Holo-interferometric patterns recorded through a panoramic annular lens

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Measurements are made inside cavities using real-time holographic recording and a panoramic viewing system.

ABSTRACT

In the present paper, holo-interferometric fringe patterns are recorded within a cavity using two opposing collinear panoramic annular lenses. One panoramic annular lens is used to illuminate the cavity wall with coherent light, and the resulting intensity distribution is holographically recorded through the second panoramic annular lens. Interference fringes are obtained in real time by comparing holograms recorded before and after the cavity shape is modified. Future plans are discussed for practical implementation of the method including the use of digital image processing with a minicomputer for automatically accessing and analyzing the fringe patterns recorded through the system, and the incorporation of fiber optic components for making holographic measurements within the cavity using a compact rugged probe.

1. INTRODUCTION

The fundamental concept of holographic recording was demonstrated over forty years ago when Dennis Gabor suggested the process as a possible means of improving the resolving power of the electron microscope.[1] It was not until the early 1960's, when Leith and Upatnieks produced the first high quality holographic image using a strong coherent source,[2] that widespread attention was given to holography.[3,4] The exactness of the holographic image made it invaluable for detecting faults by optical interference, and holographic interferometry has since become an important diagnostic tool in non-destructive testing.[5-8]

A small fraction of the work performed in the areas of holography and holographic interferometry relies on endoscopic inspection: a technique for imaging the inner part of a volume, or cavity, from the outside.[9] This is not surprising, since most of the studies dealing with holographic endoscopy have met with limited success, mainly because of the problems associated with panoramic imaging systems. For example, compound systems which have several refracting/reflecting parts with collinear optical axes are difficult to manufacture if high quality images are needed. Most endoscopic inspection systems use scanning techniques, but scanning precludes real time recording of the entire cavity. Fortunately, many of these problems were addressed in the development of the panoramic annular lens (PAL).[10]

The PAL maps a cylindrical cavity onto a flat surface by a technique called flat cylinder perspective (FCP). When a 38 mm (1.5") diameter PAL is positioned within a cavity a view of the cavity interior, extending from approximately fifty-three degrees off the lens axis to about eighty-six degrees off-axis and encompassing a full 360 degree surround of the axis, is mapped into a flat annular image. Figure 1, for example, shows the image obtained when such a PAL is positioned along the axis of a cylindrical pipe, the interior surface of which is covered with a test pattern. The depth of field extends from the surface of the PAL out to infinity.

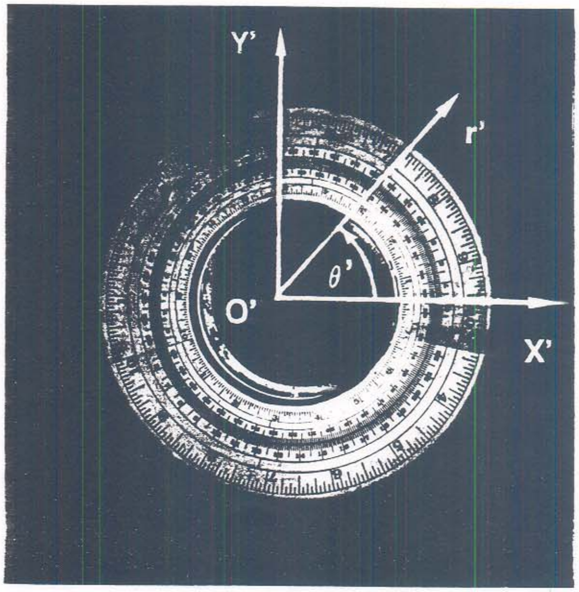

Figure 1. Image obtained when a PAL is positioned along the axis of a cylindrical pipe, the interior surface of which is covered with a test pattern. The coordinate system used to describe the image is superimposed.

Prior research has demonstrated that the lens can be used to make automated measurements within cavities using laser scanning techniques[11,12] and structured lighting.[13,14] It has also been used as the basis for the panoramic holocamera shown in Figure 2.[15] A collimated beam (1) is passed through the PAL (2) to generate a fan-shaped laser beam (3) that illuminates the film positioned within a cylindrical holder (4). As a consequence of FCP imaging, the central portion of the lens does not take part in forming the image, and the portion of the collimated illumination passing through the center of the PAL (5) can be reflected off an appropriately shaped mirror (6) onto the test surface. This configuration allows the the object beam/reference beam ratio to be carefully controlled so that a hologram(s) can be recorded when the holocamera is positioned within a cavity. The device can be used to record double-exposure and time-average holograms that can be reconstructed in white light, but it is limited in its real-time capabilities, since the film must be removed and developed after each holographic recording.

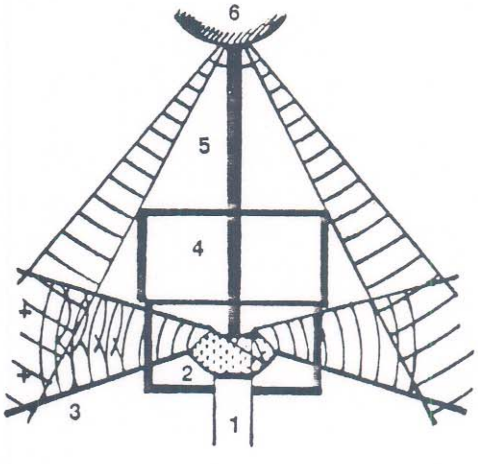

Figure 2. Schematic of a panoramic holocamera developed for tube and borehole inspection.

The present paper describes an

alternate approach to holoendoscopy in which holo-interferometric fringe patterns are recorded within a cavity using two opposing collinear panoramic annular lenses. One panoramic annular lens is used to illuminate the cavity wall with coherent light, and the resulting intensity distribution is holographically recorded through the second panoramic annular lens. Interference fringes are obtained in real time by comparing holograms recorded before and after the cavity shape is modified. Future plans are discussed for practical implementation of the method including the use of digital image processing with a minicomputer for automatically accessing and analyzing the fringe patterns recorded through the system, and the incorporation of fiber optic components for making holographic measurements within the cavity using a compact rugged probe.

2. ANALYSIS

The PAL maps a cylindrical cavity onto a flat surface by flat cylindrical perspective (FCP), producing an annular image. The cartesian (x',y') and polar (r',θ') coordinate systems used to analyze this image are shown superimposed on Figure 1. Figure 3, on the other hand, defines the cartesian (x,y,z) and cylindrical (r,θ,z) coordinate systems used to describe object space.

Referring to Figure 3, it is assumed that two opposing collinear PALs are aligned with their optical axes along the z-direction. Coherent light is projected by one PAL from the source point S to a point P located on the cavity wall. The image of P is observed by the second PAL at point O. For analysis purposes, unit vectors $\underline{e}_1$ and $\underline{e}_2$ are shown in the direction of illumination and in the direction of observation, respectively.

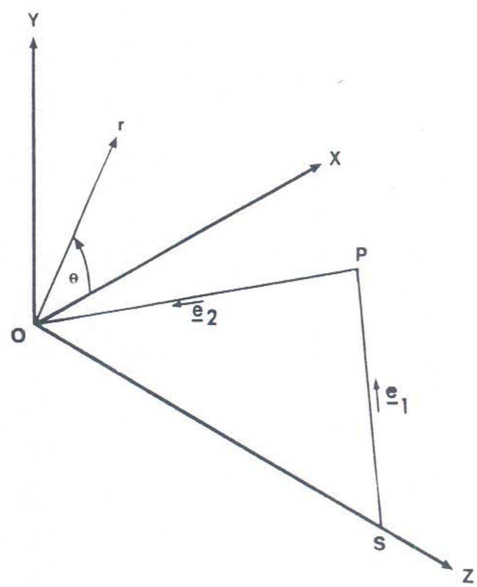

Figure 3. Cartesian (x,y,z) and cylindrical (r,θ,z) coordinate systems used to describe object space.

These vectors are important in analyzing the holographic fringes produced when two reconstructed hologram images corresponding to an undeformed and deformed surface are superimposed. In this case,

$$n\lambda = \underline{g} \cdot \underline{d} \qquad (1)$$

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

The observed displacement fringes are due to the change in optical path length which 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 light and dark fringes. As discussed above, the component of displacement measured at each point depends upon the location of the source and on the point of observation; the displacement vector is projected along the sensitivity vector which coincides with the angle bisector of $\underline{e}_1$ and $\underline{e}_2$.

When recorded through a PAL, the fringe pattern is first analyzed in the image plane. Then, the values obtained for the corresponding displacement must be mapped to object space by taking into account the separation between the PALs, the radial distance between the test surface and the optical axis of the system, the design parameters of the PALs, and the optical transformations used to illuminate the cavity wall and create the PAL image. A detailed study of this mapping and the corresponding theoretical analysis for the fringe patterns shown in the next section will appear in a subsequent paper.

3. EXPERIMENTAL

Experiments were performed with the setup shown in Figure 4 to illustrate that holo-interferometric fringe patterns can be recorded with the PAL system for cases in which the cavity moves relative to the recording system, or experiences a deformation caused by the application of mechanical loads. Two 38 mm (1.5") diameter PALs, spaced at a distance of 66 mm (2.6") apart, were positioned with their optical axes aligned with the z-axis of the coordinate system shown in Figure 3. A circular brass pipe with an inner radius, R, equal to 69.85 mm (2.75") and a wall thickness of 3.0 mm (0.117"), was mounted on a kinematic stage and positioned midway between the PALs with its longitudinal axis also along z. The inner surface of the pipe was painted white, and coherent light (λ = 514 nm) was projected onto the inner wall of a 25.4 mm (1.0") long section of the pipe using a collimated beam passed through one of the PALs. An image of the pipe in its initial position was captured through the second PAL. This requires an additional imaging lens, since the PAL captures a virtual image which forms within the PAL itself. As shown in the figure, a hologram of the wavefronts emerging from the second PAL was recorded using a thermoplastic holocamera positioned behind the imaging lens.*

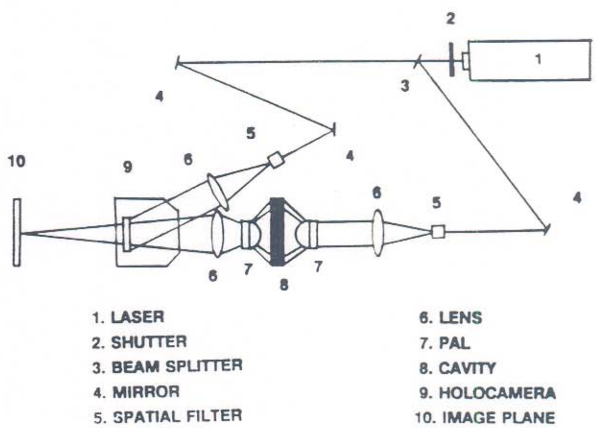

Figure 4. Experimental setup for recording real-time holograms.

Figure 5 shows a reconstruction of the fringe pattern recorded in real time after the pipe was translated along the x-axis, through a displacement u equal

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* The holocamera can also be positioned between the imaging lens and the PAL, or in the image plane. However, the latter condition causes excessive noise during reconstruction, since anomalies such as dirt and pits in the thermoplastic are recorded along with the image of the cavity.

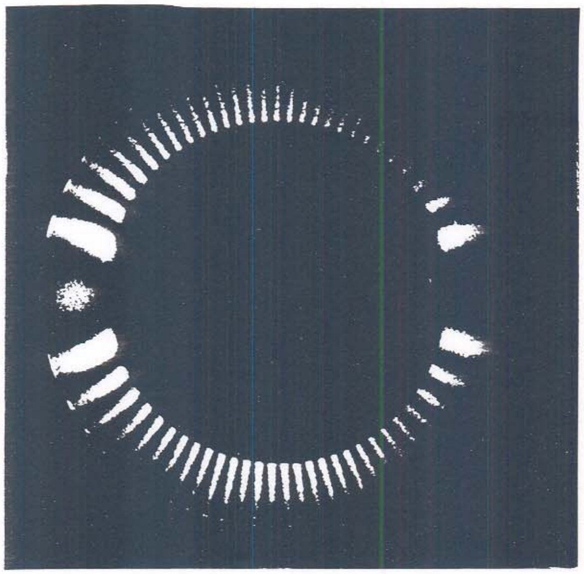

Figure 5. Holographic fringe pattern for a pipe section translated along x.

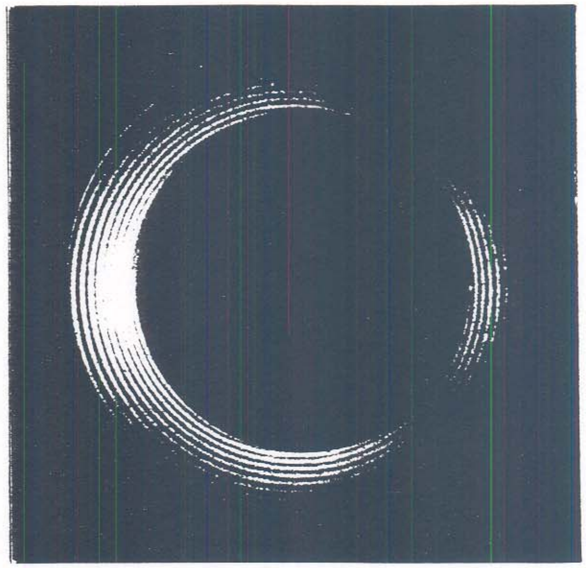

Figure 6. Holographic fringe pattern for a pipe section translated along z.

to 0.0058 mm (0.00023"). Zero order fringes are observed at θ equal to 90 and 270 degrees; maximum fringe order numbers occur at θ equal to 0 and 180 degrees.

The fringe pattern shown in Figure 6 was obtained by holographically recording the pipe in its initial position and then translating it along the z-axis, through a displacement w equal to 0.014 mm (0.00055"). In this case, a zero order fringe occurs in the middle of the annulus, and fringe orders monotonically increase from the inner to the outer boundary.

Figure 7, on the other hand, shows the result of diametrally compressing the pipe with a load of 48 grams. In this test, the pipe was supported at θ equal to 270 degrees, with the load applied at θ equal to 90 degrees.

4. DISCUSSION

4.1. Digital image processing

One of the major factors inhibiting full exploitation of holographic measurement techniques is the difficulty of getting numerical results out of holo-interferometric fringe patterns. Although there is not yet a general method available that can be used to reliably interpret holo-interferometric fringe patterns, great strides have been made to apply automated data reduction to specific applications.[16] Digital processing can consist of locating fringe centers, fitting interpolating functions, or otherwise preparing data to produce a point-by-point map of surface displacement. An alternate strategy for flaw detection is to apply pattern recognition techniques to look for anomalous holo-interferometric fringe patterns.

If the PAL system is to be commonly used as a measurement tool, some general method of simplifying the recording and analysis of complex holo-interferometric fringe patterns must be developed. One approach to this problem is to introduce

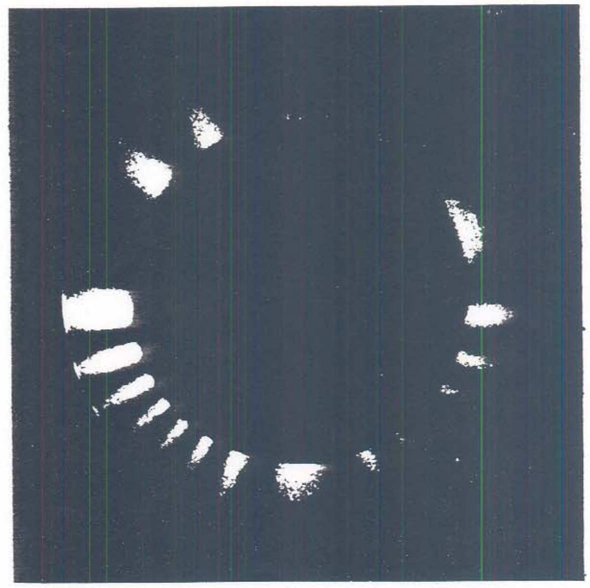

Figure 7. Holographic fringe pattern for a pipe section subjected to diametral compression.

a known carrier whose phase adds vectorially to the phase changes caused by surface deformation to produce a perturbed fringe pattern with fringe orders that monotonically increase in the direction orthogonal to the carrier. Subtraction of the carrier from the perturbed pattern aids in making peak/valley distinctions in the surface profile and unambiguously establishes the algebraic sign of the displacement vector.[17,18]

This process was automated when reconstructed images of a carrier and perturbed fringe patterns were stored digitally.[19-21] The patterns were analyzed by comparing the differences in the intensity distributions along the direction orthogonal to the carrier fringes. Real time recording with a holocamera allowed proper selection of the carrier fringe frequency necessary to create the desired monotonic response.

Figure 8 illustrates that a similar approach can be applied to the fringe patterns recorded through the PAL system. In this case, the phase changes associated with the deformation pattern shown in Figure 7 were superimposed with those associated with the pattern shown in Figure 6. The fringes in Figure 6 act as a carrier and can be oriented horizontally by linearizing the PAL image using image processing algorithms discussed in an earlier paper.[12] The deformation can be analyzed by "linearizing" the image corresponding to the modulated carrier (Figure 8), vertically scanning both images, and subtracting fringe order numbers. This process will be described in detail in a future publication.

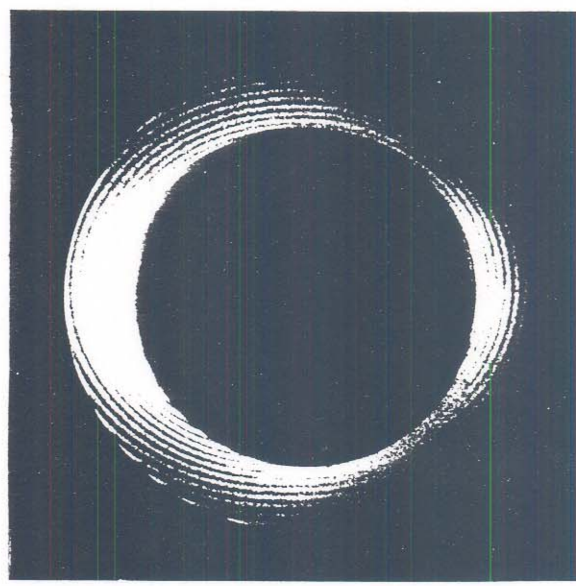

Figure 8. Superposition of the phase changes associated with the fringe patterns shown in Figures 6 and 7.

4.2. Incorporation of optical fibers

Over the last decade, the work of various investigators has demonstrated the practical uses of fiber optic elements for holography and holographic interferometry.[22] Experience has established that individual singlemode fibers provide convenient, flexible but stable illuminators for holographic interferometry, while lensed fiber optic bundles may be used to transmit holographic "images" for recording and analysis at locations remote from the actual test object. Moreover, unlensed fiber optic bundles and individual fibers may be used as flexible illuminators for pulsed laser holography and interferometry. Individual optical fibers and coherent fiber optic bundles may be used in both local and remote holographic systems, including double-exposure, time-average, and real-time holographic interferometry. Optical fibers can be fixed with respect to the object or hologram to measure relative displacements, and can be used to penetrate optically unstable interfaces which are encountered, for example, in making holo-interferometric measurements on the surface of a submerged object.

Fiber optic components may also provide the tools needed to develop a compact and rugged holoendoscope using the PAL. The length of optical fibers can be easily adjusted to allow close matching of path lengths to satisfy coherence requirements and to gain access to remote test surfaces. They provide a mechanism for conveniently changing the object illumination and observation directions so that different displacement components may be recorded, and allow the angle of the reference beam to be changed to vary the spatial frequency content of the hologram itself. In addition, fiber components can be used to adjust the reference illumination position with respect to the hologram to compensate for rigid body motion, or to introduce carrier fringes.

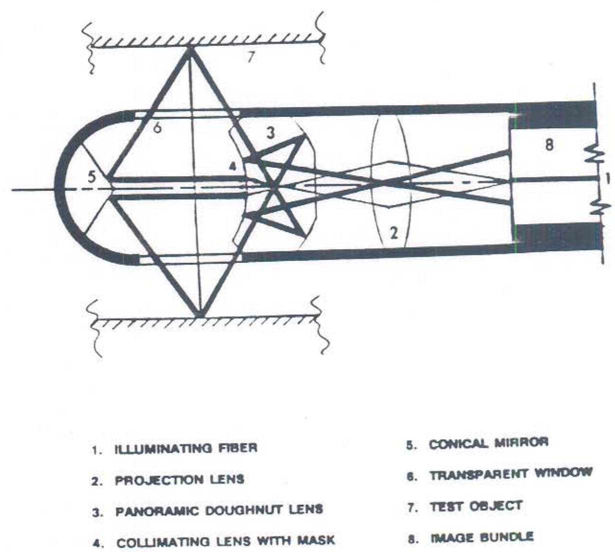

Figure 9. One of many configurations for a holoendoscope which incorporates a PAL.

These and other advantages of fiber optics are being exploited in the design and development of PAL holoendoscopes. Figure 9, for example, illustrates one of many possible configurations currently under consideration. In this example, a holoendoscope is shown inserted into a cylindrical cavity. Laser light is launched into a bidirectional fiber coupler (not shown in the figure), and one leg of the coupler, shown in the figure as a singlemode fiber labeled (1), is incorporated into the device. The diverging beam from the fiber is directed through a projection lens (2), passes through the central portion of a PAL (3), and is shaped by a collimating lens (4). The emerging beam reflects off an appropriately shaped mirror (5) and passes through a transparent window (6) onto the test surface (7). The image of the illuminated surface is captured through the transparent window (6) by the same PAL used to illuminate the cavity (3) and the virtual image is transferred by the projection lens (2) to a coherent optical fiber bundle (8). The bundle transmits the image from the holoendoscope to the recording site where the object wavefront is superimposed with the output from the other leg of the coupler.

5. CONCLUSION

This paper has described a method in which measurements are made within a cavity using real time holographic recording and a panoramic viewing system. The method, which relies on two collinear panoramic annular lenses, was applied to record holographic fringes caused by both rigid body motions and deformation.

The results obtained from this study show that a carrier fringe technique can be applied to analyze complex fringe patterns. Future plans for improving the method include the development of computer algorithms for automated analysis of holo-interferometric fringe patterns recorded through a panoramic annular lens, and construction and application of a practical measurement device which incorporates fiber optics.

6. ACKNOWLEDGEMENT

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