Plant Inspection using Portable Shearography and Electronic Speckle Pattern Interferometry

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ABSTRACT

Non-destructive Testing and Evaluation techniques are valuable tools used to determine the integrity of manufactured materials and components, either before commissioning or during regular maintenance inspection intervals. Optical interference techniques such as electronic speckle pattern interferometry (ESPI) and Digital Shearography are two such techniques, which have been shown to be of great value for the Non-destructive Evaluation of a range of materials, including ferrous and non-ferrous metals and composites.

For the last 20 years, the NDT Laboratory in the Department of Mechanical Engineering at the University of Cape Town has been involved with the research, development, and applications of the optical NDE techniques. Originally all applications were based on the use of Holographic Interferometry. However, with the introduction of computer based image processors, the focus shifted from the film based holographic techniques to the digital equivalents, namely ESPI and Digital Shearography. Until recently, all research was conducted under laboratory conditions on a purpose make vibration isolation table. However, with the award of an Armscor research contract, all emphasis was focused on developing portable equivalents of the laboratory based NDE techniques. This has led to the development of two portable inspection prototypes, the first based on Digital Shearography and the second based on ESPI.

This paper reports on the development of the two prototypes. The units and their respective underlying optical interference techniques are described in detail. Selected samples with man-made defects are then subjected to inspections using both systems. The results are presented and comparisons are drawn highlighting the advantages and disadvantages of these two optical NDE techniques.

INTRODUCTION

Non-destructive testing and evaluation techniques are widely used in the Manufacturing, Power, Petrochemical and Aircraft industry, both as a tool to certify the integrity of manufactured components as well as for routine maintenance inspections. There are many methods available and include dye penetrants, eddy current, ultrasound, x-ray, as well as optical interference inspection techniques

The Department of Mechanical Engineering at the University of Cape Town began researching optical interference techniques some 25 years ago. The initial work focused on applying holographic interference techniques to inspect objects for material defects. Because the technique utilized
holographic emulsions to capture either the double-exposure or real-time interference patterns, the process was laborious and time consuming. With the development of computer-based video capturing systems, the research shifted from the holographic techniques to the digital equivalents, namely Electronic Speckle Pattern Interferometry and Digital Shearography.

**THEORY**

Electronic Speckle Pattern Interferometry and Digital Shearography, both use a single mode monochromatic laser to produce a speckle interference pattern. For ESPI, the laser beam is passed through a beamsplitter in order to generate two laser beams. One of the beams is called the object beam and is passed through a beam expander and used to illuminate the object. The second beam, called the reference beam, is directed via a set of mirrors onto the image recording medium, typically a CCD camera. This camera is focused onto the object to be tested. This will cause the beam paths of the object and reference beams to overlap. If the beam path difference between object and reference beam is within the coherent length of the laser beam, the two beams will interfere and produce a speckle pattern, which is captured by the CCD.

With the aid of a suitable framegrabber, these images are captured and stored in a PC. The set-up, as described above is depicted in Figure 1.

The fundamental difference between ESPI and Digital Shearography is that the Digital Shearography technique omits the reference beam and only the object is illuminated. The laser light reflected off the object is then imaged through a shearing device and collected by a video camera. The function of the shearing device is to take the incoming image and split it into two. One of the two split images is then offset either horizontally or vertically with respect to the other, before being recombined with the second split image. Due to the two images being offset with respect to each other, two different parts of the image of the object overlap and produce a speckle interference pattern. Figure 2 depicts a typical Digital Shearographic set-up.

In order to use these techniques to inspect objects for defects, the object needs to be stressed during the inspection process. The methods used to stress an object include pressure, thermal, mechanical and vibration means. When the object is stressed, its surface deforms. For ESPI, this causes the beam path length of the object beam to change, which in turn causes the interference pattern between the object and reference beam to alter. With Digital Shearography, a relative displacement of one part of the object’s illuminated surface with respect to another causes the speckle pattern to change. If the speckle image captured before an object is stressed is compared with the speckle images of the object after it is stressed, areas of correlation and decorrelation can be determined. By plotting these areas of correlation and decorrelation an image can be formed, similar to the ones displayed in Figures 3 and 4, which reveal the familiar zebra-like fringes indicating the magnitude of displacement the object.
underwent during the period of stressing. Equation 1 as indicated below can be used to represent the displacement captured using the ESPI method:

$$d = \frac{n\lambda}{\cos\alpha + \cos\beta}$$  \hspace{1cm} (1)

where:  
- $d$ = out of plane displacement of the object due to the applied stress,  
- $\alpha$ = angle between the direction of object displacement and camera viewing angle,  
- $\beta$ = angle between the direction of object displacement and object beam.  
- $\lambda$ = wavelength of the laser beam  
- $n$ = no of fringes counted

Similarly, Equation 2 represents the displacement rate obtained from the Digital Shearography technique:

$$\Delta\phi = \frac{4\pi}{\lambda} \left( \frac{\partial d}{\partial x} \right) S$$  \hspace{1cm} (2)

where:  
- $\Delta\phi$ = correlation phase,  
- $d/\partial x$ = rate of displacement,  
- $S$ = magnitude of shear,  
- $\lambda$ = wavelength of the laser light,

Equation 2 above indicates that the correlation fringes along which $\Delta\phi$ is constant, represent lines of constant displacement rates. The spacing between adjacent fringes is a function of the displacement gradient according to Equation 3,

$$\frac{\partial d}{\partial x} = \frac{n\lambda}{2S}$$  \hspace{1cm} (3)

where:  
- $n$ = no of fringes.

This implies that for a given object surface area, an increase in displacement gradient will produce a corresponding increase in number of fringes.
If an object were to possess a defect, the material in the vicinity of the defect is weakened. When stressed, the defective zone of the object responds more readily to the applied stress, causing a greater localized displacement. When inspecting the generated fringe pattern, the defect is detectable as a result of the localized fringe irregularity or fringe concentrations, as seen in Figures 3 and 4, depending on the type of defect present and optical interference technique used.

Both techniques are sensitive to airborne and environmental vibrations. With ESPI any disturbance of any of the optics or movement of the object causes the beam path lengths to change and hence the speckle pattern to change. Digital Shearography on the other hand is less sensitive as any global object disturbance and will not necessarily affect the speckle pattern if the relative displacement of the object’s surface is not affected. In order to eliminate the influence of these disturbances, the optics and inspection objects are typically mounted on special vibration isolation marble or metal tables, which are suspended on a set of air cushions.

PORTABLE NON-DESTRUCTIVE TESTING PROTOTYPES

The two inspection methods described above have been proven to be most suitable for the inspection of a wide variety of objects and materials for defects which include cracks, internal voids, debonds and delaminations in composites as well as wall thickness thinning due to corrosion.1,3,4. This work had until recently been carried out in our research laboratory on a vibration isolation table, using optics mounted on sturdy magnetic bases. It was however soon realized that there was great potential in developing portable NDT equipment based on Digital Shearography and ESPI.

Portable Shearography Prototype

With the financial support from Armscor via a research contract it was decided to first develop a portable NDT inspection system based on Digital Shearography. As indicated earlier this configuration is less susceptible to environmental vibration and was considered to be more suited as a portable technique. The final configuration is depicted in Figure 5 above. As can be seen, the system consists of a tripod mounted Shearography head unit, which contains a proprietary shearing configuration to allow an image to be sheared in any direction via two mechanical controls. The laser unit is also mounted into the shearography head and the illumination direction can be adjusted. The adjustments for the built in camera module are installed on the top of the removable cover. By mounting all components contributing to the optical interference process onto one common platform, a sturdy and dimensionally stable construction was achieved. Two power supplies, one to drive the camera and one to control the laser power output can be seen on the table in Figure 5. A framegrabber equipped PC with custom written software which, besides controlling all image acquisition, framegrabber brightness, contrast, and Lookup Table configurations, image processing and image
storage routines, also allows for double-exposure or real-time inspection modes, acts as the interface between the operator and the inspection camera.

**Portable ESPI Prototype**

Following the successful completion of the Portable Shearography prototype, the development of an ESPI counterpart was initiated. The project was broken up into three phases. The first challenge was to investigate methods to meet the vibration isolation requirements of ESPI and reduce their impact on the successful operation of the technique beyond the laboratory table. The results of these investigations were reported on at the 2002 SPIE NDT conference\(^4\). The findings indicated that two methods showed success. The first was a laser chopping technique using a Lithium Niobate crystal that was pulsed in synch with the camera acquisition rate. This produced a pulsed laser beam with reduced optical output. The optimum driving voltage needed to change the polarity of the crystal was in the order of 1800-2000 Volts. The second successful technique was to use a variable shutter speed CCD camera\(^6\). With this approach the CCD integration period could be reduced via a shorter shutter period, thereby effectively “freezing the object during the image acquisition time. Because this approach did not result in a loss in laser power and there were no dangerously high voltages required, it was concluded that this method of vibration isolation should be adopted.

The second phase focused on developing a micro interferometer complete with laser diode, camera, beamsplitting optics, object beam expander and optical fiber for the reference beam. By using thick aluminium cross-sections and keeping the distances between the optics to a minimum, the impact of environmental vibration was further reduced. The final configuration ended up as a double tier configuration with the interferometer mounted above the camera. The diode laser was mounted at the rear of the micro interferometer. The final phase was to manufacture vibration isolation pads for the camera tripod legs. The final design consisted of a disk and cup between which an aircushion was wedged. The disks were connected to each tripod leg and a layer of rubber on the underside of the cup completed the isolation pad. For additional support, the isolation pads were also connected to each other via telescopically adjustable arms.

Figure 6 reveals the combination of the three phases to produce the resultant prototype. The small interferometer and camera are mounted on top of the fully adjustable tripod, which is secured to the vibration isolation pads. The same framegrabber equipped PC and custom written software as used for the Digital Shearography prototype is used.

**RESULTS**
In order to investigate the performance of the two prototypes, suitable inspection samples with man made defects were prepared. In order to simulate corrosion, two different types of samples, one to be used for thermal stressing and the second for vacuum stressing, were manufactured. For the first, acid was used to etch away some material from two sections of a 2.5mm thick aluminium panel; approximately 30% of the material thickness. The plate was then bolted to a vertical frame. A milling machine was used to remove approximately 50% of the material thickness off a section of a second aluminium panel. This panel was used as the vertical back section of an airtight chamber with a Plexiglas front panel. Finally, in order to simulate the endplate of a multiple pass shell and tube heat exchanger, two circular disks were manufactured, one defect free and one with an internal 20mm diameter void. The four samples can be seen in Figure 7 alongside.

All inspections were conducted outside the laboratory environment. The test samples were each placed on a wooden table with the defect-free side facing the NDT prototypes, thus hiding the position of the defect. Due to the mounting method of the two aluminium panels no further supports were required. The pressure chambers were clamped in a mechanical vice. No special form of vibration isolation was applied to either the objects or the prototype units. For the acid etched sample, a heat gun was used to stress the object for the inspection process. For the vacuum chamber and the two pressure chambers, a hand pump with two one-way valves was used to change the internal air pressure. Figure 8 shows the inspection environment as applied to the vacuum chamber.

Figure 9 below shows the results obtained from the inspection of the defect-free pressure chamber. A small amount of air was removed during capture of images one and two. The fringe pattern on the left, Figure 9A, is the ESPI result obtained. The symmetrical, circular fringes indicate a uniform response to
the applied stress with no apparent weakness in the structure. This is supported in the fringe patterns obtained from the shearography inspections, which are shown in Figures 9B and C. The fringe pattern is the same for both, but seem to be rotated by 90 degrees between the two images. This is because for Figure 9B, the image shear was in the horizontal direction resulting in the horizontal displacement gradient being recorded, and for Figure 9C the image was sheared in the vertical direction causing the vertical displacement gradient to be recorded. As the object displacement is symmetrical, similar shearographic fringe patterns are to be expected.

The fringe pattern obtained from the inspection of the flawed pressure chamber on the other hand, differs from the one obtained in Figure 9A, as can be seen in Figure 10. The fringe pattern is still circular, with the exception of the small circular fringe irregularity on the central fringe, at approximately 5 o’clock. This indicates the presence of a defect, which weakens the structure and causes an increased localized deflection. A similar phenomenon can be observed in the results of the investigation using Digital Shearography, as shown in Figure 11 below. The side by side double “bulls-eye” fringe pattern in the bottom portion of the horizontal shear fringe pattern, and the vertical double “bulls-eye” in the vertical shear fringe pattern of Figure 11 reveal the location of the structurally weakening void in the end cap of the pressure chamber.

The next object that was inspected was the Aluminium panel with acid corroded sections. The panel was stressed by applying heat centrally and letting the energy dissipate through the panel and displace. Figure 12 shows the results obtained from the inspections using the prototypes. The first two fringe patterns were produced using the ESPI prototype. The first is the fringe pattern result from a low level of thermal stressing. One can easily detect the locations of
the two corroded areas via the circular fringes in the left section and the top right corner section of the fringe pattern. The second ESPI fringe pattern shows the result obtained from a higher level of stressing, which is visible in the higher fringe density. What is interesting to note is that the defect on the left hand side of the panel can still be clearly seen as a fringe irregularity. The defect on the right hand side is subtler, but can still be detected due to the change in fringe direction. The difference in fringe formation indicates that the corrosion defect on the left hand side is more severe than the corrosion defect on the right hand side of the panel. The double oval fringes on the left and the two fringe dots on the right of the shearography fringe pattern in Figure 12 also clearly reveals the location of both corrosion defect areas. The sizes of the fringes can be interpreted to give an indication of the relative severity of the two defects and correlates with the ESPI results.

The results of the final test sample inspected are shown in Figure 13 below. These results were obtained by viewing the rear panel containing the machined defect area through the Plexiglas viewing window. The ESPI fringe pattern of the bottom left corner of the panel in Figure 13 very clearly reveals the presence of the defect and also provides an indication of the defect size. This can also be seen in the Digital Shearography result on the right of Figure 13. The familiar double bulls eye can be seen, revealing the large localized displacement gradient. In addition, the fringe pattern indicates a localized irregularity in the defect as seen by the difference in fringe formation in the left lobes of the fringe formation.

![Figure 13 Vacuum chamber test results, ESPI and Shearography](image)

**DISCUSSION AND CONCLUSION**

From the results it is clear that both Portable ESPI and Portable Shearography prototypes are capable of successfully detecting defects in engineering components. Both systems performed well outside the laboratory environment without any special additional vibration isolation requirements.

All results clearly show that both techniques are capable of determining the location of the man-made defects. The fringe patterns obtained from the inspection of the corroded panel indicate that the fringe density of the ESPI results, and to a lesser extent the Shearography results, are capable of inferring the severity of the defect. On the other hand Shearography is also able to indicate localized anomalies as seen in the fringe patterns of the vacuum chamber defect, which ESPI was not able to clearly reveal.
This is most probably due to the high fringe density in the ESPI result, which masked the local irregularity.

The results also highlight the difference in the information that the two inspection methods provide. Digital Shearography has the ability to detect the direction of displacement gradient, as indicated by the pressure chamber results. This also implies that care has to be taken when using Digital Shearography by ensuring that the shearing direction chosen is in line with the object’s displacement direction.

REFERENCES


