Phase Stepping Shearography and Electronic Speckle Pattern Interferometry

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ABSTRACT

Electronic Speckle Pattern Interferometry (ESPI) and Digital Shearography have been shown to be of great value for the Non-destructive Evaluation of the integrity of materials and manufactured components. The NDT Laboratory in the Department of Mechanical Engineering at the University of Cape Town has an active research group focused on the research, development and the various applications of ESPI and Digital Shearography. This work culminated in the development of portable prototype inspection systems based on Digital Shearography and ESPI.

The current portable systems, mentioned above, generate intensity based fringe patterns. By introducing a known phase shift into the speckle pattern during the image recording process, displacement fringe patterns, based on the change in phase of the laser light, can be generated. These fringe patterns differ in that they reveal distinct $2\pi$ discontinuities and are thus suited for automated inspection techniques and are also suited for object surface displacement mapping techniques.

This paper reports on the progress made in developing phase stepped ESPI and Digital Shearography. The techniques are described and applied to selected flawed composite samples. The findings are presented and comparisons are drawn between the results obtained from both phase stepping and conventional intensity based optical interference techniques. The possibility of applying phase stepping techniques to portable inspection systems is also discussed.

INTRODUCTION

The manufacturing industry of today makes extensive use of man-made materials such as GRPs and composites due to a number of factors. These include superior strength to weight ratios, cost, and the ability to produce complex geometrical shapes. The aircraft industry in particular has been using aluminium, fiberglass, Kevlar and carbon fiber composites in most of their recent productions and the new Airbus A380 will be the latest example of this design philosophy. In industries like the aircraft and aerospace, all manufactured components have to be inspected and declared fit for service prior to being commissioned and, once in use, again at regular predetermined intervals. However, with the use of these new materials, conventional NDE inspection methods such as X-ray, Eddy current, Ultrasound and Acoustic Emission that were originally developed for ferrous materials were found to be either unsuitable inspection techniques or needed to be adapted.

An optical interference technique, which was later found to be suited for the NDE inspection of a wide range of materials including composites, was developed purely by accident and called holographic interferometry. Over time, it was found that the technique was suited for the detection of defects including cracks, corrosion and material thinning, deboinds and delaminations, impact damage and moisture ingress, to name but a few. With the introduction of the personal computer and CCD camera the technique matured from the silver halide recording medium into a digital equivalent called Electronic Speckle Pattern Interferometry (ESPI) and another closely related technique called Digital Shearography. The fact that these techniques are non-contacting, have a high image resolution and can produce results in near real-time makes them very attractive.

Researchers in the Department of Mechanical Engineering at the University of Cape Town have for the last 30 years been involved in the research and development of optical interference techniques. The most recent work has culminated in the development of 2 portable prototypes, one employing Digital Shearography and the other ESPI, which have been presented at various conferences. Both prototypes are truly portable, compact and produce reliable and repeatable results when used to inspect objects for defects. The project is currently focusing on extending the capabilities of the prototypes to include phase stepping techniques, the subject matter of this paper.
OPTICAL INTEREFEERENCE TECHNIQUES

Both ESPI and Digital Shearography are based on the recording of speckle images, created when two light waves interfere with one another. In order for this to occur, the light waves have to be monochromatic, which is why single mode lasers, both continuous and pulsed, are used for these NDE inspection techniques. The fundamental difference between ESPI and Digital Shearography is that the former can be used to produce fringe patterns which represent an object’s surface displacement in response to an applied stress, whereas the later produces results which depict the first derivative of the surface displacement of an object in response to the applied stress. In order to elaborate on how this is achieved, the following schematics have been included.

Figure 1 below outlines a typical out-of-plane displacement ESPI set-up. A laser beam is split into two with the aid of a beamsplitter. The first beam, called the object beam and consisting of approximately 90% of the available laser energy, is expanded via a beam expander before being used to illuminate the object to be inspected. A CCD camera is then focused onto the object, to capture the monochromatic reflection off the object. The second beam, called the reference beam is expanded and directed onto a beamsplitter, placed in front of the camera, in order to direct the reference beam onto the camera’s CCD chip. If the beam path lengths of the reference and object beams are within the coherent length of the laser, the two light waves will interfere to produce a speckle pattern. By connecting the camera to a PC equipped with a suitable framegrabber, the video signal can be digitized, stored and processed.

The optical configuration used for digital shearography utilizes similar optical components, but differs from the ESPI configuration in that the laser beam emitted by the laser is not split into an object and reference beam. Instead, the emitted laser beam is expanded and used solely to illuminate the object. A video camera is then used to view the object through a shearing device. The shearing device is often a proprietary design, but a conventional Michelson Interferometer, as indicated in Figure 2 above can be used to illustrate the process. The laser light reflected off the object is split into two by the beamsplitter and directed onto mirrors M1 and M2. By tilting mirror M1 either horizontally or vertically, the reflected images can be misaligned, or sheared with respect to each other when recombined at the beamsplitter surface before being focused onto the CCD. The recombined lightwaves will then interfere with each other and produce a speckle pattern which can be captured as described in the ESPI process.

When an object is stressed, either mechanically or thermally, the object surface deflects. This causes the laser beam path length used to illuminate the object to change. The associated change in phase of the laser light also causes the speckle interference pattern to change. By capturing the speckle interference pattern of the unstressed object and comparing it with the speckle interference pattern of the stressed object, it is possible to locate regions of correlation and decorrelation between the two images. This produces a familiar zebra-like fringe pattern. For ESPI this can be represented mathematically by equation 1 below:

\[ \text{Equation 1} \]
\[ d = \frac{n\lambda}{\cos \alpha + \cos \beta} \]  

(1)

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

As the wavelength of the laser beam is fixed, equation 1 reveals that the magnitude of the surface displacement is directly related to the number of correlation fringes.

For Digital Shearography, a change in the speckle interference pattern will only occur if the object stressing produces a non-uniform surface displacement. Equation 2 represents the displacement rate obtained from the Digital Shearography technique.

\[ \Delta \phi = \frac{4\pi}{\lambda} \left( \frac{\partial d}{\partial x} \right) S \]  

(2)

where:  
- \( \Delta \phi \) = correlation phase,
- \( \frac{\partial d}{\partial x} \) = rate of displacement,
- \( S \) = magnitude of image 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 and magnitude of shear according to Equation 3 below.

\[ \frac{\partial d}{\partial x} = \frac{n\lambda}{2S} \]  

(3)

where:  
- \( n \) = no of fringes.

The above equation also implies that for a given object surface, an increase in displacement gradient will produce a corresponding increase in number of fringes.

If an object contains a defect, the structural integrity of the object is compromised and the material where the defect is present is weakened. When an object is stressed, a deformation of the object surface occurs. At the defect location, the surface displacement will differ due to the response of the weakened structure. As a result, both ESPI and Digital Shearography reveal the presence of defects via anomalies in the resultant fringe patterns.

**PHASE STEPPING**

ESPI and Digital Shearography, as described above, produce intensity based fringe patterns, which do not provide any information regarding the direction of object displacement. In order to quantify the object’s displacement or rate of displacement, the modulation of the laser phase due to the applied stress needs to be determined as well. This can be achieved using a technique called phase stepping. With this techniques, the phase of one of the interfering wavefronts is altered by predetermined amounts during the image capturing stage. For ESPI, this would be achieved by moving mirror M2 in Figure 1 and for Digital Shearography by moving mirror M2 in Figure 2. For a 4 image configuration, the beam path length is increased by a quarter of a wavelength \( (\pi/2) \) between each of four images captured before and again after the object has been stressed. The intensities of the images can be represented in equation 4 as follows:

\[ I_1(x, y) = I_0(x, y) + I_{MP}(x, y) \cos(\theta(x, y) + i \cdot \pi / 2) \]  

(4)

\[ \phi(x, y) = \arctan \left( \frac{I_3(x, y) - I_1(x, y)}{I_4(x, y) - I_2(x, y)} \right) \]  

(5)
\[ \beta(x, y) = \phi_a(x, y) - \phi_b(x, y) \]  
\[ (6) \]

where \( i = 1, 2, 3, 4 \)

\( \phi_a(x, y) \) = phase distribution after stressing,

\( \phi_b(x, y) \) = phase distribution before stressing.

With the aid of equation 5 it is possible to determine the phase distribution of the speckle interference pattern. This process also eliminates the background noise, represented in equation 4 as \( I_B(x, y) \). By determining the phase distribution both before and after the object is stressed, equation 6 can be used to calculate the change in phase of the laser light due to the object surface displacement. Because \( \beta \) repeats itself at 2\( \pi \) intervals, the fringes in the resultant image are of a saw tooth profile and the slope of the profile is used to determine the direction of object movement.

**DEVELOPMENT AND SAMPLES**

In order to be able to perform phase stepping, a mechanism capable of translating the mirrors at increments equal to \( 1/8^{th} \) of the applicable laser wavelength had to be found. For this purpose a stacked PZT actuator with a maximum displacement of 6 microns at a repetition rate of 150Hz was sourced and coupled to a PC board level power supply. The system was first calibrated in order to determine the correct voltage steps needed to move the actuator surface in 79 nm increments, the distance required for a 633 nm laser. Custom software was then developed to control the PZT power supply, as well as the image acquisition, manipulation and display routines. These modules where then finally added into the existing software program which was originally written as part of the portable prototype project.

Three samples were chosen for testing purposes. The first was an aircraft grade aluminium composite sandwich panel, consisting of two outer aluminium skins with aluminium honeycomb filler. These panels were used as the outer cladding of South African made satellites. Two defects had been created in the panel. The first was a skin debond, created by destroying some of the aluminium honeycomb at one of the panel’s edges, and the second was a defect created by removing a 12mm diameter section of the rear skin. Both defects were not visible on the panel’s inspection side facing the NDT set-ups. The second sample chosen was a 500 mm section of an Oryx Helicopter rotor blade. The blade was made up of an outer carbon fibre skin, which encased a fibre honeycomb core. The leading edge contained a solid composite spar. The outside of the leading edge was covered with an aircraft grade aluminium strip in order to reduce abrasion. Three defects were introduced into this sample. Across the width of the blade three 48mm circular defects were created as follows: a 48mm circular hole saw was used to cut through and remove the skin off one of the sides. For the first hole closest to the leading edge, no honeycomb was removed. At the second hole where the blade thickness was 40 mm, 20 mm of the thickness of the honeycomb was removed. The entire honeycomb was removed beneath the third hole, which was closest to the trailing edge. As with the first sample, the defects were not visible from the inspection side. The third sample selected was a 400mm section of a Unmanned Aerial Vehicle (UAV) composite fibreglass wing. With the exception of reinforcing spars, the wing was hollow. The wing was covered with a fibreglass composite skin, which was made up a fibrous honeycomb sandwiched between two fibreglass sheets. The underside of the wing had an inspection hole, used to install specialised electronic components. Via this hole, it was possible to get at the inner fibreglass layer of the top wing skin. A press was used to slightly crush a 35mm circular section of the honeycomb and at the same time crack, but not break the same section of the inner skin sandwich. The three sample can be seen in Figure 3 below.

![Image](image-url)  
Figure 3. i) Aluminium Composite panel, ii) Oryx blade section, iii) UAV section (insert: impact area)
RESULTS

During the inspection process each sample was placed on the inspection table and simply held in position between 2 magnetic clamps. For all three samples hot air was used to stress the object after the initial image(s) of the object had been captured. As the computer program generates the resultant fringe pattern in real-time, the images were immediately available. Once the desired fringe intensity had been obtained, or the location of the defect was clearly visible, the image processing routine was halted and the final image stored.

Figure 4 shows the results obtained from the ESPI investigation of the aluminium panel. For reference purposes, the intensity-based result is also provided. In all three images the presence and location of the circular defect can be seen in the circular fringe irregularity in the bottom left of the three images. The semicircular fringe concentration at the top of the left vertical edge also reveals the presence of the internal delamination. What is also noticeable is the change in fringe profile between the left image and the centre and right image, which are phase fringes. The image on the right in particular, which in the result of a sine and cosine filtering process applied to the centre image, clearly shows the saw tooth profile of the phase fringes and improvement in fringe quality.

![Figure 4. ESPI results of aluminium panel](image)

Figure 5 contains the fringe patterns acquired from the Digital Shearography inspection of the same panel. For the inspection the shearing direction was set in the horizontal direction, thus making the system sensitive to the horizontal displacement gradient. The first image in the set is the result of the intensity based Digital Shearography configuration, the second the phase stepped result and the final image the filtered version of the central image. In all three images, both defects are clearly visible. An interesting result is the double circular fringe pattern created by the circular hole defect. This is due to the amount of applied shear being more than the width of the hole. The deflection is thus a comparison between the displacement of the defect zone and the adjacent flat zone for both images. Another finding worth noting is that different defects respond to the applied stress at different rates. The Digital Shearography results reveal different fringe intensities between the two defects, the gradient for the delamination is greater than for the hole defect. In comparison, the ESPI results do not exhibit the same finding. This is because, the ESPI results were obtained immediately after the thermal heating had been applied, whereas the Digital Shearography results were obtained only after a certain amount of cooling had occurred.

![Figure 5. Shearography results of aluminium panel](image)

Figure 6 below are some of the ESPI results obtained from the inspection of the UAV wing section. In all three results, the circular fringes in the upper half of the images reveal the location of the defect. The formation of the lower elliptical fringes are due to the overall surface deformation and should not be confused with a defect. Here
again, the filtered phase result displays the best fringe information. A closer analysis of the fringe pattern of the phase fringes reveals that the defect deforms in the opposite direction to the overall surface displacement, something which cannot be determined from the intensity fringes.

![Figure 6. ESPI results of UAV wing section i) intensity fringes, ii) phase fringes, iii) filtered phase fringes.]

The Digital Shearography results in Figure 7 below provide a completely different pattern, but still reveals the presence and location of the defect via the familiar double bulls-eye fringe pattern. The fact that they are horizontally next to each other indicates that the image shearing occurred in the horizontal direction. The benefit of having phase fringes becomes evident when having a closer look at the double bulls-eye fringes. They are opposite in phase, which would be expected when analysing the displacement gradient of a bubble shaped deformation.

![Figure 7. Shearography results of UAV wing section i) intensity fringes, ii) phase fringes, iii) filtered phase fringes.]

The following fringe patterns are a selection of the results obtained from the inspection of the Oryx rotor blade section. Figure 8 below are the ESPI results of the intermediate and shallow defect. The fringe pattern on the left is the intensity based result. One can clearly see the fringe concentrations highlighting the presence and location of 2 defects, as well as a higher fringe density for the intermediate defect when compared with the shallow defect. The phase fringes in the central image as well as the filtered version on the right offer the same information as discussed above. In addition, the phase fringes reveal that the deformation of the defect area is towards the camera. The benefit of filtering the phase fringes can also be clearly seen.

![Figure 8. ESPI results of Oryx rotor blade section i) intensity fringes, ii) phase fringes, iii) filtered phase fringes.]

The Digital Shearography results of all 3 defects in the vertically placed helicopter section can be seen in Figure 9 below. The familiar double bulls-eye again reveals the defect locations. As with ESPI, the Shearography results also provide an indication about the defect severity through the number of fringes recorded, the deepest defect being at the bottom of the images and the shallowest at the top. For this inspection set-up, the object was placed
approximately 1.2m away from the shearing device, which was enough to view a 400mm wide inspection area. Here as well the phase fringes reveal the double bulls-eye fringes are opposite in phase, indicating a positive displacement gradient across one side of the defect, followed by a negative displacement gradient across the other side of the same defect. Figure 9 also reveals that the filtering routine is effective in producing an image with defined fringe intensity discontinuities.

![Figure 9. Shearography results of Oryx rotor blade i)intensity fringes, ii)phase fringes, iii)filtered phase fringes.](image)

**CONCLUSION AND DISCUSSION**

From the above results it is evident that phase stepping ESPI and Digital Shearography were successfully implemented and that all defects in the selected samples were detected. The results are comparable with the intensity based results, but have the added benefits that they are depicted more dramatically and that the object deformation direction can be determined. The results also indicate that the fringe density can be used to evaluate the severity of the defect. The sine and cosine filtering routine improves the fringe quality to such an extent, that further post processing using a computer based phase unwrapping algorithm, suitable for generating a 3 dimensional displacement map, should be considered.

It is difficult to determine whether ESPI or Digital Shearography is better suited as a NDT technique. ESPI fringes are readily interpretable, whereas some people experience difficulty in interpreting the fringes produced using Digital Shearography, as well as locating the position of the detected defect. In addition, the quality of ESPI fringes is generally better than those produced using Digital Shearography. On the other hand, whole body displacements, which do not provide any information as to the presence of a defect, are recorded with ESPI, but to the most part are not captured using Digital Shearography. This plays an important role when considering portable versions of the technique. Global vibrations are detrimental to the ESPI process, and thus care has to be taken to eliminate the influence of these vibrations on the portable system. This becomes even more critical when phase stepping is considered, as system stability is required during the acquisition of the four phase stepped images.

Due to the results obtained as well as the compact nature of the PZT actuator the authors are currently working on redesigning the Portable NDT prototypes to include phase stepping functionality.

**REFERENCES**