Endoscopic inspection and measurement

John A. Gilbert
University of Alabama in Huntsville, Dept. of Mech. Eng.
Huntsville, AL 35899

Donald R. Matthys
Marquette University, Physics Dept.
Milwaukee, WI 53233

C. M. Lindner
University of Alabama in Huntsville, Dept. of Mech. Eng.
Huntsville, AL 35899

ABSTRACT

The design of a panoramic viewing system and its application to cavity inspection and measurement are discussed, along with the general properties of a special panoramic annular lens (PAL). Various examples are described, showing how the PAL can be used for simple inspection or for precision contouring of interior walls of cavities using techniques such as moire, holointerferometry, and Electronic Speckle Pattern Interferometry (ESPI).

1. INTRODUCTION TO RADIAL METROLOGY

Optical methods have been used for decades to inspect surfaces and to make stress analysis measurements, but most techniques have been applied on the outer surfaces of structural components. More recently, primarily due to the introduction of new tools such as fiber optics and microelectronic devices, it has become feasible to make measurements on interior surfaces. However, fiber-based systems as well as the more conventional non-fiber-based systems, suffer from a limited field of view. Ideally, an optical device for making measurements on the inner surface of a cavity should provide a panoramic view of the entire cavity.

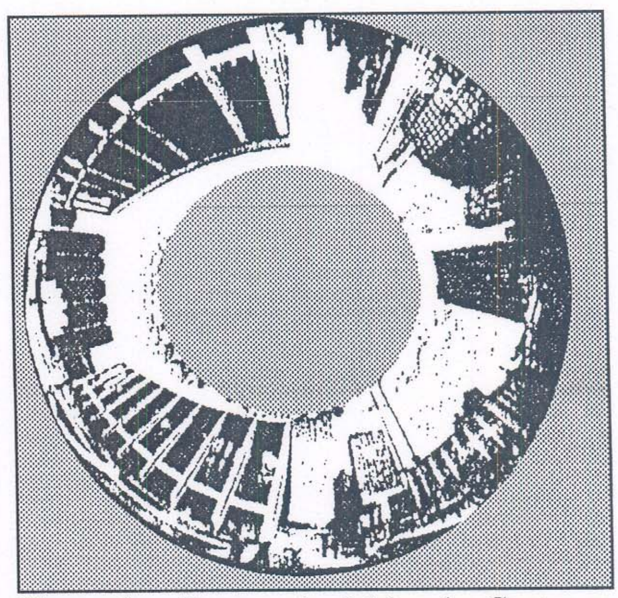

Figure 1. Courtyard of Lincoln Center as viewed through a PAL.

The first attempt to patent a system for panoramic imaging was made by Mangin in 1878,[1] and since that time numerous other devices have been patented.[2] Most of these devices depended on a scanning system or on a complex set of lenses. However, in 1984 Greguss invented a simple lens known as a panoramic annular lens (PAL) capable of giving a full 360 degree surround image of the area around the lens. The utilization of this lens with digital cameras and computer programs to inspect and measure the interior walls of cavities is known as radial metrology.[3] Such a PAL-based system produces an annular shaped image of sufficient resolution and low enough distortion to allow direct visual inspection for the determination of gross flaws or distortions in the interior surfaces of pipes and fuel lines. If precision measurements of wall deformation are required, standard moire, holographic, or ESPI methods can be used, though then a simple linearizing transformation must be performed. As an example of the type of image produced by a PAL, Figure 1 shows a photograph of the courtyard of Lincoln Center obtained by pointing a PAL equipped camera at the sky. Note that a satisfactory image is obtained from ground level to sky. In fact, the PAL is almost afocal, and obtains an image from right up against the lens surface out to infinity. Also, it can be seen that objects to the front of the lens are imaged to the interior of the annulus and objects to the rear of the lens appear on the outer part of the annulus.

2. CHARACTERISTICS OF A PAL

The PAL is a single piece of high index glass with spherical surfaces. The general shape of a PAL is shown in Figure 2 where the thick lines represent mirrored surfaces. The ray diagram of Figure 3 shows how rays from a surrounding cavity form a virtual image within the body of the lens. An external transfer lens is used to produce a real image on a suitable sensor. Although some adjustment of viewing angles is possible by modifying the PAL design, the lens basically produces an image of the cylindrical surround of the lens which looks about 25 degrees forward and about 20 degrees backward. The angular resolution varies as the viewing angle changes from front to back but is generally about 5 milliradians. After a little practice, most observers adjust to the distortion of the annular image, but if it is desired to present a more traditional image, or it the image is being used in precision measurements, the image can be

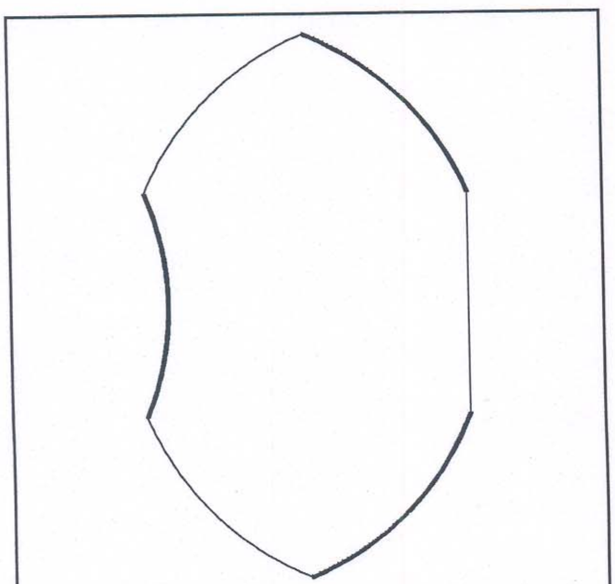

Figure 2. Physical shape of a PAL. Heavy lines indicate mirrored surfaces.

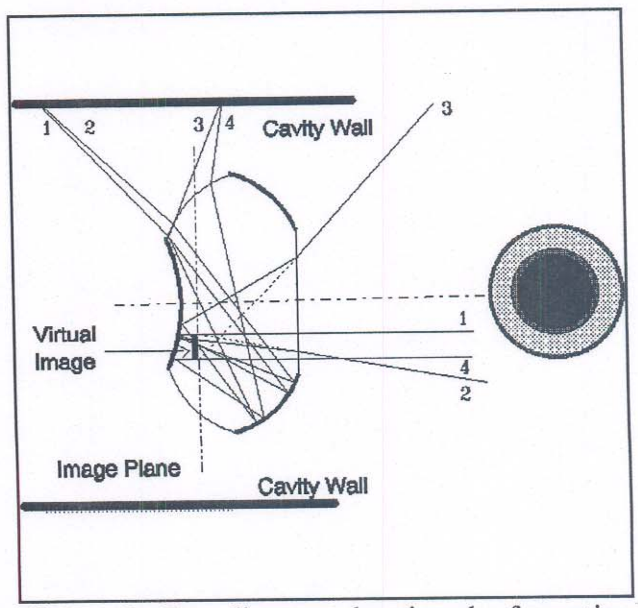

Figure 3. Ray diagram showing the formation of an annular shaped virtual image in the interior of a PAL.

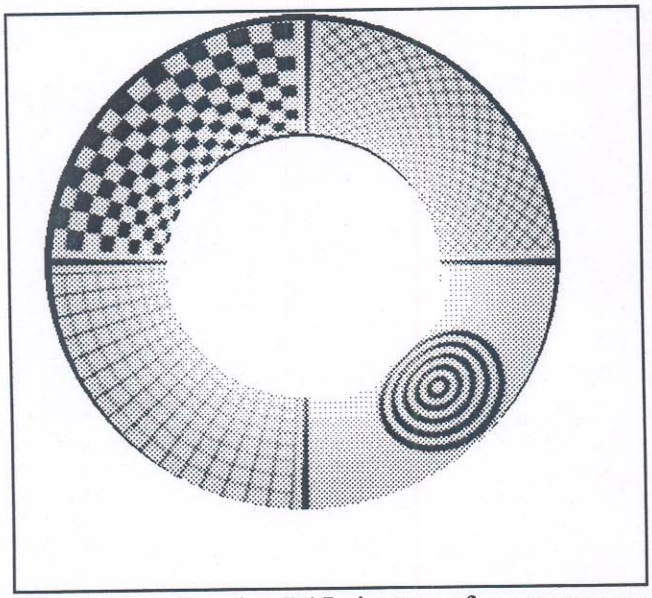

Figure 4. Annular PAL image of a pattern on the interior wall of a pipe.

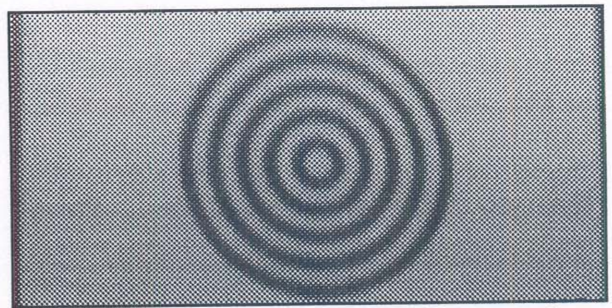

Figure 5. Linearized version of one quadrant of the image shown in Figure 4.

linearized by applying a simple two-stage mapping. A section of the annulus is selected from the image; next this section is rolled along its outer rim with radial lines from the center to the rim transferred as vertical lines to a rectangular image. This image is then stretched vertically to produce a linearized image similar to what would be seen by an observer looking directly at a part of the cavity wall. Figures 4 and 5 show a section of a PAL image, first in its original annular image and then in its linearized form.

3. ILLUMINATION

Since the PAL is commonly placed in the interior of cavities and pipes, illumination techniques must be considered. The effective acceptance angle of the PAL is quite small, and the PAL is a rather slow lens, compared to traditional lenses. Therefore, it is important to consider methods for introducing sufficient light to produce bright images.

When the cavity being studied is relatively short, particularly if it is open at both ends, traditional lighting methods can be used. In the study of the rocket motor discussed later in this paper, a standard floodlight system was used to illuminate the rocket exhaust chamber. However, in cases where the cavity is long and narrow, the lighting system must be built into the PAL system. A ring of small incandescent lamps mounted around the base of the PAL and its camera has proven succesful in illuminating many interiors. Another approach is to mount the PAL and its camera inside a plastic tube which can be illuminated with optical fibers. This plastic tube acts as an optical waveguide and by cutting the end of the tube at an angle a belt of light can be projected around the PAL. For phase sensitive measurements where coherent light must be used, a dual PAL system has been successfully

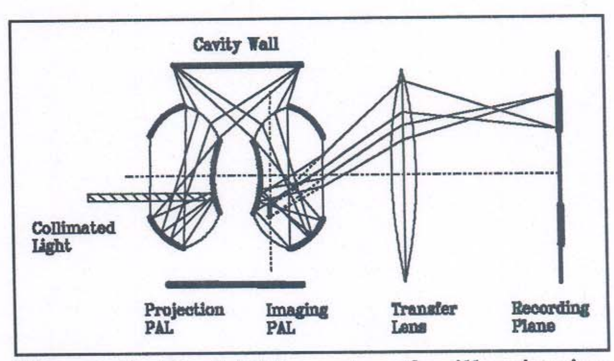

Figure 6. Dual PAL system for illuminating and viewing an interior surface.

employed. In such a system, two opposing PALs are coaxially aligned with an appropriate separation between them so that the belts of illumination and observation overlap. A schematic of such a system is given in Figure 6.

4. VISUAL INSPECTION

In many cases, simple visual inspection of the interior walls of a pipe or cavity may give sufficient information about the system being studied. A description of various examples of such measurements follows.

Figure 7 shows an RL10 rocket engine. It was desired to obtain a photograph of the interior wall of the rocket exhaust chamber to determine information about cracks and the condition of welds around the walls.. Figure 8 shows a PAL image of the interior of the rocket exhaust obtained by illuminating the inner walls with a floodlight and pointing a PAL down the axis of the rocket. If it is desired to contour an interior surface of a cavity, this may be accomplished by illuminating the cavity wall at an oblique angle using the unexpanded beam produced by a laser diode. Figure 9, for example, illustrates how this approach can be used to visually detect inclusions located on the inner wall of a pipe. In this case, a laser diode and a rotating mirror produce a scan, which was originally circular, that traces out shapes in the annular image which are similar to those of the inclusions. The resulting PAL image is shown in the left half of Figure 9. The four quadrants of the image were linearized and the resulting images are shown in the right half of the figure. The lower portion of each trace represents a constant radial

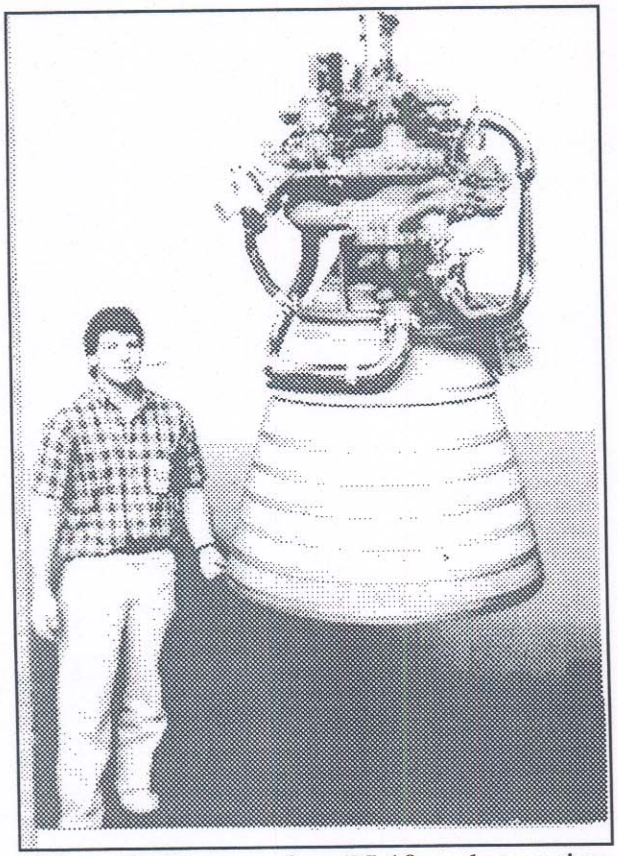

Figure 7. Picture of an RL10 rocket engine.

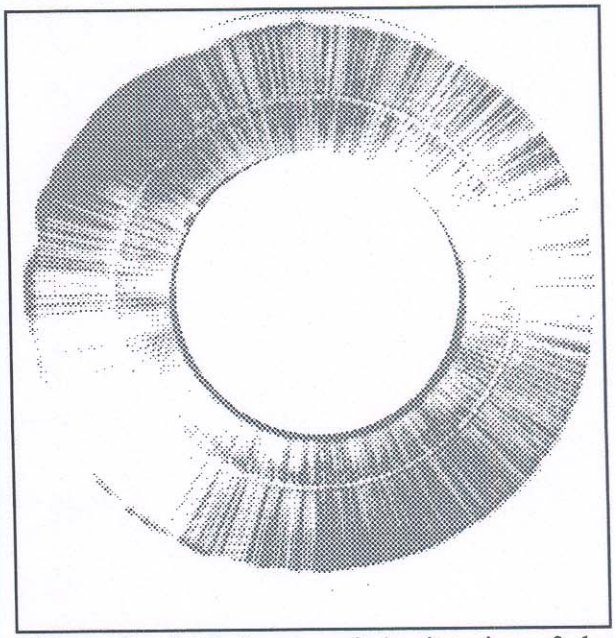

Figure 8. PAL image of the interior of the exhaust chamber of RL10 shown in Figure 7.

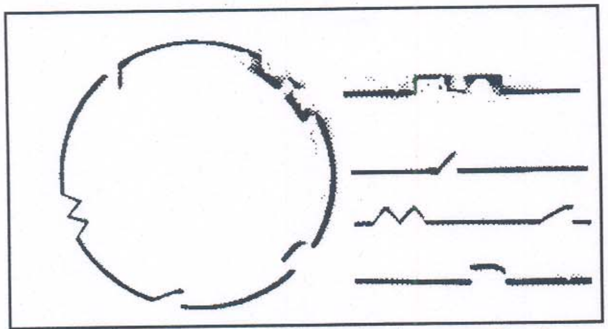

Figure 9. A pipe with inclusions on its inner wall illuminated by a laser scan line. Images on right show linearized images of the four quadrants.

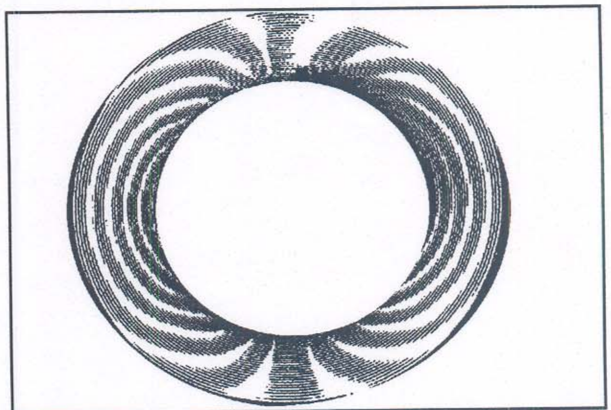

Figure 10. Moire pattern from a pipe with a grid on its interior wall.

distance from the optical axis of the PAL to the wall of the pipe. The shape and dimensions of the inclusions can easily be observed and measured with respect to this baseline using a relatively simple edge finding algorithm. The optical system can be aligned so that measurements are based on a linear calibration curve.[4,5]

Moire is another technique using amplitude variations that can be used to make accurate displacement measurements of the interior wall of a pipe.[6] The type of image produced by double exposure after a 10.16 mm (0.4 in) transverse translation of a pipe whose inner surface has been covered by a grid of pitch 1.27 mm (0.05 in) by 10.16 mm (0.4 in) is shown in Figure 10. A discussion of the analysis of these fringes is given in Reference 6. Another method for

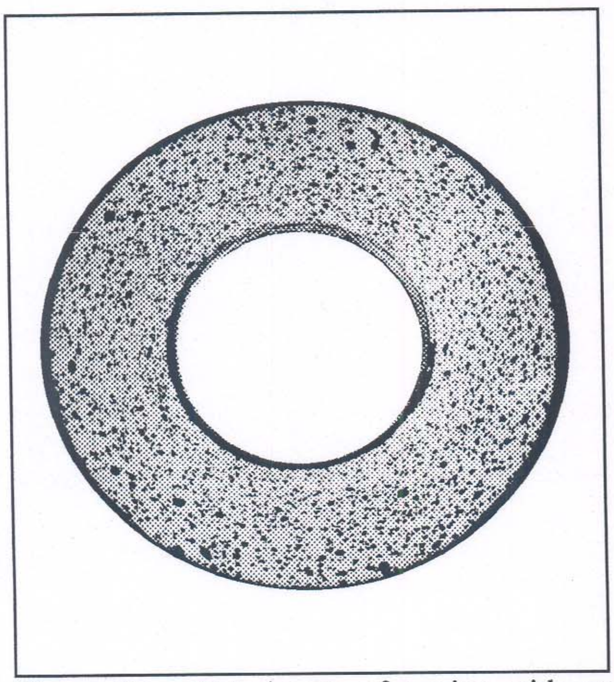

Figure 11. PAL image of a pipe with an artificial speckle pattern projected onto its wall.

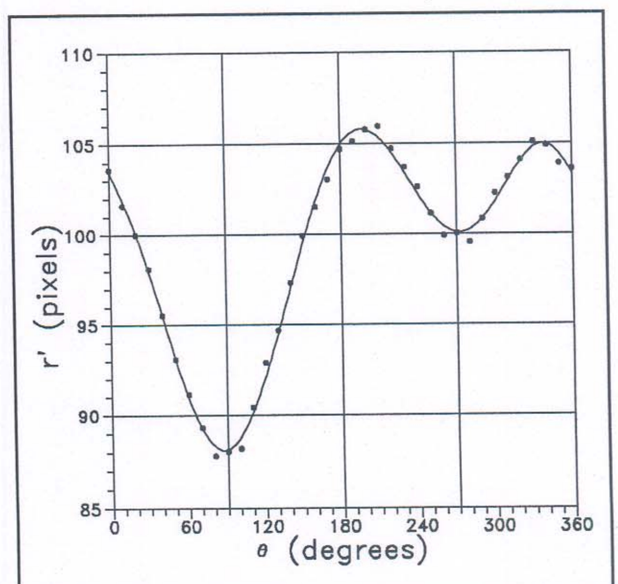

Figure 12. Deformation vs. angle obtained by applying correlation techniques to speckle patterns on wall of pipe in Figure 11.

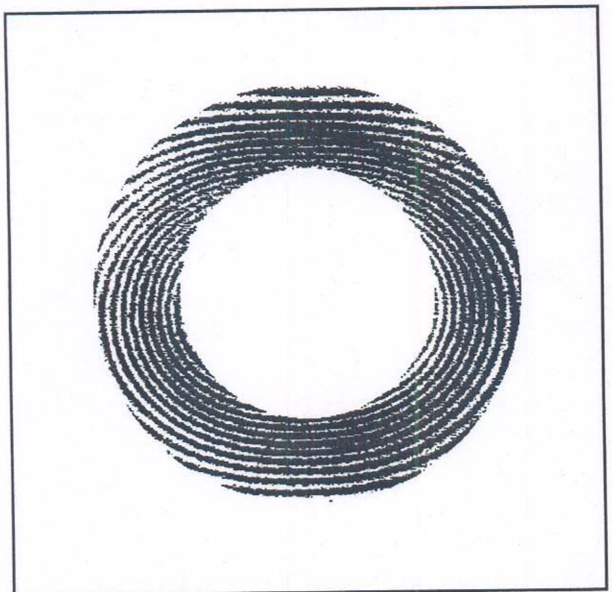

Figure 13. Holointerferogram of interior of a pipe loaded with a vertical line force.

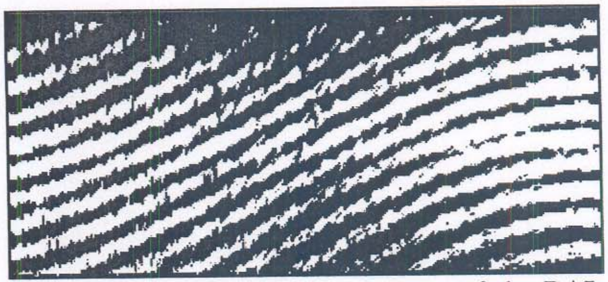

Figure 14. A linearized quadrant of the PAL image shown in Figure 13.

using radial metrology is to project artificial speckle on the interior surface of a pipe.[7] After the pipe is loaded, a second image of the speckle pattern is taken and digital correlation is used to measure displacements between the two states of the pipe wall. As an example, Figure 11 shows the type of image obtained when the pipe wall is viewed through the PAL, while Figure 12 shows the results of applying digital correlation to two images, the first taken before the pipe was loaded, the second after applying a line force along the top of the pipe.

5. INTERFEROMETRIC DEFORMATION MEASUREMENTS

The preceding examples show that radial metrology with a PAL can be used for direct observation and for relatively large displacements (on the order of millimeters). However, the system can also be used for precision interferometric measurements (on the order of microns), since in interferometry the detector need only be sensitive enough to record fringe patterns. Figure 13 shows a holointerferogram obtained by loading a test pipe similar to the one used earlier for a demonstration of a speckle correlation measurement. However, this time the deformation is only a few microns. Figure 14 shows a linearized quadrant of the image shown in Figure 13. This linearized image can be analyzed in exactly the same way as a holointerogram obtained through a traditional lens, applying carrier subtraction, phase unwrapping, etc.

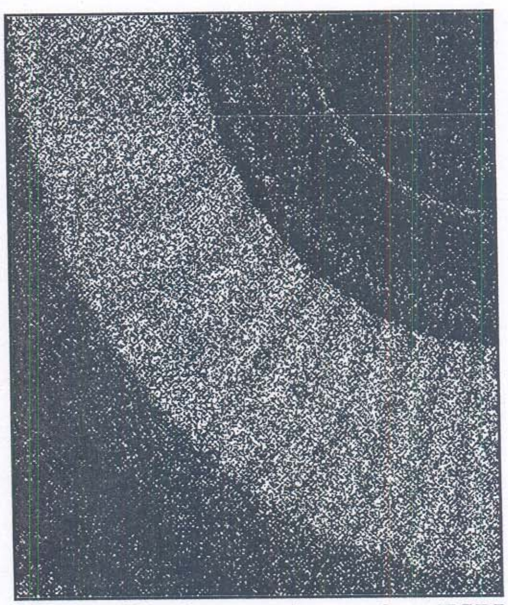

Figure 15. One quadrant of an ESPI pattern obtained through a PAL.

Finally, Electronic Speckle Pattern Interferometry (ESPI) can be done with a PAL. Efforts to do so have just been started, but preliminary tests show that it is feasible. A quadrant of an ESPI pattern taken through a PAL is shown in Figure 15. Although the small effective aperture of the PAL presents some difficulty in controlling speckle size, early results show that it can be done.

6. CONCLUSIONS

The panoramic annular lens has made possible the inspection and analysis of the interior walls of pipes and cylinders without the need for rotating lenses or the registration of sets of images. Whether the information desired can be obtained by simply looking at the annular PAL image or whether image linearization and interferometic techniques are needed to measure deformations at the micron level, radial metrology with a PAL offers a simple direct method for obtaining the desired results.

7. ACKNOWLEDGEMENTS

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