Holographic interferometry using substrate guided waves

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Abstract. A new tool for experimental mechanics called substrate guided wave (SGW) holo-interferometry is described. The approach relies on recording and reconstructing time-average, double-exposure, and real-time holograms using light waves guided to the hologram by a dielectric sheet or substrate waveguide. The study illustrates that SGW holo-interferometry can be used to isolate the reference wavefront from the environment surrounding the hologram and can be applied to measure the mechanical properties of the substrate itself. These attributes are discussed along with experimental work performed to develop and refine the technique.

Subject terms: holographic interferometry; nondestructive evaluation; metrology; waveguide holography.

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1 Introduction

Holographic interferometry is a powerful and versatile tool in experimental mechanics and has been used productively for nondestructive evaluation to visualize flow fields, characterize vibration modes, reveal deformations, determine stresses and strains, and detect cracks and subsurface flaws. However, there are some situations where investigators working with conventional approaches to holo-interferometry encounter difficulties and are unable to obtain satisfactory results. For example, it is virtually impossible to successfully record a meaningful interferogram under conditions where turbulent air, water, or other unstable environmental conditions produce changes in the index of refraction of the reference wavefront. Moreover, many holographic recording systems are complex and/or difficult to miniaturize. These and other problems can be partially solved by employing a new technique called substrate guided wave (SGW) holo-interferometry.

This paper includes a brief introduction to guided wave techniques and reviews some of the work underlying the development of SGW holo-interferometry. This new technique is described along with the equations required to interpret the associated fringe patterns. Experimental tests, conducted to demonstrate SGW holo-interferometry, also illustrate some of its potential advantages. Results show that the technique can be applied to record double-exposure, real-time, and time-average holo-interferograms.

2 Substrate Guided Wave Holography

SGW holography relies on recording and reconstructing holographic images with light waves guided to the hologram by a dielectric sheet or substrate waveguide. The basic concept of the edge-illuminated hologram was initially reported by Lin[1] in 1970. Suhara et al.[2] subsequently referred to the product of this holographic construction as a waveguide hologram. This type of hologram has diffraction properties similar to those found in the total internal reflection hologram studied by Stetson.[3] Intensive investigations followed in which waveguide holograms were used in applications ranging from optical computing and information processing[4] to artistic displays.[5,6] Several interesting properties of waveguide holograms, recently discussed by Huang and Caulfield[7] and Putilin et al.[8] include the image-to-background contrast, multiple utilization of the illumination beam, the twin image effect, and the multimode image blurring effect.

As illustrated in Fig. 1, light may be coupled by a prism, a grating, or other edge-lighting mechanism into a sheet of transparent material having two surfaces that are locally parallel and optically polished. When the index of the material is higher than that of its surroundings, light is transmitted through the substrate by total internal reflection. The waveguide is referred to as multimode, because different rays follow different coarse zigzag paths. A portion of the transmitted light can be coupled into a photosensitive emulsion (silver halide, photopolymer, dichromate gelatin, or photoresist) placed in direct contact with the substrate. When the portion of the light guided by the substrate is used as a reference and/or object wavefront for holographic construction, the process is referred to as SGW holography.

There are several distinct advantages of using the SGW

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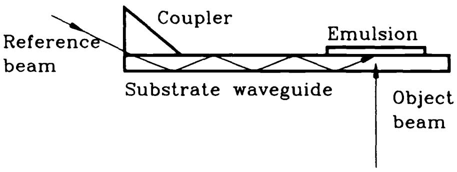

Fig. 1 SGW holograms are recorded when the reference and/or object wavefront are transmitted to the recording plane using a substrate waveguide.

approach over more conventional holographic recording methods. The optical systems used to reconstruct conventional holograms are often complex and may require considerable alignment; the light source must have good spatial coherence (for reflection and rainbow holograms) and temporal coherence (for transmission holograms); and off-axis illumination increases the size of the overall recording system, while undiffracted light, passed through the hologram, poses a safety hazard to the viewer. SGW holographic systems, on the other hand, are portable, robust, and relatively easy to align. A monomode fiber, for example, can be used to guide light to a hologram placed in direct optical contact with the substrate. In addition, the illumination can be edge introduced and guided by total internal reflection through the substrate. Consequently, the system is compact and can be easily miniaturized. Moreover, the illuminating beam is encapsulated within the substrate and only the holographic image is diffracted. This allows the hologram to be viewed close to the recording plane without the danger of eye damage associated with the undiffracted light produced during off-axis reconstruction.

3 Holographic Interferometry

Unlike ordinary photography where only the amplitude of the light intensity is recorded, the holographic process records both the phase and amplitude of the light scattered from an object. Phase information is important, because comparisons can be made between holograms recorded as a test surface moves. This process, called holo-interferometry,[9–11] produces a set of interference fringes that may permit the detection and measurement of surface displacement.

The time-average technique, developed by Stetson and Powell,[12] can be used to reveal contours of constant amplitude on the surface of a vibrating object. In this technique, a holo-interferogram is produced by generating a hologram by exposing a film plate for a period of time during which the test object executes many cycles of steady vibration. In this case, the intensity of the reconstructed image is

$$I \propto J_0^2\left[\frac{2\pi}{\lambda}(\mathbf{g}\cdot\mathbf{d})\right] , \tag{1}$$

where λ is the wavelength of the coherent light used to record and reconstruct the hologram and $\mathbf{d}$ is the displacement vector of the surface point under consideration. The sensitivity vector $\mathbf{g}$ is defined by $(\hat{e}_2-\hat{e}_1)$; $\hat{e}_1$ and $\hat{e}_2$ are unit vectors in the directions of illumination and observation, respectively.

The variation in intensity is characterized by being a maximum when the argument of the Bessel function is equal to zero and having succeeding maxima that decrease in value. When the displacement is zero, the reconstructed image is the brightest; consequently, regions having no motion, or nodes in the vibratory pattern, exhibit the greatest intensity. Dark fringes occur at the roots (zeros) of J_0^2; the particular root on the interferogram can be determined by counting from the nearest stationary point on the object, marked by the very bright fringe corresponding to the nodal location. The roots of J_0 are tabulated and their values can be used together with the known values of the sensitivity vector to determine the amplitude of the object motion in the direction of the sensitivity vector.

If a hologram is recorded of the object while it is vibrating in only one of its vibration modes, then a photograph of the reconstruction from that hologram will display the vibration mode in a simple topographical map of fringe contours. For example, with normal illumination and observation.

$$N_i=\frac{4\pi w}{\lambda} , \tag{2}$$

where w is the displacement component along the line of sight and N_i are the roots of the Bessel function. This presumes that the sensitivity vector is essentially constant across the surface of the object and that the vibratory motion is unidirectional. If this is not the case, vibration analysis may require more than one holographic perspective per mode.

A second technique, usually referred to as double-exposure holo-interferometry, generates a high-contrast fringe field by interfering two object wavefronts reconstructed from the same doubly exposed hologram. In this case, dark cosine fringes appear in the space around the test object. These fringes are associated with the changes in optical path length resulting from changes in the test object occuring between exposures. As such, double-exposure holo-interferometry provides a permanent record of the phase changes that occurred between exposures, but no history of information describing the changes over time as they actually occurred.

Real-time holo-interferometry, on the other hand, provides a cosine fringe field that changes as the test object changes. Fringes are generated directly by interfering the actual coherent wavefront from the object with a reconstructed holographic "reference" wavefront. To generate high-contrast real-time fringes, this approach requires that the object illumination and reconstructing reference beams be adjusted to yield object wavefronts of nearly equal intensity and that both beams and the hologram be located in exactly their original positions relative to the test object during reconstruction of the reference wavefront. This latter (most critical) requirement can be met, although with some difficulty, by precise repositioning of the hologram after its removal for processing elsewhere; or, more effectively, by processing the hologram in place.

Fringe patterns, obtained using either the double-exposure or the real-time approach, are governed by

$$n\lambda=\mathbf{g}\cdot\mathbf{d} \tag{3}$$

where n is the fringe order number, λ is the wavelength of the coherent light used to record and reconstruct the hologram, and $\mathbf{d}$ is the displacement vector of the surface point under consideration. As discussed earlier, $\mathbf{g}$ is the sensitivity vector defined by $(\hat{e}_2-\hat{e}_1)$.

In these cases, the observed displacement fringes result from the change in optical path that occurs between recordings. These path length changes give rise to a distribution of phase differences between the reconstructed wavefronts, which results in areas of constructive or destructive interference and are seen as a set of light and dark fringes. The component of displacement measured at each point depends on the location of the source and on the point of observation; the displacement vector is projected along a sensitivity vector, which coincides with the angle bisector of $\hat{e}_1$ and $\hat{e}_2$. Therefore, when a relatively flat surface is oriented normal to the angle bisector of $\hat{e}_1$ and $\hat{e}_2$, the interferometer senses only the out-of-plane displacement component w, and Eq. (3) becomes

$$n\lambda = 2w(\cos\phi) \ , \tag{4}$$

where 2ϕ is the angle between the propagation vectors in the directions of illumination and observation.

4 SGW Holo-Interferometry

When recording holo-interferograms, the reference wavefront needs to be stable during and between holographic recordings. Unfortunately, perturbations caused by changes in the environment surrounding the hologram are difficult to avoid in conventional holographic systems. On the contrary, SGW systems can be designed to protect the guided wave from these perturbations. Moreover, the guided wave can be used as the object beam so that changes in the mechanical, thermal, or optical response of the substrate can be measured.

The following section describes a series of tests conducted to illustrate these attributes and demonstrates that double-exposure, real-time, and time-average interferograms can be recorded and reconstructed using the SGW approach.

5 Experiments

Figure 2 shows the basic set-up used to record SGW holo-interferograms. A 20- × 12- × 2-cm poly(methylmethacrylate) (PMMA) block is used as a substrate to guide light from a 100-mW krypton laser to a 6- × 6-cm, Agfa 8E75 silver halide plate. The oblique incident angle of the reference beam, equal to approximately 70 deg, is controlled using a combination of mirrors. A cylindrical lens is used to diverge the incident beam in the vertical direction before it enters the substrate. A 45-deg glass prism is used to guide light into the substrate; the prism and the silver halide plate are optically coupled, and mechanically attached, to the substrate using index matching oil. The steep incidence angle of the guided wave coupled with the diverging illumination produce a relatively uniform illumination over the recording plane.

The setup shown in Fig. 2 was used to study a 7.62-cm-diam edge-clamped, centrally loaded disk. The disk was positioned so that the normal to its surface was oriented along the angle bisector of the illumination and observation directions. In this case, the sensitivity vector is normal to the test surface and Eq. (4) holds. A holographic recording of the undeformed disk was made on the silver halide plate. The center of the disk was displaced under load 3.81×10^{-3} cm and a second holographic recording was superimposed on the initial recording. The silver halide plate was removed from the substrate and developed in a darkroom. Figure 3 shows the reconstruction when the processed double-exposure hologram was reattached to the substrate using matching oil and illuminated with the reference beam. The fringe pattern corresponds to displacement measured normal to the plane of the clamped disk. In this case, the deflection of the disk at a distance r from its center is given by[13]

$$w=\frac{Pr^2}{8\pi D}\log\frac{r}{a}+\frac{P}{16\pi D}(a^2-r^2) \ , \tag{5}$$

where

$$D=\frac{Eh^3}{12(1-\nu^2)} \ . \tag{6}$$

Equations (5) and (6) are for a disk of radius a and thickness h with Young's modulus and Poisson's ratio of E and ν, respectively. The load P can be determined from the change in deflection of the center of the disk imposed between exposures. In this experiment; $a=3.81$ cm, $E=27.58\times10^5$ kPa, $h=0.318$ cm, and $\nu=0.35$. The location and number of the fringes shown in Fig. 3 agree well with theory.

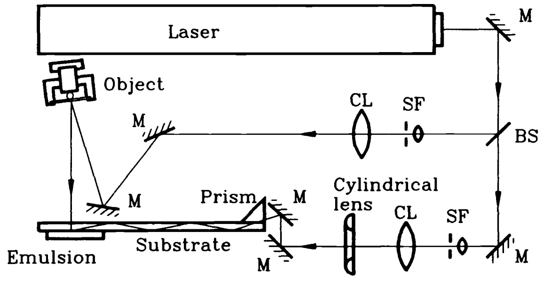

Fig. 2 Experimental setup used to record substrate guided wave holo-interferograms; M, BS, SF, and CL stand for mirror, beamsplitter, spatial filter, and collimating lens, respectively.

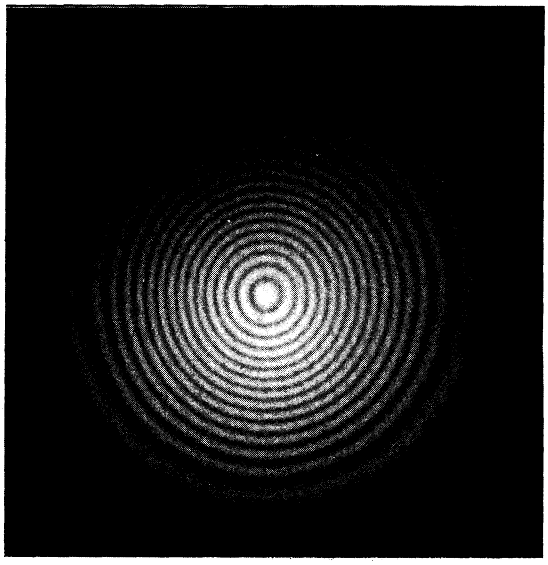

Fig. 3 Holo-interferometric fringe pattern corresponding to the out-plane displacement of an edge-clamped, centrally loaded disk.

One of the major factors inhibiting full exploitation of holo-interferometry is the difficulty of getting quantitative results from the holographic interferograms. Indeed, by itself the interferogram does not even contain sufficient information to determine the direction or sign of the surface displacement component being measured. This is illustrated in Fig. 3, which corresponds to an outward movement of the disk; the same pattern would have resulted had the disk moved inward. This problem can be solved by utilizing the method of carrier fringes.[14] The objective of this method is to superimpose a monotonic phase change across the field of view; ideally, the carrier pattern should be localized on the surface on the specimen. The approach is to superimpose a known carrier with the deformation and then to subtract the carrier. This process is conducted by digitizing the two interferograms and computationally subtracting the fringes.[15] Carrier patterns can be generated by moving the specimen, changing the illumination or reference beams, or moving the hologram itself.

Well-localized carrier fringes can be generated quite easily in SGW holo-interferometry. Figure 4(a), for example, shows the reconstruction of a carrier pattern produced by slightly changing the incident angle of the light coupled into the waveguide. In this case, the interference fringes localize in the plane of the silver halide emulsion. A simple lens can be used to image the object surface onto the plate. This approach not only maintains proper localization but reduces the coherence requirement on the source used for reconstruction, thereby, allowing holo-interferograms to be viewed using white light. Figure 4(b) shows the modulated carrier recorded after the disk is loaded. Figure 4(c), on the other hand, shows the circular fringes, produced in the form of a moiré pattern, when the holo-interferograms shown in Figs. 4(a) and 4(b) are optically superimposed. Figures 4(a), 4(b), and 4(c) were all reconstructed using white light.

A third experiment was performed by imaging the front surface of a 7.62-cm-long, 2.54-cm-wide, 0.07-mm-thick cantilever beam onto the recording plane using a simple lens. The cantilever beam was acoustically excited into steady-state vibration using a loudspeaker positioned behind it. An accelerometer, mounted on the rear upper corner of the free end of the cantilever, was used to detect resonant frequencies. Figure 5 shows white-light reconstructions of four time-average holograms, each recorded with an exposure time of three seconds. The fringes in the patterns represent movements normal to the surface of the cantilever. Figures 5(a) and 5(b) correspond to first torsional modes recorded at frequencies of 949 and 1165 Hz, respectively; whereas Figs 5(c) and 5(d) correspond to second torsional modes recorded at 2981 and 3088 Hz, respectively. The patterns are slightly different from those predicted on the basis of theory; however, anomalies can be attributed to the eccentric mass loading produced by the accelerometer.

A final experiment was performed to illustrate that real-time recording methods can be used to observe changes in the substrate itself. The experimental setup is shown in Fig. 6. A collimated object beam was produced by replacing the previous test object with a mirror. A holographic grating was made by recording the interference pattern produced by the free-space and guided waves. After development, the hologram was repositioned on the waveguide. A collimated wavefront was reconstructed by the guided wave on the observation screen placed in the path of the reconstructed beam.

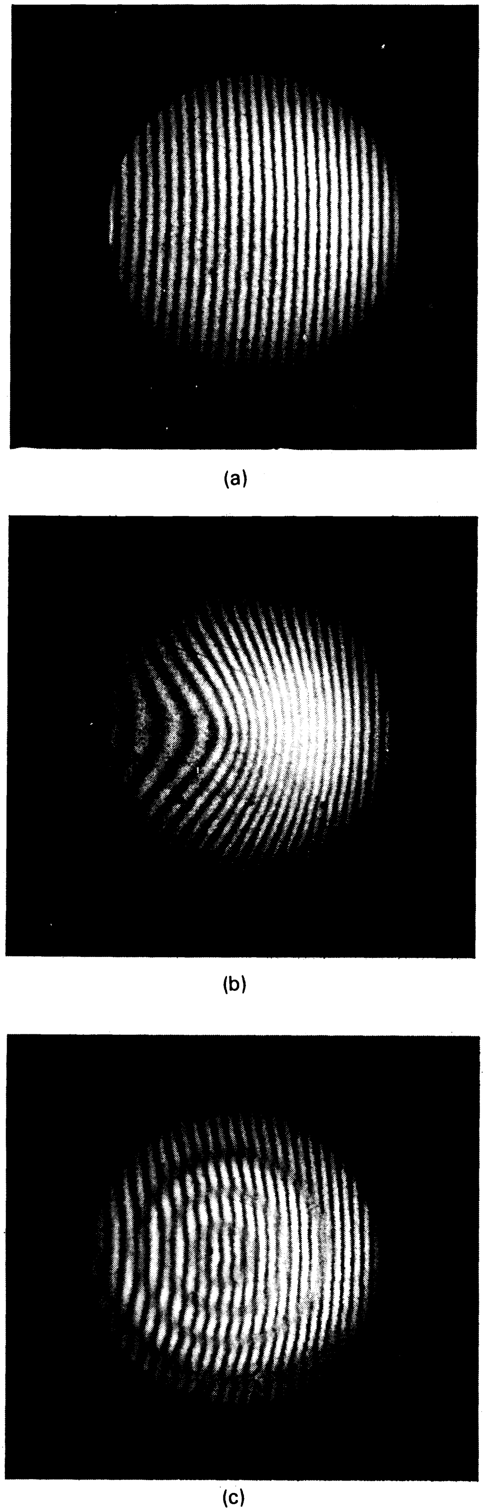

Fig. 4 Method of carrier fringes can be used to determine the sign of the displacement component being measured: (a) carrier pattern, (b) modulated carrier pattern, and (c) optical superposition of (a) and (b).

Changes in the substrate can be easily monitored with this setup. For example, the temperature response of the substrate was monitored using the carrier fringe method. Before heating the substrate, the guided illumination beam was adjusted to create the set of horizontal carrier fringes shown in Fig. 7(a). After the substrate was heated with a hairdrier, the ori-

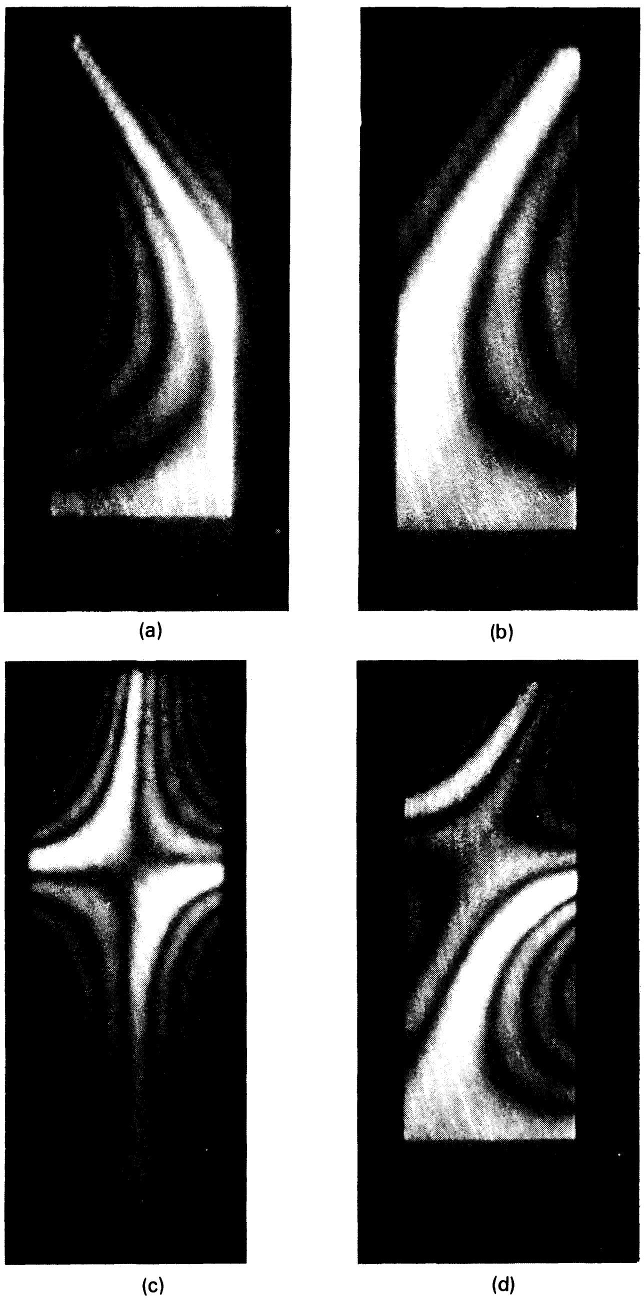

Fig. 5 Time-average holo-interferograms showing torsional modes recorded on the surface of a cantilever beam acoustically excited into steady-state vibration using a loudspeaker: (a) 949, (b) 1165, (c) 2981, and (d) 3088 Hz.

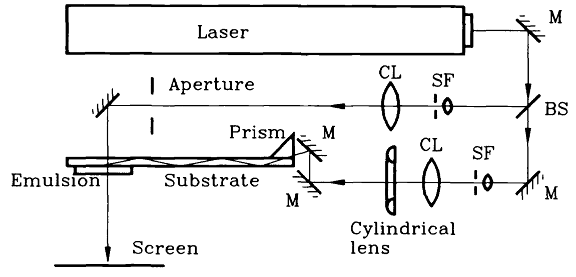

Fig. 6 Experimental setup used to demonstrate that the response of a substrate can be monitored using real-time SGW holo-interferometry; M, BS, SF, and CL stand for mirror, beamsplitter, spatial filter, and collimating lens, respectively.

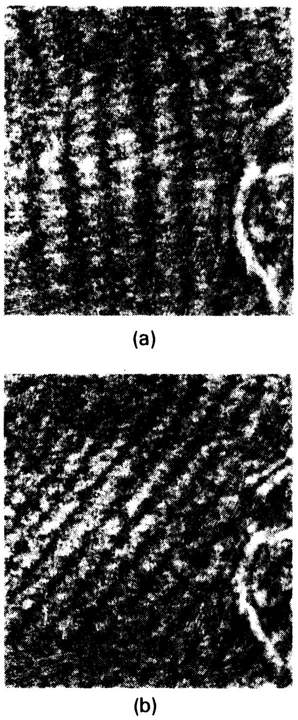

Fig. 7 Holo-interferograms recorded before and after a substrate was heated: (a) initial carrier pattern and (b) modulated carrier pattern.

entation of the fringes changed. A typical result is shown in Fig. 7(b). A similar approach could be applied to measure other optical and mechanical responses. A future paper will report on the development of SGW sensors.

6 Conclusions

It has been demonstrated that SGW holo-interferometry is a powerful new tool for nondestructive testing. Double-exposure, real-time, and time-average fringe patterns have been generated. A well-localized carrier pattern can be introduced simply by modulating the incident angle of the reference beam guided through the waveguide. Moreover, the substrate can be monitored and used as a sensor.

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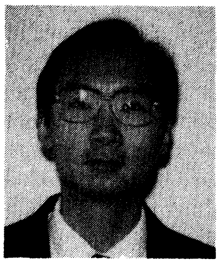

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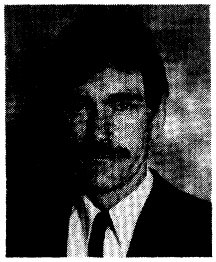

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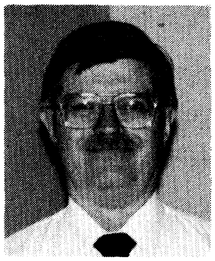

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