Evaluating Low Cost Portable Shearography on Aircraft Components

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Abstract. Non destructive testing is an important application in the production of safety critical components and the maintenance thereof. Digital Shearography is an emerging NDT technique, particularly suited for the detection of defects within composite structures as found for example in the aircraft and aerospace industries. This paper presents the initial results of a project aimed at developing a low cost portable NDT prototype based on the principles of digital Shearography. As part of the cost saving measures the system is designed to operate off a laptop using a FireWire interface.

The final system is used to inspect a helicopter rotor blade section and a UAV wing section for man made defects. The results are presented and discussed and clearly indicate that the prototype detects all the defects and is able to present the results in various forms including a 3D displacement gradient map. The paper is concluded with an analysis of the performance of the prototype.

Introduction

Non-destructive Testing (NDT) forms an important part of the production and maintenance cycles of safety-critical components in many industries. While aerospace, automotive and defense-related industries are making increased use of composite materials in their most demanding applications, it is often realized that conventional NDT techniques are not suited for the inspection of these composites and there thus is a lack of NDT techniques suited for these components. There are emerging NDT techniques such as Infra-red Thermography and Digital Shearography which show promising results when applied to composite structures.

Two factors however hinder the acceptance and adoption of such techniques for NDT inspection purposes, particularly in the aerospace industry. The first is the recognition and inclusion of such techniques into the manufacturer prescribed maintenance procedures and the second is the usually prohibitively high cost of the NDT equipment. The first can be addressed via a structured certification process to validate the emerging NDT methods as suitable complimentary inspection techniques. This paper attempts to address the cost factor issue by presenting a low cost digital shearography prototype.

Digital Shearography is an optical, non-destructive testing technique, suitable for the detection of a range of defects including delaminations and debonds, cracks, corrosion, moisture ingress and porosity, to name but a few. The University of Cape Town’s NDT Laboratory has been involved in the research and development of optical interference techniques for many years, culminating in the development of a number of portable Digital Shearography testing units as well as a portable ESPI system [1]. Up to this point, interest
in this technique has been largely on a research level owing to its cost and complexity and the results have been documented in a number of papers [1,2,3].

Figure 1: Existing Portable Digital Shearography Unit

Advances in digital camera technology, camera interfacing protocols and software programming environments have made it possible to consider using “entry level” technologies coupled to an off-the-shelf laptop to produce a fully functional digital shearography prototype. In addition it was decided to refrain from using proprietary 3rd party software in order to avoid expensive development and run time license fees. This paper outlines the progress of this project.

Theory

Digital Shearography was originally developed for strain measurement as it is an optical interference technique used to reveal an object’s surface displacement gradient in response to an applied stress. There are many ways to stress the object during the inspection process, the most common being thermal, pressure or vacuum stressing. Each object to be tested possesses unique structural or material characteristics and there thus is no standardized inspection procedure or object loading method suitable for all types of composites to be inspected. As the technique is so sensitive to the resultant displacements, the magnitude of the applied stress is very small, making it a truly non destructive inspection technique.

Because defects in objects usually induce strain concentrations due to structural weakening, the presence of a surface or subsurface defect is easily revealed as strain anomalies or concentrations within the displacement gradient pattern. Moreover, a rigid-body motion is not associated with a strain, thus shearography is desensitized to such displacements. This is an important advantage of shearography, and improves the suitability of the technique for in-situ applications.

The shearography technique is based on the recording of speckle images, created when two light waves interfere with one another [4]. In order for this to occur, the light waves have to be monochromatic, which is why single mode lasers are employed. The expanded laser beam is used to illuminate the object. A video camera is 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 below, 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 interfere with each other and produce a speckle pattern which can be captured and digitized using a PC.

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 de-correlation between the two images. This produces a familiar zebra-like fringe pattern. For Shearography this can be represented mathematically by equation 1 below [5].

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

(1)

where:

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

Equation 1 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 2,

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

(2)

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.

The above process produces intensity based fringe patterns, which do not provide any information regarding the direction of the object displacement rate. In order to quantify this, the phase of the laser can be modulated using a technique called phase stepping. Using the micro phase stepper, 4 instead of only 1 images are captured both before and after the image is stressed. Between each image acquisition the stepper mirror is adjusted by an
amount equal to an increase of $(\lambda/4)$ of the beam path length, which corresponds to a phase change of $(\pi/2)$ in the image. The intensities of the 4 images can be represented in equation 3 as follows [6]:

$$I_i(x, y) = I_B(x, y) + I_{MP}(x, y) \cos(\theta(x, y) + i \cdot \pi / 2)$$  \hspace{1cm} (3)

$$\phi(x, y) = \arctan\left( \frac{I_3(x, y) - I_1(x, y)}{I_4(x, y) - I_2(x, y)} \right)$$ \hspace{1cm} (4)

$$\beta(x, y) = \phi_a(x, y) - \phi_b(x, y)$$ \hspace{1cm} (5)

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 4 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 5 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. Equation 2 can be used to determine the magnitude of the displacement gradient.

**Method**

A discussion of the cost of a typical shearography system requires some knowledge of the hardware typically used. The following components (also illustrated in Figure 2) contribute significantly to the overall cost:

i. A high resolution digital camera, lens and framegrabber.

ii. A selection of optics.

iii. A monochrome, coherent laser to illuminate the specimen.

iv. A piezoelectric actuator and controller (PC card).

v. A purpose built computer for housing the PC cards, as well as manipulation, display and storage of real-time video.

The University’s existing portable shearography system uses two PCI cards. The cards not only contribute to the cost of the system, but also necessitate the use of a purpose built portable PC instead of a laptop, which makes the final solution heavier, but does not limit the portability of the technique. Figure 3, on the following page, shows the conceptual layout of the existing unit.
The new unit uses a 1.3 mega-pixel CMOS FireWire camera. The advantage to using FireWire cameras in portable applications is that they derive their power from the FireWire bus, and do not require host PC modifications, as many PC’s and laptops come equipped with FireWire ports. These cameras are also significantly cheaper than their CCD and Camera Link equivalents. An epoxy-sealed, unloaded piezoelectric (PZT) actuator was used in a custom-made housing. These unpackaged PZT’s are more cost effective than their preloaded alternatives.

Another cost reduction is achieved through the use of a custom-designed controller circuit board, which acts as both a digital-to-analogue converter for the PZT and a power regulator for the laser. It derives power from the camera’s power bus and communicates with the host PC via the same FireWire cable. Thus the entire shearography system operates from a single FireWire cable. In the case of a laptop operation, auxiliary power may be supplied using a 12V DC connector. Figure 4 below illustrates the solution.

Finally, the software application was rewritten using Microsoft C++ library routines in order to eliminate the use of expensive imaging libraries.
Results

The final prototype was tested on 2 aircraft components as shown in Figure 5 below. The first is a helicopter rotor blade section which is constructed of a shaped honeycomb core and covered with a carbon fibre skin. The leading edge of the blade is protected with bonded stainless steel sheeting, which is shaped to the profile of the blade. 9 defects were artificially introduced into the blade section by cutting 38 mm holes into one side of the blade, each to a different depth. The second sample used was a UAV wing section, made of fibreglass and honeycomb laminate. A low impact damage section was created by marginally crushing a 25 mm circular section of the bond between the honeycomb and inner skin.

Both samples were inspected from the defect free side and were stressed thermally using an infra-red heating lamp, as seen in Figure 6 above. The results of the inspection process can be seen below. Figure 7a clearly depicts the 9 phase stepped bulls-eye fringe patterns, revealing the presence and location of the man-made defects. The varying levels of fringe density indicate the changing degree of severity of each defect. Figure 7b is the filtered result of the first image. The result is a significant improvement on Figure 7a and the image contains the important fringe discontinuities required for the automated phase unwrapping sequence, the result of which is shown in Figure 8a below.
The software routine successfully unwrapped the displacement gradients into a greyscale map, which when converted into a 3D pseudo colour map as seen in Figure 8b displays both the overall object displacement gradient as well as the localised maxima and minima displacement gradients associated with each defect.

The UAV results similarly confirmed that the prototype successfully completed the inspection process. As seen in Figures 9a and b, the presence of a defect within the global displacement gradient in response to the thermal stressing is clearly visible, both in the fringe intensity result and the phase map result. Both samples were first heated from behind and then inspected whilst cooling. The displacement gradients captured correctly identify the direction of the out-of-plane gradient as being negative when the image is scanned from left to right. Figure 10b, the unwrapped 3D displacement gradient map, supports this.
Discussion

The developed test unit achieved a significant cost reduction, in the order of 50%, by using lower cost components where available, a higher level of OEM integration, and custom-written software. Its performance was satisfactory, acquiring conventional intensity-based and phase-stepped interference images which were used to successfully detect flaws in two different aerospace components. The phase-stepped images that were obtained were of sufficient quality to be filtered and phase-unwrapped to reveal the surface displacements.

In comparison to the existing shearography implementation, the new testing unit produced images that are of a slightly lower quality, particularly in conventional intensity-based shearography. The FireWire camera exhibits a poorer signal to noise ratio and appears to be less sensitive than the CameraLink version used in the prior prototype. It was also noted that the repeatability of the phase stepping module, if used over an extended period of time, needs to be investigated, as a minimal amount drift in the preset PZT steps was noted. The impact of these two aspects is marginal though, as the unit produced perfectly usable results.

References

[1] D Findeis, J Gryzagoridis, E Xaba, D Reid-Rowland, “Aircraft tires inspection using portable shearography and electronics speckle pattern interferometry” Non-Destructive Testing Laboratory, University of Cape Town, pp1, 2000


