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FIBER OPTIC SENSING FOR NDE AND PROCESS CONTROL

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ABSTRACT

Many optical techniques are being developed for the inspection of completed parts and for the sensing of manufacturing processes as part of process control schemes. Optical techniques are attractive because of their noncontacting nature and their ability to obtain information from a hazardous environment. However, many of these techniques currently require delicate alignment and calibration, which make them impractical outside the laboratory. In addition, the methods themselves may be hazardous if beams of high intensity laser light are used in the sensing process.

The application of fiber optics to laser sensing techniques has the potential to make them more practical and safer in an industrial environment. This paper discusses three optical techniques which use fiber-optic technology to make them more robust and safe. The first uses fibers to deliver pulsed laser light for a vision system which is capable of viewing high luminosity processes. The second also uses fibers to deliver pulsed laser light, but for the purpose of generating ultrasound in a region where a normal ultrasonic transducer could not be used. The third application uses fibers in the arms of a heterodyne interferometer which can be used to detect vibrations or ultrasonic waves.

INTRODUCTION

Optical measurements for inspection or process control are desirable for a number of reasons. The techniques are usually noncontacting, with the hardware often at a distance from the part being measured. This permits delicate parts or parts which are in an hazardous environment to be inspected. However, the optical instruments are also often very delicate and require precise alignment and calibration. These features prevent their application in practical situations, although they may be very useful in a well controlled laboratory. Fiber optics can make such instruments more robust and even safer since the high intensity light can be confined to the fibers and is therefore less of a hazard.

Three applications of fibers to optical instruments are discussed in this paper. The first example is a vision system [1,2] for high luminosity processes, such as arc welding, that uses laser light delivered by two fiber-optic cables to overwhelm the light of the process so that clear images can be obtained. Another general area of interest at the Idaho National Engineering Laboratory (INEL) is the use of pulsed-laser energy as a source of sound or ultrasound [3]. Lasers have been demonstrated to be very useful in creating sources of ultrasound at the surface of a molten weld pool, where no practical contacting ultrasonic transducer could be used. The use of fiber-optic cables to deliver the pulsed light has the potential to make the technique more practical and safe. Using multiple fibers with variable time delays may enhance the capability of the laser to generate ultrasound. A third area of application is in sensing of motion [4,5]. Interferometers have been shown to have the capability to sense motion caused by ultrasonic waves or vibrations at the surfaces of materials. The use of fiber optics in the arms of these interferometers can decrease the need for delicate alignments and provide a more stable system for use in the field.

VISION FOR HIGH LUMINOSITY PROCESS

The INEL vision system [Figure 1] uses a pulsed nitrogen laser to illuminate the region around a weld pool [1,2]. The original system used a xenon strobe to illuminate the weld pool directly, and later versions used direct laser light for illumination. In the present system the light from the laser is coupled into two fibers which transmit the light to the region around the pool. The fibers provide a flexible method of putting the light exactly where it is needed without the necessity of adjusting mirrors or lenses in a complex optical delivery system. The fiber optics also allow the laser to be positioned well away from the welding area so it cannot be damaged by spatter or smoke from the welding process. In addition, the intense laser light is confined to the fiber, partially eliminating the potential eye hazard from the laser.

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The bright light from the laser overwhelms the light from the welding arc for the length of the laser pulse (about 10 ns). During this time a video camera system equipped with an image intensifier tube is used in a time-gated mode as a very high speed electro-optical shutter. The shutter is synchronized with the laser pulse and therefore acts to accept most of the laser energy reflected from the weld site, but at the same time accepts only a very small fraction of the continuous emission from the welding arc. The synchronized laser and shutter are driven at 30 pulses per second to yield a single laser exposure per video frame. Additional reduction of the arc light is achieved by using a narrowband spectral filter at the wavelength of the laser emission. For the nitrogen laser, this is in the ultraviolet, which is far down the black-body spectrum of the arc.

The light from the laser is split by a partially transmitting mirror into two equal parts. Each part is then focused onto the end of a 600 µm diameter fused silica fiber. Focusing is accomplished by mounting the fiber in a fiber-optic steering coupler which allows three-axis motion of the fiber-optic cable end. Alignment is necessary only once unless the system is subjected to a severe shock.

Figure 2 shows gas metal arc welding (GMAW) of heavy-section aluminum alloy plate. The typical video picture without laser or shuttering is shown in Fig. 2a. Some evidence of the wire electrode can be seen below the rim of the gas cup, but there is little detail regarding the groove. The bright elliptical area represents the arc light surrounded by a rather large depression in the welding pool. A great deal more detail is to be seen with the laser illumination (Fig. 2b). This photo shows a shadow projected across the weld preparation ahead of the pool; information from the shadow could be used for seam tracking.

The current sensor hardware is well enough developed to produce the required imagery of the pool and groove geometry for a variety of welding conditions. The emphasis now is on development of techniques for real-time computer processing of the video images to extract the required data (e.g. pool position and width) [6].

LASER GENERATION OF ULTRASOUND

Fibers are also being used to transmit light from pulsed or amplitude modulated lasers for generation of ultrasound. Pulsed laser light has been demonstrated by many investigators [e.g., 7,8] to be capable of generating ultrasound in liquids and solids. In research at INEL on sensing of GMAW, a pulsed Nd-YAG laser with a pulse length of about 10 ns and pulse energy of 10 mJ is used to generate sound in a molten weld pool during the welding process. The laser beam is focused on a predetermined position of the weld pool. At this energy level transient stresses are generated by two mechanisms: thermoelastic expansion and ablation. The dominant cause of the transient stress which leads to stress wave propagation in the part is the ablation of small amounts of the surface. The transmitted ultrasound is detected by a piezoelectric or an electromagnetic-acoustic transducer (EMAT). The signal received provides information about the properties of the pool including the geometry and defect generating conditions. This information can be input to an intelligent controller in a sensing and control system for a completely automated welder [9].

Previous work using piezoelectric transducers in pulse-echo and pitch-catch modes has demonstrated the capability of using contacting ultrasonic techniques to determine the geometry of the molten/solid interface [10] and to detect conditions which could lead to defect formation [11]. However, the couplant which is required for piezoelectric transducers is a potential source of contamination in the weld and may be difficult to use under industrial conditions.

Several modifications to the experimental system are being considered to make it fieldable. The laser beam must be delivered to the weld via a fiber optic cable to reduce personnel hazards in the work area and to increase the area of excitation on the weld so that the total weld may be inspected. Work is underway on this fiber-optic delivery system. A fiber-optic delivery system also provides the potential to produce arrays of laser generated acoustic sources with varying delays and spacings to tailor the sound beam in the sample [12].

LASER SENSING OF VIBRATIONS AND ULTRASOUND

Heterodyne interferometers are currently used in several laboratories for noncontacting measurements of small displacements. For example, a system developed by Ringermacher [5] is being used to detect the motion induced by modulated laser light on coated parts (a schematic of this system is shown in Figure 3). The motion is dependent on the quality of the bond between the part and the coating. The light beam in the reference arm of the interferometer is shifted in frequency by the acousto-optic (AO) modulator. When this beam is combined with the beam from the sample arm, they interfere and the photocell picks up the beat frequency between the two beams which, under static conditions, is just the frequency of the AO modulator. When the sample moves, the frequency and phase of the sample beam also change due to the change in path length in the sample arm. Thus the beat frequency is modulated according to the sample motion - the frequency deviation from the static value is directly proportional to the velocity of the sample and the phase deviation from the static value is directly proportional to the displacement of the sample.

The system requires delicate alignment, which may vary for different parts with different reflectivities. However, by using fiber-optic techniques, the system can be made more robust and potentially fieldable. Figure 4 is a schematic of a multimode fiber-optic version of the same system. The multimode fiber was used so that more light could be gathered from the test specimen. Interferometric detection is still possible due to the use of a long coherence length stabilized laser and a heterodyne technique. The initial beam is split into a reference arm and a sample arm with the light in the reference arm again shifted in frequency by the AO modulator. The two beams are then focused onto two 50 µm diameter fibers which are coupled together. The light in the sample leg is split into two parts in the coupler. One part goes back through the reference leg and is lost (except for a small portion which reflects from the end of the fiber). The other part goes to the sample, which in this case is a piezoelectric transducer with a mirror mounted on its face. Light reflecting off the mirror travels back through the sample fiber, through the coupler, where it splits again. One portion is again lost in the sample input arm but the other combines with the reference beam and the interference of the two beams is detected by the photocell.

The main advantage of this scheme is that alignment is not required to recombine the reference and sample beams since that is done in the fiber coupler. This alignment is very critical since the beams must be colinear for detectable interference to take place. A small change in the position of the sample can change this alignment severely in the standard version of the interferometer. The major source of difficulty with the fiber-optic system is the additional reflection from the fiber tip of the sample beam in the reference arm that causes an additional interference signal in the light detected by the photocell. This source of noise can be eliminated by coating the fiber tip with an antireflection coating.

A heterodyne interferometer was recently assembled at the INEL. One of the first uses of this instrument will be sensing vibrations in thermal protection tiles to determine the quality of the bond to the substrate. These tiles are diffusely reflecting. However, to optimize the signal during development of the interferometer, a mirror was mounted on a piezo pusher. Figure 5 shows the raw light intensity data (top two traces) from the output arm of the multimode fiber coupler. The heterodyne beat signal from the fiber coupler was sampled in quadrature (i.e., sampled twice, one-fourth of a wavelength apart). Software converted these data into displacements, shown in the bottom trace of Figure 5. The measured peak-to-peak displacement amplitude is approximately 2100 nm, more than three times the wavelength of the laser light. The noise in the signal is approximately 40 nm, due mainly to the light reflected in the reference arm; this noise will be eliminated with an antireflective coating as discussed above. Notice how the raw frequency increases when the transducer's velocity is high and decreases when the transducer's velocity is slow at the peaks. Figure 6 shows the displacement measured for a smaller amplitude (less than one wavelength of light) sinusoidal driving signal at 17 kHz; here the noise level is much more apparent.

The multimode fiber optic sensor as implemented requires no critical alignments in the optics other than the launching of the light into the fiber, and the detection system has been shown to have a large dynamic displacement range (from less than one wavelength of light to multiple wavelengths of light). Since the signal demodulation is done in software, the detection system is easily modified to be highly adaptable for different situations in the field. All of these facts make the sensor a potentially fieldable system.

CONCLUSION

The use of fiber optics in an industrial environment has many potential advantages. The biggest advantage is the safe delivery of high power light, as in the weld vision system and the laser generation of ultrasound. A side benefit of using fibers is flexibility in placing the light exactly where needed. This is very helpful in the scanning of a part or process such as in ultrasonic inspection. These examples of sensor research using fiber optics at the INEL demonstrate the potential of developing field capable systems.

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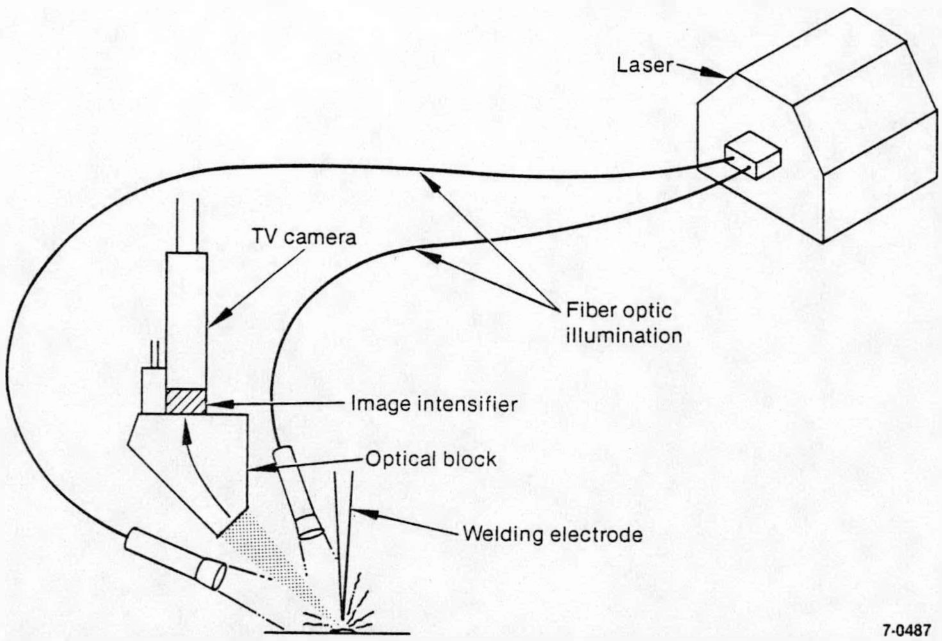
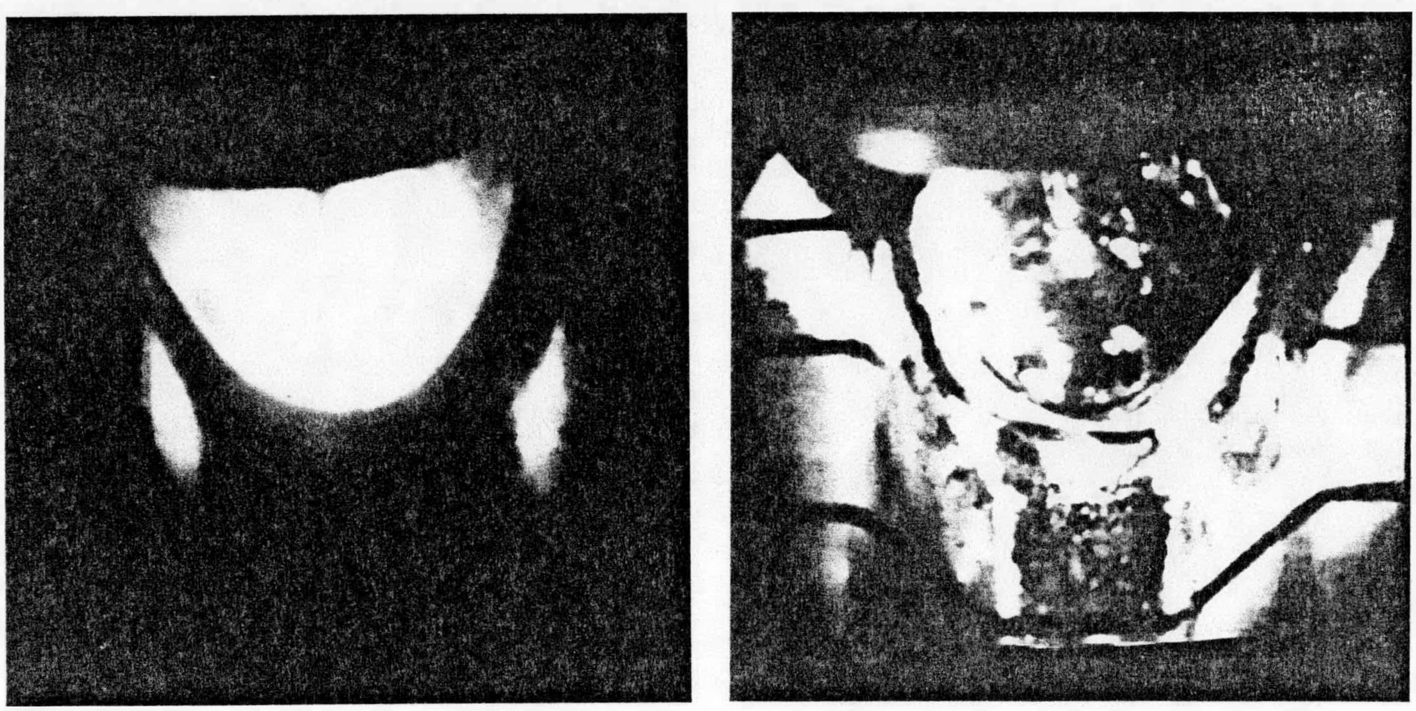


Fig. 1: Schematic of the weld vision system.



a. GMAW on aluminum without laser illumination.

b. Using laser illumination and shadow to reveal groove geometry.

Fig. 2: Video frames of the welding process.

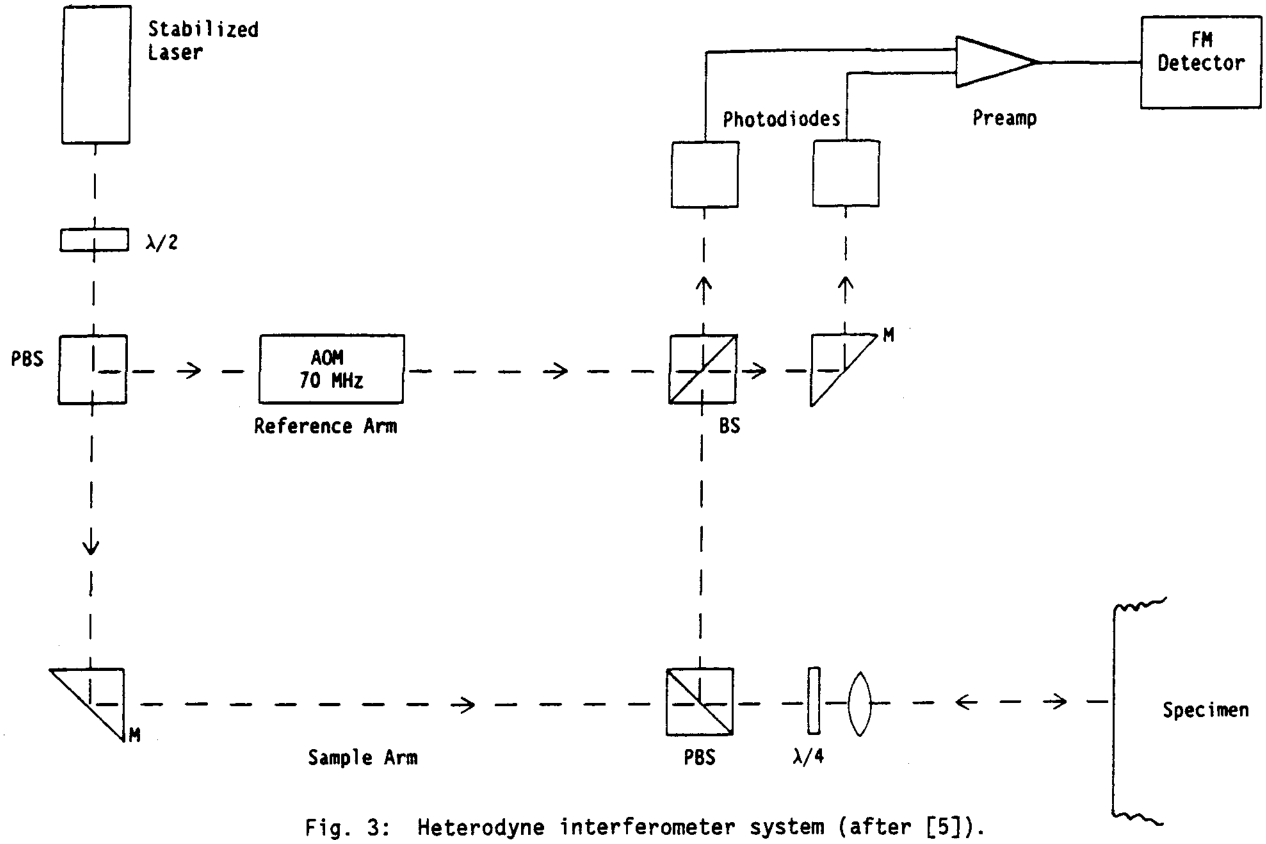


Fig. 3: Heterodyne interferometer system (after [5]).

PBS	Polarizing Beamsplitter
AOM	Acousto-Optic Modulator
λ/2	Halfwave Plate
λ/4	Quarterwave Plate

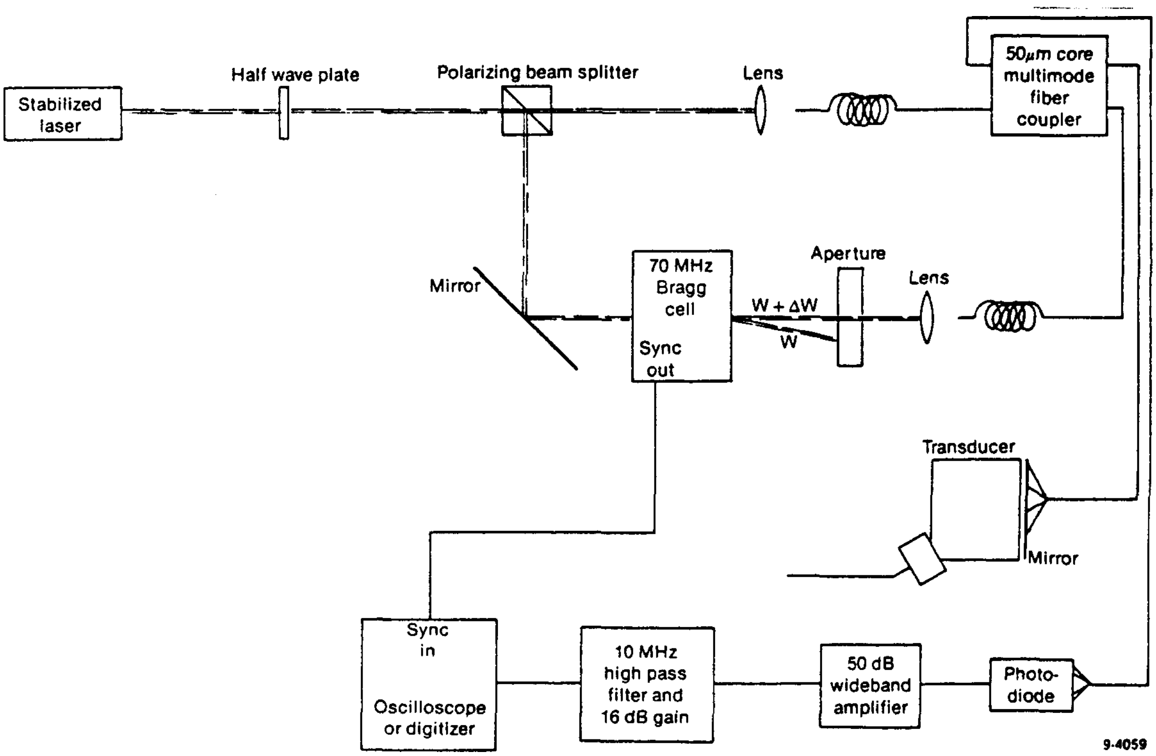


Fig. 4: Fiber optic heterodyne interferometer system.

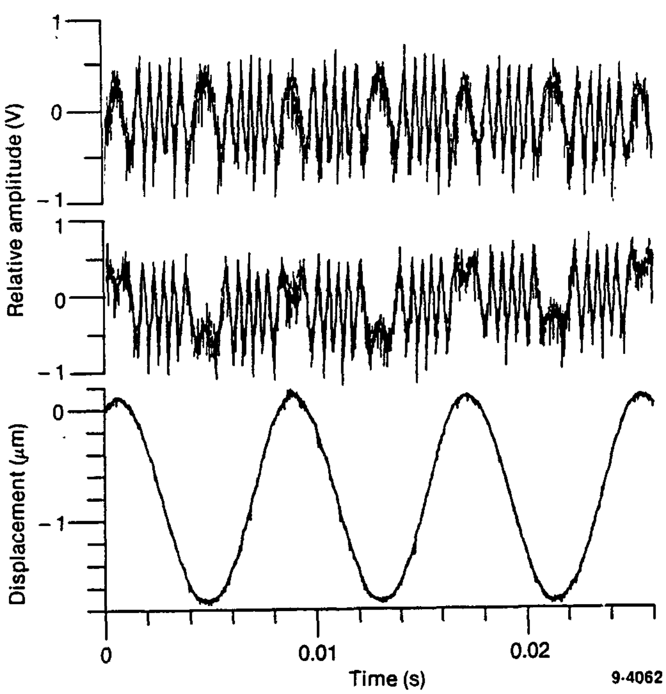


Fig. 5: Raw quadrature and displacement data points for a large amplitude 100 Hz source.

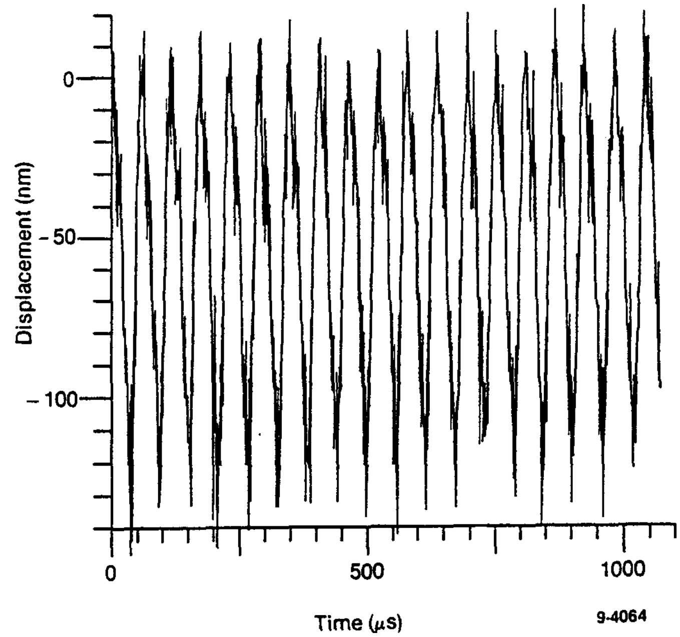


Fig. 6: Measured displacement versus time for a 17 kHz source.