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Dynamic surface displacement measurement in 1-3 and 1-1-3 piezocomposites

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The sensitivity of 1-3 piezocomposites can be improved by the addition of a third phase or interlayer around the piezoceramic rods which results in a composite with 1-1-3 connectivity. In the current investigation, dynamic surface displacements of both 1-3 and 1-1-3 piezocomposites were measured using a laser Doppler heterodyne interferometer. Dynamic displacement profiles showing the nonuniform deformation of the piezoelectric rod and the nonpiezoelectric polymer were obtained at 10 Hz, 100 Hz, and 1.0 kHz. Measurements of the displacement at the center of the piezoelectric rod were performed over the frequency range from 10 Hz to 27 kHz. Three different interlayer conditions were considered. The experimental measurements demonstrated that both the surface displacement profile and the maximum rod displacement varied with frequency and interlayer properties. The dynamic displacement profiles were also compared with previously measured static displacement profiles. © *1998 American Institute of Physics.* [S0021-8979(98)06722-X]

I. INTRODUCTION

Piezocomposites with 1-3 connectivity have been used extensively for hydrophone applications because of the improved hydrostatic performance over a homogeneous piezoceramic. In a 1-3 piezocomposite, the piezoceramic rod and the nonpiezoelectric polymer will have different deformations when subjected to an external electrical or mechanical stimulus. The deformation of each constituent depends on the relative compliance of the ceramic and matrix phases. This locally nonuniform deformation eventually determines the overall electromechanical behavior of the composite. Previous experimental and theoretical work[1–3] have demonstrated that significant increases in hydrostatic sensitivity can be achieved by adding a third phase or interlayer around the piezoceramic rod which results in the so-called 1-1-3 piezocomposites.

Li and Sottos[1] measured the static displacement field in 1-3 and 1-1-3 piezocomposites to determine the influence of a thin interlayer on the performance. In their experiments, a single lead zirconate titanate (PZT) rod embedded in a matrix of Spurr epoxy (Polysciences, Inc.) was used as the sample. In order to investigate the influence of a distinct layer between the rod and the polymer, samples with three different interface conditions were fabricated. In the first type of sample (I), the rods were embedded in the matrix with no special interface treatment or coating. In the second type of sample (II), a thin polymeric coating that is softer than the bulk matrix was used for the interlayer. Finally, in the third type of sample (III), a even softer thin polymeric coating was used for the interlayer. The fabrication, interphase compositions, interphase Young's modulus and interfacial adhesions of the three types of samples have been reported in greater detail by Li and Sottos.[1]

The single rod samples were actuated with a constant voltage of 300 V. The interferometrically measured out-of-plane displacement profiles were highly dependent on the properties of the interlayer. The addition of a thin compliant interlayer region effectively decoupled the piezoelectric rod from the matrix leading to a significant increase in rod displacement and non-uniformity of the displacement profile across the sample. The experimental profiles were also found to be in good agreement with theoretical predictions

Because piezocomposites are used extensively in other applications such as ultrasonic transducers and sensors for acoustic imaging and medical applications, it is also important to investigate the dynamic response of the piezocomposite as well as the static. In the current work, dynamic displacement profiles are measured on piezocomposite samples with interlayers identical to those used by Li and Sottos.[1] The influence of the interlayer properties on the displacement profiles is investigated as function of driving frequency. Dynamic displacements are compared to the static profiles obtained previously by Li and Sottos.[1]

II. EXPERIMENTAL METHOD

Experimental characterization of piezocomposites can be roughly divided into two categories. The first category involves measuring dielectric and piezoelectric constants using the direct piezoelectric or the resonance method outlined in the IEEE standard.[4] However, to perform measurements of piezoelectric properties over ranges of several decades in frequency, nonresonance measurement techniques must be used. For this case, the second category of experimental techniques which involve optical measurement of acoustic displacements generated by applying an electric field is appropriate. Rittenmyer and Dubbelday[5] measured the effective, temperature-dependent piezoelectric coefficients over a frequency range from 0.1 to 100 kHz using laser Doppler

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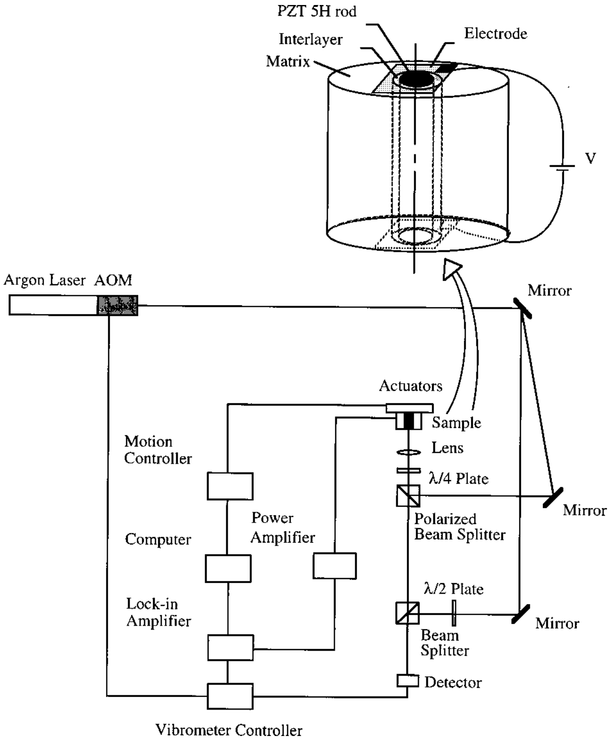

FIG. 1. Schematic of laser Doppler heterodyne interferometer.

vibrometry. Li, *et al.*[6] reported a direct measurement of the complex piezoelectric response of sol-gel derived PZT thin layer in a spectroscopic mode over a frequency range of $100-10^4$ Hz by Michelson–Morely interferometry. The performance of 1-3 and 1-1-3 piezocomposites at a fixed frequency of 2.0 kHz has been investigated by Sottos *et al.*[7] using a heterodyne interferometer. The surface displacement profile of a 2-2 piezocomposite at low frequency was measured by Zhang *et al.*[8] with a double-beam laser dilatometer.

Li and Sottos[1] used a heterodyne microinterferometer to measure the static displacements of a single rod piezocomposite. Displacement profiles were obtained by scanning a photodetector across an image of the sample surface. The phase of the image signal was continuously compared to a reference signal from the corner of the image plane. In the current work, a laser Doppler heterodyne interferometer is adopted to measure the dynamic displacement profiles. The Doppler frequency deviation for laser light of wavelength λ reflected normally from a moving surface at velocity ν is given by the Doppler shift equation as

$$f_D=\frac{2\nu}{\lambda}. \tag{1}$$

The Doppler frequency deviation caused by the harmonic vibration of the surface of the piezocomposites is measured interferometrically and then converted to the surface velocity and displacement.

A diagram of the laser Doppler heterodyne interferometer used for the dynamic displacement measurements is shown in Fig. 1. A single frequency, linearly polarized laser beam of wavelength 514.5 nm from an argon laser (Lexel Laser model 3500) is incident upon a 40 MHz acousto-optic modulator (AOM) producing two beams which are sent along different arms of the interferometer. One beam is shifted in frequency by 40 MHz and is used as a reference beam. The other beam which is with the same frequency as the beam incident upon the AOM is sharply focused at normal incidence on the sample surface. The two beams are recombined in a beam splitter and then incident on a stationary photodetector. The intensity of the light arriving at the photodetector is

$$I=I_r+I_s+2\sqrt{I_rI_s}\,\cos\left[2\pi\left(40\ \text{MHz}+\frac{2\nu}{\lambda}\right)t\right], \tag{2}$$

where I_r and I_s are the intensities of the reference beam and the sample beam, respectively. Any out-of-plane velocity of the sample surface produces a corresponding frequency shift in the signal arriving at the photodetector. The photodetector converts the intensity of the light into voltage and sends the signal to a vibrometer controller (Polytec OFV 3001). The Doppler frequency shift is decoded using the FM demodulator in the vibrometer controller and produces an output voltage which is proportional to the velocity of the sample surface. A digital lock-in amplifier (Stanford Research) is then used to measure the output of the vibrometer controller. The sample is mounted onto a stage that can be moved using two actuators in order to obtain the displacement profiles. The actuators (Newport model 850B) are controlled by a microcomputer-controlled motion controller (Newport model PMC200P). Both the lock-in amplifier and the motion controller are interfaced with a Power Macintosh via the IEEE-488.2 interface.

III. RESULTS

The piezoceramic rod was actuated by applying an ac voltage across the piezocomposite sample. The lock-in's built-in oscillator was used to supply the harmonic driving voltage for the sample. The signal was then amplified to 300 V. Two types of measurements were made on the three different types of samples. In the first type of measurement, the surface displacement profiles were obtained at different frequencies. In the second type of measurement, the displacement at the center of the rod was measured as a function of frequency.

A. Surface displacement profiles

Surface displacement profiles were obtained by scanning across the center of the rod and the surrounding matrix at a speed of 0.09 mm/s. *In situ* measurements of the surface displacements of samples I, II, and III were made at 10 Hz, 100 Hz, and 1.0 kHz and plotted as a function of radial distance from the center of the rod in Figs. 2–4, respectively. The surface displacement profiles were dependent on both the type of interlayer and the frequency. At low frequency (10 Hz), both the magnitude and the shape of the surface displacement profiles were comparable to those of the static displacement profiles measured and predicted by Li and Sottos.[1] Sample type III had the highest rod displacement and the greatest nonuniformity in the displacement profile across the surface. Sample type II had a greater rod displace-

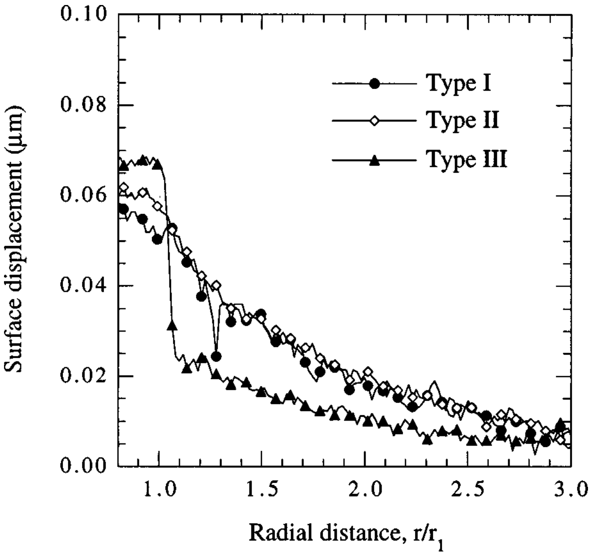

FIG. 2. Dynamic displacement profiles measured across the composite sample surface at a frequency of 10 Hz.

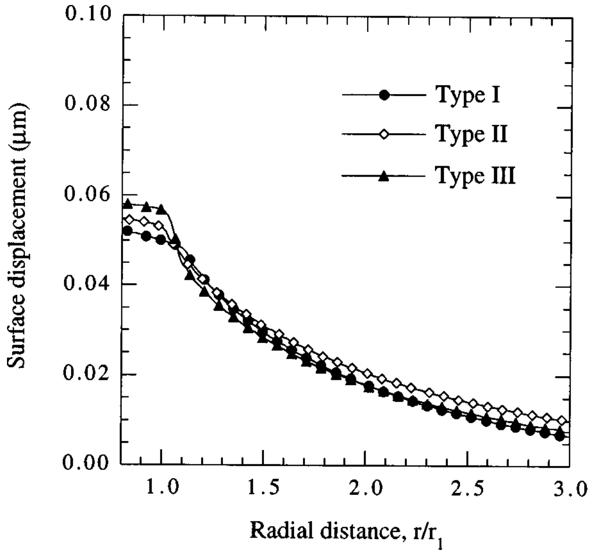

FIG. 4. Dynamic displacement profiles measured across the composite sample surface at a frequency of 1.0 kHz.

ment than the no coating sample (type I) and a much more similar profile in the matrix. As the frequency increased, the influence of the compliant coating decreased. At the highest frequency (1.0 kHz), the displacement profiles were nearly the same.

B. Displacement at the center of the rod

To further investigate the dependence of the displacement of the rod on frequency, the laser beam was fixed at the center of the rod and then the sample was driven by an ac voltage with frequency changing from 10 Hz to 27 kHz. Displacements at different frequencies were normalized by the displacement at 100 Hz and plotted as a function of frequency for samples I, II, and III in Fig. 5. At frequencies lower than 100 Hz, the signal was noisy due to limitations of the vibrometer controller. The displacements of all three samples decreased as the frequency increased from 100 Hz to 10 kHz. The displacement of sample III decreased the most significantly, while the displacement of sample I decreased the least. An increase in the displacement was observed near 20 kHz due to mechanical resonance of the sample.

IV. DISCUSSION AND CONCLUSIONS

A laser Doppler heterodyne interferometer was utilized to investigate the dynamic surface displacement of 1-3 and 1-1-3 piezocomposites. Although the dynamic surface displacement profiles were similar to the static surface displacement profiles, some interesting differences were also observed. The influence of the interlayer between the PZT rod and the bulk matrix on the out-of-plane displacement profile

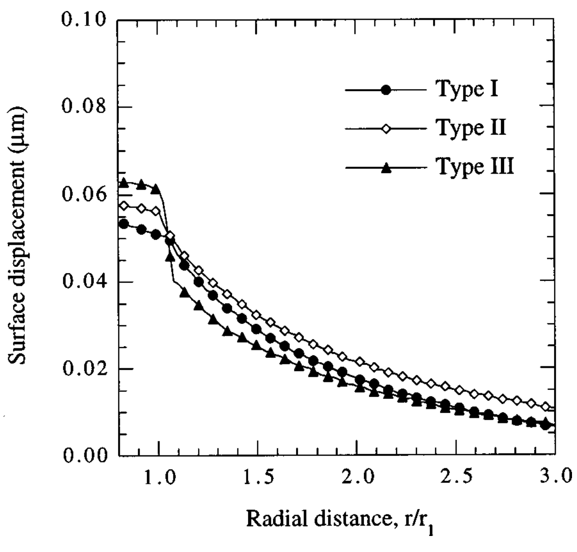

FIG. 3. Dynamic displacement profiles measured across the composite sample surface at a frequency of 100 Hz.

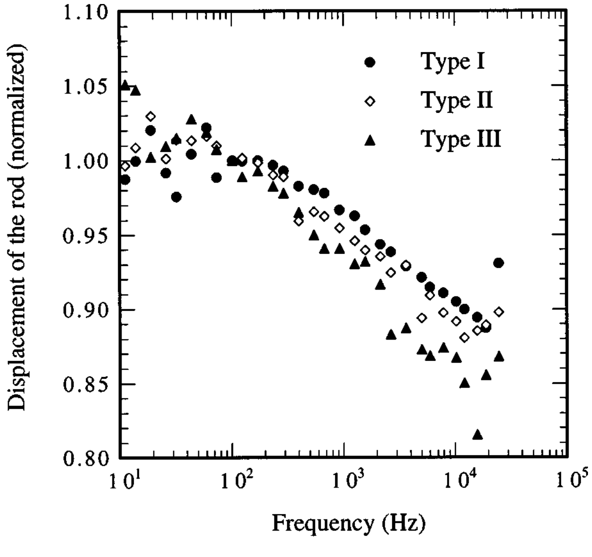

FIG. 5. Normalized displacements at the center of the rod as a function of frequency.

was dependent on both the properties of the interlayer and the vibration frequency. At low frequency, the sample with the most compliant interlayer had the most nonuniform surface displacement profile and the largest rod displacement as in the static case. As frequency increased, the influence of the compliant interlayer tended to decrease and the surface displacement profiles of the 1-1-3 piezocomposites with softer interlayers became more uniform and approached those of the 1-3 piezocomposites.

The displacement at the center of the rod decreased by over 15% as the frequency increased from 100 Hz to 20 kHz. Similar phenomena have been reported by Rittenmyer and Dubbelday[5] for 0-3 piezocomposites and by Li *et al.*[6] for 2-2 piezocomposites. This decrease may be caused by a change in the dielectric constant of the PZT rod or due to the clamping of the sample in the lateral direction. The displacement of the piezocomposite with a soft interlayer decreased more rapidly than that of the piezocomposite with no interlayer as the frequency increased. This effect may be related to the damping effect of the polymeric interlayer.

Static models for predicting piezocomposite behavior such as those presented by Li and Sottos[1,2] accurately describe the low frequency behavior of 1-3 and 1-1-3 piezocomposites. However, these models are not capable of predicting the changes in response with frequency observed in the current experiments. More detailed dynamic models are required to understand the behavior.

ACKNOWLEDGMENTS

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