} , \tag{4}$$

where ρ is the density of air, P is the ambient pressure, V is the membrane volume, f is frequency, c is the speed of sound in air, k is Boltzmann's constant, T is the temperature Kelvin and γ is the ratio of the constant-pressure and constant-volume heat capacities (c_p/c_v). The calculated sensitivity limits for a capacitive air transducer are summarized in Fig. 1.

For interferometric transducers, Wagner and Spicer [14] concluded that the sensitivity of such sensors, regardless of interferometer type, is on the order of $10^{-15}\ m/\sqrt{Hz}$ for a 1 mW, 632.8 nm laser source. In the specific case of a path-stabilized Michelson interferometer the minimum detectable displacement is

$$\delta_{min} = \frac{1}{\mathbf{k}} \sqrt{\left(\frac{h\nu\Delta f}{\eta P_0}\right)} \left(\frac{2^{1/2}[1+\cos(2\mathbf{k}d)]^{1/2}}{\sin(2\mathbf{k}d)}\right) , \tag{5}$$

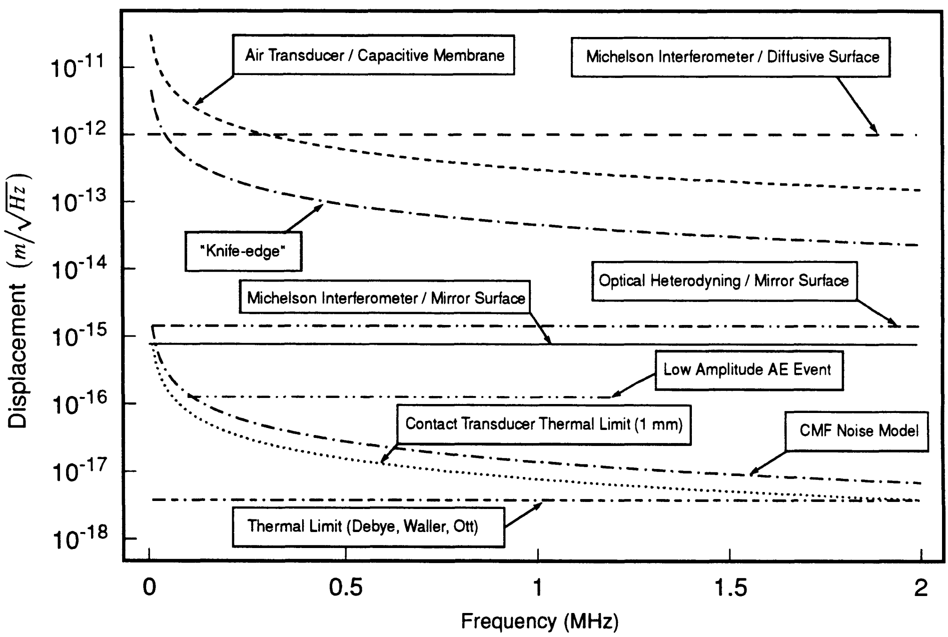

Figure 1. Sensitivities of various transducers, AE event level and thermal vibration limits

where d is the quiescent displacement of the dithering mirror, ν is the laser frequency, h is Planck's constant, Δf is the bandwidth, **k** is the light wave vector, P_0 is the laser power, and η is the quantum efficiency of the photodiodes. In our calculations we use a laser power of 7 mW and a quantum efficiency of 0.9. The results are included in Fig. 1.

For the knife-edge and optical heterodyne sensors calculations we use the expressions of Whitman and Korpel [15], and Palmer and Green [3]. The knife-edge technique, while quite sensitive for high-frequency harmonic (CW) signals, is inherently narrowband because maximum sensitivity is achieved when the probe beam diameter is equal to one-half the acoustic wavelength. It is also important to note that a knife-edge has directional sensitivity; it will not detect acoustic waves traveling at right angles to the plane defined by the laser, point of incidence and detector. The minimum detectable displacement for a knife-edge system is [3]

$$\delta_{min} = (2e\Delta f/\eta P_0)^{1/2}(D/F_1)\left(\Lambda/\left(4\sqrt{2\pi}\right)\right), \qquad (6)$$

where e is the electron charge, P_0 is the laser power, η is the quantum efficiency of the photodiode, F_1 is the focal length of the probe beam lens, D is the beam diameter, and Λ is the acoustic wavelength. For our results, presented in Fig. 1, the same parameters as those used in the interferometer calculations are used. In addition we used a beam diameter of 1 mm, a focal length F_1 of 10 cm and the acoustic wavelength was varied with frequency based upon the acoustic velocity in aluminum.

The optical heterodyne technique is based upon a Doppler shift of the laser probe beam relative to the reference beam. Both beams are frequency shifted by an acousto-optic cell and recombined on a photodetector to produce sum and difference frequencies. Such a system directly determines the velocity of the sample surface. Displacement can be determined by dividing the particle velocity by the angular frequency. The minimum detectable displacement for an optical heterodyne system, using the same parameters and symbols as the calculation for the knife-edge system, is [15]

$$\delta_{min} = (2e\Delta f/\eta P_0)^{1/2}(\lambda/\pi). \qquad (7)$$

THE HFHS TRANSDUCER

The HFHS transducer (Fig. 2a) is a refinement of the NIST SRM [16]. Fortunko and Hamstad [17] have optimized the cone geometry, backing mass and pre-amplifier electronics performance parameters. The HFHS sensor exhibits better sensitivity than the NIST SRM and, owing to rugged design, shielded electronics and the capability to mount it, is suitable for field applications. A schematic of the receiver front-end noise model developed by Fortunko[18] (CMF Noise Model) is included in Fig. 2b.

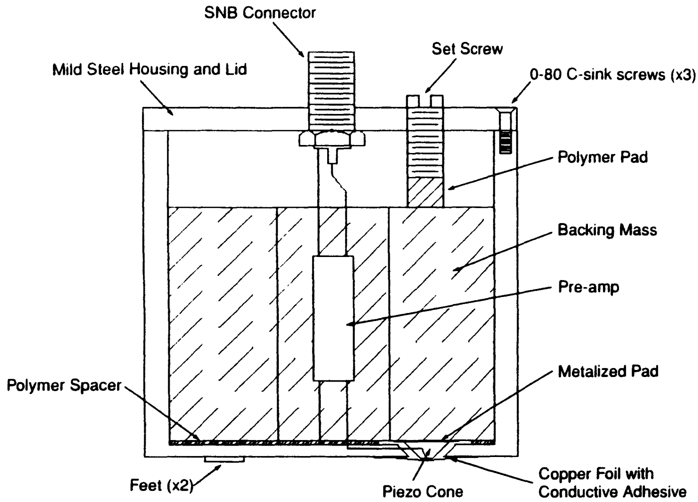

Figure 2a. Cross-section of HFHS direct-coupled transducer.

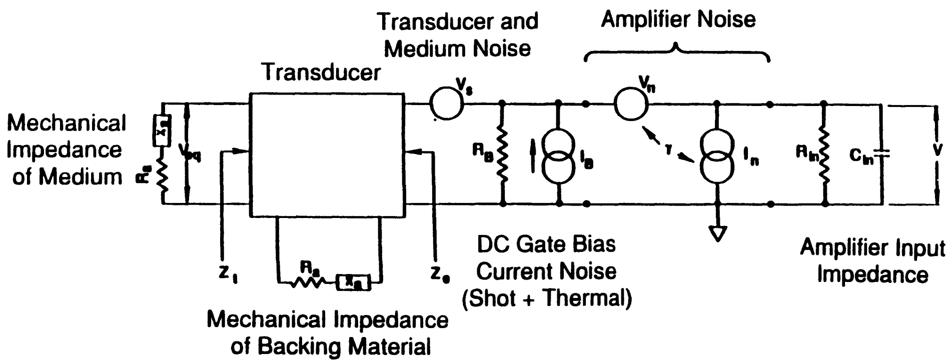

Figure 2b. Receiver front-end noise model.

MEASUREMENT CONFIGURATION

To determine the sensitivity limit of the HFHS transducer, a polarized-optics, path-stabilized Michelson interferometer is used. The sample used for the sensitivity measurements is an aluminum half-cylinder with a diameter of 609.8 mm and a thickness of 177.8 mm. The source used to generate surface acoustic waves is a HFNP conical-type transducer placed one half-radius distant from the center of the cylinder. The HFHS transducer is situated 95.25 mm from the HFNP transmitting transducer on the surface of a 7075 (T-6) aluminum alloy block and the optical beam probe is incident equidistant on the opposite side (see Fig. 3). A stable oscillator, fed through a gated, linear amplifier drives the HFNP transmitting transducer with a narrowband tone-burst. The HFNP then symmetrically generates a narrowband surface acoustic wave (SAW) which is detected by

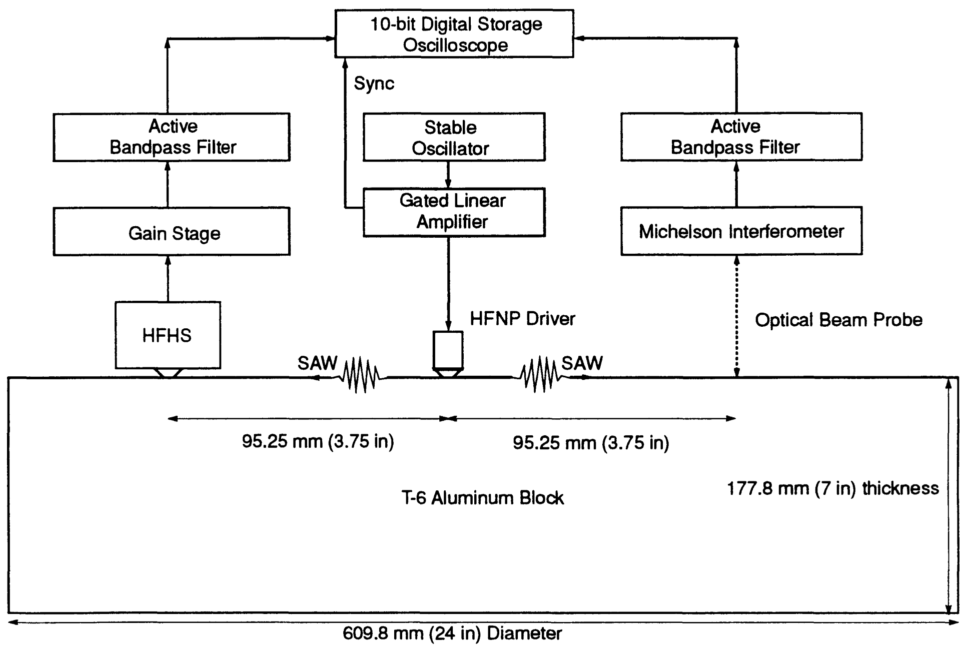

Figure 3. Displacement measurement configuration.

both sensors. 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 HFHS transducer is recorded. The linearity of the HFHS transducer's output voltage vs. displacement is verified separately to prevent signal clipping effects. Next, we determine the signal and noise RMS values using appropriate "crest" factors [19] which account for the spectral characteristics of the SAW signal and noise forms.

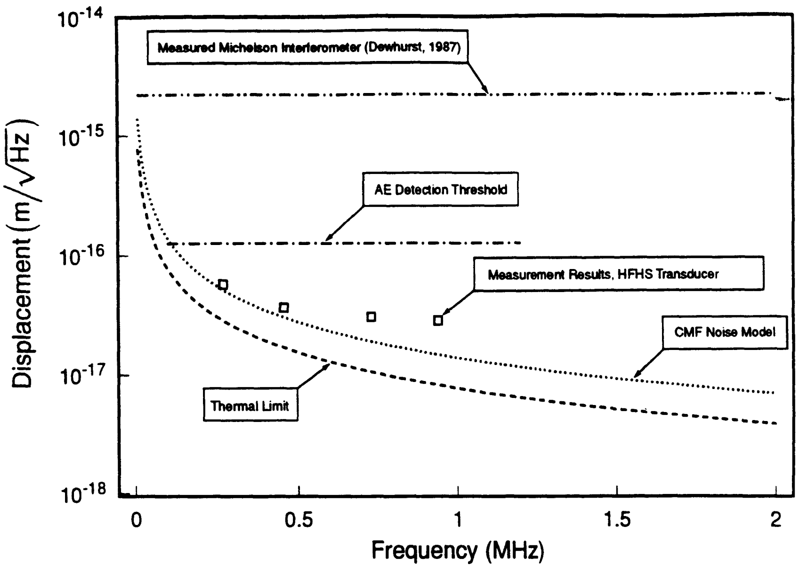

Figure 4. Measured minimum detectable displacement for the HFHS transducer.

RESULTS

We find that the HFHS transducer exhibits sensitivity approaching $3 \times 10^{-17}\ m/\sqrt{Hz}$ on an aluminum substrate at room temperature. Furthermore, the new HFHS exhibits broadband behavior from 20 kHz to 1.2 MHz [12], has sensitivity within 6 to 10 dB of the "thermal rattle" limit of aluminum and is in good agreement with the model, which accounts for noise introduced by the electronics. The results of our measurements are summarized in Fig. 4. In addition, Fig. 4 also shows the "thermal rattle" level for aluminum, the calculated noise floor for the HFHS electronics, the AE detection threshold and the measured sensitivity of a Michelson interferometer from reference [1].

CONCLUSIONS

Based upon an analysis of published results and our own calculations and measurements, we find that a contact piezoelectric transducer (HFHS) exhibits the sensitivity required for observing AE events in metals and ceramics. In particular, we have found that our HFHS transducer, a practical, rugged, shielded transducer with internal gain, exhibits sensitivity well below (10-16 dB) the necessary sensitivity to monitor AE in metals. Using a Michelson interferometer we have verified the performance of the HFHS transducer and found it to be less than 10 dB above the "thermal rattle" limit of the aluminum substrate.

The current HFHS transducer design appears to be well-suited for wide-band AE studies on high modulus materials such as aluminum, steel and ceramics. Future work will seek to extend the capability of these sensors to lower modulus materials.

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