

## POINT-SOURCE/POINT-RECEIVER MATERIALS TESTING

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### INTRODUCTION

Conventional measurements in the ultrasonic testing of materials, when used as the basis of a materials characterization procedure, typically rely on one or two piezoelectric transducers operating as source and receiver, attached to a specimen to launch and detect ultrasonic waves in the object to be characterized. Measurements of signal arrival time (or velocity) and amplitude (or attenuation), possibly as a function of frequency, are then correlated with the composition and the macro- and micro-structure of the material, which may include voids, flaws and inclusions distributed through a region of the material. While relative measurements of the time-of-flight and ultrasonic amplitudes do not present extraordinary measurement challenges, absolute measurements do. It is unfortunate that absolute quantities are often required since they are difficult to obtain reliably with a conventional piezoelectric transducer-based ultrasonic system. For this reason, a considerable effort over the past decade has been undertaken to develop and improve non-contact methods for generating and detecting ultrasonic signals in materials. However, a limiting factor of all the existing non-contact measurement systems is the care required for their use and their reduced sensitivity in comparison to those utilizing piezoelectric transducers.

Over the past several years notable advances have been made in the development of quantitative acoustic emission methods in which the signals emitted by a source in or on a structure are detected by one or more receiving transducers at the surface of the structure. Knowing the transfer characteristics of the sensors and the appropriate dynamic Green's functions of the structure, the temporal and spatial characteristics of the emission source can be recovered from the detected signals by signal processing techniques [1, 2]. An essential assumption in such a measurement procedure is that the material encompassing the source and receiver points is homogeneous, isotropic, elastic and non-attenuative. While the Green's functions for an anisotropic material can, in principle, be computed, none appear to have been published. It is known that the propagation of acoustic emission signals from a source to a receiver point is influenced not only by the geometry of the specimen but also by the material's macrostructure specified in terms of its size, shape and for composite materials, the ply configuration. In addition, the wave propagation is strongly affected by the specimen material's

microstructure, including its anisotropy, heterogeneity, elastic, inelastic and viscous properties, and its wave attenuation characteristics. To determine these variables it is proposed to utilize an ultrasonic testing system analogous to that used in exploration geophysics, consisting of a well-characterized point source and point receiver. This is shown schematically in Figure 1. If both the source and receiver possess known temporal characteristics, then the principal advantage of a point-source,

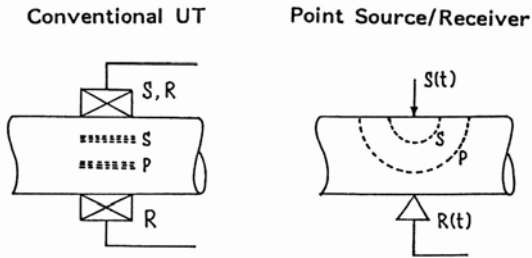


Fig. 1 - Conventional ultrasonic and point-source/point-receiver testing configurations.

point-receiver system over a conventional ultrasonic system is that quantitative ultrasonic measurements are possible. Although the geometric characteristics of the wave propagation may be more complex than those for the case in which plane waves are used, these effects can be accounted for in the detected signals to recover the material-related wavespeeds and attenuation properties. Because the excitation and detection regions are small, the required specimen surface preparation is minimal

and furthermore, specimens of arbitrary geometry can be easily tested, in particular those which are neither planar nor flat.

#### WAVE PROPAGATION, SYSTEM CHARACTERISTICS AND SIGNAL ANALYSIS

The basis of a point-source/point-receiver testing system is a source and a receiver whose temporal and spatial transfer characteristics are known and a theoretical basis by which the measured signals can be identified, interpreted and processed to recover the characteristics of the propagating medium. The term "point" refers ideally to a signal source or detection region whose lateral dimension is much smaller than the effective wavelength of the highest frequency component of interest in the measured signal. This wavelength will also be much shorter than any dominant dimension of the specimen.

##### Wave Propagation

The analysis of transient elastic waves between a point source and a point receiver in a bounded structure is discussed in several papers [c.f. 3]. The displacement signals  $u_k$  detected at a receiver location,  $\underline{x}$ , in a structure from an arbitrary source  $f(\underline{x}',t)$  located at  $\underline{x}'$  having source volume  $V$  can be written as a sum of contributions due to a monopole, dipole and higher-order terms. The monopole source contribution to the signal can be rewritten compactly as

$$u_k^{(m)}(\underline{x},t) = F_j(t) * G_{jk}(\underline{x}/\underline{x}',t) \quad (1)$$

where  $F_j(t) = \int_V f_j(\underline{x}',t) dV$  is the total force acting throughout the source volume and  $G_{jk}(\underline{x}/\underline{x}',t)$  is the dynamic Green's function of the structure. It is a function of time only for a point source. For all the monopolar sources utilized in this paper, the force is always a force normal to the surface of the specimen, i.e.,  $F_z$ . The dipole contribution to the signal can be rewritten compactly as

$$u_k^{(d)}(\underline{x},t) = M_{ij}(t) * G_{jk,i}(\underline{x}/\underline{x}',t) \quad (2)$$

where  $M_{ij}(t) = \int_V \underline{x}'_i f_j(\underline{x}',t) dV$  represents the moment tensor of the source

and  $G_{jk,i}(\vec{x}/x',t)$  is the spatial derivative of the Green's function. This representation is used to model many thermoelastic sources [4].

A solution to the forward problem can be readily computed for a specimen of flat plate-like geometry. That is, given the thickness of the specimen, the material's longitudinal to shear wavespeed ratio and the source/receiver separation, the dynamic Green's functions appearing in Eqs. (1) and (2) can be found using one of the available algorithms [3, 5]. If the measurement system includes a point receiving transducer whose output voltage signal is related to the input displacement signal by the sensor's transfer function,  $R(t)$ , then the results given by Eqs. (1) and (2) must be further convolved with this transfer function to obtain the output voltage signals of the system corresponding to each of the excitations.

An important example is shown in Figure 2. This is the normal displacement signal computed for a vertical force source acting on a plate specimen and detected at the epicenter point on the back surface of the plate directly under the source point. This example was obtained for a 7090 Al/SiC composite 1.884 cm thick whose longitudinal and shear wavespeeds were 0.708 cm/ $\mu$ sec

and 0.368 cm/ $\mu$ sec, respectively, with zero wave attenuation. Thus, this result represents the behavior expected for an ideal material. The signals corresponding to other types of source and receiver configurations can be computed similarly. It is seen that the arrivals of both the P- and S-waves can be easily identified. Hence, even though the force was applied normal to the specimen surface, both longitudinal and shear wave modes are excited. The identification of the wave arrivals is possible, provided that the source/receiver separation is not larger than

about  $10h - 15h$ , where  $h$  is the thickness of the plate. It is also clear from the waveforms shown in the figure that while the wave arrivals are readily identifiable, the signals characteristically possess a "tail"; that is, each wave is geometrically dispersed as it propagates through the specimen. This dispersion is unrelated to the properties of the medium and its presence in a signal must be removed if the correct material-related frequency characteristics of a measured signal are to be determined.

Additional insight is gained by considering the evaluation of the displacement signals in the frequency domain. This has recently been carried out for the case of a viscoelastic medium [6]. It is found that the Fourier phase function of the P-wave arrival of the velocity signal is given by

$$\phi(\omega) = kL + \mathbf{A}/kL \quad (3)$$

where  $k$  is the wavenumber,  $L$  the source/receiver separation and  $\mathbf{A}$  is a correction factor approximately equal to 2. The first term of the phase function is identical to that derived for plane waves [7]. The amplitude

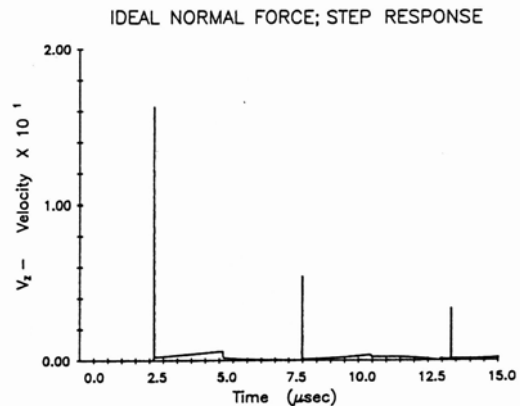


Fig. 2 - Ideal epicentral velocity signal; Step normal force excitation; Zero attenuation.

corresponding to the first shear wave arrival can be processed similarly and the phase functions of other source types are expected to exhibit a similar form [8].

### Source and Receiver Characteristics

The ideal point source and point receiver with perfect impulse response can only be approximated with real sources and receivers. However, in order to achieve acceptable signal-to-noise ratios, it is possible to use transducers with a finite aperture provided that the generated and detected acoustic fields in the specimen are uniform and resemble those expected from a point source and point receiver. Equally important is that the transduction characteristics of the source and receiver are known. This includes both the primary and secondary quantities being generated and detected. The temporal transfer characteristics of both source and receiver must be known a priori or determined in a calibration experiment; they must possess an appropriate frequency response relative to the material property being investigated. There are, however, many measurement situations in materials whose viscous dispersion and wave attenuation is sufficiently low so that only a measurement of the arrival of a signal is required and a complete characterization of the sensor is not needed. In these cases, conventional piezoelectric point sensors sensitive to the wave motions normal to the surface of the specimen can be used. With such a sensor the measurement is simplified since no special surface preparation of the specimen or critical transducer alignment with the specimen surface is required. Obviously, in all cases the source and the receiver must possess an adequate signal-to-noise ratio to permit signal identification and subsequent processing operations to be performed reliably. A discussion of various point-sources and receivers and their operating characteristics is given in Ref. 9.

### Signal Identification and Waveform Analysis

According to the convolution equations (Eqs. (1) and (2)) for a source of known type and time function and for a specified source-receiver separation, only the time-dependence of the input source function and output displacement signals is required to invert these equations to recover the dynamic Green's function corresponding to the particular testing geometry and specimen material [10]. If the measurement system consists of a source whose excitation is an impulse or a Heaviside step and the receiver is a high-fidelity displacement or velocity sensor, then the detected signals will correspond directly to the dynamic Green's function of the specimen, thus requiring no further signal processing. This observation emphasizes the advantage of using a source and a receiver possessing ideal characteristics.

Once the Green's function has been determined, the ultrasonic wavespeeds can be recovered by identifying the arrival times of the P- and S-wave signals. If the instant of excitation is known, only the first arrivals of these signals need to be determined. When this is not known, the arrival of other signals propagating through the specimen are needed. The 3P signal corresponding to the longitudinal wave propagating three times through the specimen is identified in the actual waveform shown in Figure 3. The longitudinal and shear wavespeeds of the material can be recovered from the measured arrival times according to the formulae shown in the figure.

The frequency-dependence of a particular wave arrival is determined by properly windowing that portion of the waveform containing the signal amplitude and transforming this amplitude to obtain the Fourier phase

function of the signal. Once this function is found, it is substituted into Eq. (3) which, in turn, is solved numerically to obtain a solution for the dispersion relation of the wave in the material. Once the dispersion relation has been found, the phase and group velocities,  $c (= \omega/k)$  and  $v (= \partial \omega / \partial k)$ , can be evaluated.

Since the computed, ideal waveform corresponds to the propagation in a non-attenuative material, the attenuation of either the P- or the S-wave amplitude in a real material can be determined by making a comparison of the measured and computed waveform amplitudes of the corresponding wave arrivals. It follows that the frequency dependence of the attenuation can be determined by processing the windowed signal amplitude in the frequency domain to form its magnitude spectrum  $V(f)$  and evaluating

$$\alpha(f) = 20 \log_{10} [V(f) / V_{\text{ref}}(f)] \quad (4)$$

where  $V_{\text{ref}}(f)$  refers to the magnitude spectrum of the wave velocity amplitude of the non-attenuated, ideal signal.

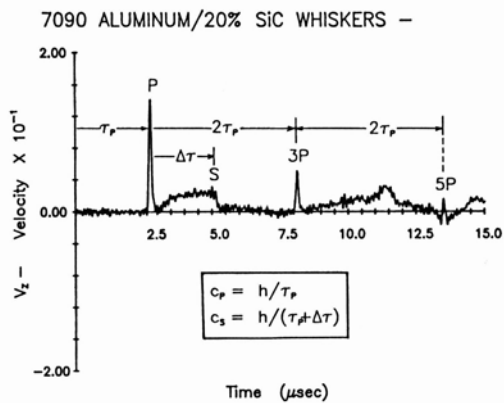


Fig. 3 - Measured epicentral velocity signal; Step source. (Wave arrivals are indicated).

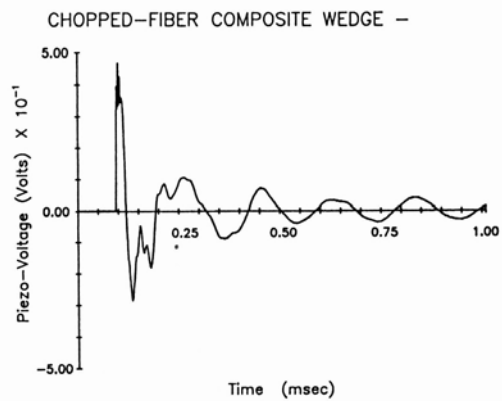


Fig. 4 - Ultra-absorptive chopped fiber composite; Step source; Piezo-electric transducer detection.

## MEASUREMENTS

The measurement system utilizing a point-source/receiver resembles a system used to make quantitative acoustic emission studies. The exception is the presence of the input source element which may or may not have a sensor attached to it in order to generate a synchronization pulse with the excitation signal. The normal velocity signal at epicenter corresponding to a step excitation on a specimen of a 7090 Al/SiC metal-matrix composite was shown in Figure 3. Measurement of the arrivals of the P- and S-wave amplitudes leads at once to the recovery of the longitudinal and shear wavespeed values,  $c_p = 0.700$  cm/μsec;  $c_s = 0.380$  cm/μsec. These are within 3% of the values determined in a conventional ultrasonic measurement.

Since in these measurements only the time of arrival of a particular wave is required, an uncalibrated piezoelectric point transducer can often be used. The waveform obtained in a highly attenuative, chopped fiber/epoxy, wedge-shaped specimen having a non-uniform layer of another material on one side is shown in Figure 4. The detection region of the

specimen was left unprepared and hence the piezoelectric transducer with the excess couplant exhibited considerable ringing. However, even for this unfavorable testing situation, the first P-wave arrival is easily detected and can be used to determine an effective longitudinal wavespeed value for this material.

To determine the orientation dependence of wavespeeds in a sample, an array of transducers is required. In the simplest configuration, the receiving elements are located equi-distant about the source point. The sensors may be on either side of the sample, but they should be within 10h - 15h of the source so that the first P- and S-wave arrivals can be clearly identified in the detected signals. An example of the results of waveform measurements made in a specimen of graphite-epoxy comprised of 32 plies whose layup was at ( $\pm 45^\circ$ ) is given in Figure 5. Shown are the wavespeeds of the P-wave in various directions of the material. To obtain this result, the fracture of a capillary was used as a monopolar source with eight point piezoelectric sensors placed at various angles about it. The time of the first arrival was measured in each of the detected waveforms and the wavespeed was computed by dividing the arrival time into the source/receiver separation.

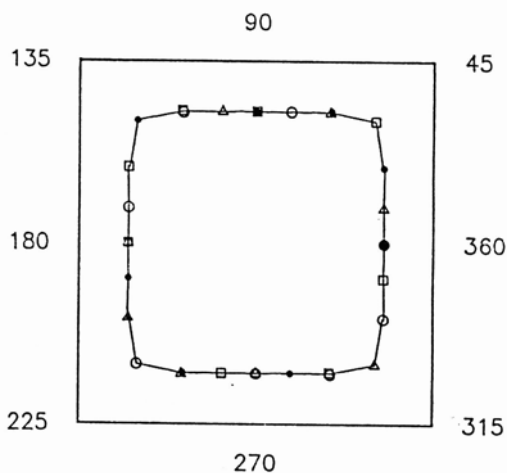


Fig. 5 - Wave velocity surface in 32-ply Graphite/Epoxy; Layup; ( $\pm 45^\circ$ ).

The graphite-epoxy specimen possesses a four-fold symmetry. This can be determined from inspection of the detected signals or from knowledge of the material's fabrication. Recognizing this symmetry, it is possible to generate additional pseudo-points by projecting each of the measured data values in directions oriented at 180, 90, -90 degrees to those measured. As the results of Figure 5 demonstrate, the twenty-four additional points all lie on the same wavespeed surface. This finding verifies the consistency of the measurement results.

Application of the Fourier phase analysis method for determining the dispersion relation and the frequency-dependent phase velocity of the longitudinal wave in a 6061 Al/SiC metal-matrix composite specimen is shown next. The signal resulting from a capillary fracture source detected at epicenter with a piezoelectric point transducer whose response approximated a velocity sensor is shown in Figure 6(a). Also indicated is the windowed, first arrival of the P-wave signal. From the magnitude spectrum it is found that the signal contains little energy above 8 MHz reflecting the frequency response of the transducer and amplifier used to detect the signals. Because the low-frequency correction is only significant at frequencies below 0.5 MHz, it is omitted from the dispersion relation of the derived phase velocity shown in Figure 6(b). It is seen from the latter that the phase velocity between 3 and 10 MHz is nearly constant at 0.690 cm/ $\mu$ sec. At lower frequencies there is a decrease to lower wavespeed values which is due principally to the response of the piezoelectric transducer used to make the measurements and the omission of the low-frequency correction.

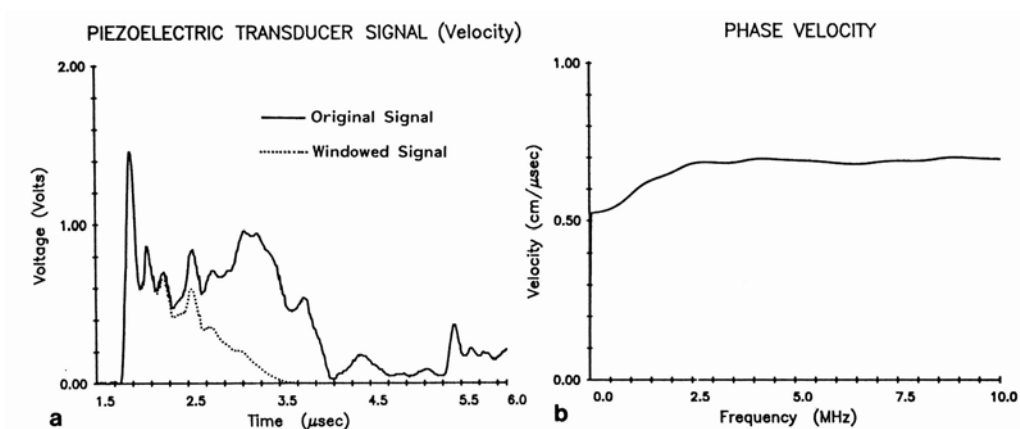


Fig. 6 - Wave dispersion measurement in a metal-matrix composite (a) Original, P-wave windowed signal; (b) Derived phase velocity.

An example of an attenuation measurement is shown in Figures 7(a)-(b). The velocity signal resulting from a step force applied in a 7090 Al/SiC metal-matrix composite specimen was shown in Figure 3. In the procedure, the first P-wave is windowed and compared to the computed response for the ideal case of a non-attenuating material shown in Figure 2. The Fourier magnitude spectra of the measured and ideal P-wave amplitudes are shown in Figure 7(a), while the result obtained from applying Eq. (4) is shown in Figure 7(b). In this example, only a relative measure of the attenuation of the longitudinal wave is determined since the vertical scale in Figure 3 was not calibrated absolutely and the magnitude of the force drop of the source used to generate the signal in this experiment was not measured.

In the waveforms detected in extremely absorptive materials, only the lowest frequencies are able to propagate and, hence, an unambiguous

#### 7090 ALUMINUM/SiC COMPOSITE - DAMPING MEASUREMENT

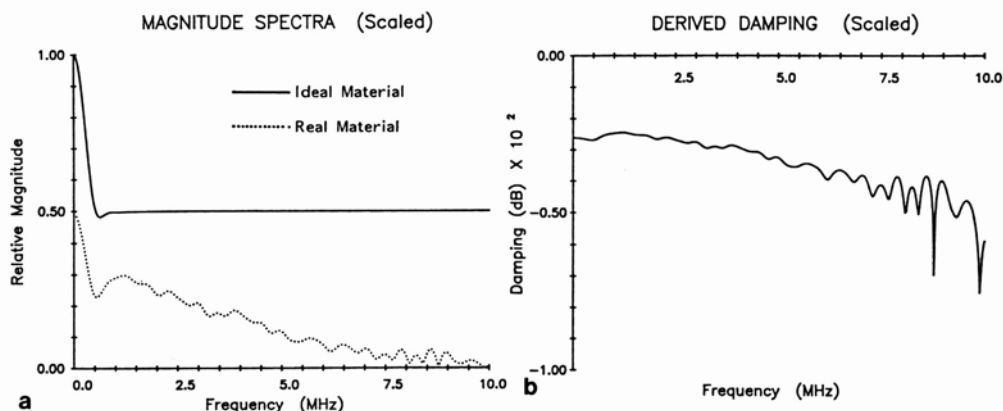


Fig. 7 - Wave attenuation measurement in a metal-matrix composite (a) Magnitude spectra of ideal, real signals; (b) Derived attenuation.

identification of the particular wave arrivals may be difficult. In such cases it may be advisable to choose an epicentral testing configuration with a sufficiently thick specimen so that the separation of the P- and S-wave arrivals is distinct in the detected signals. In cases in which only the lowest frequency components of the signal are propagated, it may also be necessary to consider other sensors to detect the signals.

The few examples shown here were used to illustrate the various signal analysis procedures described in the previous section. Numerous additional examples obtained in a variety of different materials are contained in a full length paper [9].

## CONCLUSIONS

The components and characteristics of a point-source/point-receiver material testing system have been described by which the ultrasonic wavespeeds and attenuation can also be determined as a function of frequency in a variety of materials. The method utilizes a source and receiver whose transduction characteristics are known or can be determined in a calibration experiment. The measurements require a minimal amount of surface preparation and they can be made on specimens which are neither planar nor flat. Information regarding the propagation characteristics of both longitudinal and shear wave components is possible from a single waveform. It is also possible to select an excitation source whose time characteristics result in high energies at low frequencies which facilitates measurements in ultra-absorptive materials. It was demonstrated that while the characteristics of the wave propagation are more complex than those for plane waves, the existence of a theory of transient elastic waves permits a proper interpretation of the detected signals, provided that appropriate and calibrated point sources and receivers are utilized to make the measurements and the source/receiver separation is known. Results of several experiments were shown in which a composite material's longitudinal wavespeed can be recovered from the detected waveforms. It was demonstrated that by using an array of sensors, the wave velocity surface of a material can also be determined.

A procedure was also described by which the frequency-dependent wavespeeds and attenuation can be determined from the detected signals. The wavespeeds are recovered from an analysis of the Fourier phase functions of the normal velocity amplitudes corresponding to the arrival of either the longitudinal or shear wave signals. An analysis of the Fourier magnitude spectra of these signal amplitudes are compared to the magnitude spectra of the corresponding wave amplitudes for an ideal, non-attenuating specimen. With the continued development of non-contact point-sources and receivers, this measurement technique shows great promise as a powerful tool for characterizing micro- as well as macro-structural features of a large number of materials under a variety of measurement conditions.

## ACKNOWLEDGEMENTS

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## DISCUSSION

Mr. Marvin Hamstad, University of Denver: Wolfgang, what kind of fiber volumes were you using typically in these samples? And would you comment on the effect of fiber volume on this approach?

Mr. Sachse: In the graphite/epoxy specimens?

Mr. Hamstad: Yes. Or even the aluminum composites.

Mr. Sachse: The graphite/epoxy specimens typically had a fiber volume ranging from 63-67%. The metal-matrix aluminum composites contain about 20% silicon carbide.

Mr. Hamstad: Could you comment on what the effect would be if it was, say, 60 percent?

Mr. Sachse: I don't know the answer so I'll answer your question with a plea. If someone could supply us with samples to test, we would be delighted to test them and return them, unharmed. With the small number of specimens we only recently obtained, we had no way of investigating this. But I have no way of knowing the answer to your question. I have only two small specimens that I obtained only recently.

From the Floor: I was interested in the use of the capacitive transducer. Was it a standard one; did it suffer from sensitivity limitations, or have you developed a new type of sensor?

Mr. Sachse: It was developed by my colleague, Dr. Kim. A special feature about this capacitive transducer--I have not seen another like it--is that it is self-aligning with the surface of the specimen. This is achieved by having the electrode resting on a small ball. Thus one only needs to polish a very small section of the sample. We have several versions of this transducer with the smallest element about 1.2 millimeters in diameter. In using this sensor, one only needs polish or have a small, smooth surface of that dimension available on the specimen.

In use, the plate is brought in contact with the sample, and the ball permits a self-alignment of the moving electrode with the sample. A very fine micrometer adjustment is used to set the gap.

From the Floor: What was the sensitivity of the transducer?

Mr. Sachse: The answer depends on the gap dimension, the bias voltage and the charge amplifier sensitivity. In our system the charge amplifier sensitivity was 0.25 V/pf, so when we use a gap of 5  $\mu\text{m}$  and a bias supply of 30 volts, we have a sensitivity of approximately 100 mV/ $\text{\AA}$ . You can see from the waveforms we obtained that they are very good.