NONDESTRUCTIVE EVALUATION USING SHEARING INTERFEROMETRY

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INTRODUCTION

Coherent shearing interferometry involves the interference of a coherent optical wavefront with a spatially shifted version of itself. The resulting interference pattern carries information which for small shears (spatial shifts) can be related to the gradients of the phase of the wavefront. The primary advantage of this optical technique is that it is relatively insensitive to rigid body motion. A coherent wavefront that is transmitted through a body or is reflected from the surface of a body will carry information about the resulting stress state or deformation of the body. This information can be used for nondestructive evaluation applications using optical shearing methods in order to identify defects such as cracks and disbonds. In this paper, we will first give a brief review of various shearing methods, and then describe in detail the use of Coherent Gradient Sensing, a diffraction grating shearing technique that was developed by Tippur, Krishnaswamy and Rosakis [1,2,3], for the optical detection of cracks in bodies.

METHODS OF SHEARING INTERFEROMETRY

As shearing interferometry has developed, several methods have been proposed in which each uses a different device to create the shearing effect. Wedge shearing interferometry [4] utilizes a refractive wedge placed in front of one half of an imaging lens. This technique is limited to use on diffuse surfaces since it requires that each point on the surface scatter the incident coherent wavefront such that the scattered rays that are imaged by the lens after passage through the refractive wedge will map to a different point than the ones that are imaged directly. The light rays passing through both the wedge and the lens thereby provide a spatially shifted version of the wavefront formed by those rays passing directly only through the lens. This technique cannot, however, be used with specularly reflective (or transparent) bodies because a ray of light incident on such bodies reflects (or transmits) as a single ray that might pass either through the wedge-lens combination or through only the lens; hence in this case a point on the object does not map to two points on the image plane. Also, the wedge shearing scheme requires a secondary reconstruction operation involving optical filtering in order to make the fringe information visible. The

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sensitivity of this technique (related to the amount of shearing) is dictated by the angle of the wedge used and is not subsequently adjustable.

A modified Michelson-type shearing interferometer has been developed by Sharma et al [5]. This is similar to a conventional Michelson interferometer where the incident wavefront is split into two by means of a partial mirror and two right prisms are used to retroreflect the two wavefronts. Wavefront shearing is done by translating one of the prisms relative to the other. Both diffuse and specularly reflective surfaces can be analyzed with this technique. If a diffuse object is used, this technique also requires subsequent optical filtering in the fourier plane to reconstruct the fringes. The sensitivity of this method can be adjusted by controlling the amount of translation of the prisms.

It is also possible to use a conventional interferometer to digitally record the phase of a wavefront, and to subsequently perform a numerical differentiation operation to obtain the phase derivatives. One such scheme is that of Owner-Petersen [6] who generates speckle shearing by capturing a digital interferogram representing a displacement field and performing numerical differentiation on the image to yield displacement gradients. This technique is inherently simpler since it requires no physical shearing element. Further, the sensitivity of the method is only a function of the step size of the numerical differentiation scheme used; however, the resolution of the digitizing camera must be sufficient to record the high density of fringes that might occur through possible rigid body motion of the object. Numerical shearing is applicable to specularly and diffusively reflective surfaces, as well as transparent bodies. In the case of diffuse surfaces, however, speckle noise must be removed prior to numerical differentiation and this can be done by using phase-stepping techniques.

The rest of this paper will be devoted to a description of the use of a shearing interferometer -- Coherent Gradient Sensor (CGS) -- developed by Tippur, Krishnaswamy and Rosakis [1-3]. This scheme uses two diffraction gratings spaced slightly apart to create sheared images. Presently, this technique only accommodates specularly reflective surfaces or transparent bodies. However, it produces real-time shearing fringes thereby eliminating the need for a high-resolution recording device. Also, the sensitivity of the method can be adjusted by simply changing the separation distance between the gratings.

COHERENT GRADIENT SENSING

The grating shearing interferometer of Patorski [7] and Moire Deflectometry of Glat and Kafri [8] are some of the techniques related to the Coherent Gradient Sensor. CGS is a shearing interferometer with on-line spatial filtering, and is a full-field optical technique which allows relatively large surface areas to be inspected. CGS can be used in transmission and reflection modes, both statically and dynamically. In transmission mode, the CGS fringe pattern that results can be related to the planar stress gradients in the transparent specimen. For specularly reflective specimens the fringe pattern can be similarly related to the gradients of the specimen surface displacement.

The experimental setup of CGS in transmission mode is shown in Figure 1. A collimated laser beam is incident on the specimen of interest. Before transmission through the specimen, the beam is a coherent, planar wavefront; after transmission the wavefront is no longer planar but is perturbed from its planarity due to the mechanical deformation of the specimen. This perturbed wavefront then passes through the first diffraction grating G1, and, assuming without loss of generality that the gratings have a sinusoidal transmittance, is diffracted into three different orders: zeroth and positive/negative first orders. These diffracted orders on transmission through the second grating G2 are in turn each diffracted into three orders resulting in a total of nine different wavefronts. All of the diffracted wavefronts are then collected by the filtering lens L1. At the back focal plane of the filtering lens a two-dimensional aperture is placed such that only two of the nine wavefronts are allowed to pass for subsequent imaging through the imaging lens L2. The working principle of this method is better brought out with the aid of Figure 2. It can be seen that by using two diffraction gratings, the incident wavefront is duplicated into a number of identical wavefronts that propagate in different direction. The use of a filtering lens and aperture combination then isolates two of these wavefronts -- E_{10} and E_{01}-- for subsequent imaging. These two wavefronts which are sheared with respect to each other then interfere to form the CGS fringe pattern at the image plane.

The details of the working of the Coherent Gradient Sensor are explained by means of a first order diffraction theory in [1-3] and are not repeated here. It is shown there that in transmission mode, the fringes observed using CGS can be related to the gradients of the sum of the in-plane stresses in the specimen -- the direction of the gradient operation being perpendicular to the lines of the diffraction gratings. Thus, the fringe relations applicable to transmission mode CGS applied to plate specimens are:

$$ch\frac{\delta(\sigma_{11}+\sigma_{22})}{\delta x_1} = \frac{mp}{2\Delta}, \qquad m = 0,1,2... \tag{1}$$

$$ch\frac{\delta(\sigma_{11}+\sigma_{22})}{\delta x_2} = \frac{np}{2\Delta}, \qquad n = 0,1,2... \tag{2}$$

In the above, h is the nominal thickness of the plate specimen; c is a stress-optic property of the material of the specimen; p is the pitch of the diffraction gratings; Δ is the spacing between the two gratings; σ_{11} and σ_{22} are the in-plane stresses in the plate; and m,n are integers representing fringe orders for x_1- and x_2- gradient fringes respectively. Note that the sensitivity of the technique depends on the spacing Δ and the pitch p of the diffraction gratings, the first of which is very easily adjustable.

A setup similar to that shown in Figure 1 can be used to obtain information from specularly reflective bodies. In this case, the fringes obtained using CGS can be shown to be related to the gradients of the surface shape (or displacements) of the object. The details of CGS in reflection mode are given in references [2,3]. In this paper, only results of the use of CGS in transmission mode are presented.

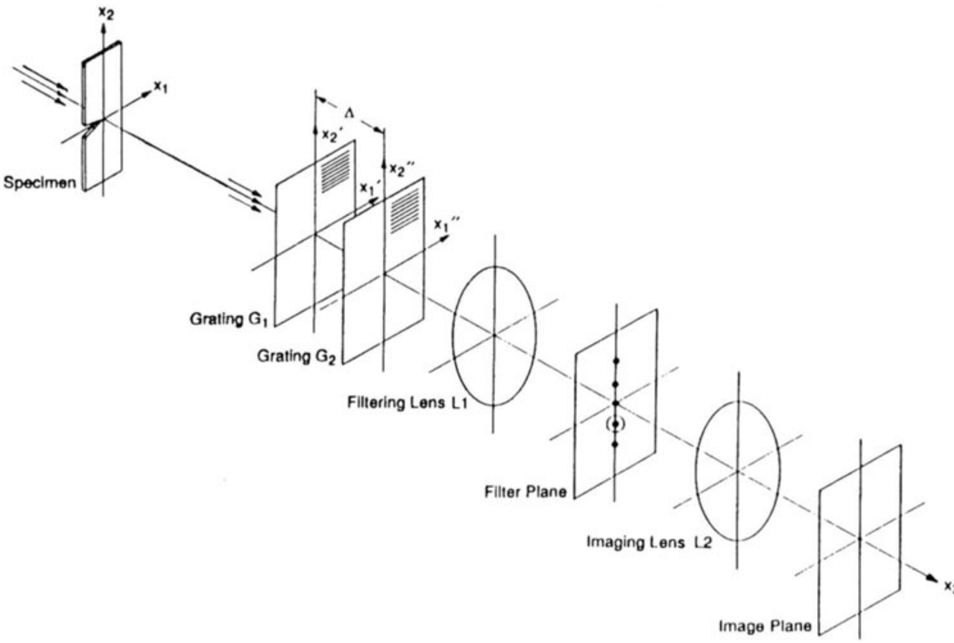

Figure 1. Schematic of CGS set-up in transmission mode.

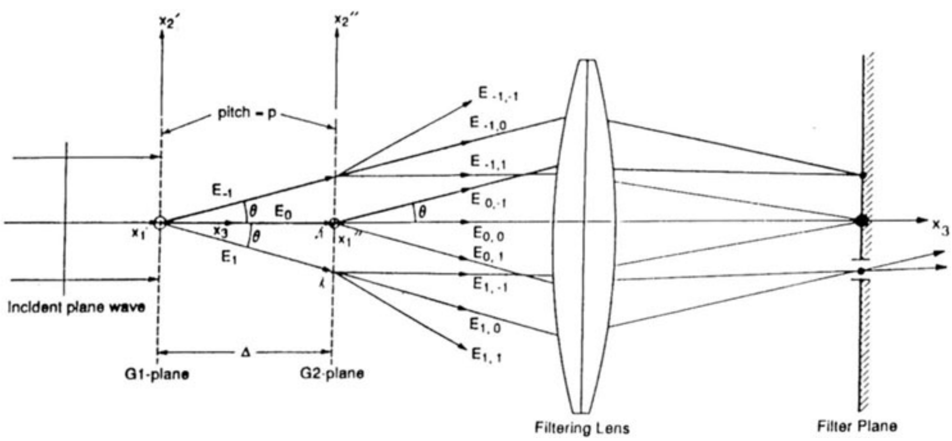

Figure 2. Principle of wavefront shearing using diffraction gratings.

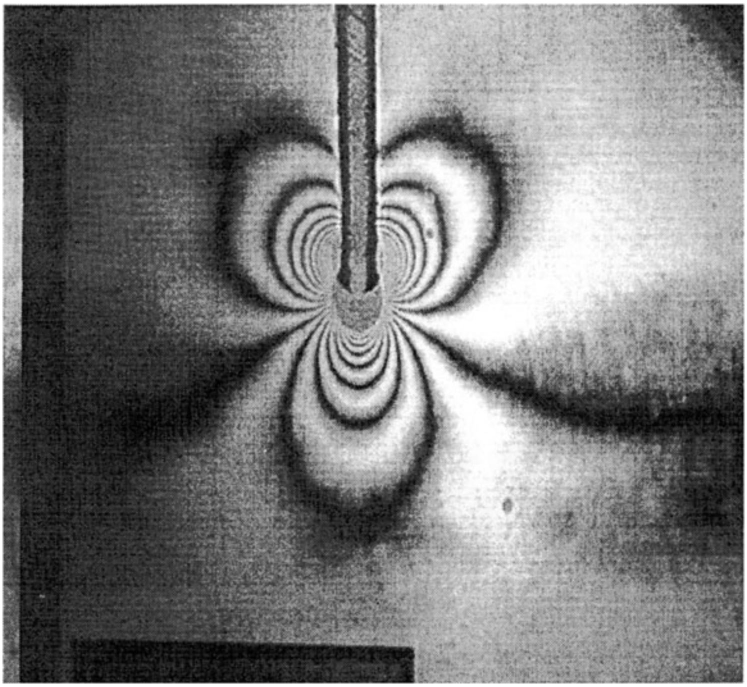

Figure 3. CGS fringe pattern for an edge-crack PMMA specimen. The shearing direction is along the crack-line.

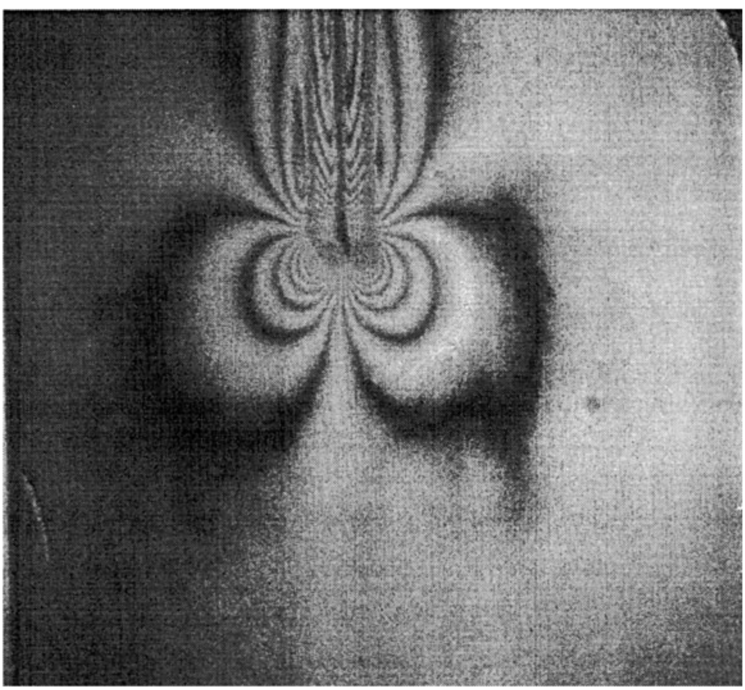

Figure 4. CGS fringe pattern for an edge-crack PMMA specimen. The shearing direction is perpendicular to the crack-line.

RESULTS

Figure 3 shows a typical interferogram obtained from a PMMA specimen containing an edge-crack and which was loaded in a three-point bending configuration. Since this was in transmission mode and the grating was oriented with the lines perpendicular to the crack-line (which was along, say, the x_1 axis), the fringes here correspond to contours of the x_1-gradient of $(\sigma_{11}+\sigma_{22})$. Figure 4 is for the same specimen, but with the grating lines oriented parallel to the crack-line such that the x_2-gradient of $(\sigma_{11}+\sigma_{22})$ was obtained. It is possible to quantitatively analyze the fringes to obtain mechanical parameters such as the stress-intensity factor that govern the criticality of a crack in terms of its propensity to grow larger.

Figure 5 is the fringe pattern for a center-cracked PMMA specimen, and Figure 6 shows the effect of the interaction of two cracks such as might be obtained in multiple-site damage along a row of rivets in a lap-joint. In this case again the gratings were oriented such as to provide a spatial shear in the direction along the crack-line. Figure 7 show the interaction of a hole and a crack emanating from it. In all these cases, it is seen that a well-defined fringe pattern is obtained that can be used to identify the existence and type of a variety of commonly occurring defects in structures.

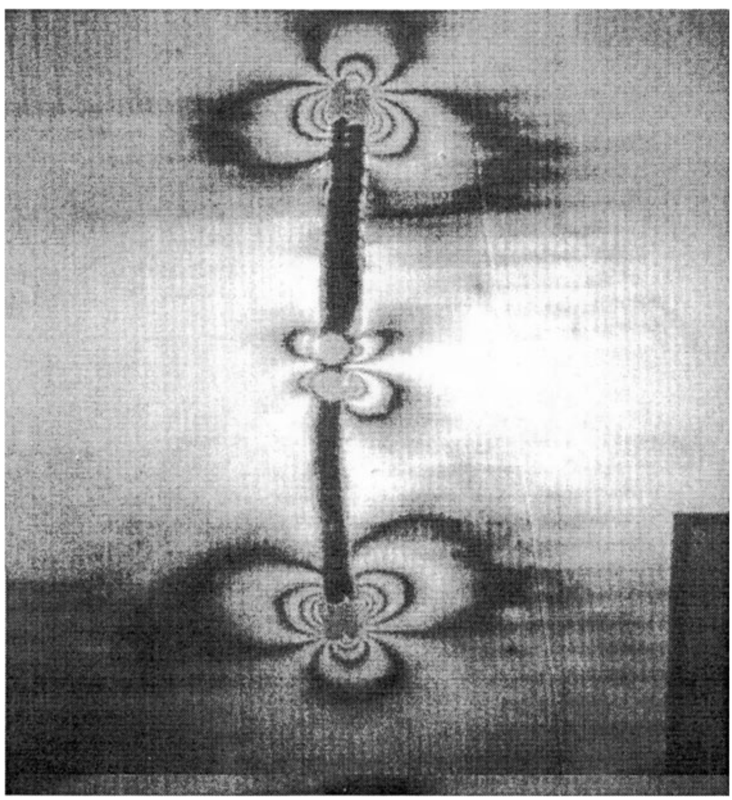

Figure 5. CGS fringe pattern for a center-crack PMMA specimen. The shearing direction is along the crack-line.

CONCLUSION

Shearing interferometry is an increasingly important tool for optical non-destructive evaluation of structures. A number of shearing schemes have so far been proposed by a variety of researchers. The method of Coherent Gradient Sensing [1-3] is one such tool that uses diffraction grating elements to provide the shearing mechanism. The method works well in transmission and specular reflection modes for use with transparent or polished surfaces. In view of the real-time nature of the technique, its relative simplicity as well as the ability to tune the sensitivity of the method, CGS can be a viable optical NDE tool. One area of future work is to adapt this technique to accommodate diffusely scattering surfaces as well, and this is an area of ongoing investigation.

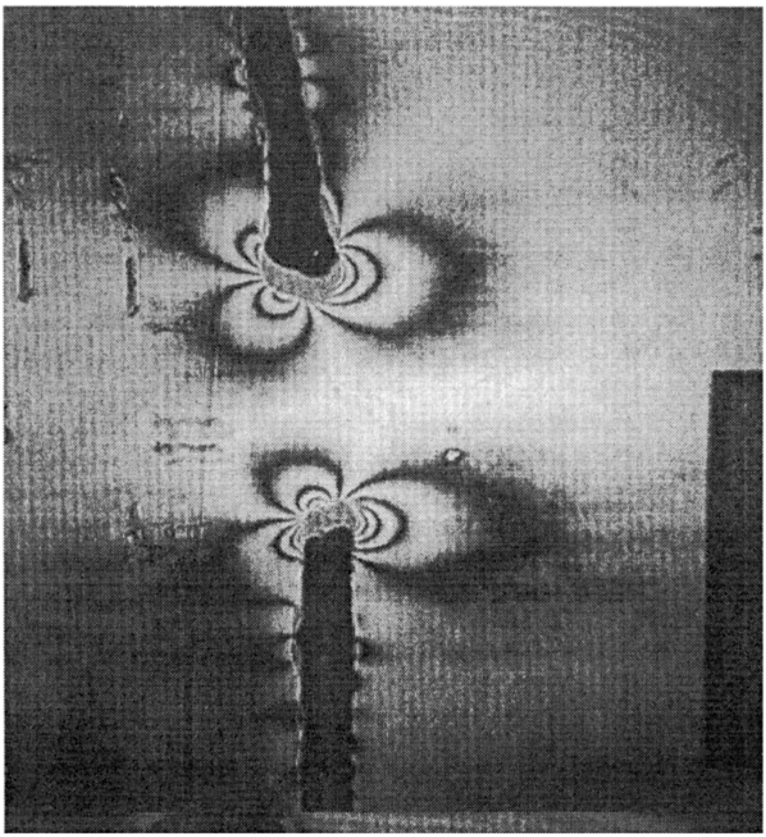

Figure 6. CGS fringe pattern showing interaction of two cracks in a PMMA plate. The shearing direction is along the crack-line.

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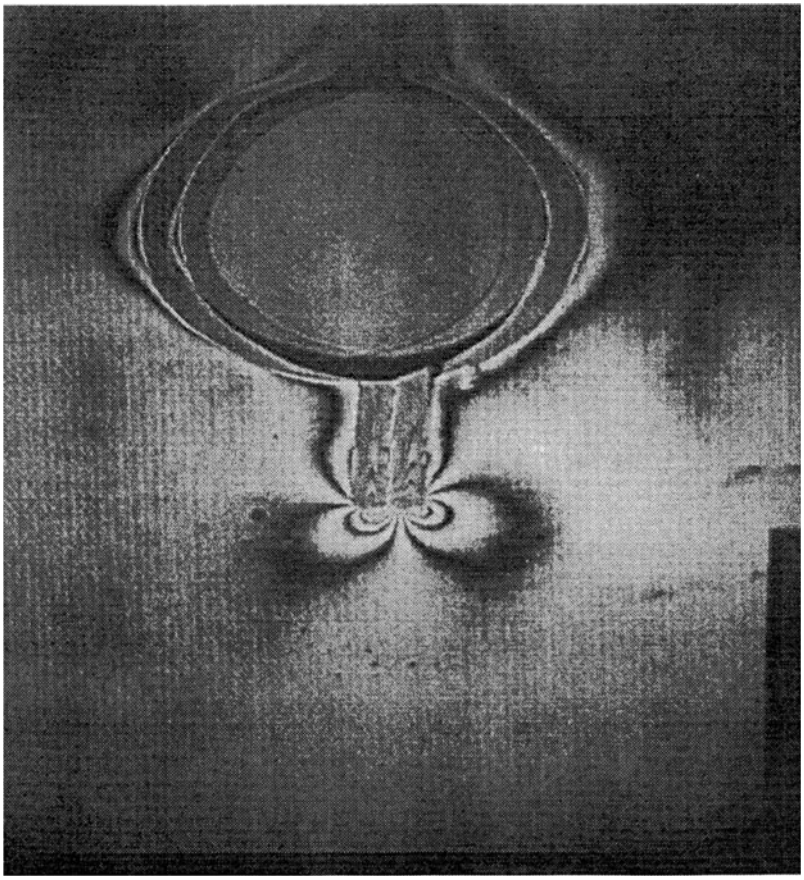

Figure 7. CGS fringe pattern for a crack emanating from a hole in a PMMA plate. The shearing direction is along the crack-line.

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