Review of Scientific Instruments

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Cite as: Review of Scientific Instruments **57**, 264 (1986); https://doi.org/10.1063/1.1138926
Submitted: 30 August 1985 • Accepted: 17 October 1985 • Published Online: 04 June 1998

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Self-aligning capacitive transducer for the detection of broadband ultrasonic displacement signals

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(Received 30 August 1985; accepted for publication 17 October 1985)

This paper describes a self-aligning capacitive transducer for detecting broadband ultrasonic signals in structural components. The fixed electrode is the specimen surface while the adjustable electrode is pivoted on a ball mount so designed that the electrode aligns itself parallel to the specimen surface when pressed against it. The working gap between the adjustable electrode and the specimen surface is set by a mechanically driven differential micrometer. The design of the transducer permits minimization of the electrode gap to maximize the sensitivity of the transducer to small amplitude, surface displacement signals. It is demonstrated that such a capacitive transducer is well suited to obtaining a high-fidelity response to transient surface displacement signals which are of broad bandwidth and low amplitude.

INTRODUCTION

An understanding of wave motions and their source characteristics in an elastic or inelastic body requires a detailed analysis of the broadband signals detected by transducers sensing the motions of the specimen surface. The surface motions of the body are described in terms of the normal or tangential displacements or their time derivatives, i.e., velocities and accelerations. Since the general wave motions are nonplanar, transducers approximating point sensors are sought to minimize transducer aperture effects. The field characteristics of a sensor approximate those of a point sensor, provided that its aperture is much less than the wavelength of the dominant frequency component of the detected ultrasonic signal. A review of various transduction techniques which form the basis of a variety of ultrasonic point sensors is included in Ref. 1.

Most of the commercially available transducers are based on piezoelectric elements, producing signals which are generally not proportional to the surface displacements nor its time derivatives, except in a few specialized designs which, up to now, have been used principally in laboratory measurements. Transducer designs for sensing the normal displacements of a flat surface in the MHz-frequency range include a small-gap capacitive transducer,[2–5] optical interferometers,[6–9] and a conical piezoelectric element transducer.[10] The small-gap capacitor and the optical interferometer form the basis of transducers which are essentially of non-contacting type, capable of yielding an excellent displacement response over long time durations of a signal and imposing negligible loading effects on the sensed area of the structure.

The piezoelectric point sensor is a contact-type transducer and generally possesses a greater sensitivity than a capacitive type, but because of its geometry, its output signal corresponds to a displacement signal for only a few ray arrivals. Furthermore, its performance appears to be strongly dependent on the contact pressure between the piezoelectric element and the specimen.

Noncontact transducers are generally less sensitive to surface motions of a specimen than piezoelectric, contact transducers. The need to detect weak acoustic emission signals from sources such as microcracks in materials has motivated a search for means of increasing the sensitivity of the noncontact sensors.

I. OPERATING PRINCIPLES

Figure 1 is a schematic drawing of the capacitive transducer and its associated electronics, including its bias supply and charge amplifier. The elements of the capacitive transducer are a movable electrode and the conductive surface of a specimen. If the leakage capacitance is negligibly small because of an arbitrarily small gap, the output of the charge amplifier, specified in terms of a voltage, is given by

$$V = \eta Q = \eta V_s C = \eta V_s \epsilon S / x, \quad (1)$$

where η is a voltage to charge sensitivity of the charge amplifier, Q is the charge on the electrode, V_s is the bias voltage, C is the capacitance, ϵ is the dielectric constant of the medium comprising the gap, and S is an effective surface area of the capacitor electrodes. If the specimen surface undergoes a wave motion described by its normal displacement, $\Delta x(t)$, where t is the time variable, one obtains a change in the output voltage of the charge amplifier $\Delta V(t)$ given by

$$V + \Delta V(t) = \eta V_s \epsilon S / [x + \Delta x(t)]. \quad (2)$$

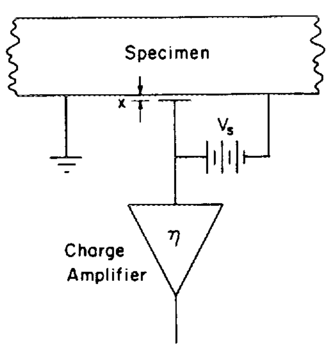

FIG. 1. Schematic diagram of the capacitive transducer and its associated electronics.

In an actual experiment, the initial capacitor gap x is usually set at several micrometers or less. The peak amplitude of a typical normal displacement signal resulting from acoustic emission sources such as the fracture of a glass capillary or the formation of a microcrack may be less than 1 nm. Thus, $\Delta x \ll x$ and Eq. (2) can be expanded in a Taylor series, to obtain

$$V + \Delta V(t) = \frac{\eta V_s \epsilon S}{x}\left[1 - \frac{\Delta x}{x} + \left(\frac{\Delta x}{x}\right)^2 - \cdots\right]. \quad (3)$$

Since the charge amplifier used in the experiments has no dc response, its output signal will be insensitive to the dc component of the input. Also, if Eq. (3) is combined with Eq. (1) and the higher-order terms in $(\Delta x/x)$ neglected, the result is

$$\Delta V(t) = -(\eta V_s \epsilon S/x^2)\Delta x(t). \quad (4)$$

Since the voltage signal $\Delta V(t)$ is linearly proportional to the bias voltage V_s and inversely proportional to the square of the initial gap dimension x, increased transducer sensitivity is obtained by decreasing the initial gap at a sacrifice of the maximum applied bias voltage which is limited by a breakdown of the dielectric medium comprising the gap. The diameter of a typical electrode forming a capacitive transducer may be on the order of a few mm and as small as 1 mm. Because a small gap is sought for maximum sensitivity, an alignment of the movable capacitor electrode parallel to the surface of a specimen is thus an essential requirement. The critical element of the capacitive sensor described here is a ball and pivot joint which provides a neat solution to the electrode-specimen surface alignment problem.

It is clear that the change in the gap dimension $\Delta x(t)$ can be determined from Eq. (4) by measuring the voltage $\Delta V(t)$ and substituting the known values of the capacitor characteristics. The determined $\Delta x(t)$ corresponds to the wave normal displacement signal provided that the adjustable electrode of the transducer remains stationary during the time the measurement is made.

II. CAPACITIVE TRANSDUCER ASSEMBLY

Figure 2 shows a detailed cross-sectional view of the self-aligning capacitor transducer assembly. Shown as part 1 at the top, aligned with the surface of the specimen, is the movable, circular electrode. The results to be shown have been obtained with transducers having electrodes 6.35 and 3.18 mm in diameter but other electrode sizes and shapes up to a maximum practical diameter of approximately 15 mm can be used equally well. The electrode is connected to the charge amplifier and the bias supply voltage via a BNC connector (part 10). The electrode is surrounded by an insulating block (part 2) which is, in turn, encapsulated by a stainless-steel shield (part 3). The surface of the electrode and insulating block is polished optically flat. A sleeve (part 4) is press fit onto the stainless-steel jacket (part 3). The entire assembly is mounted onto a stainless steel ball, 19.05 mm in diameter (part 5), which has a 7.94-mm-diam hole drilled through it to accommodate the sleeve (part 4). The ball is mounted onto the stainless-steel tube (part 9) and the joint silver soldered.

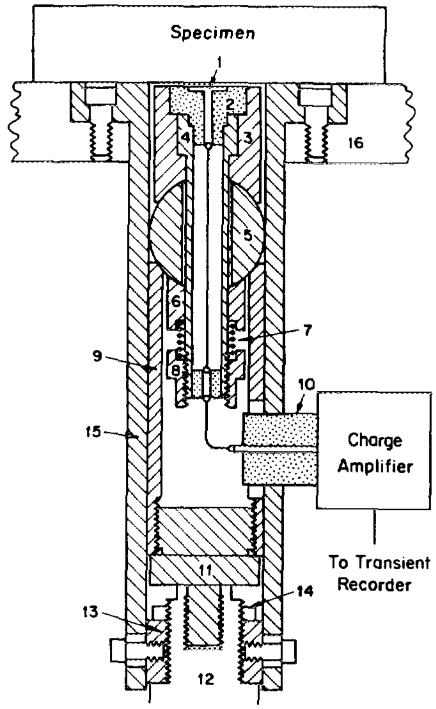

FIG. 2. Cross-sectional view of the self-aligning capacitive transducer assembly. Part numbers refer to those used in the text.

Butting against the bottom side of the ball, outside the sleeve, is a metallic bushing (part 6) which has a spring (part 7) pressing against it in compression. The amount of compression is adjusted by a drive nut (part 8). The entire upper electrode assembly and the bottom bushing (part 6) are held in place against the ball by a compressive spring force. A threaded adaptor (part 11) connects the stainless-steel tube (part 9) to a fine differential micrometer (part 12) which has total span of only 0.25 mm and a resolution of approximately 0.1 μm. The outside flange (part 13) is fastened to the differential micrometer by a clamping nut (part 14). The flange also serves as a mounting block for the entire assembly to part 15, the outer tube. This, in turn, is attached to a specimen holding fixture (part 16) to insure that the adjustable electrode remains stationary during a measurement.

The clearance between the sleeve (part 4) and the ball (part 5) is sufficient to permit the electrode to rotate freely over a range of 5°. The alignment of the micrometer flange (part 13) parallel to the specimen surface within this angle is easily achieved in most measurement situations.

In using the capacitive transducer as a detector of ultrasonic displacement signals, the gap is initially set at about 0.1 mm by adjusting the flange height. Then, the differential micrometer is adjusted to drive the entire electrode assembly into contact with the specimen so that the electrode aligns itself parallel with the specimen surface. Next, the micrometer is readjusted to obtain a particular gap dimension. Because of the self-aligning nature of this transducer, the entire surface of the specimen need not be polished optically flat. The only requirement is that the local area of the test specimen, which forms the fixed plate of the capacitor, must be optically flat.

The design of the fixture was such that there were two, fixed points to minimize the variation of gap spacing resulting from temperature changes of the transducer assembly. As shown in Fig. 2, the entire electrode and tube assembly fits snugly inside another thick-walled tube (part 15) which is made of stainless steel, the same material used in the construction of the capacitor adjustable electrode assembly. The top portion of this outer tube is attached to the specimen mounting block (part 16) by four screws. Near the bottom of the exterior stainless-steel tube (part 15) are two vertical slots by which the inital height adjustment of the differential micrometer can be made. The interior and exterior parts are held together by screws passing through the slot. Any change in the capacitor gap resulting from thermal expansion (or contraction) of the outside tube is compensated by a similar action of the inside capacitor assembly.

III. EXPERIMENTS

A test of the capacitive transducer for the detection of transient ultrasonic displacement signals was made by breaking a glass capillary at the center of the surface of a glass plate of dimension 6×6×1/2 in. (15.2×15.2×1.27 cm) and detecting the transient signals with the transducer located at the epicentral position on the opposite side of the plate. The surface of the plate was coated with a nickel film 0.5 μm thick which was connected to ground. In the experiments described here, the dielectric medium in the gap was air and the gap was set at 6 μm. A bias voltage of 30 V was used. The charge amplifier has a voltage to charge sensitivity of 0.25 V/pC and a bandwidth ranging from 10 kHz to 10 MHz. The output of the charge amplifier was sampled at 60 MHz and digitized to 10-bit resolution. A typical waveform is shown in Fig. 3. Also shown in this figure is the expected theoretical normal displacement signal from a vertical step source which was computed using the computer program developed by Ceranoglu.[11] The rise time of the first P-wave arrival is observed to be less than 0.1 μs, which is the bandwidth limit of the charge amplifier.

The results shown in Fig. 3 are in good agreement with those obtained previously by Hsu and Hardy.[4] The time

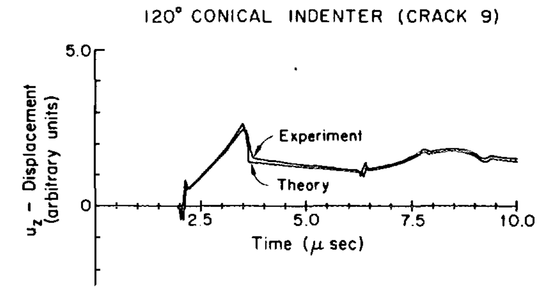

FIG. 4. Computed and measured epicentral displacement waveforms of a crack formed by a conical indenter pressed against a glass plate; synthesized by two dipole sources (horizontal: 1.0; vertical: 0.05).

function of the capillary fracture can be approximated by a Heaviside step function. There is excellent agreement between the theoretical and the measured signals up to the arrival of the 5P ray signal, or 10.9 μs. This observation confirms that the operation of this capacitive sensor is a normal displacement sensor with excellent fidelity. The slight deviation between the theoretical and measured responses after the 5P-wave arrival is probably evidence of wave damping effects in the glass specimen which are not included in the computation of the theoretical waveform. The first reflection from the side wall of the specimen arrives after 26 μs and thus does not appear in the figure.

The same transducer was used to detect the epicentral displacement signal caused by the formation of a mode I crack whose source of acoustic emission has been shown to be of dipolar source type.[12] The penny-shaped mode I crack was generated by pressing vertically a conical indenter of tungsten carbide of semiapex angle 60° onto the surface of a plate of soda-lime glass 0.49 in. (1.24 cm) thick. A normal to the crack plane is parallel to the horizontal surface of the plate. The detected crack signal is shown in Fig. 4. A detailed analysis of such crack signals has shown that their vertical one whose magnitude is about 5% of the horizontal ones.[12] The signal synthesized from such a dipolar source is compared in Fig. 4 to the detected crack signal. The synthetic waveforms were computed using the algorithm developed by Ceranoglu.[11]

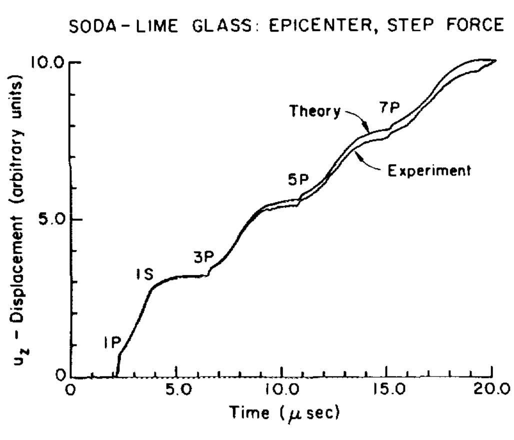

FIG. 3. Computed and measured epicentral displacement waveforms corresponding to a step excitation on a thick glass plate.

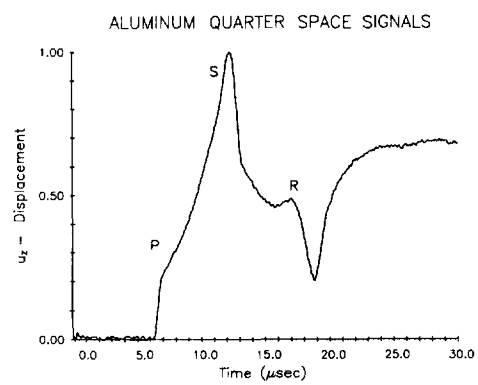

FIG. 5. Measured displacement signal on a quarter space specimen of aluminum. Source and receivers are located 1 in. from the edge.

A final demonstration of the operation of the capacitive transducer is for the detection of signals in a quarter-space specimen for which the theoretical waveforms are as yet unavailable. The quarter-space specimen was fabricated from a block of 6061-T6 aluminum of dimensions, $4\times5\times6$ in. ($10.2\times12.7\times15.2$ cm). The source was a step function, vertical force obtained by the brittle fracture of a glass capillary on one face of the quarter space at a distance of 1 in. (2.54 cm) from the 6-in. edge of the block. The capacitive sensor was located on the 5×6 in. face at a distance of 1 in. from the edge of the block. The detected displacement signal is shown in Fig. 5. The first *P*-, *S*-, and surface-wave arrivals are easily identifiable and are marked *P*, *S*, and *R* in the figure.

ACKNOWLEDGMENT

The support of the National Science Foundation through a grant to the Materials Science Center at Cornell University is gratefully acknowledged.

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