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Miniaturized capacitive transducer for detection of broadband ultrasonic displacement signals

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This article describes a miniaturized version of the capacitive transducer for the detection of broadband, ultrasonic displacement signals at the surface of a specimen. The overall size of the capacitive transducer is a cylinder of 11.11 mm in diameter and 22.86 mm in length, in which four different sizes of the sensing area of the capacitive electrode have been successfully tried, ranging from 1 to 5 mm in diameter. Examples of detected waveforms resulting from such excitations as a glass capillary fracture and the formation of cracks on the surface of a specimen are provided using the specimens of glass and epoxy plates, respectively. The amplitudes of the detected signals are shown to be proportional to the displacements normal to the surface of the specimen. These small transducers are especially well suited for measurements on a laboratory specimen which requires several of them to study an acoustic emission source, to characterize an elastic (or a viscoelastic) behavior of the material, or simply to study the wave propagation.

INTRODUCTION

For the study of (i) an acoustic emission (AE) source such as the formation of cracks[1–3] and irradiation by photon or electron beams[4–6] on the surface of a specimen, (ii) the propagation of transient elastic waves through the bounded medium,[7,8] (iii) the characterization of an elastic[9] or a viscoelastic[10] medium, and so forth, the most desirable type of waves to be detected is the displacement signal or their time derivatives, i.e., velocities or accelerations, since elastodynamically these quantities are directly calculated or needed to calculate other relevant physical quantities. Most of the commercially available transducers are based on piezoelectric elements whose outputs are generally neither proportional to the surface displacements nor their time derivatives, except in a few specialized designs employing a conically shaped element[11] which detects signals proportional to the surface displacements with good sensitivity, but for only a few ray arrivals because of its constructed geometry. Other noncontact displacement transducers are small-gap capacitive transducer[12–16] and optical interferometers,[17–20] both of which are less sensitive than the conical transducer, but yield an excellent displacement response over a relatively long-time duration of signals. All these transducers, regardless of contact or noncontact type, are quite bulky and hence very difficult to employ in experiments that require an array of displacement transducers.

In this article we describe a miniaturized capacitive transducer whose overall shape is a cylinder with dimensions of 11.11 mm in diameter and 22.86 mm in length. Because of its small size, we have successfully used several of them in various experiments for the investigation of brittle fracture of solids[3] and thin-film acoustics[21] and also for the characterization of a viscoelastic medium.[10]

Figure 1 shows a schematic drawing of the capacitive transducer and its associated electronics including its bias supply voltage V_s and charge amplifier whose output voltage to charge sensitivity is denoted by η. V_s can be supplied either from a battery or from a low-noise voltage power supply. The charge amplifier used was an ac amplifier whose output had no dc component. It also had such a high input impedance (order of 10^{12} Ω or higher) that virtually no current flowed in the quiescent state. During its operation which detected transient signals lasting typically less than a few milliseconds, the charge drain was so low (order of a few pC) that V_s remained essentially constant throughout the whole measurement period. In the miniaturized version of the capacitive transducer, the gap between the surface of a specimen and the transducer electrode is maintained with a Mylar polyester film of thickness x which is typically about several μm. If the wave motion resulting from AE sources such as a glass capillary fracture and the formation of cracks causes the surface of a specimen to change its position by Δx, which is usually much smaller than x, then the change in the charge amplifier output voltage ΔV is, according to Ref. 22,

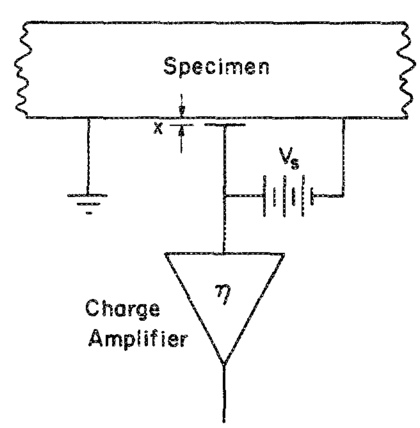

FIG. 1. Schematic diagram of the capacitive transducer and its associated electronics.

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$$\Delta V(t) = -(\eta V_S \epsilon A / x^2)\Delta x(t),$$

where A is the area of the capacitive electrode and ϵ is the dielectric constant of the medium that fills the gap, i.e., that of the Mylar film. The above equation indicates that the charge amplifier output $\Delta V(t)$ is linearly proportional to the normal surface displacement $\Delta x(t)$.

I. MINIATURIZED CAPACITIVE TRANSDUCER ASSEMBLY

Figure 2 is a cross-sectional view of the miniaturized capacitive transducer assembly together with those of the specimen, transducer mounting block (part 13), and clamping nut (part 12). Part numbers are those shown in Fig. 2. The movable unit (part 3) holds a capacitive electrode (part 1) which faces the surface of the specimen through the dielectric, that is, the thin Mylar polyester film (part 11). The electrode which is made of optically polished stainless steel is electrically insulated from its holder (part 3) by the material chosen to be "Macor" (part 2), which is a machinable glass-ceramic manufactured by the Corning Glass, Inc. An n-type subminiature BNC connector (part 7) was connected to the sensing electrode (part 1) by soldering a very fine wire (B&S gauge 40) to them. Both ends of the spring (part 5) were slightly squeezed into the pockets of part 3 and part 6 and are held in both pockets by friction. The constant of the spring used here was rated to be 1.524 N/mm. The assembled unit (parts 3,5,6, and 7) was slid into the jacket (part 4) until the top surface of part 3 extruded out of the jacket by a modicum (typically 2 mm), which can be adjusted by varying the position of part 6 and fixed by a clamping set screw (part 9) butting against the flat area provided on the side wall of the part 6 as indicated in the figure. There is a second clamping set screw (not shown in the figure) with exactly the same function, which is located at 90° apart, but at the same height on the jacket.

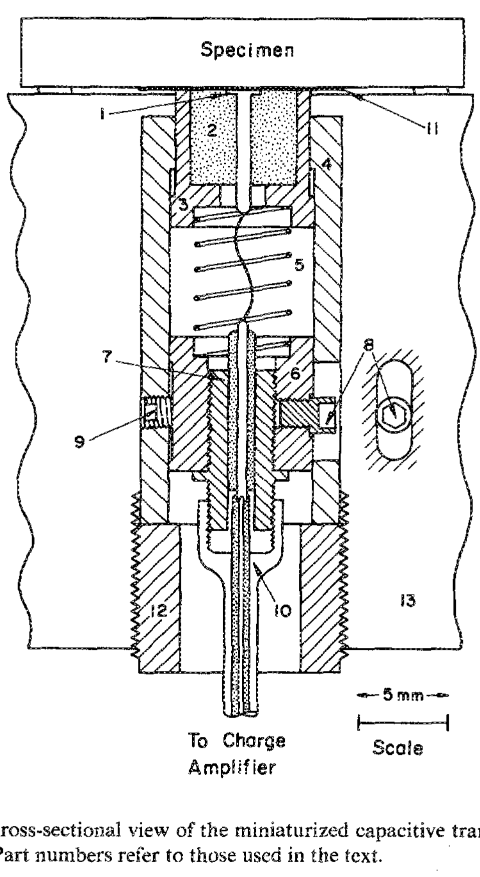

FIG. 2. Cross-sectional view of the miniaturized capacitive transducer assembly. Part numbers refer to those used in the text.

The rotational motion of the assembled inside unit, which may damage the fragile wire, has been kept to minimum by screwing a hex-head allen screw (part 8) into part 6 through the slot provided in part 4. The round head of the screw fits snugly inside the slot (see a separate side view of part 8 provided in the figure) and is free to move along the slot. This screw prevents the parts 6, 5, and 3 from rotating during the adjustment of a position of part 6 inside the jacket (part 4). The shape of the outside jacket is a cylindrical tube whose outside diameter and length are respectively, 11.11 and 22.86 mm. The assembled unit including parts 3, 5, 6, and 4, which were all made of stainless steel, was then slid in the mounting block (part 13) and held fixed by the clamping nut (part 12). At this stage the top surface of part 3 was slightly extended above the level of the top surface of the mounting block. A p-type BNC connector (part 10) was then joined with its counterpart (part 7) and also connected to a charge amplifier through a very flexible shielded cable which was kept less than 15 cm long.

In preparation for a measurement a dielectric Mylar thin film was laid down on the top of part 3 and then a specimen was mounted, pushing the dielectric film and part 3 slightly downward. This downward motion was maintained to be less than 0.25 mm by the adjustment of a position of part 6 as mentioned above. This exerted both on the dielectric film and on the surface of the specimen facing the top surface of part 3 a compressive stress, which was calculated to be less than 1.23×10^{-2} MPa. This negligible stress ensures that the surface of a specimen is almost traction free and contributes to a minimum distortion of the surface displacement caused by the arrivals of wave motion, as will be shown in the next section. It is emphasized that care should be taken to minimize the stress acting on the dielectric film in order for the capacitive transducer to detect a surface displacement free of distortion. Through the adjustment of a position of part 6, this stress was minimized but not eliminated. During the operation of the transducer, both the surface of a specimen facing the capacitor assembly and the mounting block are maintained at a ground potential, and the bias voltage V_s to the electrode (part 1) is supplied through the charge amplifier. The whole assembly is then ready for taking data.

A photograph of assembled capacitive transducers with circular electrodes of four different diameters (1, 1.5, 3, and 5 mm) is shown in Fig. 3.

II. EXPERIMENTAL RESULTS

In all the experiments described here, a 6.35-μm-thick Mylar polyester film has been used as a dielectric medium between the capacitive electrode and the surface of the specimen. The entire electronic block diagram is displayed in Fig.

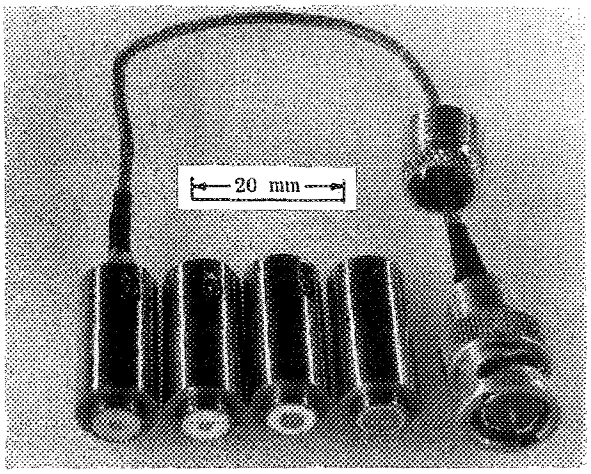

FIG. 3. A photograph of the miniaturized capacitive transducers with four different sizes of the electrode whose diameters are, respectively, 1, 1.5, 3, and 5 mm.

4, where the Mylar dielectric film is not shown. The bottom surface of the plate facing the capacitive transducers was coated with 0.3-μm-thick chromium film, which served as a ground plane. The detected signals by the capacitive transducers were amplified by the charge amplifier whose bandwidth extended from 10 kHz to 10 MHz. The output of the charge amplifier was fed into a transient digitizer which digitized it at a 60-MHz sampling rate with a 10-bit resolution. The output of the charge amplifier was visually displayed in the x-y scope and also brought into the microcomputer for its storage and processing of the stored signals.

The first part of experiments carried out was a breaking of glass capillaries whose inside and outside diameters were 0.05 and 0.08 mm, respectively. The capillary was laid on the top surface of a specimen as shown in Fig. 4. The razor blade attached to the miniature load cell and roughly aligned squarely to the capillary was slowly brought down, making a gentle point contact with the capillary. The contact force was indicated by the load cell. As the contact force gradually increased to a certain level, the glass capillary abruptly broke into two pieces, and the output of the load cell dropped to zero. The maximum output of the load cell at the time of the capillary fracture was brought into the microcomputer via the A/D converter. No damage to the specimen surface by the action of the capillary fractures was observed. The capillary fracture, which resulted in a vertical, single force drop, acted as a simulated acoustic emission source whose temporal behavior resembled a Heaviside step function. The generated elastic waves propagated through the specimen and were detected by the capacitive transducers. Then, the razor blade was moved up and other capillary fracture experiments were performed in a similar way.

Figure 5 shows experimental and theoretical waveforms, both obtained at epicenter. The former was detected with a 3-mm-size capacitive transducer and the latter calculated when a glass capillary was broken by the razor blade with a measured force drop of 1.99 N at the center of the top surface of a 15-cm-square and 9.68-mm-thick soda-lime glass plate. The theoretical waveform and the ordinate on the right-hand side of the graph were obtained from the algorithms developed by Ceranoglu and Pao.[8] p- (longitudinal) and s- (shear) wave speeds and the density of a glass specimen used for the theoretical calculation were 0.582 cm/μs, 0.350 cm/μs, and 2.5 g/cm^3, respectively. Excellent agreement is noted between theory and experiment up to 3p-wave arrival, after which divergence between them is seen to

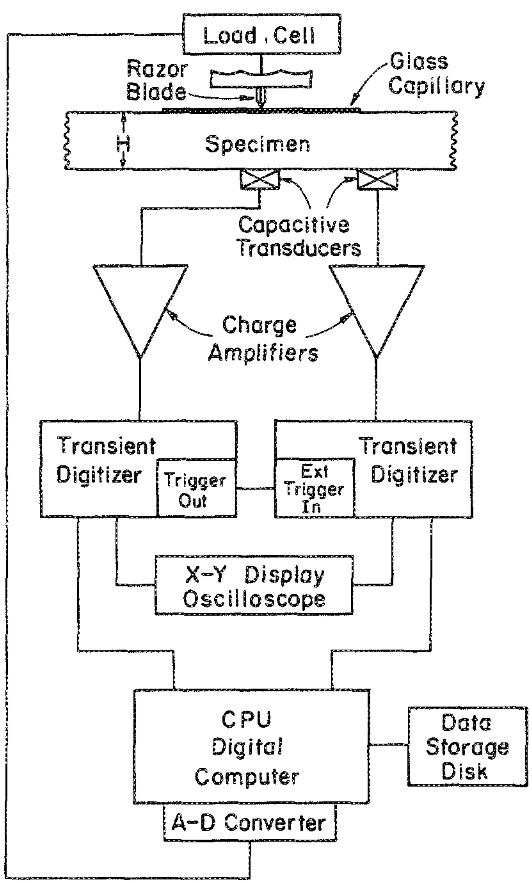

FIG. 4. The entire electronic block diagram of an AE signal detection system with a glass capillary fracture setup.

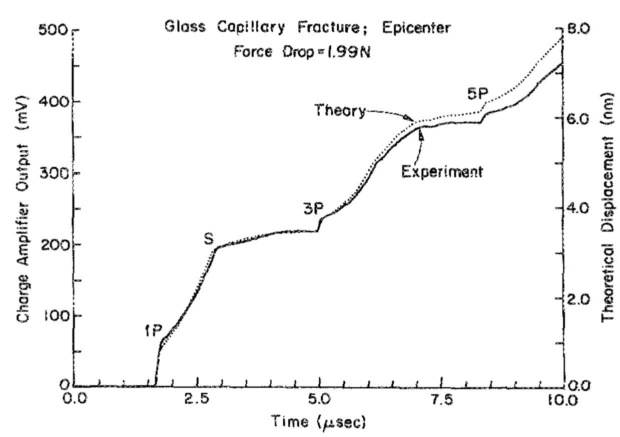

FIG. 5. Measured and calculated displacement waveforms at epicenter due to a glass capillary fracture on the glass plate. A 3-mm-size capacitive transducer was used.

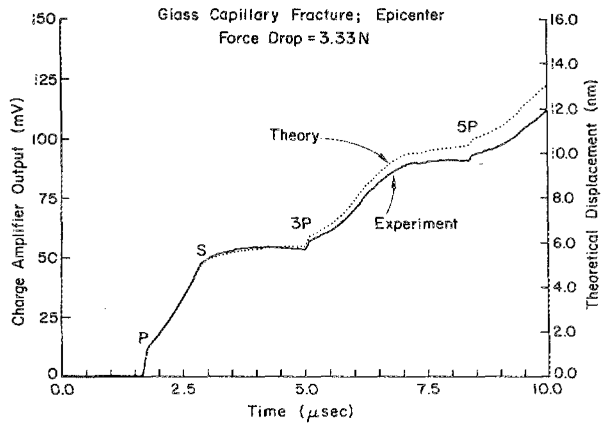

FIG. 6. Measured and calculated displacement waveforms at epicenter due to a glass capillary fracture on the glass plate. A 1-mm-size capacitive transducer was used.

be gradually increasing. Similarly obtained curves are also shown in Fig. 6 with the same glass specimen, but with a 1-mm-size capacitive transducer, when a glass capillary fracture resulted in a force drop of 3.33 N. The capacitance of the 1-mm-size transducer was estimated to be 3.3 pF using the dielectric constant of the Mylar film equal to 3.0. The curve shown in Fig. 7 was obtained under the same conditions as those in Fig. 6 except that a 8.89-mm-thick epoxy plate was used as a specimen and the capillary fracture strength was only 1.18 N. Note a quite-sensitive charge amplifier output despite a low force drop. This is probably due to the low modulus of stiffness of the specimen and also implies that the 1-mm capacitive transducer, which may be considered as an almost ideal point receiver, can be used in studying viscoelastic properties of the medium[10] in a point-source/point-receiver (PS/PR) configuration for the testing of materials.[9]

Finally, the razor blade was replaced by the diamond Vickers indenter, which was gradually brought down, making a gentle contact with the top surface of the glass plate and eventually generating two mutually perpendicular, half-penny-shaped cracks that acted as the sources of acoustics emission. No glass capillary was present in this case. The load applied through the indenter at the instant of the crack formation was again measured by the load cell. Displayed in

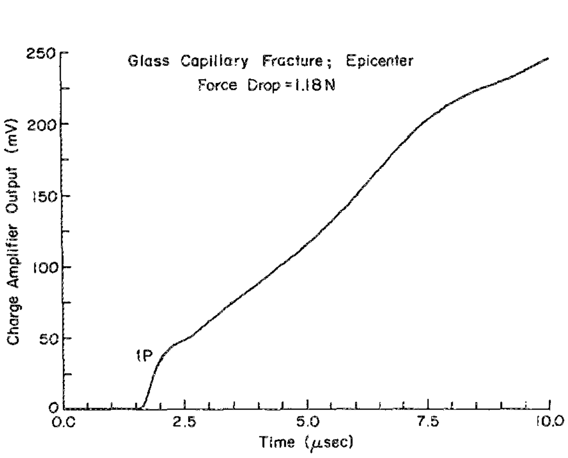

FIG. 7. Measured displacement signal at epicenter due to a glass capillary fracture on the epoxy plate. A 1-mm-size capacitive transducer was used.

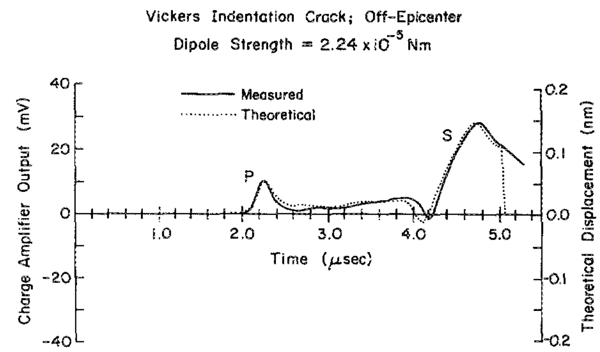

FIG. 8. Measured and calculated displacement waveforms at the off-epicentral position due to a formation of Vickers indentation cracks on the surface of the glass plate. A 3-mm-size capacitive transducer was used.

Fig. 8 is a Vickers indentation crack signal obtained with a 3-mm-size capacitive transducer using a 9.60-mm-thick soda-lime glass specimen. The signal was detected at a position of 19.05 mm away from epicenter on the bottom side of the specimen. The angular coordinate of the receiver is aligned with one of the normals to the crack planes. The procedures for obtaining the theoretically recovered curve shown as a dotted line in the figure, the theoretical displacement indicated on the ordinate of the right-hand side, and the dipole strength associated with the crack formation are described in detailed in Ref. 3.

ACKNOWLEDGMENT

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