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Experimental mechanics from a different perspective

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ABSTRACT: A variety of new sensors and optical techniques have been developed for panoramic inspection and measurement. These techniques, often categorized under the name radial metrology, rely on a panoramic annular lens (PAL). This paper describes the attributes of the PAL and some of the progress made by incorporating radial metrology into experimental mechanics.

1 INTRODUCTION

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. However, many geometrically complex structures contain cavities and holes which must be periodically examined to evaluate performance and/or assess structural integrity. Inspection and measurement within such regions traditionally rely on boroscope inspection. Video cameras are used to view larger cavities, whereas, optical endoscopes (either rigid or flexible fiber optic based) provide optical access to more confined spaces. However, fiber-based systems, as well as the more conventional non-fiber-based systems, suffer from a limited field of view (full field forward viewing boroscopes); or, provide discontinuous images of the cavity (rotating mirror boroscopes). These limitations led to the development of radial metrology (Gilbert et al. 1987, Greguss et al. 1988, Matthys et al. 1989); a collection of optical methods which rely on a *Panoramic Annular Lens* (PAL) (Greguss 1984).

This paper describes the attributes of the PAL and some of the progress made by incorporating radial metrology into experimental mechanics.

2 THE PANORAMIC ANNULAR LENS

As shown in Figure 1, the PAL is a single element

imaging block comprised of three spherical optical surfaces and one flat optical surface. Two of the spherical surfaces are mirrored while the third spherical surface and the flat surface are not.

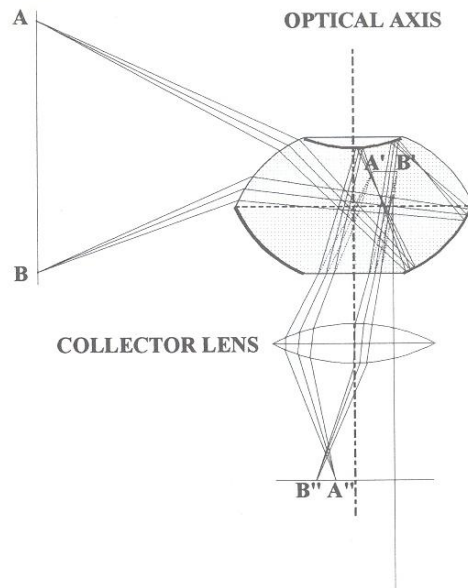


Figure 1. Panoramic annular lens system.

Rays leaving points A and B are refracted upon contacting the first spherical surface, and reflect off the rear mirrored spherical surface. They travel forward in the lens and strike the front mirrored spherical surface. Reflected back, the rays are refracted at the rear flat optical surface and diverge as they exit the lens. The divergent rays leaving the flat optical surface at the back of the PAL can be "back traced" to form virtual images corresponding to points A and B at the points labeled A' and B'. A biconvex lens, labeled as the collector lens, forms real images of these internal points at A'' and B''. Imaging all points contained within the field of view produces a flat annular image.

As illustrated in Figure 2, the optical axis of the PAL is defined by a line perpendicular to the flat surface which passes through the centers of curvature of the three spherical surfaces. A longitudinal axis, labeled Z, is chosen to coincide with the optical axis. Two other axes, labeled X and Y, are established in a plane defined by the physical equator of the lens. They are chosen to form a right handed triad with the longitudinal axis. Spherical coordinates (ρ, α, θ) may also be defined with respect to the origin.

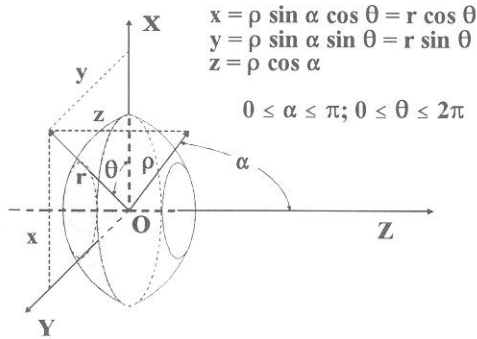


Figure 2. Coordinate systems and spherical coordinates used for radial metrology.

In Figure 2, the angles α and θ are called the field angle and the radial position angle, respectively. The field angles corresponding to the points labeled A and B in Figure 1 are called the upper and lower field angle, respectively. They define the limits on the field of view and are a function of the index of the glass used in the PAL.

Figure 3 shows a 38mm (1.496in) diameter PAL made from Schott SF14 glass ($n=1.76$) in which $\alpha_u = 65^\circ$ and $\alpha_l = 110^\circ$. When the area between these field angles is rotated around the optical axis through a radial position angle of 2π , a cylinder is described.

This continuous field of view is mapped by a collector lens onto a flat annular image. This PAL has been characterized in terms of spherical aberration and coma, distortion, image plane curvature, and the modulation transfer function (Richter 1992). In general, the acceptance angle varies with the field angle; the amount of spherical aberration is proportional to the acceptance angle. The magnification varies quadratically and image plane curvature is cubic.

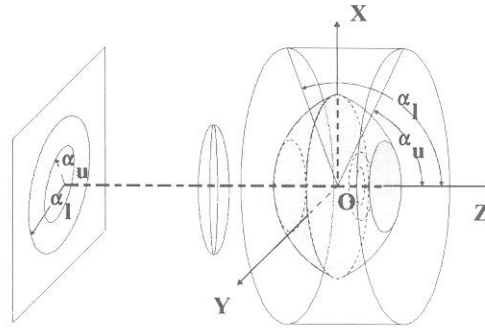


Figure 3. PAL and the field of view.

From an experimental mechanics standpoint, the resolution of the PAL varies from the forward viewing edge to the back viewing edge with an angular resolution of approximately 6 millirads. Even though the PAL is not strictly afocal, objects appear to be in focus from the lens surface to infinity. The transmittance varies less than five percent over the visible light range; however, since the PAL is both refractive and reflective, it does not possess the same performance for all wavelengths.

In radial metrology, the aspect ratio of an area is defined as height divided by width. In real (or object) space, height is measured as the longitudinal distance relative to the optical axis of a lens; width corresponds to the circumferential distance measured around the optical axis. In image space, height is measured as a radial distance relative to the center of an image; width corresponds to a circumferential distance measured around the image center.

When a conventional lens is used for radial metrology, a cylinder, whose inside surface is composed of a uniform grid of squares, is mapped into the image plane as a series of evenly spaced concentric rings representing equally spaced lines drawn around the circumference of the cylinder; radial lines represent the longitudinal lines drawn along the length of the

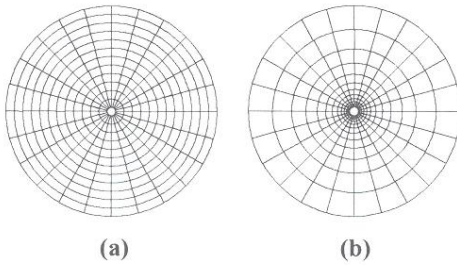


Figure 4. A square grid wrapped around the inside wall of a cylinder becomes (a) a conventional polar map when recorded with a conventional lens; and, (b) a constant aspect ratio polar map when recorded with a PAL.

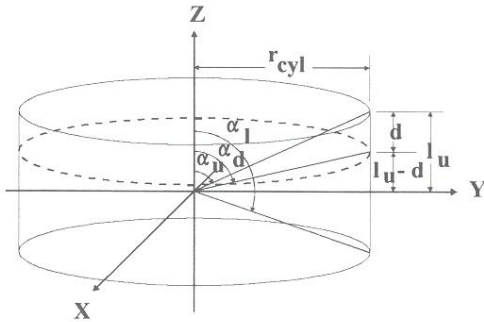


Figure 5. Coordinate system axes and angles.

cylinder at constant circumferential positions. Figure 4(a) illustrates that, in the case of the conventional lens, square elements having a real space aspect ratio of unity are mapped to an image comprised of segments which have different image plane aspect ratios. The PAL maps the same uniform grid of

squares into the constant aspect ratio polar map illustrated in Figure 4(b).

The mapping function can be characterized analytically (Lehner et al. 1996). Referring to Figure 5,

$$\alpha_d = \tan^{-1} \left(\frac{\kappa(r_d + r_i) \tan(\alpha_u)}{\kappa(r_d + r_i) - 2(r_d - r_i) \tan(\alpha_u)} \right) \quad (1)$$

Equation (1) shows that once the angle from the origin to the upper edge of a cylinder is known in real space, the angle from the origin to any point can be determined from measurements taken in the image plane. In the equation, κ is the aspect ratio, r_i is the inside radius of the image, and r_d is the radial distance the point in question. The aspect ratio for the 38mm (1.496in) diameter PAL shown in Figure 3 is approximately 0.75.

3 VISUAL INSPECTION

The wide field of view of the PAL makes it possible to construct systems which can view salient features relative to their surroundings. This may be important in cases where chemical deposits cause corrosion, or where combinations of thermal and mechanical stresses cause wear or produce cracks. Such conditions are typically encountered in nuclear power plants and in rocket engines where many components, designed to function at high temperatures and pressures, must be periodically inspected to avoid catastrophic failures. Figure 6, for example, shows a 7.62cm (3.0in) diameter *Panoramic Video System (PVS)* prepared as a deliverable under a NASA contract to inspect the Space Shuttle Main Engine (SSME).

The PVS relies on a PAL {1} to capture a cylindrical view of the region surrounding the lens through a transparent window {2}. Incandescent illumination is distributed over the cylindrical field of view using a

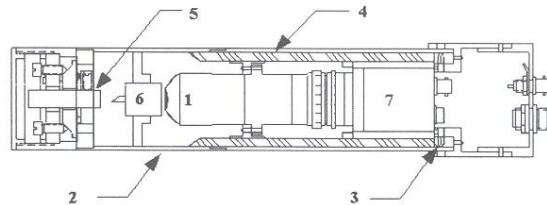


Figure 6. A Panoramic Video System (PVS); 1. PAL, 2. transparent viewing window, 3. incandescent light ring, 4. cylindrical waveguide, 5. laser diode, 6. rotating mirror and motor, and 7. digitizing camera.

light ring {3} and an optical waveguide {4}. Measurement capabilities are provided by projecting structured light into the field of view using a laser diode {5} and a rotating mirror driven by a motor {6}. Panoramic images are acquired with a digitizing camera {7} and stored in a modified image enhancer. The enhancer includes menu driven image processing software to linearize the annular images and make measurements within cavities.

Figure 7, for example, shows a reconstruction of the digital image acquired and stored when the PVS is positioned along the axis of a cylindrical pipe, the interior surface of which is covered with a test pattern. The test pattern contains a different pattern, *i.e.*, diamonds, squares, checkerboard, and concentric circles, in each quadrant of the cavity wall. The image was photographed directly from a VGA monitor; the insert corresponds to a linearized version of the fourth quadrant produced by using digital image processing.

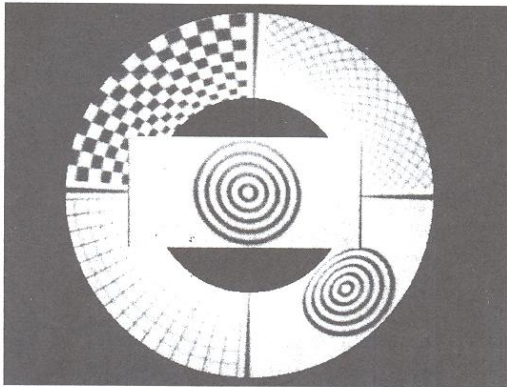


Figure 7. A linearized segment superimposed on a test image acquired using the PVS shown in Fig. 6.

Two stages of linearization are needed: (1) tangential linearization and (2) radial linearization. In the tangential linearization, a wedge-shaped portion of the annular image of the inside of the pipe is converted into a rectangular section. This is accomplished by 'rolling' the annular image along its outer circumference and moving all the pixels between the contact point and the center of the image to an appropriate location on a vertical line in the final rectangular image. Next, because the annular image is not linear in the radial direction, a vertical stretching of the rectangular image is required; this second process is radial linearization (Matthys et al. 1991a).

Ongoing work with the PVS includes identifying and locating internal flaws, measuring the depth of surface cracks, comparing design contours to actual part

contours, performing automated dimensional inspections, and characterizing the geometrical relationships between components in complex assemblies.

Future plans call for incorporating the PAL into television systems designed to inspect sewer lines as part of new construction acceptance programs. These systems will be used to pinpoint and size hairline cracks, locate the position of offset joints, and detect lost aggregate in concrete pipe. They will also be used to troubleshoot collection systems for leaking joints, root intrusion, and protruding taps.

4 AMPLITUDE MEASUREMENT

When measurements are made using structured light, linearization of the annular image may be beneficial. Figure 8, for example, shows the results obtained from a PVS designed 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 interpretation becomes clear when the image is linearized. Figure 9, for example, shows a linearized version of the lower portion of the annular image. The bottom of the trace represents a constant radial distance from the optical axis of the PAL to the wall of the pipe. The shape and dimensions of the inclusions can be easily observed and measured with respect to this baseline using a relatively simple edge finding algorithm. The optical system can be designed so that measurements are based on a linear calibration curve.

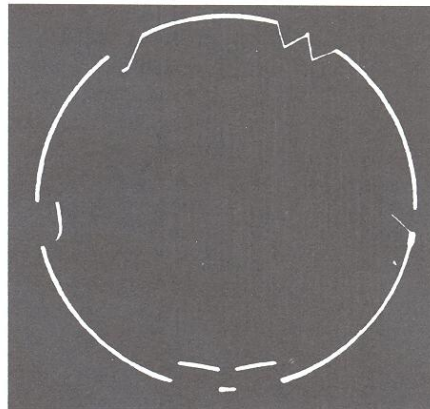


Figure 8. PAL image showing a laser scan over inclusions located on the wall of a cylindrical pipe.



Figure 9. The lower portion of the image shown in Figure 8 is linearized to facilitate optical measurement.

As opposed to using a single line trace, it is possible to record moiré fringes corresponding to displacement fields obtained by combining inscribed or projected gratings (Gilbert et al. 1991). Full-field displacement patterns can also be recorded using the method of speckle photography and digital correlation (Matthys et al. 1991b).

5 PHASE MEASUREMENT

A pair of lenses can be used to make phase measurements. In this case, one PAL is used to illuminate the cavity while the other is used to view the inner wall. Figure 10, for example, shows a setup used to record holographic interferograms. A cylindrical stop was positioned between the panoramic lenses to block stray light from entering the observation lens. Image quality was enhanced by mounting an annular shaped mask on a glass plate located in the image plane of the transfer lens (component 11). The object and reference beams were both vertically polarized to maximize interference at the thermoplastic plate. Data

Translation video capture software was employed to record the holographic information. The filter operations and contrast adjustments provided by the software were used to enhance image quality.

Figure 11, on the other hand, shows a holographic interferogram obtained when a diametral load is applied to a section of pipe.

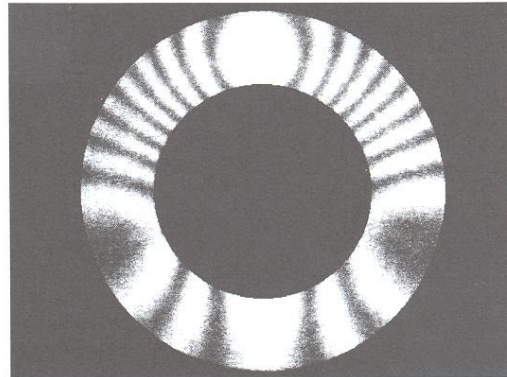


Figure 11. Panoramic holointerferogram obtained by applying a vertical compression to pipe.

The interpretation of this pattern requires the application of standard interferometric analysis techniques such as phase shifting and phase stepping methods, heterodyne holographic interferometry or carrier fringe methods (Matthys et al. 1995). Since the distortions inherent in the PAL image make this process difficult, they must be removed by the linearization procedure described earlier.

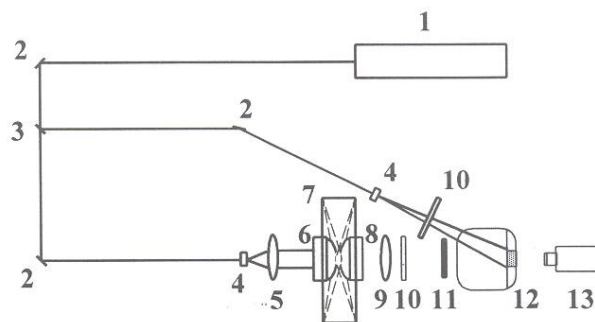


Figure 10. Experimental setup; 1. laser, 2. mirror, 3. beam splitter, 4. spatial filter, 5. collimating lens, 6. illuminating PAL, 7. inlet liner, 8. imaging PAL, 9. transfer lens, 10. polarizer, 11. mask, 12. thermoplastic holocamera, 13. CCD camera.

The same optical setup allows time average holo-interferograms to be recorded (Lindner & Gilbert 1995). Figure 12, for example, shows the modal response of a liner used in a turbopump designed for use in the Space Shuttle Main Engine (SSME).

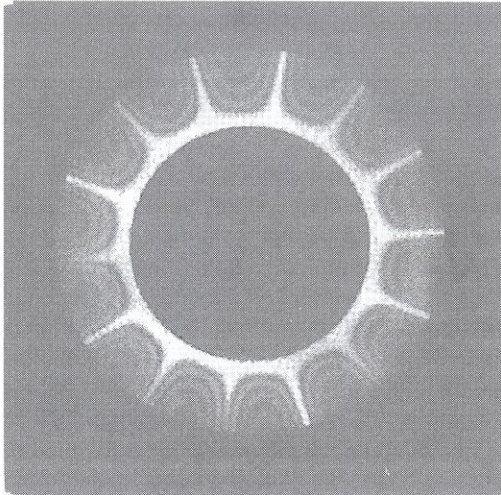


Figure 12. A time average holointerferogram recorded on the inner surface of a turbopump liner.

Electronic speckle pattern interferograms can be captured by making slight modifications in the optical system. This process will be reported in the near future.

6 CONCLUSION

The PAL produces a panoramic image of its surroundings, making it possible to perform a variety of inspection and measurement tasks. PAL systems can be applied to verify the condition of internal components or to predict problem areas and potential failure sites in structural, geomechanical, geotechnical and geo-environmental systems. Commercial applications include pipeline inspection, detection of surface and near-surface cracks in weldments, detection of seams and foldovers in castings, monitoring of wear, detection of structural failures and surface quality inspections.

7 ACKNOWLEDGMENT

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