ADAPTIVE HETORODYNE LINE-PROBE INTERFEROMETER FOR ENHANCED DIRECTIONALLY-SENSITIVE DETECTION OF ULTRASOUND

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INTRODUCTION

Optical methods provide a non-contact method of detecting ultrasound at the surface of a test object. Unlike conventional piezoelectric transducers, which require a couplant, optical detection provides an absolute calibration of the ultrasonic displacement amplitude. In addition, they can have a broader bandwidth and a higher spatial resolution of detection than conventional piezoelectric transducers. All these advantages however typically come at the expense of sensitivity. The best extant optical detectors still suffer from a two order of magnitude sensitivity gap with respect to conventional piezoelectric transducers.
In this paper, we describe an adaptive heterodyne interferometer receiver using wave mixing in photorefractive bismuth silicate (BSO) crystals which is configured as a line receiver that is directionally most sensitive to ultrasound impinging normal to the line, and is significantly less sensitive to ultrasound impinging in other directions. Such a system is attractive in situations where the ultrasonic scatter from a specific direction is to be selectively pulled out in the presence of scatter from other "noise" sources. The line probe system also provides a way to bridge the sensitivity gap that optical detection thus far has suffered vis-à-vis piezoelectric detection. Results of applications to nondestructive testing of metal surfaces are presented.

ULTRASOUND DETECTION

In previous work, Pouet et al [1] have presented an adaptive heterodyne interferometer to obtain measurements at a *point* of ultrasound propagating on a rough surface. In this paper, we present a modification of that system to measure ultrasound using a *line* probe. The advantages of using line detection are: (i) selective sensitivity to ultrasound propagating normal to the line, and (ii) ability to bridge the gap of nearly two-orders of magnitude that currently exists between optical interferometric and conventional piezoelectric ultrasound transducers.

Directional sensitivity is important in ultrasonic nondestructive testing, because it enables selective discrimination of the signal. Conventional piezoelectric surface acoustic wave transducers are directionally sensitive [2], enabling them to pick up echoes from

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fatigue cracks emanating from rivet holes where the scatter of the impinging ultrasound from the rivet itself is not of importance. Optical interferometers using point detection, on the other hand, are sensitive to ultrasound *omni*-directionally, and as such any reflection from a crack may be lost in the scatter from the rivet. Omni-directionality is clearly not desirable in this and other similar situations such as ultrasound propagation in anisotropic media. An interferometer, which uses *line* illumination however becomes directional. To extract the optical phase from a line probe, it is necessary to use a self-referential interferometer, that is one where the reference beam is derived in some fashion from the object beam itself, and therefore the two interfering beams are perfectly "speckle-matched" so that constructive interference occurs along the entire optical wavefronts. It is possible to configure line probes using the Sagnac interferometer [3,4], the Fabry-Perot interferometer [5], and the recently developed class of adaptive interferometers using double phase conjugation [6,7] where the speckled object beam is converted to a planar wavefront that still retains the ultrasonic signal of interest, or using wave-mixing where a reference beam is created that is speckle-matched with the object beam [1,8]. The interferometer described here uses wave mixing in BSO crystals.

The sensitivity advantage of conventional piezoelectric transducers (currently two orders of magnitude [9]) is because they collect and integrate the ultrasonic signal from a large probe area. The sensitivity of a line optical probe can also be increased by collecting the ultrasonic signal over its entire length, provided it is possible to maintain the same optical power density over the entire length of the probe as can be provided at the focal spot of a point interferometer. Assuming that sufficient optical power is available, the only factors limiting the optical power density are the damage thresholds of the specimen under test and that of the photodetector, and spreading the optical power over a larger area is clearly preferable to dumping it all into a small spot.

The set up of the adaptive line-probe interferometer (Fig. 1) is similar to the one described by Pouet et al [1]. Three beams are derived from the same coherent laser source. One of these is taken to the object and, by means of a lens system that includes a cylindrical lens of F-number one, is shone onto the object as a line probe of length L and line thickness much smaller than the wavelength of the ultrasonic signal to be measured. The light scattered back by the specimen is collected by the same lens system and is delivered to

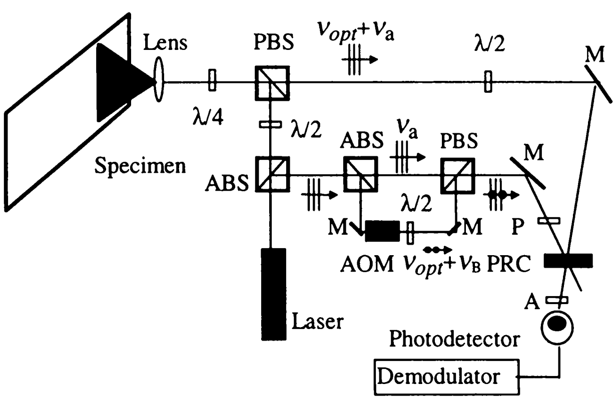

Figure 1. Schematic of the optical set-up. ABS: adjustable beam splitter; PBS: polarizing beam splitter; AOM: acousto-optic modulator; PRC: photorefractive crystal; P: polarizer; A: analyzer.

a 5 mm wide by 10 mm high by 10 mm thick BSO photorefractive crystal (PRC) as the object beam. The other two beams are made to be collinear with each other, but with one of them orthogonally polarized with respect to the other and also frequency shifted by an amount ν_B= 40 MHz using an acousto-optic modulator. Both these beams are also brought to the BSO crystal such that they make an angle of about 5° to the object beam. The beam that is not frequency shifted acts as the reference or pump beam. The object beam and the reference beam are of the same optical frequency and have essentially the same linear polarization and therefore create a standing interference pattern leading to the formation of a holographic grating in the PRC. The crystal orientation is such that this grating vector is along the [001] crystal axis, and a sinusoidal electric field of 6 kV/cm at 3200 Hz is applied to enhance the diffraction efficiency (see Ref. 1 for details).

Theory of Line Detection

Consider a plane harmonic ultrasonic surface wave traveling on the test object making an angle θ to the x-axis (see Fig.2):

$$U(x,z,t) = U\cos\{2\pi\nu_a t - (k_a x\cos\theta + k_a z\sin\theta)\} \tag{1}$$

where $\mathbf{k}_a = k_a\{\cos\theta \mathbf{e}_x + \sin\theta \mathbf{e}_z\}$ is the propagation vector for the ultrasound; $k_a=2\pi/\lambda_a$ is the ultrasonic wave number; λ_a is the ultrasonic wavelength; ν_a is the ultrasonic frequency; and U is the ultrasonic amplitude. The optical line probe is oriented along the z-axis, and therefore measures $U(0,z,t)$. The optical phase of the transmitted object beam is affected by the ultrasonic displacement and can be written as: $\varphi(z) + 2k_{opt}U\cos(2\pi\nu_a t - k_a z\sin\theta)$ where the first term is a spatially random phase variation due to scattering from the rough object surface; and the second term is due to the ultrasound induced path-change; and $k_{opt}=2\pi/\lambda_{opt}$, where λ_{opt} is the optical wavelength.

The optical phase of the frequency-shifted readout beam can then be written as: $\varphi(z)+2\pi\nu_B t$ where the first term is the same spatially random phase variation as that of the scattered object wave since the wavefronts are perfectly matched; and the second term is due to the frequency shift introduced by the AOM. This beam contains information about the ultrasound since the time response of the crystal is such that the recorded grating cannot adapt to the high-frequency changes in the object beam. Interfering the transmitted object and diffracted readout beams results in an intensity fringe $\tilde{I}(z,t)$ at the photodetector:

$$\tilde{I}(z,t) = \tilde{I}_o\{1 + M\cos[2\pi\nu_B t - 2k_{opt}U\cos(2\pi\nu_a t - k_a z\sin\theta)]\} \tag{2}$$

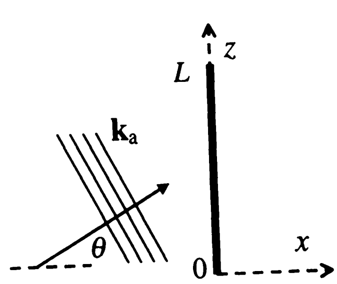

Figure 2. Surface ultrasonic wave propagating at different angles to the line.

where M is the modulation depth, and $\hat{I}_o$ is the average optical intensity density. The photodetector provides a current that is proportional to the total intensity (Eqn (2)) integrated over the entire length of the probe line. The demodulated photodetector output signal is:

$$V(t) = \hat{I}_o L M k_{opt} \operatorname{sinc}\left\{\frac{k_a L \sin\theta}{2}\right\} U(t) \tag{3}$$

where $U(t) = U\cos\left\{2\pi v_a t - \frac{k_a L \sin\theta}{2}\right\}$, which is the ultrasonic signal amplitude at the midpoint of the line probe. The sinc function indicates that there will be signal roll off as the angle of incidence of the ultrasonic wave deviates from normal incidence, i.e. the line probe will be directionally sensitive. The extent of roll off, and consequently the extent of directionality of the line receiver, depend on the parameter $k_a L$, with higher frequency and consequently shorter wavelength ultrasonic signals experiencing a more rapid roll off.

Experimental Results

The directional sensitivity of this line-probe interferometer is clearly seen in the experimental results shown in Fig. 3. A 5 MHz pzt transducer was used to generate Rayleigh waves in a 12 mm thick aluminum block. The line source was kept at a distance of 37 mm from the source, and the probe line was rotated with respect to the ultrasound propagation direction. The effective line probe length L in this experiment was estimated to be about 1.7 mm, which corresponds to about three wavelengths of the ultrasonic signal. Also shown in Fig. 3 for comparison are the results for the case of a point probe, obtained by replacing the cylindrical lens with a spherical lens of the same focal length. Clearly, the point probe is omni-directional exhibiting no directional sensitivity, whereas the line probe is highly directional

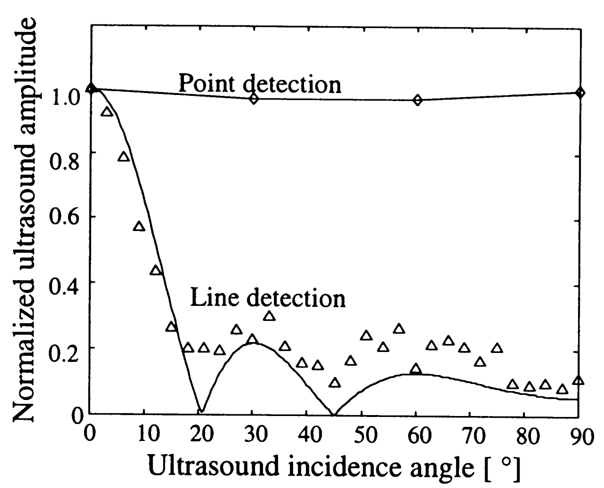

Figure 3. Sensitivity of the line probe to ultrasound propagating at different angles to the line.

It can be seen from Fig. 3 that the first minimum sensitivity point occurs when the ultrasound propagation angle makes an angle of 20° to the line probe. Fig. 4 (b) shows experimental results that demonstrate this. In this experiment a 20 mm thick aluminum sample was cut so that it has a 50 mm long 10° v-shaped notch at one of its edges. A pulsed Nd:YAG laser generated 2 MHz and 5 mm wide surface plane waves and a 1.7 mm wide line probe was kept at the same place as the aluminum sample was scanned over 52 mm of its length (Fig 4(b)). It can be seen In Fig. 4 (b) that the normalized ultrasound amplitude recorded is much smaller from v-shaped notch. The extra drop at the center of the sample is because the most of the ultrasound is reflected outside the probe line.

The signal-to-noise ratio for single-side band detection and normal incidence, assuming shot-noise limited sensitivity [10] can be expressed in our case as:

$$SNR = \sqrt{\frac{\langle i_{signal}^2 \rangle}{\langle i_{noise}^2 \rangle}} = k_{opt} UM \left\{ \frac{\eta \hat{I}_0 L}{4h\nu_{opt} B} \right\}^{1/2} \tag{4}$$

where i_{signal} and i_{noise} are the signal and noise currents in the photodetector; η is the quantum efficiency of the detector, B is the electronic detection bandwidth, ν_{opt} is the optical frequency, and h is Planck's constant. Thus, the *SNR* can be increased by increasing L while keeping the optical power density uniform along the length of the probe. This is experimentally demonstrated by measuring the *SNR* as the effective line width is changed (without changing the optical power density) by use of an aperture. For this experiment, a 2 MHz transducer was used to harmonically excite a mirror onto which the optical line probe was focused. The photodetector signal was monitored directly on a spectrum analyzer, and the amplitudes of the carrier signal, the ultrasonic side-bands, and the noise level were all measured for different effective probe lengths L. The *SNR* calculated for different line probe lengths (Fig. 5) exhibits the expected linear behavior when plotted against $\sqrt{L}$ except when
the line length increases beyond a certain value when the *SNR* does not increase anymore.

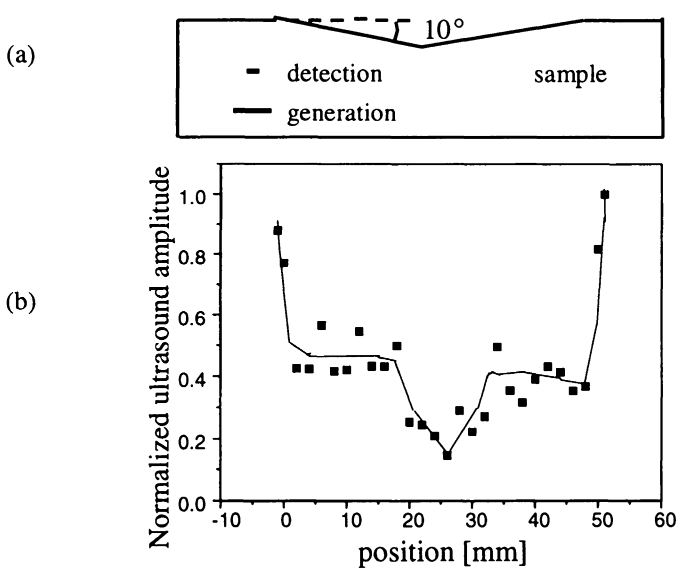

Figure 4. (a) Measurement setup, (b) signal amplitude as a function of position.

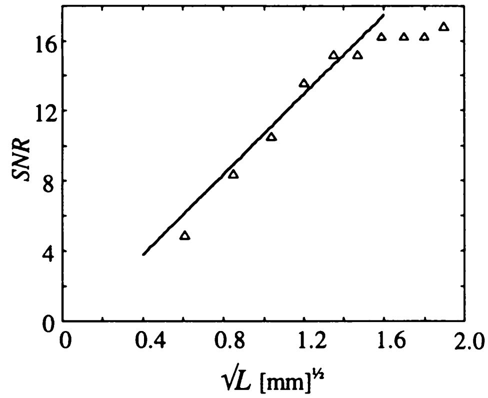

Figure 5. Variation in Signal to Noise Ratio as the probe line length is changed.

We attribute this to the fact that the photorefractive crystal dimensions and the overlap region of the writing beams restrict the effective line length from being increased beyond a certain point even though the line length on the object surface may be increased. Furthermore we are neglecting here the *SNR* degradation due to multiple scattering within the PRC.

It is well known that the ultrasonic displacement amplitude can be obtained independent of the optical reflectivity of the test object when a heterodyne point detection scheme is used [3]. This is of course true for heterodyne line detection as well. From the *SNR* measurements we can estimate that the ultrasonic amplitude is approximately 2.6 nm. The minimum detectable ultrasonic signal (for a *SNR* of unity) for this case is found to be 0.26 nm. In principle, it is possible to increase the sensitivity several fold. Note that for point probe detection, the focal spot size is typically 50 μm. Comparing this with a line probe effective length of 1.7 mm (with line width at 50 μm) used in the experiment of Fig. 2, the *SNR* gain is a factor of 5.5, at the same power density as that of the point probe. If the probe length can be increased to 5 mm, the gain in *SNR* will be a factor of about 10, bringing the sensitivity of the optical detector to within the same order of magnitude as that of conventional pzt transducers. Of course, this assumes that a 100 fold increase in optical power can be obtained, and indeed it can if an appropriate pulsed laser source is used. Issues regarding the time response of the crystal are more critical when a pulsed laser source is used, but these are not insurmountable, and efforts to implement such a system are ongoing at our Center.

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