Simultaneous Shearographic and Thermographic NDT of Aerospace materials

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Abstract

The paper describes the simultaneous use of Digital Shearographic and Infrared Thermographic techniques when testing aerospace structures made of honeycomb and composite materials. Non Destructive Testing of the structures was accomplished using a proprietary portable Shearographic system, produced at the Mechanical Engineering department of the University of Cape Town, and a relatively inexpensive new comer to the Infrared Thermography field, known as IRISYS Universal Thermal Imager. Simply, both systems were employed to image the component simultaneously and record the effect of it cooling down after heated with the hot air from a hair drier or a heating lamp. The techniques proved effective in identifying defects such as the crushed honeycomb core in a section of the wing of an unmanned aerial vehicle (UAV) and the de-laminations at different depths in the main rotor blade of an Oryx helicopter. The images indicating the defects as produced by the Shearographic system are visually more dramatic, particularly when enhanced by phase stepping and colour techniques. On the other hand the Thermographic images besides indicating the position of the flaw, gave information regarding the temperature of the region of the defect relative to the cooler surrounding material. In addition there was the indication that during the cooling down, the infrared system continued to indicate the presence of the flaws/defects for longer period of time than the Shearographic system. It is suggested that in similar tests, the temperature data be coupled to the out of plane displacement gradients with view to provide quantitative thermal stress results.

1. Introduction

Non-Destructive Evaluation technology that combines the features of remote means of full field examination and rapid qualitative analysis of defects on a given component, requiring only visual access to its surface, must be of interest to aircraft maintenance.

1.1 Digital Shearography

Digital Shearographic Speckle Interferometry (DSSI) NDT is an emerging technique very well suited for the inspection of components in the aerospace industry. It is a laser based speckle interferometer optical technique, originally developed for strain measurement. The technique is highly sensitive to surface displacement gradients, resulting from subsurface flaws associated with internal de-bonds, de-laminations and
cracks. A typical configuration of electronic/digital Shearography is illustrated in Fig. 1 featuring an image shearing device. There are several image shearing devices described in the literature, as for example the one shown in Fig. 2, illustrating the principle.

Figure 1. Schematic diagram of typical Shearography set-up

Figure 2. Image Shearing device based on the Michelson interferometer
Jones and Wykes (1) give an excellent treatise on the subject of speckle interferometry with regard to the measurement of surface displacements, gradients and applications in the Non Destructive Field. The Shearographic NDT technique relies on examining the result of digitally subtracting two images of an object under test, which were obtained with mild stressing of the object. This mild stressing in fact, changes the dimensions of the object which has an effect on the intensity of the speckled image. (Surfaces illuminated with a laser have a characteristic granular appearance). The intensity of an object’s image, resulting from the subtraction of the intensities of two images, one obtained before and one subsequent to some form of mild stressing, is given by the following expression:

\[ I_r = I_i - I_f = 4\sqrt{I_1 I_2} \sin \left( \theta_1 - \theta_2 \right) \sin \frac{1}{2} \Delta \varphi \]  

where \( I_i, I_f \) are the intensities of the object’s images before and after stressing, and \( \Delta \varphi \) is the phase change that occurs due to the speckle pattern being altered. A modified Michelson interferometer as shown in figure 2 will yield fringes that indicate surface displacement gradients. The intensity at a point \( p \), in the common portion of the sheared image (along the x axis), is the result of superposition of light scattered from two adjacent points separated by a small distance \( S \). When the object is stressed the surface will deform and the phase of the light arriving at \( p \) would have emanated from the two points of the surface that are displaced by different amounts. The out-of-plane surface displacement \( \Delta \delta p \) of the point in question, can be approximated by the following expression when neglecting the higher order derivatives since the separation \( S \) of the two adjacent points on the surface contributing to the illumination at \( p \) is relatively small.

\[ \Delta \delta p = \delta p(x+dx) - \delta p(x) = \frac{\partial^2 \delta p}{\partial x^2} S^2 + \frac{\partial^2 \delta p}{\partial x^2} S^2 + \ldots \]  

The phase of the light arriving at \( p \) will suffer a phase change given by

\[ \Delta \varphi = 4 \pi \frac{\Delta \delta p}{\lambda} \]  

Where \( \Delta \delta p \) and \( \lambda \) are the out-of-plane (normal) surface displacement contribution of the two points on the image (illuminating point \( p \)) and the wavelength of light source respectively. The maximum correlation of the wave-fronts and therefore the creation of (black) interference fringes occur when the resulting intensity of the difference of the two images is zero, implying that in equation (1) \( \sin \Delta \varphi \) must be zero therefore

\[ \Delta \varphi = 2N\pi \quad N= 0,1,2,3 \]  

Combining equations 2, 3, and 4 we obtain the normal displacement gradient

\[ \frac{\partial \delta p}{\partial x} = \lambda N / 2S \]
A number of fringes (N), that appear superimposed on the image of the surface of the object under test, are lines of constant gradients of out-of-plane surface displacements, along the direction of the shear or lateral shift created by tilting one of the mirrors of the modified Michelson interferometer. Clearly the sensitivity of the instrument depends on the amount of tilt of the mirror and hence the value of shift S. Furthermore by enabling a pan control on the mirror (see figure 2) in addition to the tilt, gradients in any direction are obtainable. Shearographic measurements are achieved practically in real time and are relatively insensitive to environmental vibration, thereby making the equipment portable and therefore suitable to use in the industrial/production environment. Figure 3 depicts the second in the series of portable Shearographic prototypes developed by the authors. More recent developments have introduced a technique known as Phase-stepping which involves the controlled micro-displacement of one of the mirrors, in the Shearographic set-up, by means of a calibrated piezoelectric transducer. Each micro-displacement of the mirror introduces a phase step of a quarter of the wavelength of the laser beam. Subsequently to the mirror being advanced through four steps it is returned to its initial position. After each phase-step a speckle pattern is captured by the imaging system and the phase of the speckle pattern is calculated using the four images with a suitable algorithm. The phase difference before and after deformation is calculated from these two sets of four images and using the image processing software a phase map will be produced consisting of fringes that range from black to white and suddenly back to black in a “saw tooth pattern” throughout the image. The nature of the technique requires, as mentioned above, minute stressing of the component prior to the capture of the second set of four images. The stressing of the object may be accomplished in many instances by mild heating with the hot air from a hair drier or the radiant heat from a heating lamp. Obviously if this form of stressing an object is employed, the surface displacements are in fact thermal expansions and therefore strains generating thermal stresses.

Structures fabricated using composite techniques i.e. fiber reinforced composite materials, tend to behave extremely well under Infrared Thermographic examinations. The reason is that because of the nature of these materials, damage mechanisms such as impact for example, create flaws or discontinuities on them which are parallel to the surface and thus provide resistance to the heat flow. In addition, these materials have low thermal diffusivity modulus which permits or allows a reasonable time to observe the heat flow and the capture of images of the object’s behaviour under test.

1.2 Infrared Thermography

Infrared Thermographic systems have been used for the detection of impact damage in aerospace structures made from honeycomb and composites. These systems operate in real time producing pictures known as thermograms through optics that are sensitive to infrared radiation. Thermographic non-destructive testing is performed in active or passive modes. Active mode involves the mild heating or cooling of the object and
observing the transient heat flow generating thermal gradients and therefore developing a transient thermogram. Defects in an object are warmer than the surrounding material because of their inability to transfer the heat readily and therefore will appear as bright spots surrounded by a cooler material normally depicted as dark background. A given surface radiates an amount of thermal energy at a given temperature as a function of its emissivity, a property that relates this amount to the idealised maximum that a “black body” is capable of emitting. Since variations of infrared intensity are related to surface temperatures it is imperative that the surface under test possesses uniform emissivity. Typical Thermographic instruments have a sensitivity of 0.05 °C or better and variations of emissivity across the surface can cause false indications. Therefore uniform emissivity is required to ensure accuracy in temperature measurement, while high values of emissivity ensure greater radiant intensity and easier detection by the instrument’s sensor. When the temperature of a portion of the surface of a body is uniformly increased, the body expands locally under the influence of the material’s coefficient of thermal expansion $\alpha$, and the temperature difference $\Delta T$ between the heated and unheated portions of the surface. A localized thermal stress $\sigma_t$, will develop because of the existence of the temperature difference

$$\sigma_t = \varepsilon E = \alpha(\Delta T)E \quad \text{.................................} \quad (6)$$

where $\sigma_t$ denotes the thermal stress, $\varepsilon$ is the local strain the material experiences due to thermal expansion and $E$ is the Young’s modulus. Just as the elastic properties of composite materials tend to be anisotropic, their thermal properties are frequently different between the fibre reinforcements and the matrix. To complicate matters further some carbon fibre composites exhibit different coefficients of thermal expansion in the directions of the material symmetry axes, hence affecting the thermal stress corresponding to these directions. The prospect of measuring different expansion in different directions can perhaps be facilitated because of Shearography’s ability to indicate or measure strain in any desired direction. Substituting expression 5 for the local strain into equation 6 yields a useful expression for the determination of the coefficient of thermal expansion along any direction chosen.

$$\alpha = (\lambda \ N / 2S) / \Delta T \quad \text{........................................} \quad (7)$$

2. Experimental procedure and results

The experiments were conducted in the NDT laboratory using our proprietary Shearographic apparatus which is also equipped to perform the phase stepping technique. The Shearographic “head” was positioned on the laboratory’s optical table facing the test specimens and linked to the personal computer. The computer is also equipped, in addition to the customary hardware, with a Matrox digitizer, a phase stepper and contains our own software which is used to control the Shearographic data acquisition, perform the phase stepping technique and enhance the images with colour and filtering routines. The test pieces utilized in this study were prepared from the wing of an unmanned aerial vehicle (UAV) and the main rotor blade of an Oryx helicopter. The defects, such as the crushed honeycomb core in the section of the wing of the (UAV) and the de-laminations at different depths in the main rotor blade of the Oryx
helicopter were simultaneously exposed to Shearographic and Thermographic testing. For example figure 4 depicts the UAV test specimen (in the background) resting on the optical table illuminated with the Helium-Neon (HeNe) laser, with the Shearographic system’s optical head (right) and the IRISYS Thermal system (left), in the foreground.

Figure 4. UAV test specimen viewed with DSSI and Thermography systems

The experiments were performed following a testing procedure which consisted of initially acquiring and storing in the computer an image of the test specimen. This image would act as the reference state for the Digital Shearography testing. Following the mild heating of the specimen (from the rear) using a heating lamp for a specified short time interval the “defects” became visible. Almost instantaneously the specimens reacted to the radiant heat which was typically applied for the duration of a few seconds (between 2 and 5 seconds). The characteristic signature of the thermal image (bright = hot spots, surrounded by dark = cooler material) was visible simultaneously with the typical live Shearographic fringe pattern. Within a few seconds after turning off the heating lamp, sufficient fringes had developed for the second Shearographic image to be captured and stored in the computer, while at the same instant we attempted to capture and store the corresponding image which was being displayed in the screen of the IRISYS Thermal Imager’s PDA. The results from the testing proved fairly rewarding and promising. The following figures (5 to 10) depict typical results obtained during the experiments with the “flawed” specimens. They are presented in a hierarchical order so as to highlight various aspects on the subject of this paper.
Figure 5. UAV test specimen showing location of impact damage from left to right in an Intensity, Phase stepped and filtered Phased stepped DSSI images.

Figure 6. Oryx test specimen showing location of de-lamination in Phase stepped and colour Phased stepped DSSI images. Horizontal shear, approx. 5 sec heating

Figure 7. Oryx test specimen showing location of de-lamination in Phase stepped and colour Phased stepped DSSI images. Vertical hear, approx. 5 sec heating
Figure 8. Oryx test specimen showing location of de-lamination in colour filtered Phased stepped DSSI images obtained with horizontal and vertical shear respectively. Approx. 2.5 seconds of heating on the far side.

Figure 9. Oryx test specimen showing location of two de-laminations in Phased stepped and filtered Phased stepped DSSI images, together with the corresponding image from the IRISYS Thermal Imager.
3. Conclusions

The objective of the experiments was to test the hypothesis that the non-destructive testing of composite materials employing simultaneously DSSI and Thermal imaging techniques could yield information regarding the location of flaws/defects. In addition by combining the information yielded by the results from both techniques, bearing in mind that thermal stressing of the object was effected, thermal stresses on the component and directional thermal expansion coefficients on the material could be deduced. The evidence as shown in figures 5 to 10 confirms indisputably that both techniques, that is DSSI and Thermography, detect and display quite readily the location of discontinuities that could be flaws or defects in composite materials. The indication of the presence of a defect is quite dramatic in the form of fringes in the interferograms manifested by the DSSI testing, particularly if a phase stepped technique has been applied with colour and filtering routines (figures 5-8), or the contrast of colour between hot spots (defects) and surrounding cool undamaged material as depicted in the thermograms (figures 9-10) produced by the IRISYS Thermal Imager. There was evidence that during the cooling down of the specimens, the infrared system continued to indicate the presence of the flaw/defect for longer period of time than the Shearographic system. The amount of heating of the specimen as expected has a direct effect on the number of fringes that one observes in the Shearogram and the colour contrast in the corresponding Thermogram. In fig. 9 we observe two delaminations which are at different depths in the specimen, therefore it is not surprising that the one closer to the surface would exhibit more fringes in the Shearogram and brighter colour in the Thermogram by comparison to its companion, because the surface above it would
get hot quicker. It is therefore possible to quantify the depth of de-lamination below the surface by the number of fringes or the temperature indicated above it. Attempts to deduce the thermal stress or calculate the directional thermal expansion coefficient of the material were shelved because doubtful data accuracy. Although the results were repeatable, in that the trend did not change with repeated trials, their accuracy is in dispute on account of human error in the synchronization and timing of the events. For example during repeated tests uncertainty was noted in the exact time period of heating the specimen with the lamp, the record of subsequent time lapse until the exact moment of “grabbing” the Shearographic image, which should also coincide with the freezing and storing of the image displayed by the Thermography equipment, the latter being a very critical event. It is felt that there is great potential in exploring further this technique, therefore effort is currently being directed toward linking the two systems electronically by devising a reliable timing and critical events synchronization method to be supported by the computer controlling the Shearography system.

References

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