A Comparison of Results Obtained from Alternative Digital Shearography and ESPI Inspection Methods

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Abstract

Digital Shearography (DS) and Electronic Speckle Pattern Interferometry (ESPI) are two optical interference techniques used, amongst other, in the field of non destructive testing. DS captures the rate of surface displacement and ESPI the displacement of an object in response to an applied stress. The addition of phase stepping techniques allows for the surface displacement of the object to be reconstructed. By applying a suitably large shear to the DS process, pseudo ESPI results can be obtained without all the inherent environmental vibration considerations associated with ESPI, thus potentially extending the use of conventional DS equipment to ESPI applications.

This paper describes the above mentioned inspection techniques and examines the fringe pattern results and unwrapped displacement map results obtained from DS, pseudo ESPI and conventional ESPI techniques applied to 2 samples containing defects. In particular the results from the DS and pseudo ESPI techniques are compared with the reference ESPI results to determine how well they correlate, which ultimately attempts to determine the suitability of the extended DS technique as an alternative ESPI inspection technique.

1. Introduction

Optical interference techniques such as Digital Shearography (DS) and Electronic Speckle Pattern Interferometry (ESPI) are non-contacting, whole field inspection techniques used to detect and record the surface displacement of an object in response to an applied stress. ESPI records the direct surface displacement as a result of the applied stress and DS captures the rate of surface displacement resulting from the applied stress\(^{(1,2,3)}\). These two techniques are primarily used in the field of non destructive testing and evaluation as a defect detection tool and can be applied to both ferrous and non ferrous metals. There also is a lot of interest in its use as inspection techniques for composite materials\(^{(4,5)}\).
2. Theory

Although both techniques share the same optical components, their setups and methods by which the interference or speckle patterns are produced are different. Both use a single mode monochromatic laser to produce the required speckle interference pattern. For ESPI, the laser beam is passed through a beamsplitter in order to generate two laser beams. One of the beams, the object beam, is passed through a beam expander and used to illuminate the object. The second beam, the reference beam, is directed via a set of mirrors onto the camera recording medium, the CCD sensor. The camera is focused onto the object to be tested, which causes the laser light reflected off the object to interfere with the reference beam and produce a speckle pattern at the CCD image plane. This set-up is depicted in figure 1 below.

The fundamental difference between ESPI and DS is that the DS technique omits the reference beam, only the object is illuminated. The laser light reflected off the object is then imaged through a shearing device before it is recorded by the 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 monochromatic image of the object overlap and produce a speckle interference pattern. This setup is shown in figure 2 above.

In order to use these techniques to inspect objects, 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, whilst the reference beam path length remains unaltered. This causes the interference pattern between the object and reference beam to change. 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 mapped. By plotting these areas of correlation and decorrelation an image containing zebra-like fringes is formed. For ESPI these fringes indicate the magnitude of displacement of the object, with DS the

Figure 1. Typical ESPI Set-up

Figure 2. Typical DS set-up
generated fringes indicate the relative displacement of two superimposed regions of the object, as defined by the shear set by the shearing device. Equation 1 as indicated below can be used to represent the displacement captured using the ESPI method:

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

\[(1)\]

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 DS technique:

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

\[(2)\]

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

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

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

\[(3)\]

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

This implies that for a given object surface area, an increase in the displacement gradient will produce a corresponding increase in the number of fringes.

The above process can be extended to a phase stepping technique which allows the phase of the laser light to be extracted and thus the direction of object displacement to be determined. This is achieved by altering the laser beam path length by \((\lambda/4)\) increments between successive image acquisitions. Instead of only one image being recorded as for the above methods, sequences of 4 images, both before and after the object deformation, need to be acquired before a resultant fringe pattern can be generated. The intensity of the 4 images can be represented by equation 4 below:

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

\[(4)\]

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

\[(5)\]

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

\[(6)\]
where \( i = 1, 2, 3, 4 \)
\( I_B = \) intensity of the background noise
\( I_{MP} = \) intensity of the modulated phase
\( \theta = \) phase of the 2 interfering neighbouring pixels
\( \phi_a(x,y) = \) phase distribution after stressing,
\( \phi_b(x,y) = \) phase distribution before stressing

Equation 5 determines the phase distribution of the speckle interference pattern and eliminates the background noise, represented by \( I_B(x,y) \). 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. As \( \beta \) 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.

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 and thus special vibration isolation approaches are adopted. The benefits of ESPI are that the results provide a direct surface displacement map. Surface perturbations due to defects can therefore be easily identified and very often the size and proximity of the defect can be directly extracted from the fringe pattern.

DS on the other hand is less sensitive to global object disturbances. Typically these disturbances affect the whole environment and as the two images in the shearing device are derived from one image, the disturbance affects both images in equal magnitude and the relative displacement of the object’s surface is not affected. When it comes to using the technique for NDT/E purposes, local perturbations cause a localized change in the displacement gradient, which is readily detected in the fringe pattern. The added benefit with the technique is that the overall object displacement is uniform which produces a uniform displacement gradient and relative few fringes. A closer look at figure 3 ii) however shows that the circular defect of image one interacts with image two and vice versa. The resultant fringe pattern is thus the result of a combination of the 2 anomalies and the generated fringe pattern in figure 3iii) is thus not a true reflection of the magnitude of the defect, but rather a distorted elliptical butterfly shape.

![Figure 3. i) Defect in plate, ii) Sheared defect image, iii) Resultant fringe pattern](image)

### 3. Experimental Approach
When considering the two techniques, it is clear that the direct visualizations of the displacement and detected defects when using ESPI are desirable, but the fringes due to global displacement are not. DS on the other hand is fairly immune to globally induced Vibrations. This paper thus investigates trying to combine the best of both techniques and produce a pseudo ESPI inspection process.

In order to achieve this using the DS optical configuration, a very large amount of image shear was applied between the two recombined images. This was easily achievable, as the shearing device can be independently manipulated in the X and Y direction and the magnitude of applied shear is adjustable from 0% to approximately 50% of the field of view. By applying a large amount of shear, a defect is split into 2 distinct defect regions, one in each image, without any overlap between the two. Compared with figure 3, the resultant sheared image appears as in figure 4 above, each defect region in each image clearly distinguishable from the other.

In order to apply ESPI using the DS setup, an alternative ESPI method, shown in figure 5 above(8), was proposed as follows. A flat diffuse reflective plate was placed in front of the object under inspection, to the left of the defect. The laser beam expander was set such that it illuminated the object as well as the plate. With the large amount of shear set by the shearing optics, the recombined images resulted in half of the imaged object being overlayed with this added reference plate to produce the interference speckle pattern. By shielding this plate from any thermal stressing and thus keeping it stationary, this plate acted as the reference beam for conventional ESPI inspections.
Two samples with man-made defects were selected for inspection purposes and are indicated in figure 6 below. The one on the left is a trailing edge composite section of an Oryx helicopter rotor blade. The blade was made of two fiberglass skins and was filled with Nomex honeycomb, machined to the rotor blade profile. The blade was subjected to two impact damages as seen in figure 6i). The diameter of the punched hole was approx 16 mm and some damage to the Nomex had occurred. There was however no visible damage on the front face of the rotor blade, the inspection side, as seen in figure 6ii).

The second sample chosen was a UAV wing section made of fiberglass skins and Nomex honeycomb, as seen in figure 6i) above. This particular section had a maintenance port on the bottom wing side in order to access some of the embedded controls. A low speed impact damage area was created via this port on the inside fiberglass skin. Some fiberglass / Nomex interface damage was created in the process, but this was not visible to the naked eye. For testing purposes, the sample was inspected from the unaffected upper wing side, as seen in figure 6ii) below.

In order to stress the two samples, thermal heating via an infrared lamp was applied during the inspection process. A timer was used and the distance between object and heating lamp kept constant in order to be able to repeat the stressing cycle for all inspection runs.

4. Results

The first sample tested was the helicopter rotor blade section. It was first tested using conventional DS, using a shear of 10 mm. The result of the inspection can be seen in figure 7i) below, which was taken after the sample had been heated for 6 seconds. The result clearly indicates the presence of a defect in the top half via the butterfly fringe pattern formed. The defect in the lower section is not visible, indicating that the top defect is more severe that the lower one. To calculate the dimensions of the defect, it was determined that the image to object size ratio was 1:1.9. The vertical dimension of the damage zone was approximately 31 mm and the horizontal 45 mm. Subtracting the shear magnitude from the horizontal dimension resulted in a horizontal sizing of 35mm. Both were thus greater than the manufactured 16 mm defect.
Figure 7ii) is the image obtained from the ESPI inspection. The same heating time was applied. Here as well the upper defect is identified by the black single circular fringe in the global displacement fringe pattern and the lower defect is not visible. The same magnification factor was used and thus the size of the defect was determined to be approximately 18mm which correlated well with the actual defect size.

The sample was then subjected to the pseudo ESPI inspection. For this inspection, the sample was first heated for 6 seconds and only then was the inspection process initiated and the cooling down of the object monitored. Figure 8i) is the result after 10 seconds of cooling. In the fringe pattern, the upper defect is again clearly visible, but now as two distinct defect zones. Both fringe sets are generated from the same defect. The left circular fringe is produced by the defect in image 1 interfering with a defect free zone in image 2 and the right circular fringe is produced by the defect free zone in image 1 interfering with the defect in image 2. The same magnification factor applied and the direct defect size was determined to be 16.5mm. In figure 8ii) the sequence was allowed to cool for 90 seconds before the inspection was halted. As can be seen above the fringe density is greater, but in this case the lower defect has become visible. Here again 2
defect zones are apparent and the size of the defect was measured to be approximately 19 mm. For this case, as with ESPI, the location of the defect can be directly mapped from the fringe pattern onto the object. For figure 8i) the upper left defect is mapped from the bright vertical edge and was found to be 105 mm, which correlated with the position of the defect in the object.

The UAV section was then subjected to similar thermal heating inspections. The results obtained are summarised in figure 9 above. Figure 9i) is the result obtained from the DS inspection with an applied shear of 10 mm and 1.5 seconds of thermal heating. The low impact damage zone is clearly visible in the fringe pattern. Figure 9ii) is the result obtained from the large shear inspection process with the same heating time. Here as with the rotor blade sample, 2 distinct defect areas are visible, each associated with one of the 2 sheared images. What is apparent is that the size of the defect area is different to the one obtained using DS, both in the horizontal and vertical direction. Figure 9iii) is the result of the ESPI inspection, which was set up in such a way that the left half displays the ESPI result and the right portion displays one of the 2 defect results obtained when applying the pseudo shear technique. A comparison of the two techniques shows that both reveal the presence and location of the defect and the size of the circular fringe also clearly matches for both results. For both the ESPI and the pseudo ESPI results, the calculated defect size ranged from 28 mm to 30 mm. However as with the rotor blade results, the defect size obtained using DS is greater than the defect size in the results obtained from ESPI and pseudo ESPI.

The UAV section, using the same setup configurations as described above, was then subjected to phase stepping inspections and subsequent phase unwrapping and

![Figure 9i) UAV shear result, ii) UAV pseudo ESPI result, iii) UAV ESPI + Pseudo result](image)

![Figure 10. DS phase map result and unwrapped displacement map](image)
displacement mapping procedures. Figure 10 above shows the result of the phase stepped DS inspection. The saw tooth profile of the fringe contrast from black to white is clearly evident and the telltale butterfly fringe pattern indicates the presence of the defect. Part ii of figure 10 is the unwrapped displacement plot of the surface in the region of the defect. Within the displacement field the position of the defect can be observed and the displacement gradients unwrap correctly to produce the displacement map. The elongated profile at seen in the results in figure 7 is also evident here.

The results of the pseudo ESPI setup are shown in figure 11. It can be seen that the fringe pattern indicating the defect in the left is distorted. The unwrapped displacement map in figure 11(ii), using figure 11(i) as the displacement gradient input, yields meaningless information and does not reveal the location of the defect. The result in figure 11(iii) on the other hand treats the input from figure 11(i) as ESPI phase map data and generates the correct displacement field with the detected defect repeated twice. What is interesting to note is that the left representation has a positive displacement profile and the right representation a negative profile. Relative to the defect free section of the UAV the defect displacement is positive, but relative to the defect section of the UAV the defect free section displacement is negative.

The inspection of the ESPI and pseudo ESPI setup can be seen in figure 12 below. The defect is clearly seen in the ESPI result and the dimensions of the defect tie up with the dimensions of the actual defect. Figure 12(ii) shows the displacement map of the ESPI result, the defect on the left. Here the localized displacement due to the defect can be clearly seen and its dimensions calculated. Figure 12(iii) is the pseudo ESPI displacement map of the defect representation to the right of figure 12. The result has been inverted to match up with the positive profile of the ESPI result. Comparing the

![Figure 11. Pseudo ESPI phase map of UAV](image)

![Figure 11. ii) Shear displacement map](image)

![Figure 11. iii) ESPI displacement map](image)

![Figure 12. ESPI and pseudo ESPI UAV phase map](image)

![Figure 12. ii) ESPI displacement map](image)

![Figure 12. iii) Pseudo ESPI displacement map](image)

results it is clear that the profiles are similar, but the magnitudes differ.
5. Conclusion and Discussion

From the above results it is evident that all three methods i.e. DS, ESPI and the pseudo ESPI method using a DS optical configuration were able to detect the man-made defects in the two samples considered for this paper.

The results also indicate that the fringes obtained from the pseudo ESPI approach are similar to the fringes obtained from conventional ESPI. The defect size obtained from the rotor blade results for ESPI and pseudo ESPI were within 2mm of the actual object defect size. The results obtained from the DS inspection on the other hand are both quantitatively larger than the actual defect and for the rotor blade result are twice the size of the sample defect.

The pseudo ESPI approach separates the object defect zone into 2 distinct fringe anomalies in the fringe pattern. One the one hand care needs to be taken to not interpret this result as 2 separate defects. On the other hand the doubling up of the defect results discerns true defects from possible global displacement anomalies where only one fringe anomaly would occur in the fringe pattern.

With the pseudo ESPI approach it is easy to outline and map a detected defect onto the surface of the object in order to pinpoint the defect location. Care however needs to be taken to correctly match the defect fringe location with an appropriate object reference point in the same image.

During pseudo ESPI inspections it became apparent how much more immune the system was to environmental vibrations than when the conventional ESPI configuration was employed, which is a benefit.

The phase stepped results and associated displacement maps indicate that the Pseudo ESPI approach is suitable for qualitative defect detection processes, but care should be taken to quantify the displacements as they do differ from the ESPI results. This is due to the fact that displacement obtained from the pseudo ESPI configuration is not an absolute displacement but rather a combined record of the displacements of both surfaces of the interfering images.

From the above work it is evident that alternative large shear DS methods produce comparable qualitative results to conventional ESPI approaches and thus extends the versatility of conventional DS optical configurations.

6. References


