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# Noncontacting detection in ultrasonic nondestructive evaluation of materials: Simple optical sensor and fiber-optic interferometric application

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An optical displacement sensor based on the two-beam interferometry of coherent light using two principal diffracted orders of a fine reflection blazed grating is constructed. The inherent capability of the interferometer for absolute calibration, its maximum sensitivity adjustment, and the simplicity of the configuration of its components are explained. Utilization of a single-mode optical fiber in the test arm of the interferometer to enhance the geometric flexibility of the optical system is demonstrated. The sensor's application in the noncontacting detection of stimulated ultrasonic stress waves for nondestructive evaluation of advanced composite materials is emphasized. The detected signal is digitized and recorded using an IBM PC with a plug-in data-acquisition board. The combination of high sampling rate capability of the device and optical detection has facilitated the signal processing of ultrasonic waves in order to achieve interpretation and quantification of the physical parameter of interest (i.e., displacement).

## INTRODUCTION

In nondestructive testing (NDT) of materials using low-power ultrasound, the quantitative evaluation (e.g., the interrelations between mechanical properties and ultrasonic measurements) needs to be obtained. To bridge these two sets of physical parameters, optical techniques can be utilized to gain well-characterized and quantitative information (e.g., displacements) about a body under static or dynamic loadings. Moreover, laser interferometric displacement measurement techniques for the detection and analysis of surface/transient acoustic waves, acoustic sensing, are useful due to the noninvasive characteristics of optical noncontacting sensors in ultrasonic nondestructive evaluation.

The main advantages of using optical sensors are that they are noncontacting so that no alteration of actual surface displacement occurs. They can be used in hostile environments, in particular, for high-temperature materials characterization. They are sensitive, e.g., displacements of sub-Angstrom magnitudes can be measured. Because of their ability to focus the laser beam on a spot size region, point-by-point interrogation of the surface and complete characterization of the displacement field are readily accomplished. Following the suggestion made in Ref. 1, a unique optical arrangement is designed in a Michelson-type interferometer using a blazed diffraction grating as a beamsplitter and recombiner.

## 1. REFLECTION BLAZED DIFFRACTION GRATING

A plane reflection blazed grating is shown in Fig. 1. The grating is constructed by a number of densely packed right angle prisms grooved on the surface of a plane glass block on which a thin layer of aluminum has been deposited for increased reflectivity. In contrast to ordinary (amplitude or

phase) diffraction gratings where the undiffracted (zero) order has the stronger intensity, in a blazed diffraction grating the stronger intensity is shifted to some higher order. This happens when the mirror reflection of the incident beam from the facets of prisms coincides with any particular set of diffracted orders. Consequently, the blazed grating has a higher diffraction efficiency compared to the ordinary grating. For a given optical wavelength, the intensity of the diffracted beams, in general, is a function of the shape, angle, and depth of the grooved surfaces and of the grating surface reflectivity. The angle of the principal diffraction order is solely determined by the proper choice of the wavelength used and by grating spacing (pitch). The simple relations governing such a grating's diffraction properties, grating equation and blazed angle, can be written as

$$\sin \theta = m\lambda / g + \sin \alpha,$$

$$\gamma = (\alpha + \theta) / 2,$$

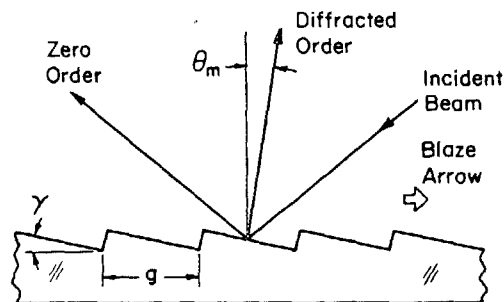


FIG. 1. Single-order blazed reflection grating.

where  $g$  = grating pitch,  $m$  = diffraction order,  $\theta$  = diffracted angle,  $\alpha$  = angle of incidence, and  $\gamma$  = blaze angle. For a more detailed analysis of diffraction blazed grating and its properties, see Ref. 2.

As mentioned previously, for the proper choice of the light wavelength, the spacing of linearly grooved surfaces, and the blaze angle, the grating behaves such that an incident coherent beam of the laser emerges in two dominant diffracted orders, e.g., the zero and the first order. Such an arrangement will provide a single-order blazed diffraction grating with two dominant orders of near equal intensity.

## II. PRINCIPLES OF BLAZED GRATING INTERFEROMETER

Referring to Fig. 2, consider the conditions where (a) the incident laser source (LS) is in a direction normal to the grating plane. In this case the undiffracted beam (0) also emerges in the direction normal to the grating (G) and the principal diffracted beam (1) emerges at twice the blaze angle with respect to normal incident direction. The latter is the natural direction of reflection from grooved surfaces; (b) the incident angle is twice the blaze angle with respect to grating normal and oriented toward the blaze arrow. In this case, the first-order beam bisects the angle between the zero order and the incident direction. Interestingly enough, this diffracted beam is along the direction normal to the grating plane; (c) in arrangement (b) if a mirror (M) is placed perpendicular to the first-order direction so that the action

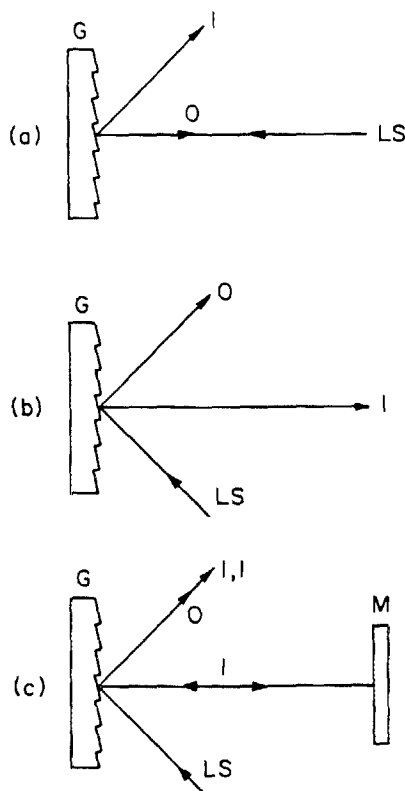


FIG. 2. Diffraction action of a fine reflection blazed grating. (a) normal incidence; (b) twice the blaze angle incidence; (c) two-beam interference from simultaneous action of (a) and (b).

of arrangement (a) is added, a two-beam interferometric system is developed. The reference arm of the interferometer is the zero order—the natural reflection of the incident beam from the grating plane—and the sensing arm is the first-order diffraction. The sensing arm after reflection from the test surface is diffracted again by the action of the grating. Consequently, the resulting first-order diffraction of the original first order (1,1) is superimposed upon the original zero-order diffraction (0) and produces an interference pattern. The unequal-path interference of these two beams is the basic optical component of the main sensor.

## III. ACOUSTIC WAVE AMPLITUDE VERSUS OPTICAL INTENSITY

The test arm and the reference arm are the two interfering coherent beams of the optical system. The phase change in the test arm with respect to the reference arm is introduced due to the distance between the grating and the surface under study. This distance will change due to surface displacement fluctuation caused by the presence of ultrasonic stress waves. In that case, the phase displacement ( $\phi$ ) is written as

$$\phi = 2kl + 2ku,$$

where  $l$  = optical distance between grating and the test surface,  $k = 2\pi/\lambda$ , optical wave number,  $u = U \cos \omega t$ , ultrasonic surface displacement, and  $\omega = 2\pi f$ , angular frequency of the ultrasonic oscillation.

The factor of 2 in the expression for the phase displacement denotes the fact that light travels twice through the optical path between the grating and the test surface. If both superposing beams of the interferometer have the same optical intensity (this is a reasonable assumption since both zero-order and first-order diffractions of the blazed grating have relatively close intensities), upon superposition the resultant optical intensity deviates from a minimum of zero to a maximum of four times the intensity of each beam, depending on the phase difference between the two beams. Using a slightly different formulation; but basically following the same straightforward derivation of the coherent superposition carried out in, e.g., Ref. 3, the total optical intensity ( $P$ ) incident upon the photosensor can be written as

$$P = C[1 + \cos(2kl + 2kU \cos \omega t)].$$

In this expression, the dc term ( $C$ ) is a function of laser light power and fringe visibility (contrast).

If the spacing between the grating and the test surface is such that it introduces a phase of  $n\pi/2$  rad ( $n$  is an odd integer), then

$$P = C[1 + \cos(\pi/2 + 2kU \cos \omega t)].$$

Therefore, the interferometric term is simply rewritten as

$$I = C \sin(2kU \cos \omega t).$$

If the amplitude of the surface displacement is much smaller than the optical wavelength,  $u \ll \lambda$ , the sine can be approximated to be equal to its argument. Thus,

$$I = 2CkU \cos \omega t.$$

This linear relationship between the instantaneous surface

displacement,  $u = U \cos \omega t$ , and the optical intensity (time averaged of the optical field) is the prime factor in the use of such a two-beam interferometer for quantitative detection.

Note that the interferometric term, representing the surface displacement, fluctuates between positive and negative values. But the total optical intensity (including the dc term,  $C$ ) incident on the photosensor is never negative. It varies from zero to a maximum of  $2C$ . However, the dc coupling of the viewing oscilloscope compensates for this dc shift and displays the bipolar voltage output of the photodetector.

#### IV. CALIBRATION AND LARGE PHASE SHIFT

The optical interferometer described earlier has the same sensitivity as any of the Michelson-type interferometers. The output of the interferometer can be calibrated so that the absolute magnitude of the surface displacement can be determined. If the surface under study is subjected to large displacement excitations ( $u > \lambda/4$ ) and the peak-to-peak signal output is noted, then the magnitude of the smaller displacements ( $u < \lambda/4$ ) can be obtained from its peak-to-peak signal output.

As was mentioned earlier, the interference of two equal-intensity beams has a magnitude which varies between two extreme opposite values depending on the relative phase difference ( $\phi$ ) between the test and reference beams. For the interferometer to operate at the point of maximum sensitivity (i.e., smallest phase shift giving rise to largest change in intensity), the relative phase must be kept constant halfway between the two limiting phases throughout the operation. Unfortunately, the presence of low-frequency mechanical and thermal fluctuations existing in the testing environment alters the proper tuning. To solve this problem, a slight modification to the optical system of Fig. 2(c) may suffice—the blazed diffraction grating can be driven by a low-frequency piezoelectric crystal at a large displacement amplitude so that the face of the grating translates at least an amount  $\lambda/4$ . This causes the passage of phase difference through the optimum point of sensitivity at the instant of high-frequency transient surface fluctuations. The frequency of the phase shifter should be low enough to allow the entire signal to be detected at the maximum operating condition (quadrature point). Through the use of this large phase shifter the interferometer can also be calibrated.

#### V. COMPARISON WITH TWO-BEAM MICHELSON-TYPE INTERFEROMETERS

The above system is simpler than the Michelson interferometer; the reflection blazed diffraction grating is the primary component of the interferometer. Through a simple rearrangement of the grating, e.g., by selecting the zero order as the sensing arm a two-beam interferometer can be formed in which the mechanical movement of the grating does not introduce any optical path difference between the first- and the zero-order beams of the interferometer. Therefore, unlike the Michelson interferometer or the previously discussed optical arrangement, this particular arrangement will not be sensitive to the low-frequency noise associated with the unwanted mechanical vibration of the reflection grating.

Moreover, in the ordinary Michelson interferometer only half of the laser power is utilized and the other half is fed back into the laser. The optical intensity returning into the laser might alter the laser power output which in turn might cause an increase in the signal noise level and reduce the sensitivity. The feedback problem is usually solved by using optical or acousto-optical isolators<sup>4</sup> which effectively prevent any light from entering the laser. For the two-beam unequal-path interferometer, which utilizes a single-order blazed diffraction grating, most of the energy of the incident laser beam is distributed into the zero and the first order so that very little light corresponding to the second-order diffraction is returned to the laser.

This optical sensor, like any other intensity interferometer, suffers from the lack of signal phase information. Furthermore, the necessity of tuning the interferometer at quadrature point limits the upper displacement bound to dynamic range. That is, the mechanical excitation should not shift the optical intensity onto the minimum/maximum values or pass through the peak/valley at any time during the operation.

#### VI. FLEXIBLE FIBER-OPTIC PROBING INTERFEROMETER

The use of optical fibers as a light guiding medium can be a great advantage in optical probing flexibility.<sup>5</sup> In this regard, an attempt has been made to utilize single-mode step-index fiber-optic interferometry. There are special kinds of single-mode optical fibers that preserve the state of linearly polarized light, which must be maintained in the

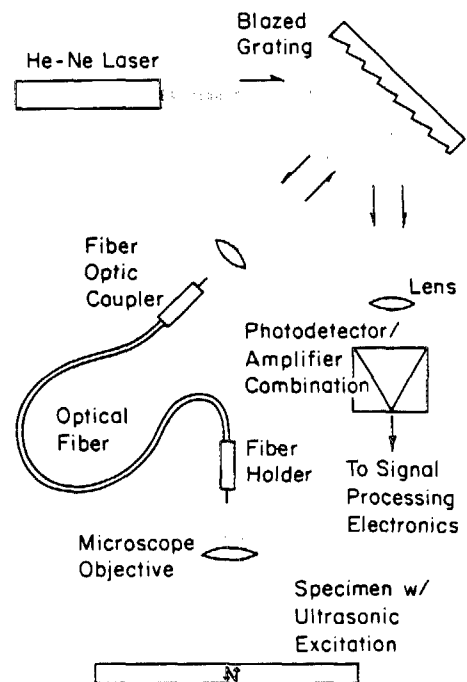


Fig. 3. A flexible single-mode fiber-optic interferometric system.

interferometric application. These types of birefringent fibers have geometric flexibility and allow the test arm of the interferometer to be isolated from the bulky optical table. There are two classes of fiber-optic sensors. In one application the fiber itself is used as a sensing device (intrinsic sensor<sup>6</sup>). In another application it is used to simply guide the optical wave through its medium (extrinsic sensor). The latter has been incorporated into the two-beam unequal-path interferometric system. The optical system shown in Fig. 3 is the optical fiber-link extension of the probing arm of the previously discussed interferometer. The test arm of the interferometer in the air medium has been coupled into the fiber medium ( $\approx 8$  m long) using a microscope objective ( $5\times$ ) to focus the beam on the carefully prepared front flat surface of the stripped-end fiber. The highly birefringent, polarization preserving single-mode optical fiber is used to operate at an optical wavelength of 630 nm. The second microscope objective provides the beam illumination and reception from the reflective surface under study. The use of an interferometric fiber-optic sensor in this fashion allows the ultrasonic scanning of the reflective surface of a stationary object which is located away from the bulky optical bench.

## VII. APPLICATION

Figure 4 represents the schematic diagram of the instrument components setup used in the experiment that follow. These are piezoelectric transducer; composite laminate specimen; small displacement-sensitive optical noncontacting ultrasonic detector, e.g., fiber-optic probing interferometer; broadband ultrasonic amplifier (PANAMETRICS, serial 5660B/475); filter; a high-speed (20-MHz ADC)

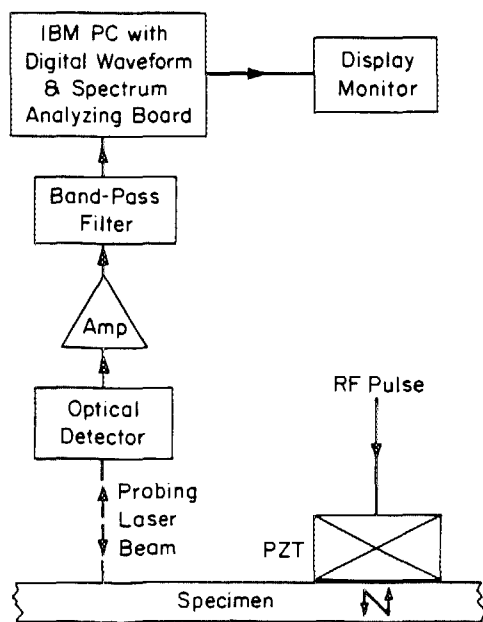


FIG. 4. Schematic diagram of an ultrasonic NDT using noncontacting optical characterization.

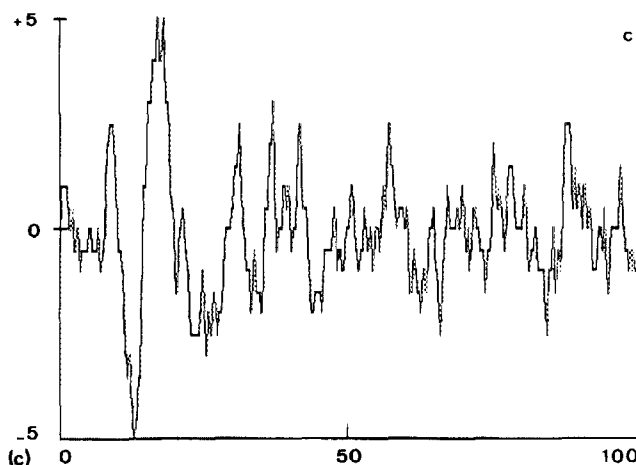
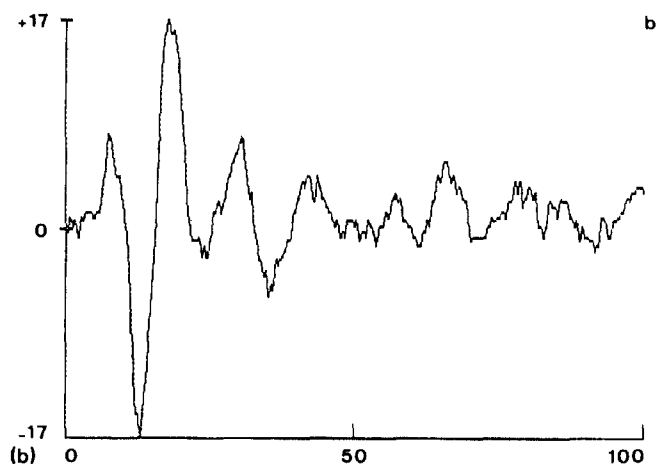
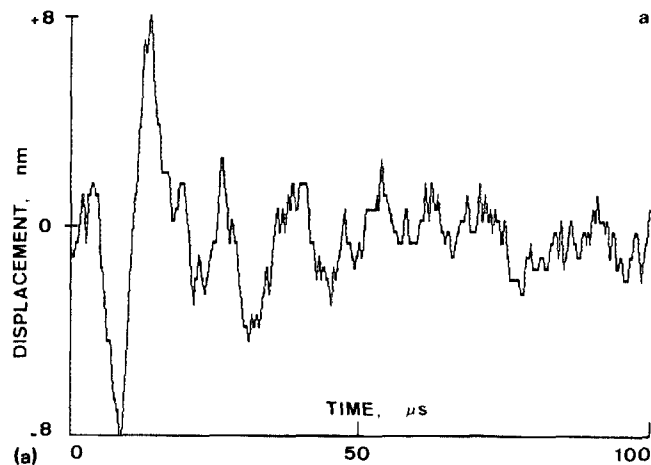


FIG. 5. Plots of optically detected ultrasonic signals. Directions of propagation parallel (a), off axis (b), and perpendicular (c) to the fiber direction.

data-acquisition system (IBM PC plug-in transient waveform recording board with 8-bit resolution); display monitor. The additional electrical/optical components used in the system are ultrasonic signal generator (MATEC model 6000) which induces the rf-pulsed or burst excitation; low-power (10 mW) He-Ne laser (EALING); high-speed photodetector (PHOTOP™ UDT-455HS).

A repetitive electronic short pulse was transmitted to drive a 1-MHz piezoelectric transducer of the thickness-expander type which was coupled acoustically to one side of a unidirectional fiber-reinforced composite laminate. The interrogation point on the same side of the specimen was mirrored for light reflectivity. Then three different transducer positions about 1-inch from the point were chosen such that the transducer could propagate elastic waves parallel to, off-axis to, and perpendicular to the fiber axis. The resultant surface displacement excitations were detected by the linear optical sensor (the fiber optic interferometric probe discussed earlier). After signal amplification and suitable filter-

ing, the information pertaining to the amplitude of acoustic disturbances was obtained. The time-domain amplitudes of the detected stress waves for the aforementioned transducer positions are shown in Figs. 5(a)–5(c), respectively. Note that the magnitude of surface displacement is larger in (b) than in (a) and is drastically reduced in (c). Surprisingly, this acoustic displacement directivity behavior was rather unexpected.

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<sup>3</sup>E. Hecht, *OPTICS, Schaum's Outline Series* (McGraw-Hill, New York, 1975), p. 126.

<sup>4</sup>M. Kroll and B. Boro Djordjevic, "A Laser Stress-Wave Probe with Sub-angstrom Sensitivity and Large Bandwidth," 1982 Ultrasonic Symposium, pp. 864–866.

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