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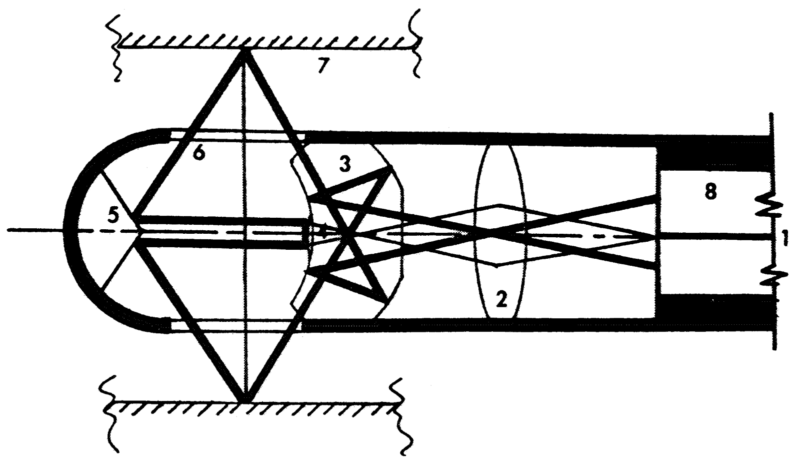
DEVELOPMENT OF AN ENDOSCOPIC PROBE FOR RADIAL METROLOGY



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Propulsion Division

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DEVELOPMENT OF AN ENDOSCOPIC PROBE FOR RADIAL METROLOGY

Grant Number NAG8-686

Period of Performance: September 22, 1987 - October 31, 1988

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The <u>goal</u> of this work was to design and build a prototype for conducting stress analysis and making spectroscopic measurements inside cavities. The <u>objectives</u> of the project were: (1) to develop a prototype for radial profilometry, (2) to explore the possibility of using the radial profilometer for spectroscopic analysis, and (3) to interface the prototype with various combinations of data acquisition and image processing equipment.

Scheduled Research

The following chart outlines the proposed research, and presents a timetable for the entire project.

OUTLINE AND TENTATIVE TIMETABLE FOR THE PROJECT

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DESCRIPTION                          MONTH   0   1   2   3   4   5   6   7   8   9

1. Radial profilometry.

   - design measurement system               ^-------^
   - build prototype                             ^-----------^
   - feasibility tests                                       ^------------------^

2. Spectroscopic analysis.

   - fiber optic delivery                   ^--------^
   - fiber optic collection                     ^----------^
   - fiber optic delivery/collection                       ^-------------^
   - quantify influences of fibers          ^-------------------------------------^
   - evaluate potential for spectroscopic                                ^------^
     analysis using prototype

3. Data acquisition and image processing.

   - upgrade existing system                 ^----------------------^
   - develop algorithms for data
     acquisition and analysis                                ^-------------------^

     FINAL REPORT                                                              ^-^
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1. Introductory Remarks

Grant No. NAG8-686, awarded on September 22, 1987, called for the development of an endoscopic probe to facilitate visual inspection and measurement inside cavities. The probe relied on a novel panoramic doughnut lens (PDL) designed and built by Professor Pal Greguss of the Technical University of Budapest. As shown in Figure 1, the PDL lens produces an annular Flat Cylinder Perspective (FCP) image where the width of the annular image corresponds to the vertical viewing angle; each concentric ring in the image plane is the loci of points recorded at a constant horizontal field angle. The research produced various endoscopic probes, computer algorithms for data acquisition and analysis, and several technical papers and presentations including a first place finish in a technical paper contest by one of the undergraduate students supported under contract. Two other undergraduates and five graduate students were partially supported under Grant No. NAG8-686; all students were U.S. citizens.

2. Contractual Period - No-Cost Extensions

Negotiations for the purchase of the required PDLs began immediately prior to the award of funding in August, 1987. As a result of unexpected delays in securing the lenses, the authors requested (in December, 1987) that the contract deadline be extended from June 21, 1988 to July 31, 1988. This request was subsequently approved on January 20, 1988.

The subcontract for PDLs was approved by the Hungarian government on March 4, 1988, and the lenses were delivered by Dr. Greguss in June, 1988. To adequately complete the proposed research, the authors requested (in July, 1988) a second extension through October 31, 1988. This request was subsequently approved on August 8, 1988.

3. Work Accomplished During the Performance Period (9/22/87 - 10/31/88)

All of the proposed objectives were either met or exceeded. The following sections briefly review the objectives and associated tasks, and are followed by a discussion of the work accomplished during the performance period.

Objective 1: Develop a prototype for radial profilometry.

- Task 1. Design the measurement system, incorporating fiber optics to increase flexibility and to gain optical access to remote test areas.
- Task 2. Build a prototype using the smallest available PDL.
- Task 3. Conduct feasibility tests for profiling. Determine the limits on the range of the system, and demonstrate the sensitivity and accuracy of the technique.

Work conducted prior to the award of the contract described and brought to practice a new device, called a radial profilometer, capable of contouring or measuring deflections on the inner surfaces of cavities [1]. A fiber-based design, shown on the cover page and detailed in Figure 2, led to the construction of an endoscopic probe which used a 40-mm diameter panoramic doughnut lens (PDL) to capture an image of the cavity. A fiber cable and a grin microlens were used to produce structured lighting for measurement purposes, and a coherent bundle of optical fibers allowed PDL images to be transmitted to a computer system for subsequent analysis (Task 1). Efforts to miniaturize the probe led to the development and construction of the 6-mm diameter rigid endoscope shown in Figure 3. This probe relied on a series of field lenses to transmit an image to the observer (Task 2). Cavities were profiled using endoscopic probes and structured light, and some limits were reported on the range, sensitivity and accuracy of the associated measurement systems [2-4] (Task 3). Figure 4, for example, shows a photograph taken from a video monitor of a test pattern drawn on the inside of a cylindrical pipe and recorded through a 40-mm diameter endoscopic probe.

Reference 3 (included as part of the appendix) describes a device, called a radial profilometer, which is capable of contouring or measuring deflections on the inner surfaces of cavities. The main advantages of the profilometer are that it is simple and relatively inexpensive, it can be miniaturized, there are no moving parts, the image is continuously displayed in the image plane, and measurements are completely automated. An analysis is presented which demonstrates that an entire cavity can be profiled simply by moving the profilometer through the cavity. Feasibility tests illustrate that the measurement system can be designed so that profiling measurements are based on a linear calibration curve. Automated analysis is also discussed including the development of computer algorithms for transforming the image for improved human viewing.

As described in Reference 3, the use of a line scan for profiling requires that the profilometer be moved through the cavity to obtain measurements over the original field of view. This procedure limits functional and real-time capabilities. Reference 4 (also included as part of the appendix) describes an alternative method for profiling in which measurements are made by digitally recording and numerically correlating artificial speckle patterns projected onto the walls of a cavity. In this case, the profilometer remains stationary during the measurement. The main advantages of the method are that it can be applied to any surface, it is non-contact and non-destructive, and the analysis can be completely automated. In addition, the method offers the potential to vary measurement sensitivity over a wide range and to access occluded or remote areas by using fiber optic components.

<u>Objective 2</u>: Explore the possibility of using the radial profilometer for spectroscopic analysis.

Task 1. Conduct feasibility tests using a fiber optic for delivery to a sample with conventional method of collection.

Task 2. Conduct feasibility tests using laser illumination and a fiber optic for collection.

Task 3. Conduct feasibility tests using fiber optics for delivery and collection.

Task 4. Quantify influences of fiber optics on spectroscopic analysis, establish required power levels, etc.

Task 5. Evaluate overall potential for conducting spectroscopic analysis using the radial profilometer.

In prior research involving fiber optic sensing of groundwater contaminants, the authors demonstrated that spectroscopic analysis can be conducted using fiber optics [5]. This work was used as background for Tasks 1-3 and led to the development of the many different PDL/fiber optic combinations described below.

A number of tests were conducted on monomode and multimode fibers to quantify effects such as microbending on spectroscopic analysis (Task 4) [6,7]. Results indicated that multimode fibers may be preferable for remote fiber spectroscopy, mainly because of their relatively large core diameters, their linear response to bending, and their ability to transmit light without modal shifts. This finding led to a series of tests conducted to establish the feasibility of manipulating light to and from the PDL using individual multimode fibers. However, this approach had to be abandoned after it was determined that light could not be adequately transferred from the PDL to the fiber. An alternative approach for light manipulation was subsequently devised using an optical fiber bundle consisting of several thousand individual multimode fibers. This required the development of an optical system for coupling the PDL to the fiber bundle.

Figure 5 shows a photograph of a coupler built to collect the spectroscopic signal from a specimen. The lens holder is approximately 1.25" long and, in addition to the PDL, contains three achromatically corrected objective lenses required to focus the PDL image onto the fiber optic imaging bundle. In the device shown, the first lens collects light from a 12mm-diameter PDL and forms a de-magnified virtual image. This image is further de-magnified by a second lens which also forms a virtual image. The latter is focused onto a 4mm-diameter fiber optic imaging bundle by a third lens, such that the image is slightly smaller that the bundle diameter.

Spectroscopic analysis was performed with the PDL/bundle combination using the system shown in Figure 6. Light is delivered to, and collected from, the specimen through the fiber bundle by focusing an 8 watt Argon laser through a 4mm-diameter hole drilled in a front surface mirror. The mirror is located approximately 1.5" from the end of the fiber optic bundle and is oriented so that the return signal, which diverges from the bundle and reflects off the mirror, can be focused and collimated into a SPEX's Triple-Mate monochromator. The signal from this monochromator is analyzed and stored to disk using a personal computer and software (see Objective 3). In addition, the inlet end of the bundle is mounted on a translation stage so that it can be accurately positioned relative to the laser source. This approach permits light to be imaged onto any point within the field of view of the PDL.

The approach used for positioning and focusing the laser at different regions within the field of view works efficiently and accurately; however, during launch, a significant portion of the incident light is scattered from the end of the bundle back into the monochromator. The scattered light acts as broad band and very intense noise as compared to the relatively low level Raman signal obtained from the surface of the specimen. In virtually all tests, the noise due to the scattered light obscured the spectroscopic signal to the point where analysis of the signal was impossible. This problem could not be overcome and the approach had to be abandoned.

One approach that may ultimately solve the scattering problem was recently evaluated by the authors in conjunction with other work performed in the area of fiber optic sensing. In this approach, an individual optical fiber is used to illuminate the surface. This fiber is surrounded by other fibers used to collect and return the signal to the monochromator for analysis. The approach was tested using a 200 micron-diameter fiber for illumination and four, 600 micron-diameter fibers to collect and transmit the return signal. The numerical apertures of the fiber optics are exploited to collect the Raman scattering as shown in Figure 7. Feasibility tests were conducted on roughened silver surfaces using an aqueous mixture of pyridine and water. Pyridine was selected because it produces an intense Raman signal and has been well characterized by other researchers. Results indicated that surface enhanced Raman spectroscopy (SERS) performed through optical fibers can be used identify pyridine at concentrations below 10 ppm.

As mentioned above, this approach could be applied to obtain spectroscopic information from the PDL as a portion of future research. To apply this technique, a fiber optic bundle would have to be purchased or specially fabricated. An illuminating fiber, located at the center of the bundle, would be coupled directly to the laser. This fiber would be focused through the central portion of the PDL to a beam steering device positioned in front of the lens. This device would direct the incoming laser excitation to illuminate the surface. The image from the PDL, containing spectroscopic information scattered from the surface, would be focused into the fiber optic bundle surrounding the illuminating fiber.

Additional tests were performed, without using fiber optics, to evaluate the potential for spectroscopic recording using the PDL (Task 5). In these tests, a laser was focused directly onto a target positioned within the field of view the lens. The endoscope-like device shown in Figure 8 was constructed to adapt the lens directly to the inlet port of a SPEX'S 1877B scanning Triple-Mate monochromator. The 16" long, 5/8" diameter PDL adapter includes two additional focusing lenses.

Feasibility tests were conducted to simulate spectroscopic analysis within a cavity. "AN" fittings made of stainless steel and aluminum were used to construct cylindrical test specimens by coupling stainless steel, aluminum, and copper tubing. As shown in Figure 9, each specimen was machined to remove one quarter of its circumference so that a laser could be directed to a region in front of the PDL. In this case, the tubing at the left was machined from copper while the AN fitting and tubing at the right were made of stainless steel.

The fitting, with tubing installed, was attached to a linear translation stage using nylon strapping bands, as shown in Figure 8. This enabled the specimen to be moved relative to the PDL adapter; thereby, simulating movement of an endoscope through a cavity. The laser was beam steered and focused on the interior wall of the fitting at the location indicated by the arrow. Scattered radiation was collected from this surface by the PDL, partially focused by the other lenses in the probe, analyzed by the spectrometer, and stored by the computer for additional signal processing.

Figure 10 shows preliminary results taken through the PDL when the surface of the copper tube was cleaned and doped with ortho-toluidine. Laser excitation of 488nm was used, and spectral information was collected over 493 to 510 nanometers using a Sperry PC and a Metrabyte DASH-16 data acquisition board. Software developed during the project was used to analyze the data and to instruct the SPEX's CD2A compudrive monochromator positioner via RS232 serial communications. A total of 5106 data points were collected and stored to disk. These data were later retrieved, manipulated, and graphed using ASYST software on a Zenith PC. The results show a large improvement in the signal to noise ratio when compared to analyses conducted with devices constructed during the early stages of the project. In general, the spectral lines are in the proper location for ortho-toluidine; however, peak resolution and signal to noise ratio could be enhanced by making further refinements in the PDL recording system.

<u>Objective 3</u>: Interface the prototype with various combinations of data acquisition and image processing equipment.

Task 1. Upgrade existing photoelectronic/numerical system.

Task 2. Develop algorithms for data acquisition and analysis from the radial profilometer.

The LSI 11/23 proposed to acquire and analyze data from the endoscopic probe was upgraded to an LSI 11/73. This task involved reconfiguring the kernal of the operating system and installing new device drivers and devices under VENIX. A General Electric CID camera, a Poynting camera control unit, and a DMA interface board were added to allow acquisition and playback of images obtained from the endoscopic probe. The camera system captures an image using a 256x256 pixel array and 256 gray levels. Extensive work had to be performed to write the driver for the DMA board and the interface program for the camera control unit. These efforts, conducted with help from Professor Donald R. Matthys of Marquette University, resulted in several thousand lines of computer code written in 'C' programming language.

Algorithms were also developed for acquisition and analysis of images recorded through a PDL. As mentioned previously, the PDL lens produces an annular Flat Cylinder Perspective (FCP) image where the width of the annular image corresponds to the vertical viewing angle; each concentric ring in the image plane is the loci of points recorded at a constant horizontal field angle. With the help of Professor Matthys, computer programs were written in 'C' to allow a user to segment and transform an FCP image so that a more conventional view can be obtained. For example, Figure 11 shows a composite photograph taken from a video monitor. In this case, a laser was used to scan inclusions placed on the inner wall of a pipe. The lower portion of the figure shows the image recorded directly through the probe, while the upper portion shows the transformed image. The size of the inclusions can be determined from the shift in the laser scan [2-4]. Other computer algorithms were developed to numerically correlate subsets extracted from FCP images.

For fiber-based spectroscopic analysis, baselines associated with the fiber optic selected, electronic noise from the monochromator (dark current), and the baseline of the clean sample surface have to be recorded and manipulated. Consequently, it was necessary to develop a new software package for acquisition and real time analysis of spectroscopic data taken through fiber optic systems. The required software package was written by Thomas Bond (a graduate student who worked on the project) and contains in excess of 3000 lines of code written in 'BASIC' programming language. The computer code not only allows a relatively low level Raman signal to be analyzed by manipulating up to three base lines, thereby removing background interferences, but accurately positions the monochromator during the analysis.

4. Bibliography

1. Gilbert, J.A., Greguss, P., Lehner, D.L., Lindner, J.L.,"Radial profilometry," Proc. of the Joint BSSM/SEM International Conference on Advanced Strain Measurement Techniques, London, England, August 24-27, 1987, Whittles Publishing, pp. 97-107.

2. Lindner, J.L., "Radial metrology," Presented at the ASCE Southeast Regional Student Conference, Vanderbilt University, Nashville, TN, April 8, 1988. Mr. Lindner's paper and technical presentation resulted in a first place finish in the technical paper competition.

3. Greguss, P., Gilbert, J.A., Matthys, D.R., Lehner, D.L., "Developments in radial metrology," Proc. of SPIE's International Symposium on Optical Engineering and Industrial Sensing for Advanced Manufacturing Technologies," Dearborn, Michigan, June 25-30, 1988.

4. Gilbert, J.A., Greguss, P., "Recent developments in radial metrology: a computer-based optical method for profiling cavities," Proc. of Optika '88, Third Int. Symp. on Modern Optics, Budapest, Hungary, September 13-16, 1988.

5. Smith, J.E., Bond, T.M., Gilbert, J.A., Leonard, K.M., "A remote fiber optic ground water monitoring system based on surface enhanced Raman spectroscopy," Second National Outdoor Action and Aquifer Restoration Conference, Las Vegas, Nevada, May 23-26, 1988, pp. 3-16.

6. Leonard, K.M., Smith, J.E., Gilbert, J.A., "Characterization of bending losses in optical fibers," Presented at the Sigma Xi Research Day, University of Alabama in Huntsville, Huntsville, Alabama, March 5, 1988.

7. Smith, J.E., Bond, T.M., Gilbert, J.A., Leonard, K.M., "Fiber optic characterizations and applications of SERS for in-situ monitoring," Proc. of the Department of Energy In-Situ Characterization and Monitoring Technologies Workshop, DOE/HWP-62, June, 1988, pp. 278-298.

5. Scientific Collaborators (Alphabetical Order)

The students listed below are all U.S. Citizens and were partially or fully funded under NASA Grant Number NAG8-686. All research was conducted under the direct supervision of the principal investigators.

Name: Bond, T.M.
Remarks: Mr. Bond worked with Professor Smith in the capacity of graduate research assistant and recently graduated with his M.S. degree in chemical engineering.

Name: Lehner, D.L.
Remarks: Mr. Lehner worked with the Professor Gilbert in the capacity of graduate research assistant and is currently working on his Ph.D. in applied optics at the University of Alabama in Huntsville.

Name: Leonard, K.M.
Remarks: Ms. Leonard worked with Professor Smith in the capacity of graduate research assistant and is currently working on her Ph.D. in environmental engineering at the University of Alabama in Huntsville.

Name: Lindner, J.L.
Remarks: Mr. Lindner worked with Professor Gilbert as an undergraduate research assistant. He is currently a senior in mechanical engineering at the University of Alabama in Huntsville.

Name: Peters, B.R.
Remarks: Mr. Peters worked with Professor Gilbert in the capacity of graduate research assistant and is currently working on his Ph.D. in applied optics at the University of Alabama in Huntsville.

Name: Petersen, M.E.
Remarks: Mr. Petersen worked with Professor Gilbert as an undergraduate research assistant. He is currently a senior in mechanical engineering at the University of Alabama in Huntsville.

Name: Wingo, D.
Remarks: Mr. Wingo worked with Professor Gilbert as an undergraduate research assistant. He is currently a freshman taking engineering at the University of Alabama in Huntsville.

Note: P. Greguss is the Director of the Applied Biophysics Laboratory at the Technical University of Budapest in Budapest, Hungary.

Note: D.R. Matthys is an Associate Professor of Physics at Marquette University in Milwaukee, Wisconsin.

6. Conclusions and Future Research

The potential for recording spectroscopic information through a PDL lens system has been clearly established, and several apparatuses have been constructed in an effort to perform chemical analysis on internal surfaces using optical fibers. Even though the fiber-based tests met with limited success, they produced interesting results which can be used as background for future work. One possible approach would make use of a special fiber optic bundle consisting of a central fiber for illuminating the specimen surrounded by several fibers to collect the spectroscopic signal.

In addition to this spectroscopic work, the authors have clearly demonstrated the feasibility for making measurements using radial metrology and, with international cooperation, have designed and built a 6-mm diameter probe for inspection within cavities. Future plans include further miniaturization of the PDL probe, the design and construction of alternative configurations for radial metrology, the use of more sophisticated computer hardware to shorten the time required for data acquisition and analysis, and the development of improved numerical algorithms and computer software to automatically extract quantitative measurements from the acquired images. After developing these tools, the authors expect to produce a three-dimensional, full-field computer vision system for routine inspection and analysis within cavities.

7. Acknowledgments

This research would not have been possible without the cooperation and technical expertise of Professor Pal Greguss of the Technical University in Budapest and Professor Donald Matthys of Marquette University. It was a pleasure to work with such talented individuals; their contributions were incorporated into a significant portion of the work described in this report. Special thanks are extended to Jonathan Campbell and Steve Richards of MSFC/NASA for their help in initiating and administering the project, respectively.

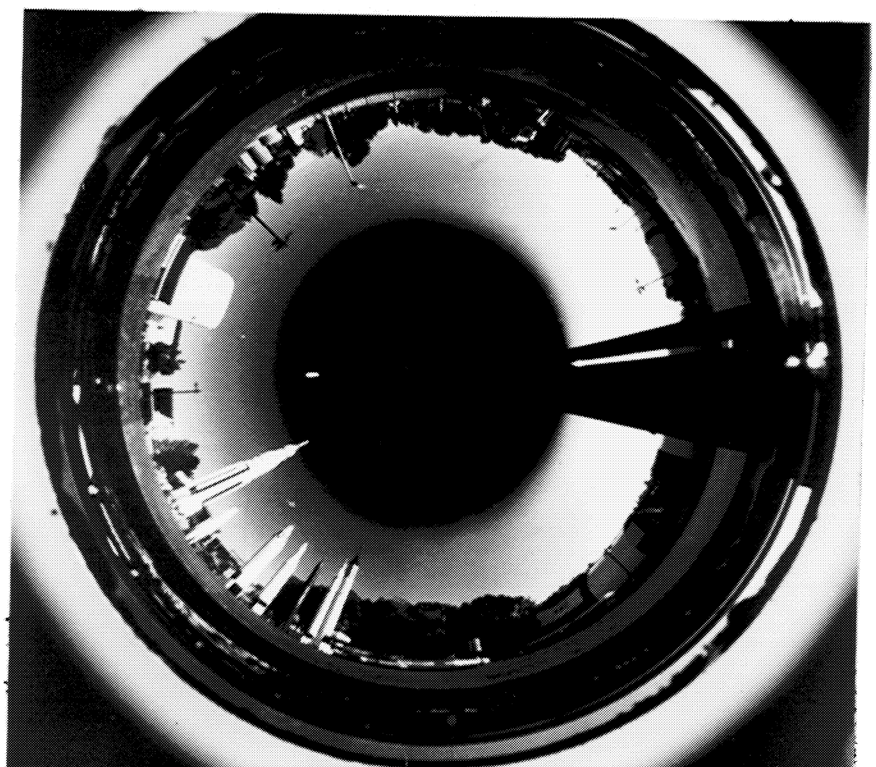
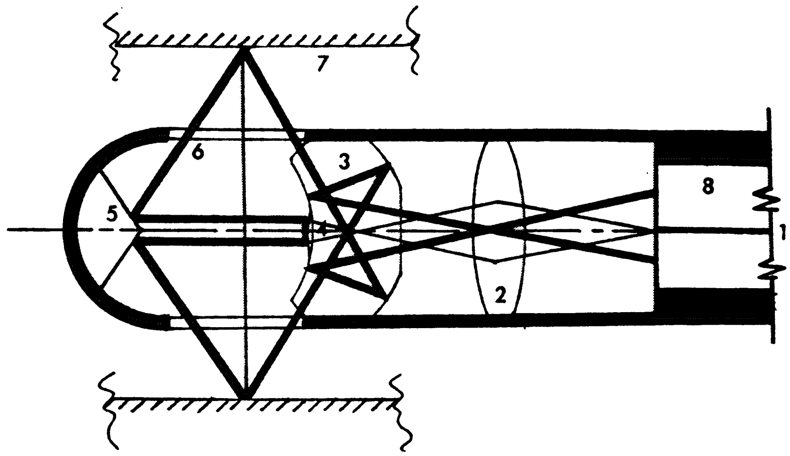


Figure 1. A full cylindrical perspective (FCP) image obtained using a panoramic doughnut lens (PDL). The photograph was taken in the Huntsville Alabama's Space and Rocket Center and was recorded by pointing the camera toward the sky.



1. ILLUMINATING FIBER FROM LASER
2. PROJECTION LENS
3. PANORAMIC DOUGHNUT LENS
4. COLLIMATING LENS WITH MASK
5. CONICAL MIRROR
6. TRANSPARENT WINDOW
7. TEST OBJECT
8. IMAGE BUNDLE TO COMPUTER

Figure 2. One of the optical configurations evaluated for radial metrology. In this example, a device called a radial profilometer is shown inserted into a cylindrical cavity. A diverging laser beam (shown launched from a fiber optic labeled (1)) is directed through a projection lens (2). The beam passes through a panoramic doughnut lens (3) and is collimated and shaped by an appropriately masked collimating lens (4) to produce a thin ring. The ring reflects off a conical 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 panoramic doughnut lens (3) and is projected by the projection lens (2) onto a coherent optical fiber bundle (8). The bundle transmits the image from the device to a computer system where changes in the image can be recorded and analyzed using digital acquisition and processing techniques.

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Figure 3. Photograph of a 6-mm diameter PDL endoscopic probe. The FCP image is transmitted to the observer by a series of field lenses; the cavity is illuminated using laser light scattered from an optical fiber wrapped tightly around the probe.

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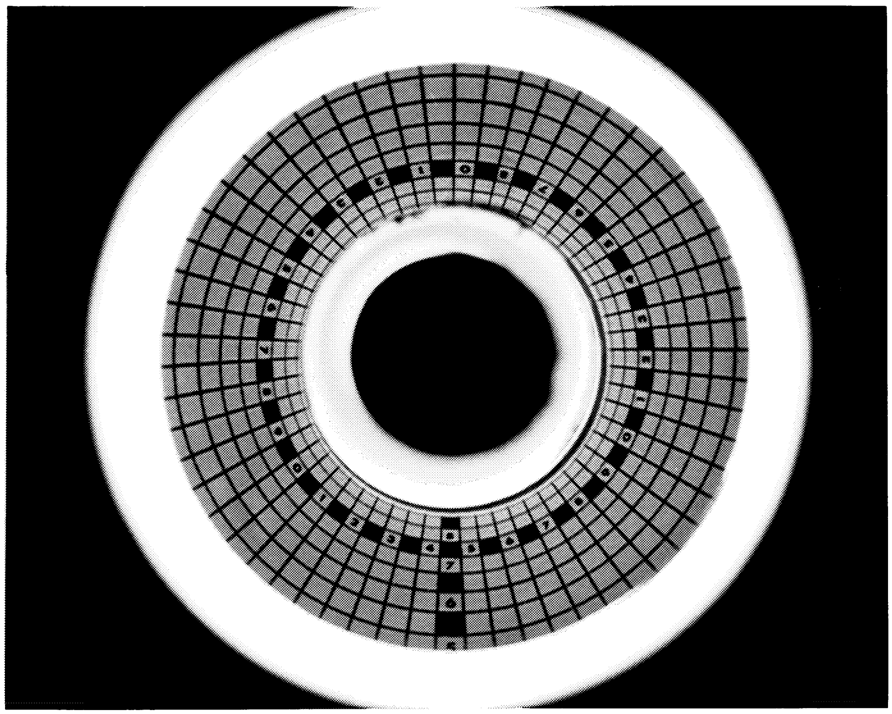

Figure 4. Square-grid test pattern on the inside wall of a pipe recorded using a 40-mm diameter PDL endoscopic probe.

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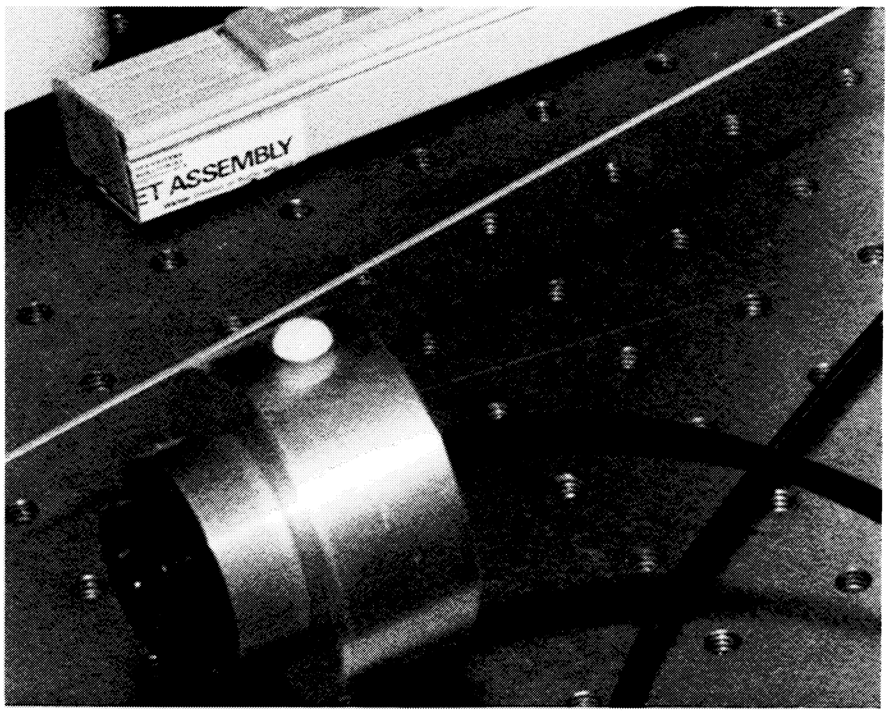

Figure 5. A photograph of the prototype coupler designed to collect spectroscopic information and focus it onto the 4mm-diameter bundle shown.

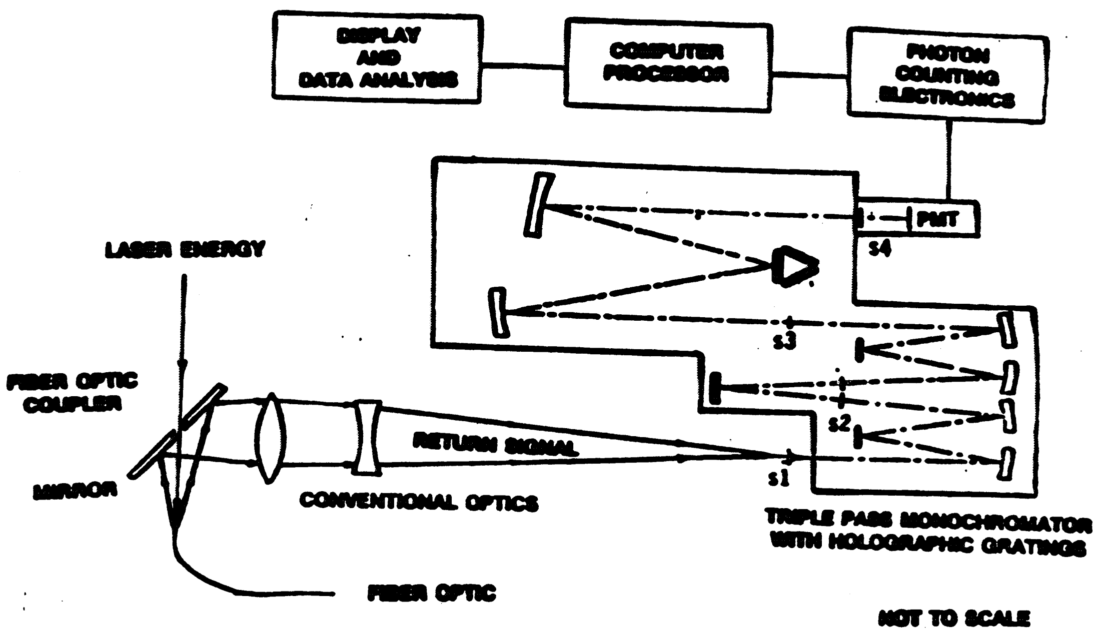

Figure 6. Experimental apparatus showing the mirror with small aperture which allowed the laser to focus on the fiber optic bundle. Light returning from the PDL over the fiber optic bundle is directed, using additional optics, to the spectroscopic analysis equipment.

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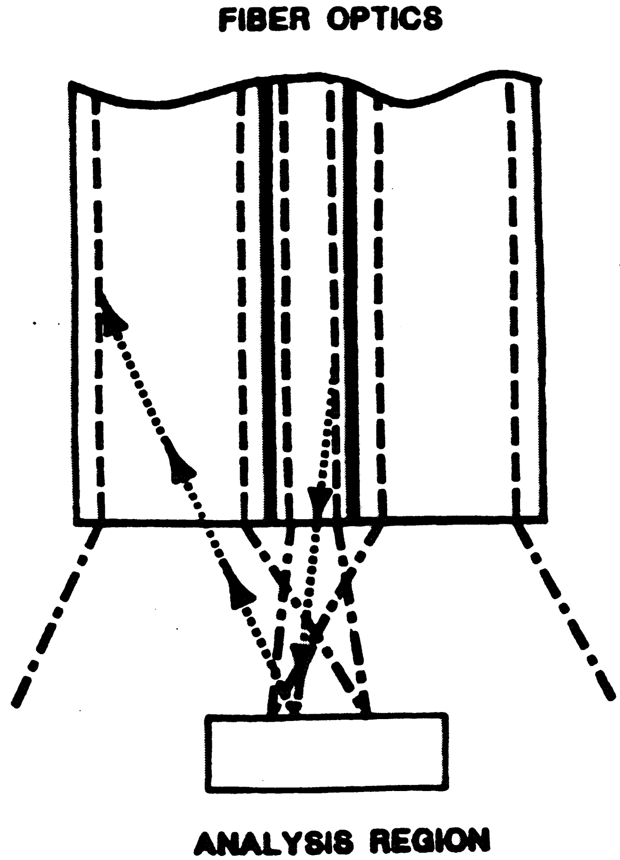

Figure 7. A method to exploit the numerical apertures of different diameter fiber optics in a bundle. Here a fiber with a relatively small core and small numerical aperture illuminates the target (analysis region). Scattered light is collected by the larger core fiber optics which have greater numerical apertures.

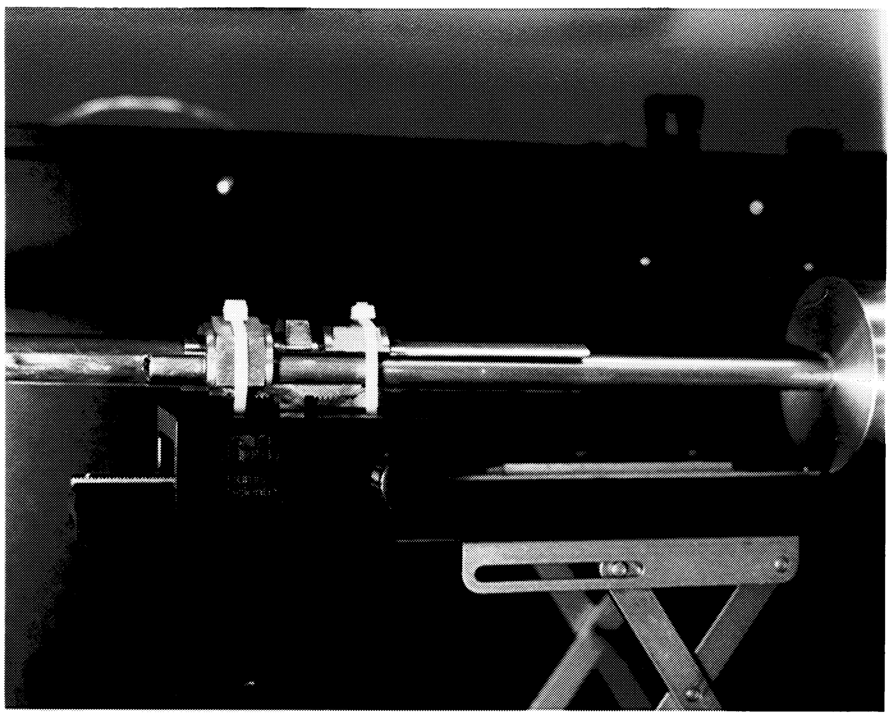

Figure 8. A photograph of the endoscopic-like device constructed to adapt the PDL directly to the spectrometer inlet port. The translation stage and specially machined fitting are also shown. The arrow in the figure indicates the location of the laser excitation.

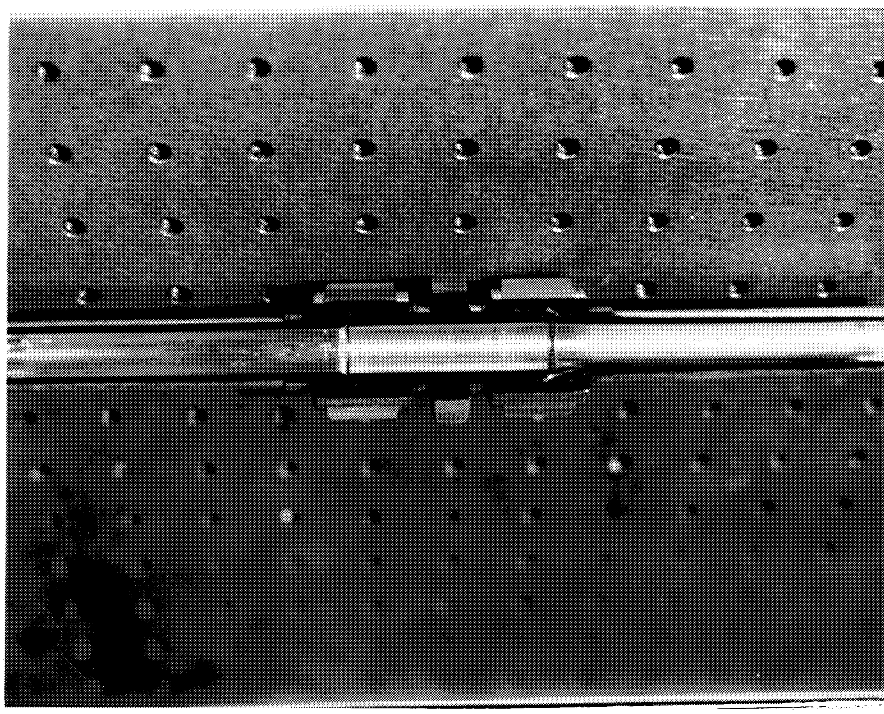

Figure 9. A photograph of the AN fitting-tubing assembly showing the 90° access port required to illuminate the inner surface of the tubing.

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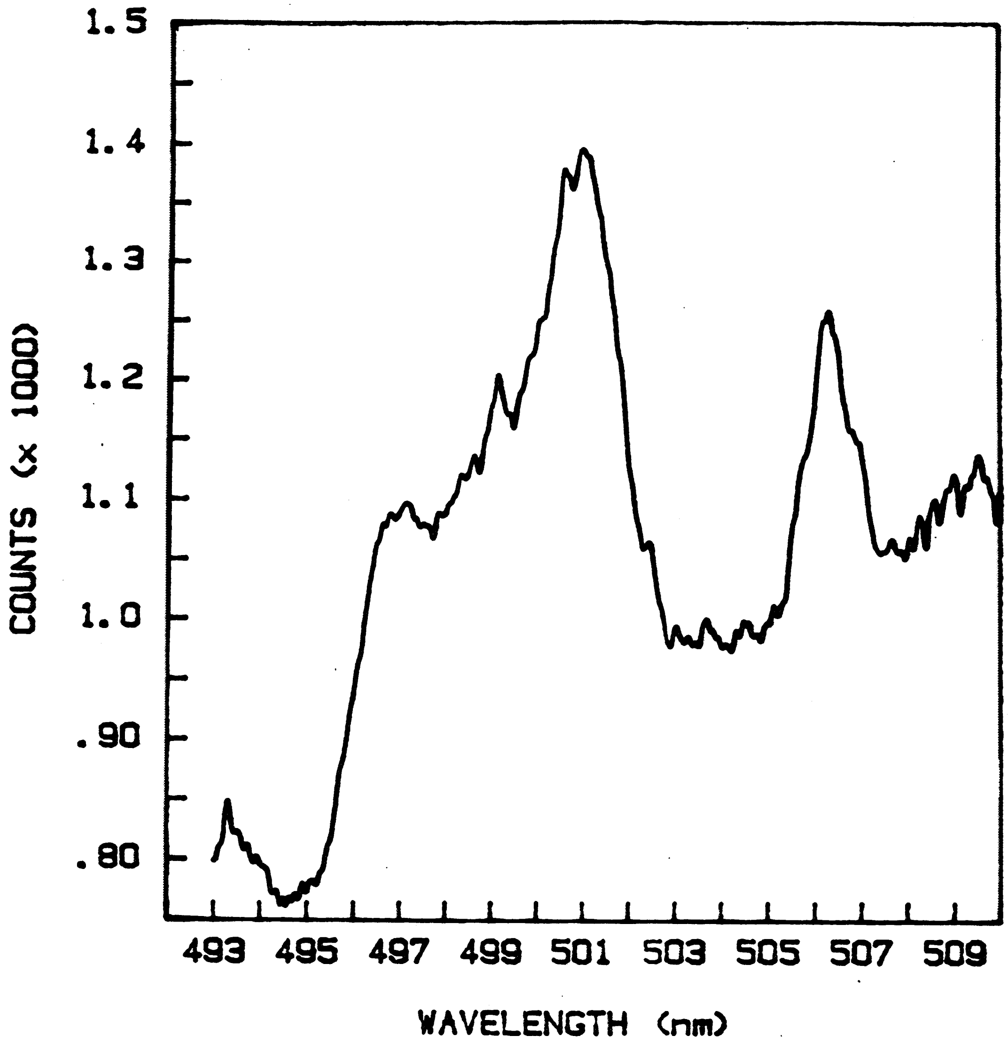

Figure 10. Spectroscopic results for ortho-toluidine dispersed on a roughened copper surface.

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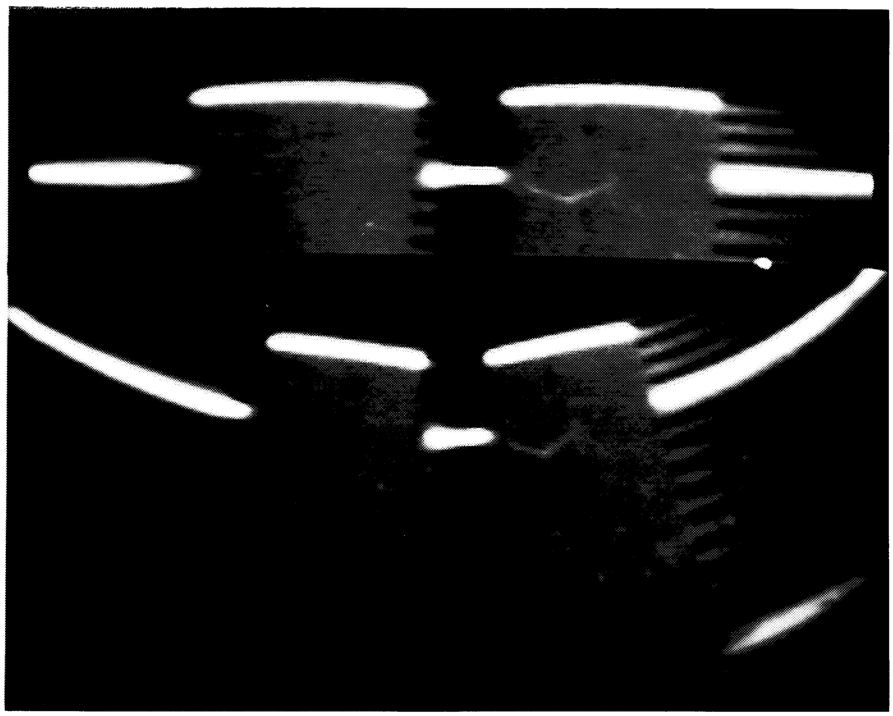

Figure 11. Photograph of a laser scan across inclusions inside a pipe. The lower portion of the figure shows the image recorded using a 40-mm diameter endoscopic probe; the upper portion of the figure shows that the image can be transformed using computer algorithms to obtain a more conventional view.

APPENDIX

Greguss, P., Gilbert, J.A., Matthys, D.R., Lehner, D.L., "Developments in radial metrology," Proc. of SPIE's International Symposium on Optical Engineering and Industrial Sensing for Advanced Manufacturing Technologies," Dearborn, Michigan, June 25-30, 1988.

Gilbert, J.A., Greguss, P., "Recent developments in radial metrology: a computer-based optical method for profiling cavities," Proc. of Optika '88, Third Int. Symp. on Modern Optics, Budapest, Hungary, September 13-16, 1988.

Developments in radial metrology

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ABSTRACT

Radial metrology combines an optical measurement technique with fiber optics and a unique lens system to study material properties and deformations on the inner surfaces of the cavities found, for example, inside pipes, tubes, and boreholes. The equations considered in designing and testing a prototype for profiling are described along with tests conducted to demonstrate proof of principle. Digital image acquisition and processing techniques are used to interpret various features appearing in the images and to transform images for improved human viewing.

1. INTRODUCTION

In a recent paper[1], some of the authors introduced a technique to make optical measurements within cavities. The measurement system included a panoramic doughnut lens (PDL) which produces an annular Flat Cylinder Perspective (FCP) image[2,3]. The PDL has been used to make holo-interferometric and speckle photographic recordings[4] and, when combined with appropriately structured illumination, can be used for profiling.

Profiling measurements are important in many areas. For example, the infiltration and inflow of ground water into sewer lines and maintenance of collection systems present major problems to a civil engineer. These problems have led to the development of pipeline television systems which are used to inspect sewer lines as part of new construction acceptance programs, or to trouble shoot a collection system for leaking joints, root intrusion, and protruding taps. Radial metrology, as proposed in this paper, enhances visual inspection and will allow a variety of measurements to be performed including the location and size of hairline cracks, the position of offset joints, and the detection of lost aggregate in concrete pipe. Other important engineering applications involve 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. Radial metrology can also be used to identify parts outside of set tolerances, and could potentially be used in biomedical applications to contour internal organs and arteries.

Many other techniques including photogrammetry[5,6], shadow moire[7-9], and projection speckle methods[10-12], have been applied for profiling, and some of these techniques have been combined with computer methods[6,8,9,11,12] to produce machine vision systems capable of acquiring one or more images of an object by an optical noncontact sensing device. In these machine vision systems, various characteristics of the acquired images are studied to measure deflections or predict the surface contour.

The profiling techniques described above have been applied mainly to study the outer surfaces of structural components. In general, the associated measuring system relies on a large number of optical and electronic components, many of which are difficult to miniaturize. Although optical fibers offer potential for miniaturization and could be incorporated into such systems to profile remote surfaces[13], fiber-based systems (as well as the more conventional non-fiber-based systems) suffer from a limited field of view. This presents a problem, for example, when profiling the inner wall of a pipe. In this case, the imaging device would have to be translated along, and rotated around, the optical axis of the device to examine all points on the inner surface of the pipe; constraints which severely limit functional and real-time capabilities.

Ideally, a device for profiling the inner surface of a cavity should be rugged, compact, and capable of obtaining an unobstructed, complete, and comprehensive image of the cavity space in every direction. Unfortunately, it is virtually impossible to develop a practical device capable of recording a sphere of vision. However, most cavities can be regarded as cylindrical rather than spherical volumes, and information can be transformed, using stretching methods, onto a flat surface creating a 2-D representation of the 3-D cylindrical surface. This transformation, called Flat Cylinder Perspective (FCP), can be performed optically using a panoramic doughnut lens[2]. Figure 1, for example, shows a photograph taken in a courtyard with the lens pointed toward the sky. The width of the annular FCP image corresponds to the vertical viewing angle, and each concentric ring in the image plane is the loci of points recorded at a constant horizontal field angle. Furthermore, the central portion of the lens can be completely removed, since it is not used to form the image.

The PDL and its unique properties lend themselves to use in radial metrology. Figure 2 is a schematic of one of many optical configurations currently being evaluated for profiling. The device, called a radial profilometer, is shown inserted into a cylindrical cavity. A diverging laser beam (shown launched from a fiber optic labeled (1)) is directed through a projection lens (2). The beam passes through a panoramic doughnut lens (3) and is collimated and shaped by an appropriately masked collimating lens (4) to produce a thin ring. The ring reflects off a conical 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 panoramic doughnut lens (3) and is projected by the projection lens (2) onto a coherent optical fiber bundle (8). The bundle transmits the image from the device to a computer system where changes in the image can be recorded and analyzed using digital acquisition and processing techniques.

The following section describes the measurement technique associated with the radial profilometer. This discussion is followed by a description of the calibration procedure and feasibility tests conducted to illustrate proof of principle. Digital image acquisition and processing techniques are also described. These techniques are used to correct for image distortion, and to interpret various features appearing in the images.

2. ANALYSIS

Figure 3 defines the cartesian and cylindrical coordinate systems used for subsequent analysis. In both systems, the optical axis of the profilometer lies along the z-direction; point S corresponds to the point of intersection formed by tracing the ray reflected from the conical mirror back to the optical axis of the profilometer (see Figure 2). Light is projected to point P at an angle α, and the image of the illuminated surface is captured at an angle β, measured with respect to a radial line lying in the r-z plane. When the surface moves normal to the optical axis, the projected image appears to shift along the z-direction through a displacement w. The corresponding radial displacement r is given by

$$r = \frac{w}{\tan[90 - \alpha] + \tan\beta} \qquad (1)$$

The relationship between r and w is nonlinear, since β varies from point to point.

The displacement along the z-direction is mapped into the image plane by the panoramic doughnut lens via a mapping function, f, as follows

$$r' = f[w] \qquad (2)$$

This function takes into account the magnification factor, and includes the FCP stretching methods used to create a 2-D representation of the 3-D cylindrical surface. Ideally, one would like to design a radial profilometer so that the nonlinear effects inherent in Equations (1) and (2) compensate one another over as large a range as possible such that,

$$r' = Cr + b \qquad (3)$$

where C and b are constants.

By measuring r' and knowing C and b, Equation (3) can be solved for r. Once r is established for a known value of θ, the z-coordinate of the illuminated point can be calculated using

$$z = \frac{r}{\sin\alpha} \qquad (4)$$

Therefore, one procedure for profiling a cavity is to initially establish a fixed global axis system in space with its z-axis aligned with that of the local system shown in Figure 3, and then to move the profilometer along the z-direction. The coordinates for r and θ are the same for the local and global systems; z-coordinates in the global system are calculated by taking into account the relative position of the local system.

3. EXPERIMENTAL

Figure 4 shows a cross-sectional view of a device built to illustrate a calibration procedure and to demonstrate proof of principle of the measurement system described above. An unexpanded beam produced by a laser (1) passes through a 90 degree prism (2) (mounted on a transparent glass plate (4)) and reflects off a rotating front surface mirror (3). The laser beam reflects off the mirror, passes through the glass plate (4), and illuminates the interior wall of a cavity (5). The figure shows a pipe being tested with its longitudinal axis positioned symmetrically with respect to the optical axis of the profilometer. In this case, the laser traces out a circular ring on the inside wall of the pipe. The image of the illuminated surface is captured by the panoramic doughnut lens (6), and is projected by the projection lens (7) onto the image plane of a conventional 35mm camera (8).

The device was designed and built to satisfy the condition in Equation (3), and was tested as shown in Figure 4 by inserting it into a circular pipe with an inner radius, R, equal to 2.25" (57.2 mm). The optical axis of the device was positioned parallel to the longitudinal axis of the pipe; the coordinate system shown in Figure 3 was used for analysis.

Figure 5 shows the image photographed when the radial profilometer is positioned at the center of the pipe. The relatively thick circle is the laser trace; thin equispaced lines were drawn on the interior surface of the pipe to visually illustrate the nonlinear mapping inherent in Equation (2).

Figure 6 was recorded after the pipe was translated along the x-direction through a displacement, u, of 0.35" (8.9 mm). Radial lines, drawn every five degrees, were superimposed on the photograph to aid in calibrating the profilometer. With θ measured from x,

$$r = \left[u^2 + R^2 + 2uR \cos(\theta + \gamma) \right]^{1/2} \quad (5)$$

where R is the inner radius of the pipe, and $\gamma = \sin^{-1}[(u \sin\theta)/R]$.

Equation (5) can be derived using simple geometry, and defines the radial distance between the pipe and the optical axis of the profilometer for any angle θ. More importantly, the equation holds for any z-coordinate, since the optical axis of the device remains parallel to the longitudinal axis of the pipe and the cross section of the pipe is constant. This makes the translated pipe ideal for calibrating the profilometer, since r' can be measured on Figure 6.

Figure 7 shows the calibration curve established by plotting r [calculated on the basis of Equation (5)] versus r' [measured along the radial lines superimposed on Figure (6)] for points taken at five degree increments as θ ranged from 0 to 360 degrees. The curve holds over a 0.70" (17.8 mm) range where the value of r lies between 1.9" (48.26 mm) and 2.6" (66.04 mm). In this range, the response is linear and governed by Equation (3) with C equal to 2.06. A value of b = -0.71" (-18 mm) is established by interpolating the curve back to r = 0. No physical interpretation can be associated with this value of b (r' at r = 0), since the central portion of the PDL contains no image. It is simply one of the parameters required in Equation (3) to evaluate r within the calibrated range.

Figure 8 clearly indicates that the profilometer can be used to visually detect inclusions of constant cross section located on the inner wall of a pipe. The ring shown in the figure was created using a rotating mirror but could have been produced as depicted in Figure 2, or formed by diffracting light through a transparency containing closely spaced concentric circles. In any case, the laser trace maps out shapes in the image plane which are "similar" to those of the inclusions. Each shape is reduced (or magnified) in size as defined by the constant, C, in Equation (3).

To be useful for internal inspection of long cylindrical cavities, a radial profilometer must be small enough to pass through the cavity, and must include a means for relaying data to a remote location. Figure 9 shows the image of a square test pattern (drawn on the inside wall of a cylindrical pipe) recorded using an optical configuration similar to that shown in Figure 2. The 4mm diameter coherent bundle used to record the image consists of several thousand individual 12 micron diameter fibers and has a resolution capability of approximately 27 line pairs per millimeter. The resolution and contrast of the image is relatively poor, since the photograph was recorded from a television monitor.

When a cavity is relatively large (several centimeters in diameter), the PDL imaging system can be fixed directly to a small vidicon, CCD, or CID camera. In this case, visual information may by relayed through coaxial cables to a remote monitoring system.

4. DISCUSSION

Direct visual interpretation of a PDL image is often difficult for the unskilled observer. With this in mind, an algorithm was developed to allow the doughnut shaped images to be linearized for viewing and measuring purposes. It must be recognized that there is no way to present a non-rectangular image in a rectilinear format without distortion. This is essentially the same problem as making a flat map of a round globe. However, the type of distortion introduced can be chosen and controlled by the choice of mapping scheme that is used (equal maximal dimensions, equal areas, etc.). The mapping used here maintains equal maximal dimensions by 'rolling' the annular image along its outer circumference and moving all the pixels between the contact point and the center of the iamge to a vertical line in the final rectangular image.

The first step in linearizing the images obtained from the panoramic doughnut lens is to specify the desired region of the annular image that is to be straightened. This is done by entering four (x,y) locations into the computer. The first two points should be on the outer circumference of the image and specify the end points of the region of interest. The third point must be on the same circumference and allows the computer to calculate the radius appropriate to the image being examined and also specifies which of the two possible segments between the first two points is desired. The last point is chosen anywhere along the inner circumference and allows the machine to determine the image height. The machine now knows the entire segment that is desired and can proceed to straighten it out.

First the center location of the annulus is calculated (this center point need not be in the portion of the image which is stored in the computer), and then the height and width of the output rectangular image are determined in units of pixels. The width will be equal to the length of the outer circumference of the selected segment, and the height will be the difference between the inner and outer radii of the annular image.

A sampling factor is selected which determines the spacing of radial lines along which samples will be taken. This same sampling factor is used to determine the separation between samples along each radial line. Starting from one end of the chosen segment, the polar coordinates of each sample along a radial line are mapped to corresponding (x,y) coordinates in the original image. The intensities of the samples calculated along each radial line are assigned to a column in the final image. Figure 10 illustrates how samples (shown as o's) in the annular image are mapped into a rectangular array. After each radial line is finished, the radial angle is incremented, and the process is repeated until the other end of the specified image is reached. If the sampling density is such that the number of converted values is larger than the array size of the final image, the values that are associated with a particular output pixel location are averaged. The example shown in the figure takes samples spaced half a pixel apart, so four values are averaged to determine the value of each pixel in the final image. Figures 11 and 12 show the results of applying the algorithms described above to portions of the images shown in Figures 1 and 8, respectively. The resolution and contrast of the images are relatively poor, since both photographs were recorded from a television monitor. The lower portion of the trace shown in Figure 8 represents the constant radial distance from the optical axis of the profilometer to the wall of the pipe. The shape and dimensions of the inclusions can be easily observed and measured with respect to this baseline.

5. CONCLUSIONS AND FUTURE RESEARCH

A new device, called a radial profilometer, has been described which is capable of contouring or measuring deflections on the inner surfaces of cavities. The main advantages of this device are that it is simple and relatively inexpensive, it can be miniaturized, there are no moving parts, the image is continuously displayed in the image plane, and measurements are completely automated.

An analysis was presented which demonstrates that an entire cavity can be profiled simply by moving the profilometer through the cavity. Feasibility tests have illustrated that the measurement system can be designed so that profiling measurements are based on a linear calibration curve. Automated analysis was discussed including the development of computer algorithms for transforming the image for improved human viewing.

Future publications will discuss the advantages and disadvantages of various configurations proposed for radial metrology. The range and accuracy for each configuration will be presented, along with appropriate discussions of the numerical algorithms and computer software used to automatically extract quantitative measurements from the acquired images. After developing these tools, the authors expect to produce a three-dimensional, full-field computer vision system which will automatically draw an isometric view of the cavity under study by recognizing and combining various features of several images taken through a radial profilometer.

6. ACKNOWLEDGEMENTS

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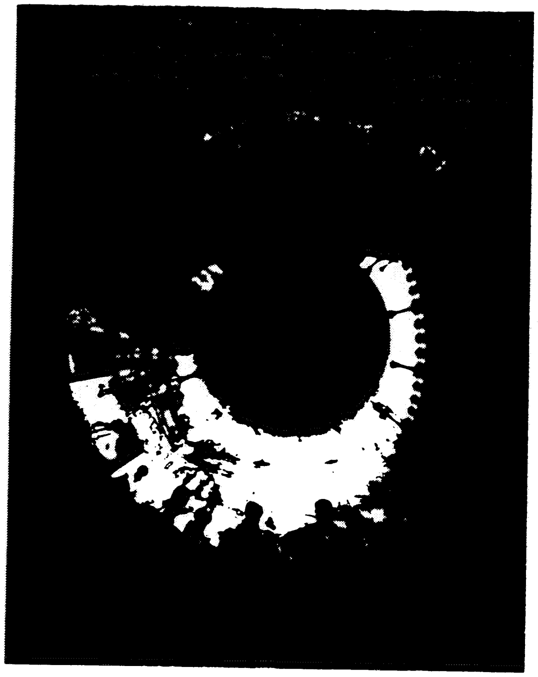

Figure 1. Photograph of a courtyard taken through a panoramic doughnut lens (PDL) imaging system.

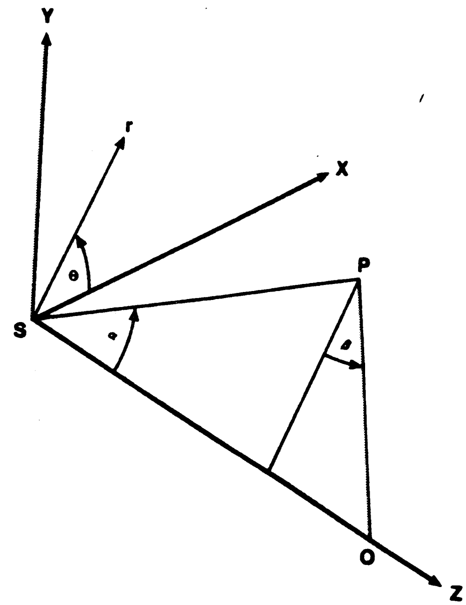

Figure 3. Coordinate axes systems used in the analysis.

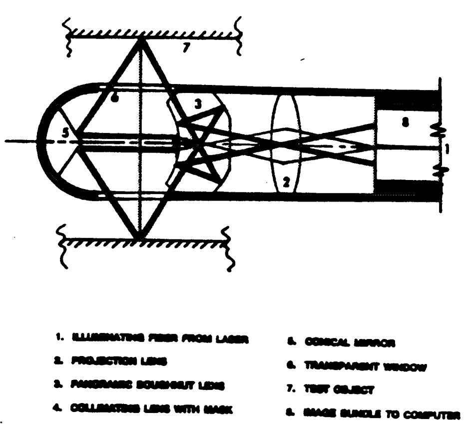

Figure 2. One of the optical configurations currently being evaluated for radial profilometry.

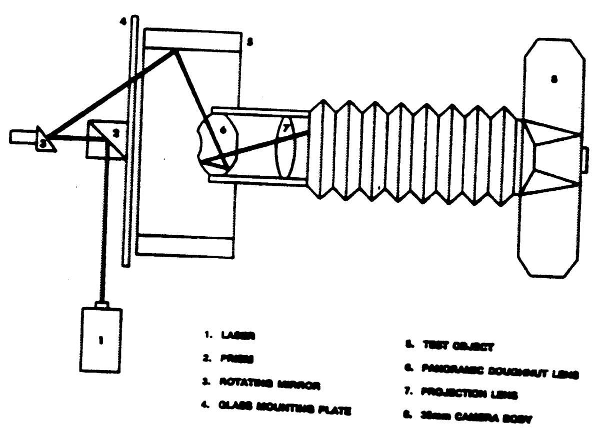

Figure 4. A prototype designed and built to demonstrate proof of principle.

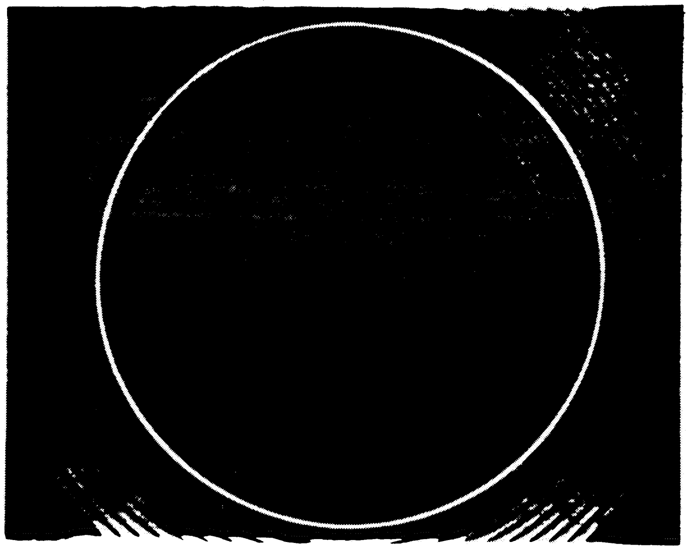

Figure 5. Image of a pipe located symmetrically with respect to the optical axis of the profilometer. The thick white line is the laser trace. Thinner dark lines were drawn equally spaced along the longitudinal axis of the pipe and illustrate the nonlinear mapping of the PDL.

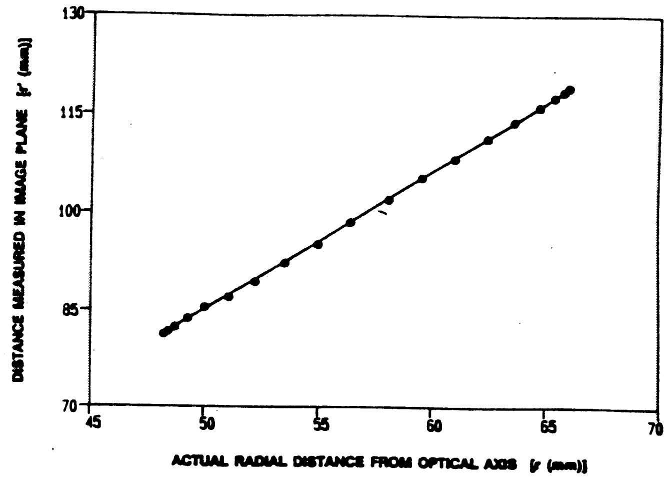

Figure 7. Calibration curve for the profilometer for displacements ranging from 0 to 0.35" (8.9 mm).

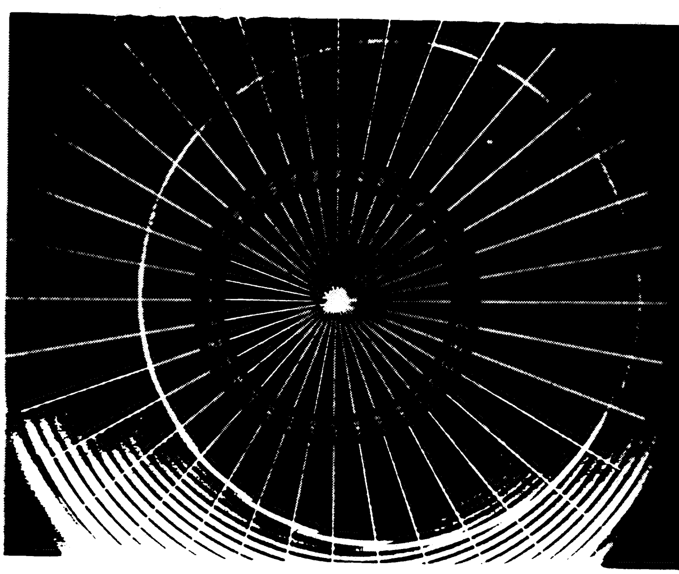

Figure 6. Image of a pipe translated 0.35" (8.9 mm) along the x-direction. The thick white line is the laser trace. Thinner dark lines were drawn equally spaced along the longitudinal axis of the pipe and illustrate the nonlinear mapping of the PDL.

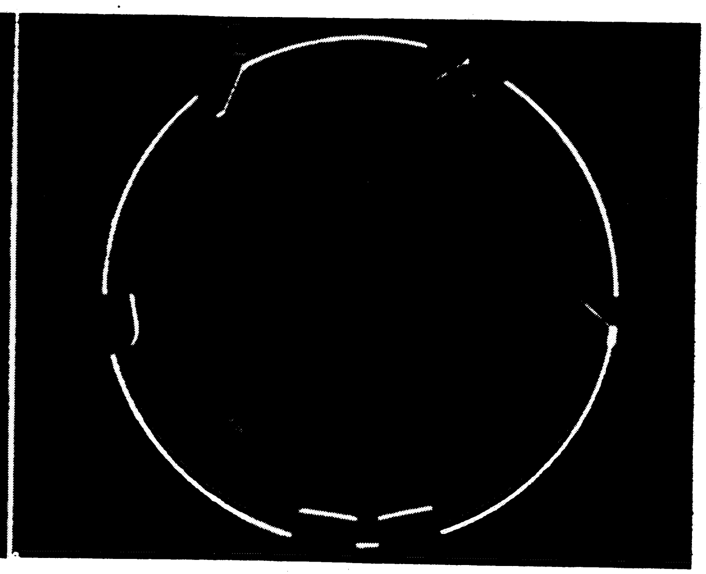

Figure 8. Laser trace obtained when inclusions are placed on the inner wall of the pipe.

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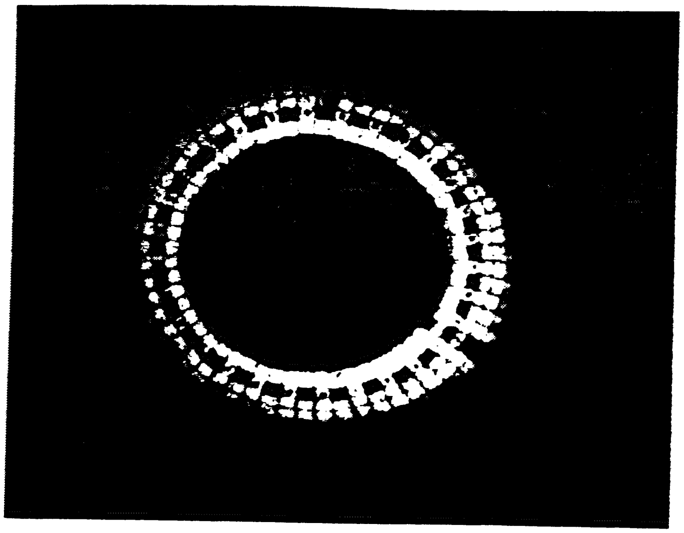


Figure 9. PDL image photographed through a coherent fiber optic bundle of a square test grid located on the inner wall of a pipe.

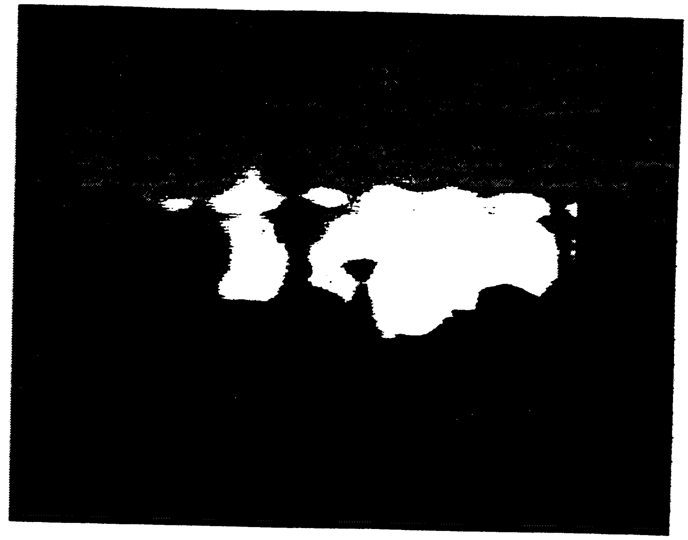
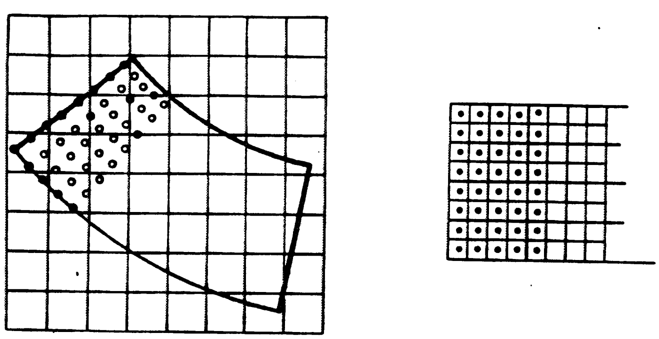


Figure 11. The digitized image resulting from applying a transformation algorithm to a portion of the image shown in Figure 1.



(a)

(b)

Figure 10. Samples (shown as o's) in the annular PDL image (a), can be mapped into a rectangular array (b).

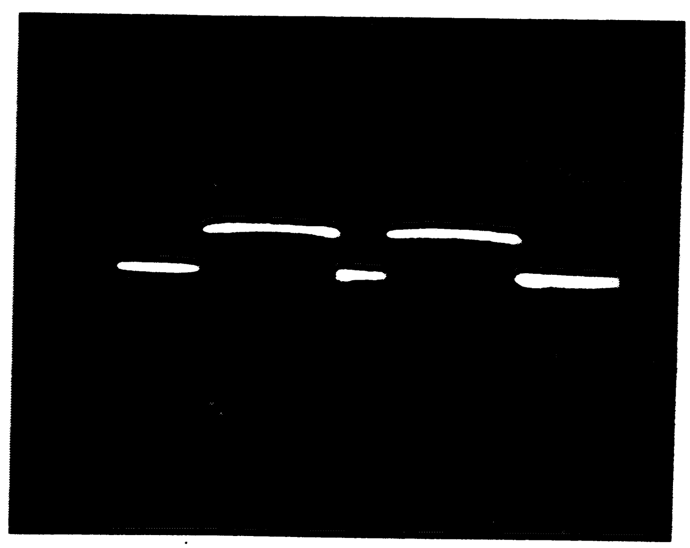


Figure 12. The digitized image resulting from applying a transformation algorithm to a portion of the image shown in Figure 8.

RECENT DEVELOPMENTS IN RADIAL METROLOGY: A COMPUTER-BASED OPTICAL METHOD FOR PROFILING CAVITIES

by

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Abstract

Radial metrology is a process devised to study the inner surfaces of cavities found, for example, inside pipes, tubes, and boreholes. This paper describes some recent advances in radial metrology and introduces a new computer-based optical method for profiling cavities. In this method, speckles are projected onto the surface under study and the speckle pattern is digitally recorded and compared to either a reference standard or to other speckle patterns recorded as the cavity changes shape. The apparent speckle movement is computed by numerically correlating small subsets extracted from each pattern. These shifts are used to measure surface deflections or to contour the cavity with respect to a reference shape.

1. Introduction

Recently, a new technique called radial metrology was introduced to make measurements within cavities[1,2]. The measurement system included a panoramic doughnut lens (PDL) which produces a 2-D representation of a 3-D cylindrical surface using Flat Cylindrical Perspective (FCP). The optical transformation performed by the PDL results in an annular FCP image where the width of the image corresponds to the angular field of view measured with respect to the optical axis, and each concentric ring in the image plane is the loci of points recorded at a constant field angle[3].

Figure 1 illustrates one of the optical configurations evaluated for radial metrology. In this example, a device called a radial profilometer is shown inserted into a cylindrical cavity. A diverging laser beam (shown launched from a fiber optic labeled (1)) is directed through a projection lens (2). The beam passes through a panoramic doughnut lens (3) and is collimated and shaped by an appropriately masked collimating lens (4) to produce a thin ring. The ring reflects off a conical 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 panoramic doughnut lens (3) and is projected by the projection lens (2) onto a coherent optical fiber bundle (8). The bundle transmits the image from the device to a computer system where changes in the image can be recorded and analyzed using digital acquisition and processing techniques.

Figure 2 demonstrates how a profilometer can be used to visually detect inclusions located on the inner wall of a pipe. In this case, the laser scan which was originally circular traces out shapes in the image plane which are "similar" to those of the inclusions. As demonstrated by Figure 3, computer algorithms can be applied so that portions of this image may be linearized for viewing and measurement purposes. The resolution and contrast of the image are relatively poor, since the photograph was recorded from a television monitor. The lower portion of the trace represents a constant radial distance from the optical axis of the profilometer to the wall of the pipe. The shape and dimensions of the inclusions can be easily observed and measured with respect to this baseline.

The equations required to analyze Figure 2 and the algorithms used to produce Figure 3 are included in Reference 2. Procedures for calibrating the profilometer and for profiling a cavity are also described in that work. The use of a line scan for profiling requires that the profilometer be moved through the cavity to obtain measurements over the original field of view. This procedure limits functional and real-time capabilities. Ideally, the profilometer should remain stationary during the measurement.

This paper demonstrates that the entire region imaged by the PDL can be profiled using a method initially developed for measuring deflections on the outer surfaces of structural components[4,5]. In this method, artifical speckles are projected onto the component using an ordinary 35 mm projector equipped with a clear glass slide splattered with black paint. Speckle patterns are digitally recorded as the surface changes shape, and the apparent in-plane movements of the projected speckles are computed by numerically correlating small subsets extracted from each pattern. These movements are related to the deflection of the surface with respect to a reference shape.

The following section describes the application of this method to radial metrology and gives an overview of the expressions considered when profiling a cavity.

2. Analysis

Figure 4 defines the cartesian (x,y,z) and cylindrical (r,θ,z) coordinate systems used for the analysis. It is assumed that the optical axis of the measurement system lies along the z-direction. Projected speckles fall on point P at an angle α, and the image of the illuminated surface is captured at an angle β, measured with respect to a radial line lying in the r-z plane. When the surface moves normal to the optical axis, the projected image appears to shift along the z-direction through a displacement w. The corresponding radial displacement r is given by

$$r = \frac{w}{\tan\,[90 - \alpha] + \tan\,\beta} \tag{1}$$

The relationship between r and w is nonlinear, since α and β vary from point to point.

The displacement along the z-direction is mapped into the image plane by the panoramic doughnut lens via a mapping function, f, as follows

$$r' = f[w]. \tag{2}$$

This function takes into account the magnification factor, and includes the FCP stretching methods used to create a 2-D representation of the 3-D cylindrical surface. Equations (1) and (2) can be combined and

$$r' = g[r]. \tag{3}$$

The function g[r] is determined by calibrating the measurement system. By measuring r' and knowing g[r], Equation (3) can be solved for r. Once r is established for a known value of θ, the z-coordinate of the illuminated point can be calculated using

$$z = \frac{r}{\sin\alpha}. \tag{4}$$

The profile of the entire surface in view may be obtained by repeating this procedure for other points in the image as required.

3. Experimental

An experiment was conducted to illustrate a calibration procedure and to demonstrate the method described above. Two 38 mm diameter PDLs, spaced at a distance of 61.7 mm (2.43") apart, were positioned with their optical axes aligned with the Z axis of the coordinate system shown in Figure 4. A circular pipe with an inner radius, R, equal to 52.5 mm (2.07"), was mounted on a kinematic stage and positioned midway between the PDLs with its longitudinal axis also along Z. A speckled slide was projected onto the inner wall of a 43.0 mm (1.69") long section of the pipe using a 35 mm projector and one of the PDLs. A 35 mm camera and the second PDL were used to photograph the speckle pattern with the pipe in its initial position. Four additional photographs were taken as the pipe was translated along the X axis, through four 2.54 mm (0.1") increments. The five photographs were subsequently digitized using a CID camera and stored as digital arrays of 256 x 256 pixels with each pixel assigned a grey level ranging from 0 to 255.

Figure 5 shows a photograph of the the FCP image of the speckle pattern recorded through the PDL with the pipe in its original position. The photograph was digitized so that the center of the annulus, C, was located in the center of the CID array at pixel coordinates C(128,128). Two 15 x 15 pixel subsets were extracted from the pattern with their centers located at points A(222,128) and B(34,128). These diametrically opposed points lie on a line parallel to the direction of translation and are located, midway between the outer and inner edges of the FCP image, 94 pixels away from point C. Ordinary correlation techniques (with Lagrangian weighting for interpixel interpolation) were applied to determine the displacement of the subsets, measured in terms of pixel shift, for each of the four translations. The location of the displaced subset coincides with the point at which the correlation coefficient attains its maximum value.

Table 1 shows the results obtained from the analysis. The pixel shift is measured in the image plane along a radial axis, r', originating from point C; a peak correlation value of 1.0 represents a perfect match.

Table 1

PT.	TRANS. ALONG r	r	PIXEL SHIFT	r'	PEAK CORRELATION
A	-10.16 mm (-0.4")	42.34 mm (1.67")	-15.35	78.65 pixels	.541
A	-7.62 mm (-0.3")	44.88 mm (1.77")	-11.05	82.95 pixels	.735
A	-5.08 mm (-0.2")	47.42 mm (1.87")	-7.05	86.95 pixels	.882
A	-2.54 mm (-0.1")	49.96 mm (1.97")	-3.20	90.80 pixels	.954
A,B	0.00 mm (0.0")	52.50 mm (2.07")	0.00	94.00 pixels	1.000
B	2.54 mm (0.1")	55.04 mm (2.17")	3.00	97.00 pixels	.954
B	5.08 mm (0.2")	57.58 mm (2.27")	6.75	100.75 pixels	.874
B	7.62 mm (0.3")	60.12 mm (2.37")	9.85	103.85 pixels	.776
B	10.16 mm (0.4")	62.66 mm (2.47")	13.20	107.20 pixels	.715

The calibration curve in Figure 6 was established by plotting r versus r', and defines g[r] in Equation (3). Measurements are independent of the z-coordinate, since the optical axis of the measurement system remains parallel to the longitudinal axis of the pipe and the cross section of the pipe is constant. The calibration is valid over a 20.32 mm (0.80") range where the value of r lies between 42.34 mm (1.67") and 62.66 mm (2.47"). In this range, the response is nearly linear with one pixel representing a radial displacement of approximately 0.71 mm (0.028"). A precise value for r may be obtained by selecting a subset centered at a point on the image plane with a given r', and numerically correlating the subset with subsets in the displaced image to compute the pixel shift. The value of r is determined by locating the point corresponding to the selected value of r' on the curve in Figure 7, and then moving up or down the curve through a vertical distance equal to the pixel shift.

4. Discussion

Table 1 shows that the magnitude of the peak correlation decreases with increasing displacement. This can be attributed to the apparent change in the size of the speckles as they move in the FCP image. Speckles moving toward the center of the image are compressed while speckles moving away from the center are elongated. This places a restriction on the range over which displacements can be measured, since peak correlations of less than 0.7 are generally suspect. Future research will focus on the development of computer algorithms to remove this distortion.

The measurement system used to demonstrate the method has some major drawbacks which limit its potential for practical application. A practical device should be packaged so that it can be easily manipulated throughout a cavity to access and profile regions of interest. Future plans include modifying the profilometer shown in Figure 1 to include a means for speckle projection. The advantages of such a device will be that is simple and relatively inexpensive, it can be miniaturized, there will be no moving parts, the image will be continuously displayed in the image plane, and measurements will be completely automated.

Finally, the method of calibration described above has the disadvantage that several speckle patterns must be recorded and analyzed. An alternative method of calibrating the system involves recording only two patterns; the speckle pattern with the pipe in its initial location, and the speckle pattern with the pipe translated along the x-direction through a displacement, u. This procedure will be demonstrated in future work.

After developing these tools, the authors expect to produce a three-dimensional, full-field computer vision system which will automatically draw an isometric view of a relatively large cavity by recognizing and combining various features of several images taken through the measurement system.

5. Conclusions

This paper discusses some recent advances in radial metrology and describes a profiling method in which measurements are made by digitally recording and numerically correlating artificial speckle patterns projected onto the walls of a cavity. The main advantages of this method are that it can be applied to any surface, it is non-contact and non-destructive, and the analysis can be completely automated. The method offers the potential to vary measurement sensitivity over a wide range and to access occluded or remote areas by using fiber optic components.

Future plans for improving the method were also discussed. These included the plans for the design and construction of a practical measurement device, the development of computer algorithms to correct for speckle distortion in the acquired images, and refinements in the method used for calibrating the measurement system.

6. Acknowledgements

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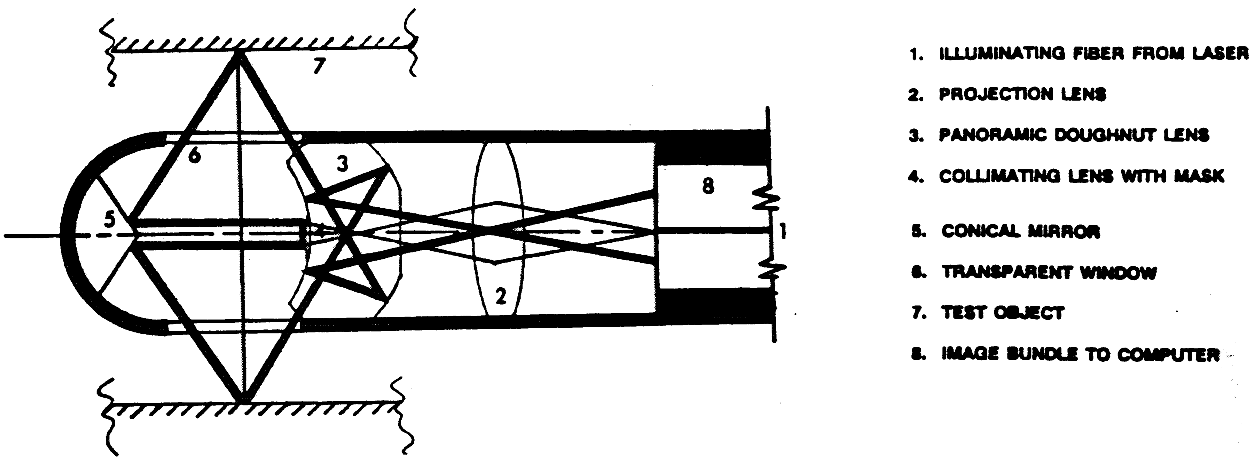

Fig. 1. Schematic diagram of a radial profilometer.

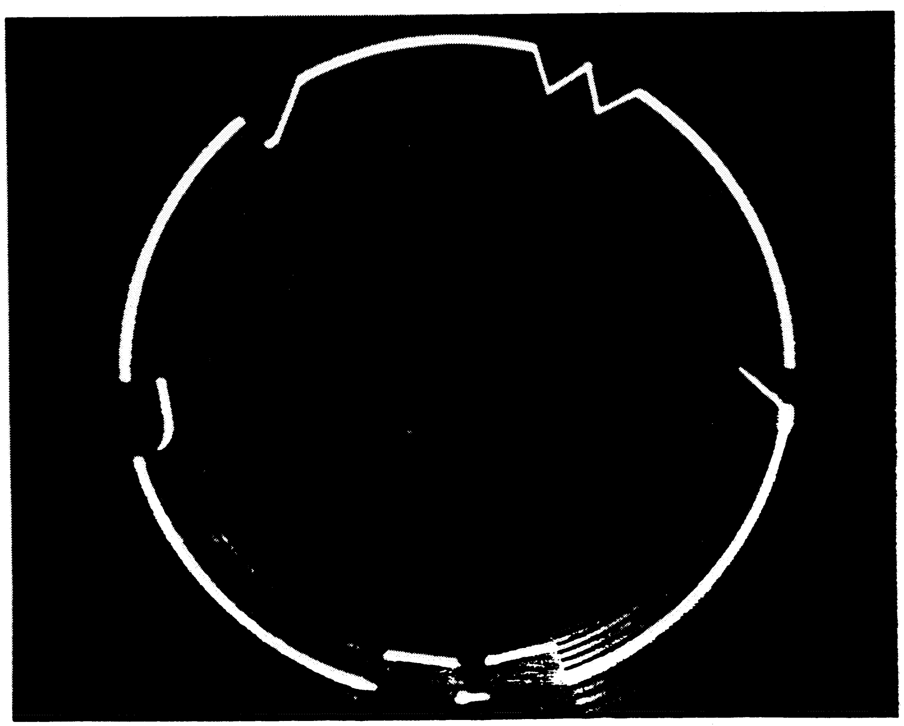

Fig. 2. FCP image taken through a PDL showing the trace obtained when inclusions are placed on the inner wall of a cylindrical pipe.

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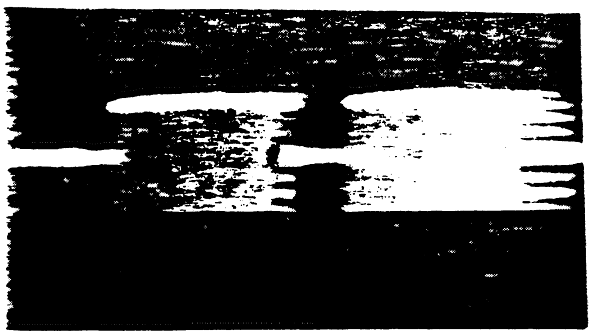

Fig. 3. Digitized image after applying a transformation algorithm to a portion of the image shown in Fig. 2.

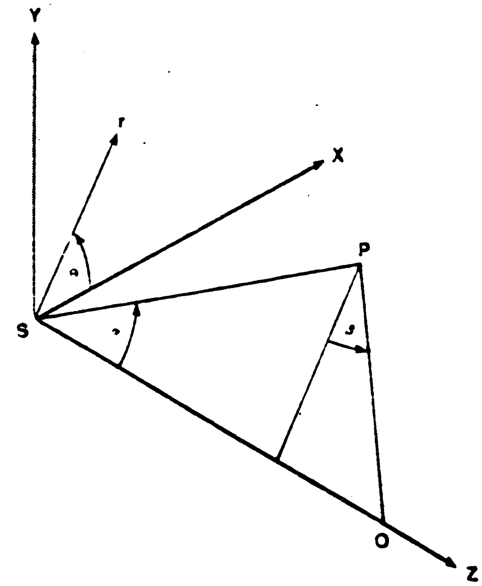

Fig 4. Coordinate axis system used for analysis.

Fig. 5. Image of the projected speckle pattern with the pipe located symmetrically with respect to the optical axis of the measurement system.

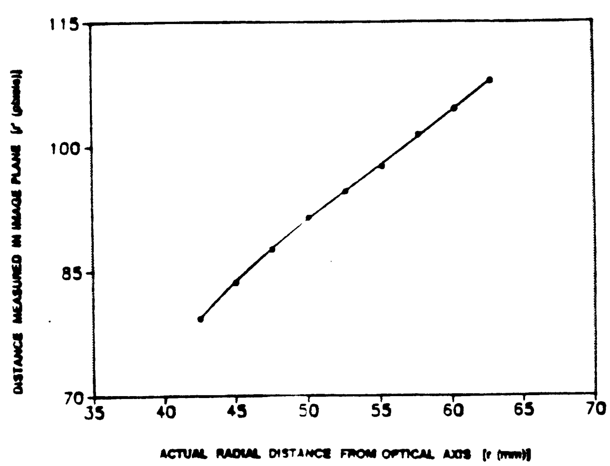

Fig. 6. Calibration curve for displacements ranging over 20.32 mm (0.8").