# SURFACE-DISPLACEMENT IMAGING USING OPTICAL BEAM DEFLECTION

S.E. McBride* and G.C. Wetsel, Jr.*

Southern Methodist University
Dallas, Texas 75275

## INTRODUCTION

Important information on subsurface material parameters and structure is contained in the dynamics of surface motion. One of the most important techniques in quantitative nondestructive evaluation is optical sensing of surface displacement; it is noncontact, sensitive, fast, and capable of high spatial resolution. Laser interferometers in various configurations provide the ultimate in sensitivity [1]; however, due to their complexity and lack of flexibility, they may not be the first choice in applications where ultimate sensitivity is not required.

An accurate, reasonably-sensitive, easily-implemented method of determining the amplitude and phase of the harmonic displacement of a surface has been recently developed [2]. The method consists of measuring the optically-magnified deflection of a laser beam reflected from the vibrating surface. Its application to the calibration of scanning-tunneling-microscope scanners has resulted in measurenents of displacement as small as a few hundredths of an angstrom unit [2]. Position-sensor detection of deflected optical beams has been used in a variety of applications including photothermal-optical-beam-deflection (PTOBD) spectroscopy [3], absolute measurement of optical attenuation [4], PTOBD imaging of surface and subsurface structure [5], photothermal displacement spectroscopy [6], and atomic force microscopy [7]; reviews of applications [8] and theory [9] have been published. In this paper we report an optical-beam-deflection surface-displacement (OBDSD) imaging system and its application to the characterization of piezoelectric transducers and samples excited by them.

## DESCRIPTION OF APPARATUS AND METHOD

As shown in the block diagram in Fig. 1, the OBDSD apparatus consists of a probe laser, optical magnification, laser-beam position sensing, calibrated XYZ translation stages, and computer-controlled data acquisition. Three types of position sensor have been used: 1) a continuous

*Review of Progress in Quantitative Nondestructive Evaluation*, Vol. 9
Edited by D.O. Thompson and D.E. Chimenti
Plenum Press, New York, 1990

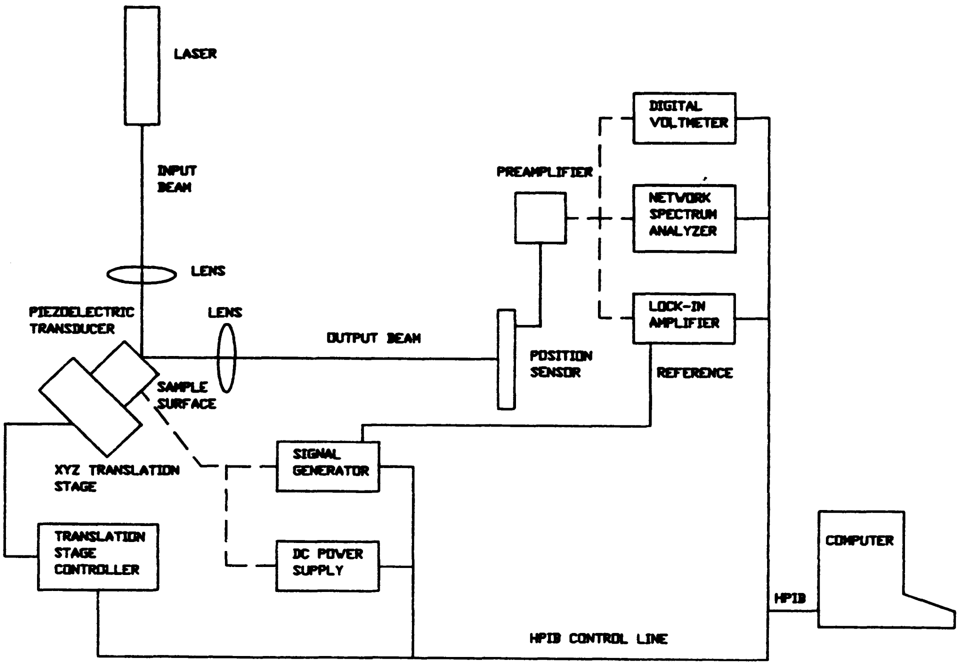


Fig. 1. Block diagram of optical-beam-deflection surface-displacement imaging apparatus.

position sensor [10] for static displacement and low audio frequencies, 2) a bicell detector [10] for frequencies up to a few MHz, and 3) a knife edge with a fast photomultiplier tube for frequencies greater than a few MHz. The output signal from the position sensor is measured using a digital voltmeter (static displacement), a lock-in amplifier (5 Hz-110 kHz), or a Hewlett-Packard 4195A network/spectrum analyzer (0.1-500 MHz). Using the lock-in amplifier or spectrum/network analyzer, the magnitude, phase difference, and frequency response of the displacement of a point on the surface of the sample can be measured. The phase difference is measured between the signal applied to the sample and the displacement signal obtained from the position sensor. The bandwidth has so far been limited to about 150 MHz by the photomultiplier preamplifiers when the knife edge is used for a position sensor and the network/spectrum analyzer is used for the detector. Data for construction of amplitude and phase images of the surface displacement are obtained by moving the sample using piezoelectric-motor-driven translation stages [11], which have a step resolution of 1 $\mu$m. The images are constructed later from the digitized data.

The optical system is shown in Fig. 2(a). The sample is located in the secondary focal plane of lens 1 with the incident beam forming an angle of approximately 45 degrees with respect to the normal to the sample surface. For an undisplaced surface, the effect of lens 1 is to focus the laser beam on the surface of the sample and the effect of lens 2 is to recollimate the beam reflected from the sample. The displacement of a point on the surface can be resolved

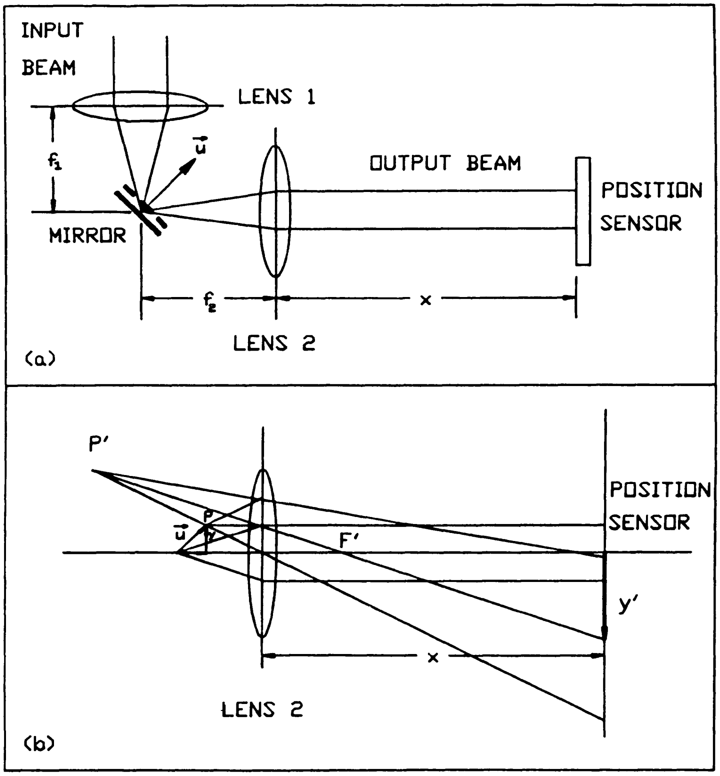


Fig. 2. (a) Schematic diagram of optical magnification system. (b) Effect of lens 2 on light from displaced point source.

into two components as shown in Fig. 2(b). Using paraxial-ray analysis, one can show that the displacement of the component transverse to the optical axis of lens 2 is magnified by the factor $m_t=(x/f_2-1)$, where $f_2$ is the focal length of lens 2 and x is the distance between lens 2 and the position sensor. The component of displacement ($u_p$) parallel to the axis of lens 2 has the effect of decollimating the beam and thus increasing the area at the detector; but, if $(m_t u_p)<<1$, the effect is negligible.

## RESULTS

For an initial evaluation of the OBDSD imaging apparatus, images of vibrating surfaces for common transducers and composite-device configurations were measured. Data are presented here for two samples: 1) an unloaded PZT-4 piezoelectric disc 25.4 mm in diameter and 3.18 mm in thickness, and 2) the PZT-4 transducer bonded to an aluminum cylinder 25.4 mm in diameter and 12.7 mm in length. The aluminum surfaces were polished for a specular reflection; a small, polished, silicon wafer was bonded to the PZT-4 transducer to provide a specularly reflecting surface.

Two commonly utilized modes of vibration of a disc-shaped transducer are the longitudinal-thickness and radial modes, which are described by one-dimensional models [12]. As an example, the theoretical frequency response of the longitudinal-thickness mode of Sample 1 is shown in Fig. 3 in the neighborhood of the first series resonance at 632 kHz. By contrast, the frequency response from 50 to 1050 kHz of the displacement of a point on the surface of Sample 1 is shown in Fig. 4, where many modes of vibration are evident as resonances. The strong resonance at 614 kHz is probably the longitudinal-thickness mode. By comparison with the radial-mode model, the first radial-mode resonance was identified as the first strong resonance (at 94.6 kHz) in Fig. 4. The remaining resonances are various "waveguide" modes that cannot be easily identified, but which illustrate the power of the OBDSD method.

In Figs. 5 and 6 are shown the amplitude and phase images, respectively, for the central area of the unloaded transducer (Sample 1). Although the frequency (614 kHz) corresponds to the first series resonance of the longitudinal thickness mode, these images reveal that the amplitude and phase change along the surface of the sample; thus, other modes are excited with substantial amplitude.

Amplitude and phase images of the central area of the surface of the aluminum cylinder of Sample 2 are shown in Figs. 7 and 8, respectively. The frequency (866 kHz) corresponds to a strong resonance of the composite device. Again, complex mode structure is revealed.

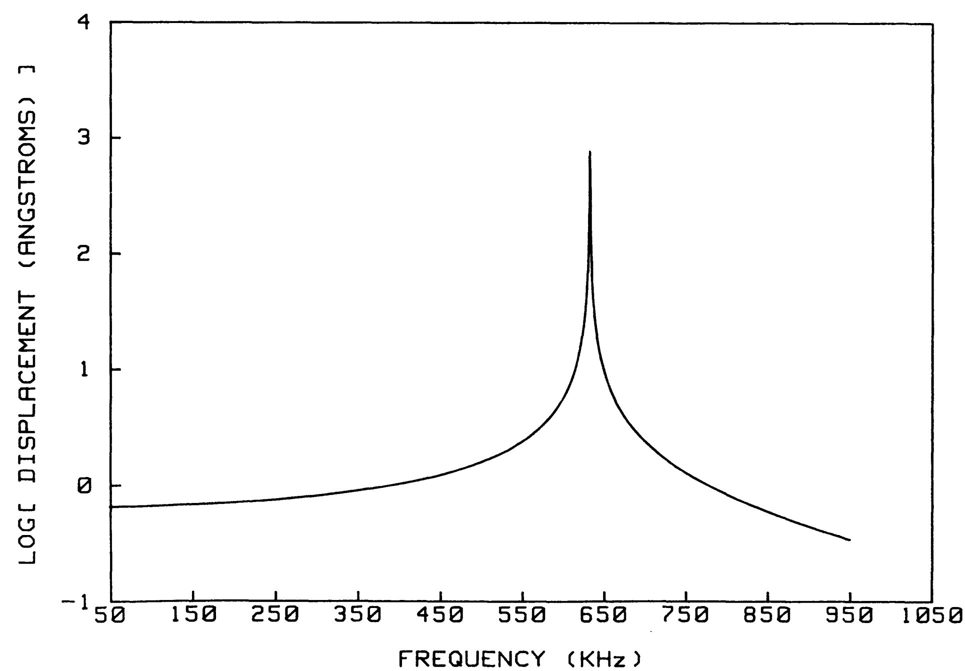


Fig. 3. Theoretical frequency response of the longitudinal-thickness mode of Sample 1.

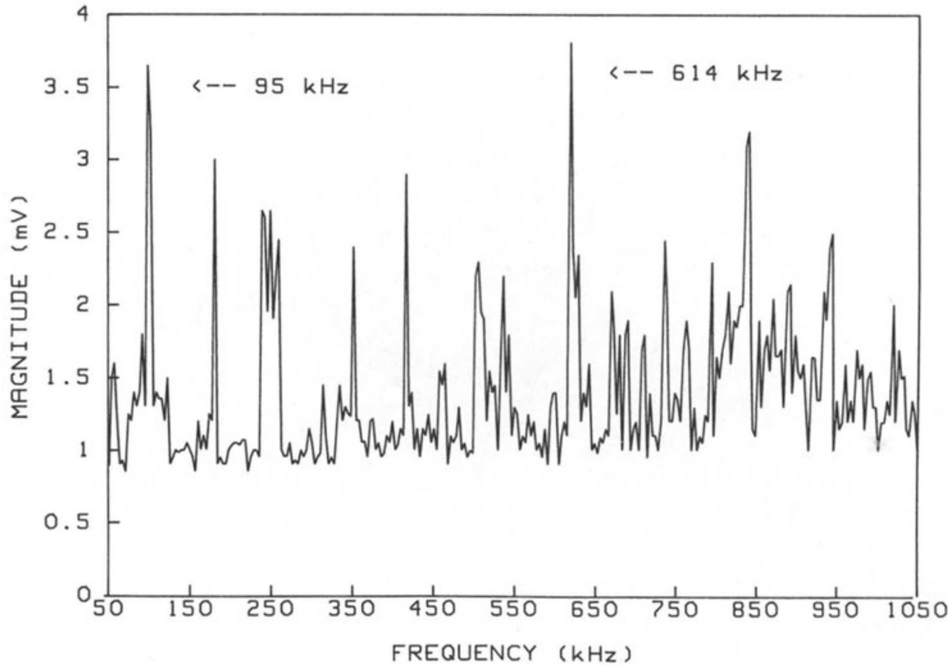


Fig. 4. Experimental frequency response from network analyzer of a point on the surface near the center of Sample 1.

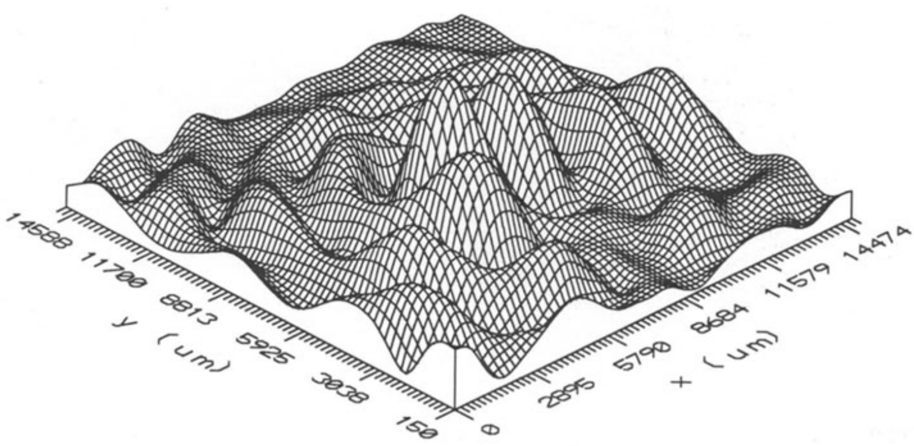


Fig. 5. Amplitude image of central area of the surface of Sample 1, f=614 kHz.

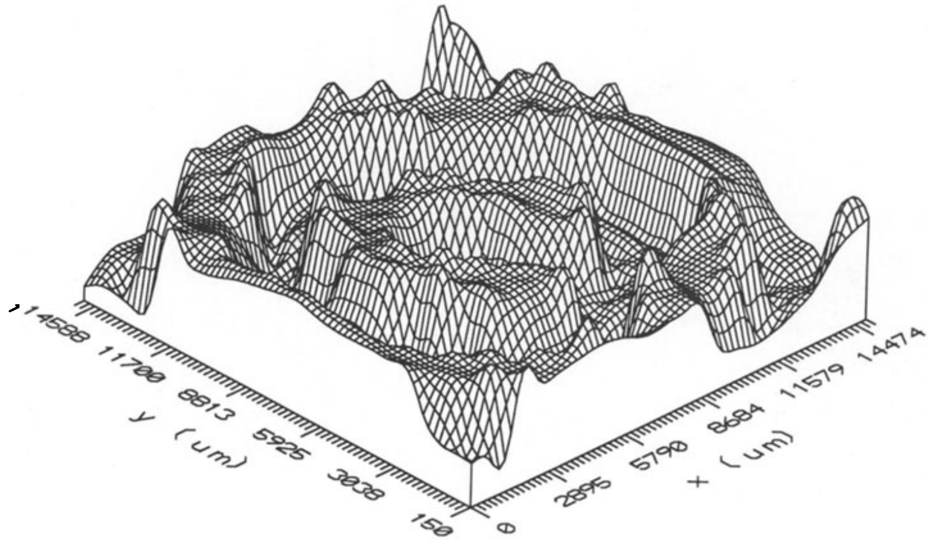


Fig. 6. Phase image of central area of the surface of Sample 1, f=614 kHz.

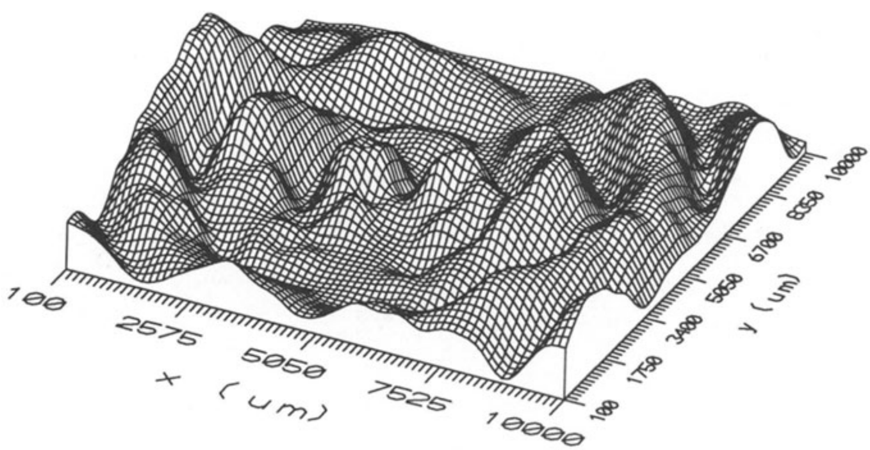


Fig. 7. Amplitude image of central area of the surface of Sample 2, f=866 kHz.

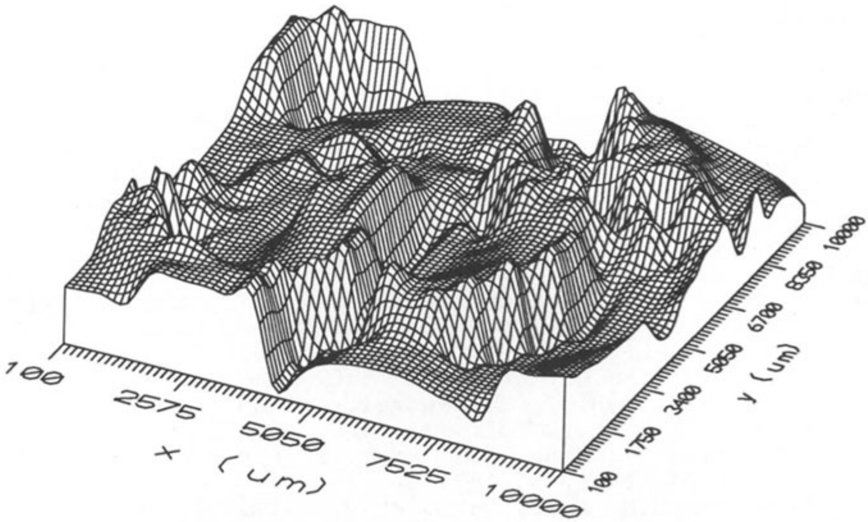


Fig. 8. Phase image of central area of the surface of Sample 2, f=866 kHz.

DISCUSSION

We have developed a computer-controlled optical-beam-deflection method that is capable of measuring the amplitude and phase of harmonic surface displacement for construction of surface-displacement images. The method has the advantages of compositional and operational simplicity, point-by-point noncontact displacement measurement, and broad dynamic range. The frequency response of this method is limited by the photodetector and subsequent electronics for knife-edge laser-beam-displacement detection.

The utility of the OBDSD system has been demonstrated by imaging piezoelectric transducers and samples bonded to them. Results have been presented that show that this technique is not only useful for quantitative nondestructive evaluation, but particularly appropriate for experimental testing of vibrational-mode modeling. Applications to other problems where surface displacement is of interest are in progress, such as direct measurement of displacement in surface acoustic wave devices.

ACKNOWLEDGEMENT

We gratefully acknowledge the skill and assistance of Wayne Johnston in the construction of our apparatus.

* Present address: Erik Jonsson School of Engineering and Computer Science, The University of Texas at Dallas, Richardson, TX 75083.

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