Comparison of Normal and Phase Stepping Shearographic NDE

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ABSTRACT

The paper presents results of non-destructive testing of composite main rotor helicopter blade calibration specimens using the laser based optical NDE technique known as Shearography. The tests were performed initially using the already well established near real-time non-destructive technique of Shearography, with the specimens perturbed during testing for a few seconds using the hot air from a domestic hair dryer. Subsequent to modification of the shearing device utilized in the shearographic setup, phase stepping of one of the sheared images to be captured by the CCD camera was enabled and identical tests were performed on the composite main rotor helicopter blade specimens. Considerable enhancement of the images manifesting or depicting the defects on the specimens is noted suggesting that phase stepping is a desirable enhancement technique to the traditional Shearographic setup.

1. INTRODUCTION

Digital Shearography is an easy to use non-contacting optical interference technique used to detect cracks and flaws in materials by measuring the rate of displacement of stressed objects. Due to technological developments and research at the NDT laboratory at the Department of Mechanical Engineering, University of Cape Town (UCT), a portable ESPI prototype and Shearography prototype have been designed and built. A paper on the findings of this project has been previously published. Shearographic NDE has an advantage over other interferometric methods because it is relatively undisturbed by environmental and airborne vibrations and therefore the next logical step in terms of research has been to improve the sensitivity of the portable Shearographic NDE prototype by introducing a phase stepping system. Research in improving the overall size of the portable Shearographic prototype is also being done in that there is a need by the South African Air Force and airplane industry for quick and effective Non-Destructive Evaluation (NDE) techniques to maintain their aircraft as well as to improve safety.

Phase-Stepping Shearographic NDE is a relatively new optical interference technique, which makes use of a Piezoelectric Crystal. The crystal, once incorporated into the Michelson interferometer goes through micro-displacements; each calibrated micro-displacement is then captured by the CCD camera and compared with a reference image. The results will show how this technique dramatically increases the sensitivity of inspection.

This paper presents results obtained by applying Conventional Shearographic NDE and Phase Stepping Shearographic NDE.

2. CONVENTIONAL SHEAROGRAPHY

Shearography is a well-established technique used to detect material and structural defects. The main difference between Conventional Shearography and Phase-stepping Shearography is that in Conventional Shearography a single interferogram is captured and compared with a reference image where as in Phase-stepping Shearography four interferograms are produced at calibrated phase shifts, which are then compared with a reference image. The object under inspection is illuminated by light emitted from a single laser beam that is dispersed by a beam expander. The light that is reflected off the object is then passed through a Michelson Interferometer, which splits the light into two
equivalent parts by using a beam-splitter (as shown in figure 1). The divided light beam then travels through the two “arms” of the interferometer. The object beam arm has an adjustable mirror which shears the image in a vertical or horizontal direction while the reference beam arm has a fixed mirror, which has the sole purpose of reflecting the light back into the beam-splitter. The divided light then recombines with aid of the beam-splitter at which point one image overlaps the other due to shearing. The recombined images of equal path length then produce a speckle interference pattern due to the monochromatic nature of laser light. Conventional Shearography is less sensitive to environmental and airborne vibrations in comparison to other interferometric methods due to the arms of the interferometer sharing a common laser path; therefore any external noise producing a change in the laser path length would affect both arms of the interferometer and hence be eliminated.

The initial step in Conventional Shearography is to capture a speckle pattern image of the unstressed object, which is then digitized and stored as a reference image. The object is then stressed by either mechanical, pressure or thermal methods. Stressing the object causes the relative displacement between two points on the surface of the object to change, which in turn causes the laser path length to change. This change of path length then alters the density distribution of the speckle pattern. If the subsequent speckle pattern is then digitized, stored and compared with the reference speckle pattern (i.e. the unstressed image), a final image will be formed which contain zebra like black and white fringe patterns.

The subtraction of the two speckle patterns (i.e. the un-stressed and stressed images) creates a final deformation pattern containing fringes. This resulting pattern can be mathematically described by the following equation:

\[
I = 2I_0 \left( \sin \left( \varphi + \Delta \varphi \right) \sin \left( \frac{\Delta \varphi}{2} \right) \right)
\]  

(1)
Where $I_0$ is the mean intensity of the resulting image, $\phi$ is the random phase distribution of the initial speckle image and $\Delta \phi$ is the phase difference caused by stressing the object. The x, y co-ordinates are left out for simplicity.

The fringes can be modeled by the following mathematical equation $^3$:

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

Where $\Delta \phi$ is the correlation phase, $\frac{\partial d}{\partial x}$ is the rate of surface displacement, $S$ is the magnitude of shear and $\lambda$ is the wavelength for laser light. The above equation shows that the correlation fringes represent lines of constant displacement rates, where $\Delta \phi$ is constant. The spacing between adjacent fringes is a function of the displacement gradient according to equation (3).

$$\frac{\partial d}{\partial x} = \frac{n\lambda}{2S} \hspace{1cm} \text{Where } n = \text{no of fringes}$$  \hspace{1cm} (3)

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

### 3. PHASE-STEPPING

Phase-stepping is a quantitative method of data measurement and is derived from the intensity integration method $^6$. The phase-stepping technique requires a minimum of three measurements (i.e. interferograms) to solve for three unknowns; however four measurements or interferograms are more commonly used. Phase-steps are produced by micro displacements of a piezo-electrically driven mirror, which is calibrated before testing can commence. Each micro displacement of the calibrated piezo-electrically driven mirror initiates phase steps of $\frac{\pi}{2}$ increments, which is equivalent to changing the path length of the beam by a quarter of a wavelength.

![Figure 2: A typical Phase-stepped Shearographic set-up](image-url)
The piezo-electrically driven mirror can be attached to either arm of the Michelson Interferometer. Figure 2 depicts a typical Phase-stepped Shearographic set-up. After each phase-step an interferogram is grabbed by the image processing system. The measured intensity $I(x,y)$ of the interferogram, at any given co-ordinate $(x,y)$, can be described by the following equation:

$$I_i(x,y) = I_{BM}(x,y) + I_{mp}(x,y) \cos(\phi(x,y) + i\alpha) \quad i = 1,2,\ldots,N \quad (4)$$

Where, $I_{BM}(x,y)$ is the background intensity, $I_{mp}(x,y)$ is the modulation intensity, $\phi(x,y)$ is the phase difference between the object and reference beam and $\alpha$ is the relative phase step (i.e. $\frac{\pi}{2}$). When four images are grabbed (i.e. when $i$ goes from 1 to 4), it is known as the 4-bucket system. Equation (4) then produces four trigonometric equations, which can be solved to eliminate the unknown background intensity $I_{BM}(x,y)$. The phase can then be described as a function of the four intensities by the following equation:

$$\phi(x,y) = \arctan\left(\frac{I_3(x,y) - I_1(x,y)}{I_4(x,y) - I_2(x,y)}\right) \quad (5)$$

The phase difference $\psi(x,y)$ can then be calculated by using the following equation:

$$\psi(x,y) = \phi_b(x,y) - \phi_a(x,y) \quad (6)$$

Where, $\phi_b(x,y)$ and $\phi_a(x,y)$ represent the phase before and after deformation respectively.

The inverse tangent in equation (5) ranges between $-\frac{\pi}{2}$ to $\frac{\pi}{2}$ but does not provide the true phase since values after $\frac{\pi}{2}$ till $\frac{3\pi}{2}$ are not within the limits. Taking into consideration the sign of the sine and cosine solves this problem. If the cosine is negative, hence it will be in the second and third quadrant then $\pi$ is added to the arctangent value to get the correct phase.

The phase difference $\psi(x,y)$ is then calculated using equation (6) and is limited to the range of $-2\pi$ to $2\pi$ and thus contains $4\pi$ discontinuities. This range is then shortened so limit is from 0 to $2\pi$ since a wave repeats itself after every $2\pi$. Taking the absolute of the phase difference is one method of shortening the range but this method produces noise, a second and better method is to add $2\pi$ to the negative result of the subtraction of the two waves.

Once the true phase difference is calculated using the image processing software a phase map will be produced consisting of fringes ranging from black to white and then suddenly changing back to black, this saw tooth pattern continues throughout the image. This drastic change occurs due to the phase difference increasing towards $2\pi$ and then jumping back to zero when the limit of $2\pi$ is reached. This means that in the final image black represents the smallest phase difference and white the largest. The regions where these discontinuities occur are called $2\pi$ discontinuities and these discontinuities are the main characteristics of phase stepping and help determine the relative direction in which deformation takes place.
These phase fringe patterns can be made even more prominent by filtering the image to reduce noise even further. Speckle noise and $2\pi$ discontinuities in phase fringe patterns are characterized by a high spatial frequency so using a low-pass filter will not only reduce noise but also smear the discontinuities, which are vital information. The solution to this problem is to revert back to sine and cosine of the wrapped fringe patterns in equation (5) since these trigonometric functions are continuous unlike the tangent function. The sine and cosine are then filtered separately using an average filter, which takes the average value of a group of neighboring $n \times n$ pixels for each pixel in the image, where $n$ is an odd integer number. The filtered sine and cosine are then put back into equation (5) so that the phase difference can be recalculated. This process of filtering can be repeated up to 30 times. Figure 3 and 4 below shows an unfiltered and filtered phase fringe pattern respectively.

It can be seen from figure 4 as compared to figure 3, that when a $3 \times 3$ average filter is applied the noise is reduced considerably.

4. EXPERIMENTAL APPROACH

The test specimen used to compare the results of Normal Shearographic NDE and Phase-stepping NDE was an Oryx helicopter main rotor blade with known manufactured defects. This is a suitable test specimen, as this technology will eventually be applied to high value engineering components in the airplane industry. The Oryx helicopter uses five main rotor blades, with each blade measuring 7m in length and 600mm in width. Figure 5 shows a picture of the Oryx helicopter main rotor blade. The helicopter blade is made from a composite honeycomb core with a carbon fiber skin construction. The blade is manufactured by first shaping the honeycomb according to the blade profile and then the multiple layers of carbon fiber skin is glued onto the structure. At the trailing edge the upper and lower skins are glued together and riveted. Aircraft grade aluminium skin is then wrapped and bonded around the leading edge to prevent wear. The helicopter blade is then balanced by adding aluminium strips to the trailing edge.
A 140mm length of helicopter blade was cut off to manufacture the test specimen. Three equi-distant 50mm diameter holes were cut out on the bottom surface of the blade using a 50mm circular hole saw, to create the defects. The hole closest to the leading edge was cut to a depth of 22mm; the middle and trailing edge holes were cut to a depth of 28mm and 17mm respectively. The thickness of the blade at those 3 points starting at the leading edge is 54mm, 49mm and 30mm. Therefore the hole closest to the leading edge is the furthest away from the inspected surface (i.e. the top surface of the blade) at a depth of 32mm.

The middle and trailing edge holes are 21mm and 13mm in depth from the inspected surface, making the trailing edge defect easiest to detect. Figure 6 shows the Oryx main blade with the three manufactured defects.

The inspection took place in a laboratory environment on a vibration free optical table. The test specimen was fixed in place on the table with magnets, with the defect free skin facing the Shearographic equipment. A domestic hairdryer was used to thermally stress the test specimen in all inspection procedures.

5. INSPECTION RESULTS

The Oryx main helicopter blade was first tested using Conventional Shearography. The first step was to capture a speckle image of the blade in its unstressed state. The software was then set to real-time mode so that the response of the object could be observed while being stressed. The blade was then stressed, for approximately 5 seconds, using thermal means. This approach allows the user to observe the object during heating and cooling. Best results were obtained during the cooling process.

Figure 6: Test Specimen with three manufactured defects

The middle and trailing edge holes are 21mm and 13mm in depth from the inspected surface, making the trailing edge defect easiest to detect. Figure 6 shows the Oryx main blade with the three manufactured defects.

Figure 7: Image of the trailing edge and middle defect obtained by Normal Shearographic NDE
Figure 7 depicts the Shearographic NDE pattern that is produced while inspecting the trialing edge and middle defects. The presence and location of the manufactured defects are clearly identified by the two “double bulls eyes”. The double bulls eye on the left of figure 7 locates the trialing edge defect whereas the double bulls eye to the right shows the location of the middle defect. It can be seen that the trialing edge fringe pattern is much more prominent than the middle defect, this is due to the trialing edge defect being deeper, and hence easier to detect, than the middle defect. The number of fringes in a defected area does usually indicate the amplitude of the localized displacement induced, which is influenced by size of defect and its depth.

Figure 8 shows the results obtained during different stages of cooling. The images in Figure 8 show that leaving the heated object to cool for a certain time period will produce more fringes. However if too many fringes are formed decorrelation will occur causing the outer fringes to breakdown and smear the fringe pattern. Therefore the correct time to capture speckle interference is left to the experience of the user.

Following the Conventional Shearographic inspection, the test specimen was inspected using Phase-stepped Shearographic NDE. The specimen from the Oryx main rotor blade was placed in the same position as for the Conventional Shearographic inspection. The method and duration of thermal stressing was also duplicated. Two adjustments had to be made for Phase-stepped Shearography: the first was to replace the standard mirror with a piezo-electrically driven mirror in the Michelson interferometer and the second adjustment was to change the mode of the software to Phase-stepped Shearography so that PZT driven mirror could be controlled by the computer allowing four images to be captured. The test procedure that followed is the same as previously described in the Conventional Shearographic inspection process.

Figure 8: Results obtained during different stages of cooling in Conventional Shearographic NDE. Image 8(a) was captured after 15 seconds of cooling, with a single fringe manifesting, image 8(b) was captured after 22 seconds of cooling, with two fringes manifesting, image 8(c) was captured after 30 seconds of cooling, with three fringes manifesting and image 8(d) was captured after 42 seconds of cooling, with four fringes manifesting.
Figure 9 shows the unfiltered results obtained by Phase-stepped Shearographic NDE. The two “double bulls eyes” can be seen once again revealing the presence and location of the manufactured defects. The more prominent double bulls eye on the left is the trailing edge defect and the one on the right is the middle defect. The Phase-stepped Shearographic NDE fringe patterns appear much more clear and prominent due to the reduction in noise accomplished by capturing and comparing four interferograms instead of one, as in Conventional Shearographic NDE. The \(2\pi\) discontinuities can also be seen in figure 9 where there is a drastic change from black to white and vice versa.

Figure 9: Image of trailing edge and middle defect, unfiltered, by Phase-stepped Shearographic NDE

Figure 10 depicts the Phase-stepped Shearographic NDE results obtained after the image had been filtered using a \(3 \times 3\) sine and cosine average filter. It can be seen that the fringe patterns are even more prominent and the grayscale is much smoother due to the filter averaging pixels in a \(3 \times 3\) neighborhood. Filtering the image also makes the \(2\pi\) discontinuities more visible. Smearing of the dense fringes on the right of Figure 10 can also be seen due to over filtering of the image and can be prevented by using other filtering methods or by reducing the number of loops of the filter.

Figure 10: Filtered result of trailing edge and middle defect by Phase-stepped Shearographic NDE
Figure 11 (a)-(d) depicts the results obtained by Phase-Stepped Shearographic NDE during the cooling process following a similar time period as the images in figure 8. It can again be seen that if the object is left to cool for a longer period of time more fringes will be formed.

Figure 11: Images of the cooling process during Phase-stepped Shearography. (a) One fringe after 15 seconds of cooling, (b) two fringes after 22 seconds of cooling (c) three fringes after 30 seconds of cooling, (d) four fringes after 42 seconds of cooling.
For completeness, Figure 12 depicts the four images in figure 11 after being filtered by a $3 \times 3$ sine and cosine average filter.

Figure 12: Filtered images of the cooling process in Phase-stepped Shearographic NDE. (a) One fringe after 15 seconds of cooling, (b) two fringes after 22 seconds of cooling, (c) three fringes after 30 seconds of cooling, (d) four fringes after 42 seconds of cooling.
6. CONCLUSION

From the results it is clear that both Conventional Shearography and Phase-Stepped Shearography are capable of detecting defects in engineering components. Both techniques performed well in the laboratory environment and being able to monitor the response of the object, when stressed, in real-time was particularly advantageous.

The results obtained show that both techniques produce a similar number of fringes when a specific defect was being observed. However the fringe patterns produced by Phase-stepped Shearography were much more prominent due to four interferograms being captured as compared to Normal Shearography, which uses only one interferogram. The use of four images instead of one and the $2\pi$ discontinuities created by the 4-bucket system drastically reduced the noise in the fringe patterns making Phase-stepped Shearography much more sensitive then Conventional Shearography and is also more suitable for phase unwrapping. The other advantage of Phase-stepped Shearography is that one can interpolate displacement rates between fringes, which is not possible in Conventional Shearography due to the sinusoidal nature of its interference fringe patterns.

The Phase-stepped Shearographic NDE results were then enhanced even further by the application of a sine and cosine average filter. The filter not only provided a greater reduction in noise but also made the image grayscale much smoother so that fringe definition would improve, however one has to be cautious not to over filter the image and thereby destroy valuable information.

It can be concluded that Phase-Stepped Shearographic NDE is a more than adequate method of increasing the sensitivity of the Conventional Shearographic inspection at a relatively small cost.

REFERENCES


