Studies on Digital Shearography for Testing of Aircraft Composite and Honeycomb Structures

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Abstract. This paper reviews shearography and its applications for testing of aircraft composite and honeycomb structures. Shearography is a laser-based interferometry in conjunction with the digital imaging processing technique for full-field measurement of surface deformation. It reveals defects in an object by looking for defect-induced deformation anomalies. It does not require special vibration isolation, and with the development of a compact and mobile measuring device (portable inspection system), it can be employed easily in field/factory environments.

Keywords: NDT; Shearography; Composite material; Aircraft

1 Introduction

Carbon fiber composite (CFC) and other lightweight constructions are used more and more for the production of aircraft parts. Modern aircraft is already equipped with such components as in the vertical and horizontal stabilizer, rudder, airbrakes and spoiler. Aircraft structures are exposed to severe in-service conditions. In order to receive a high safety of operation, possible damages must be recognized in early stages to prevent the total breakdown of the component. Consequently, non-destructive testing (NDT) is a vital process to ensure structural integrity, the investigation with respect to material and construction imperfections is of high interest.

Due to the diversity and complexity of aircraft components, the modern test engineer must become skilled in several complementary inspection methods. Optical NDT is an area that is likely to experience increasing interest for the inspection of composite materials. It offers several advantages over conventional ultrasonic inspection and many of the technical problems that have prevented its industrialization in the past have now been overcome. Electronic speckle pattern interferometry (ESPI) was used industrially for some time for vibration analysis. Unfortunately, ESPI is of limited value for NDT because of its extreme sensitivity to the environment. Laser shearography, on the other hand, overcomes the disadvantage of ESPI. The use of sheared wave fronts provides the advantage that the fringes depict changes in surface slope, rather than out-of-plane displacement. The potential advantages of shearography inspection are: (a) rapid large area inspection; (b) non-contact testing without immersion of the component or the use of water jets; (c) ability to inspect
regions that attenuate or scatter ultrasound; (d) ability to indicate structural strength in addition to providing passive defect detection\cite{1-4}.

2. Theoretical analysis

The principle of shearography is shown in Figure 1. Speckle shearography is a reliable coherent-optical method for the nondestructive testing of technical components with respect to surface and sub-surface flaws. In shearography systems, the object under investigation is illuminated by an expanded laser beam, forming a speckle pattern if the object surface is optically rough. The speckle pattern is optically processed by viewing through a shearing interferometer, and the resulting interferogram is recorded by an electronic sensor (e.g. CCD camera). Speckle interferograms, recorded before and after object deformation, are correlated, using a PC, to yield correlation fringes. The phase of these fringes is sensitive to the displacement gradient.

![Shearing Diagram](image)

Figure 1. Typical setup of shearography.

The key of shearography is ‘shearing’. Figure 2 shows the principle of shearing, and gives the calculation equation of image shear $\delta'_x$, and the object shear $\delta_x$. The point A and B is all on the object plane, they focus on one point in the image plane. The image shear $\delta'_x$ can be expressed as

$$\delta'_x = D_i(\mu - 1)\alpha$$

where $D_i$ - image distance; $\mu$ - refraction rate of the wedge; $\alpha$ - angle of wedge.

![Shearing Diagram](image)

Figure 2. Shearing Diagram.

The object shear $\delta_x$ is
If we assume an image shear $\delta_x$ in $x$ direction, the resulting intensity distribution before loading $I_1(x, y)$ can be written as

$$I_1(x, y) = U_o^2(x, y) + U_r^2(x, y) + 2U_o(x, y)U_r(x, y)\cos[\varphi_o(x, y) - \varphi_r(x, y)]$$

$$= U_o^2(x, y) + U_r^2(x, y) + 2U_o(x, y)U_r(x, y)\cos\Delta\varphi(x, y)$$

where $U_o(x, y)$ is the amplitude of object light, and $U_r(x, y)$ is the amplitude of reference light. $\varphi_o(x, y)$ is the phase of object light, $\varphi_r(x, y)$ is phase of the reference light.

Some time later, the object is stressed. The resulting intensity distribution is given by

$$I_2(x, y) = U_o^2(x, y) + U_r^2(x, y) + 2U_o(x, y)U_r(x, y)\cos[\varphi_o(x, y) - \varphi_r(x, y) + \Delta\psi(x, y)]$$

Here $\Delta\psi(x, y)$ give the phase differences between the phases of the interfering speckle patterns for the first and the second speckle shear interferograms.

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:

$$I(x, y) = |I_1(x, y) - I_2(x, y)|$$

$$= 4|U_o(x, y)U_r(x, y)|\sin[\Delta\varphi(x, y) + \frac{\Delta\psi(x, y)}{2}]\sin\frac{\Delta\varphi(x, y)}{2}$$

Subtraction immediately eliminates the bias term since it is common to both images. The result is a high spatial frequency carrier term $\sin[\Delta\varphi(x, y) + \frac{\Delta\psi(x, y)}{2}]$, amplitude modulated by a low frequency term, $\sin[\frac{\Delta\psi(x, y)}{2}]$. The carrier is nullified when

$$\sin[\frac{\Delta\psi(x, y)}{2}] = 0$$

or,$$\Delta\psi(x, y) = 2n\pi$$

where the fringe order $n = 0, 1, 2, 3, \ldots$. Although $\Delta\psi(x, y)$ retains the sign, or direction, of deformation, carrier nullification occurs identically for positive or negative values; hence, all sign information is lost and fringes depict only the absolute value of the differential displacement.

3 Experimental arrangement

A laboratory system was developed first, where a He-Ne Laser generator was used, with output power and wavelength being 50mW and 632.8nm, respectively. Specimen A of
350mm×180mm×20mm of glass fiber reinforced plastic skin and paper honeycomb was inspected by the system. In Figure 3 is shown the image, where the dark stripes represent the case of $n = 0,1,2,3, \ldots$, for $\Delta \psi(x, y) = 2n\pi$, as above-mentioned.

In Figure 4 is shown the fringe pattern of a vacuum expanding specimen B (aluminum-aluminum honeycomb with skin-to-core disbonding). A 200 mm by 200 mm section is examined with horizontal shearing. Each honeycomb cell, measuring by 6 mm by 6 mm, appears as a small double bull eyes in the horizontal direction. The skin-to-core disbonding is shown as a large anomaly.

4 Portable inspection system

In many cases, for example, maintenance or assembly of aircraft, it is not possible to transport the part to be inspected into a stationary test system. For such purposes, a portable shearography inspection system has successfully been developed and used in field inspection. In figure 5 and 6, such a system is presented. It consists of a heating lamp, which shines directly to the surface to be inspected. Debondings or other defects will show up in typical deformation patterns. The operator can view the inspection result with a notebook pc and therefore is flexible to operate on scaffolds or inside openings.
Some inspection results are shown in figure 7 and figure 8.

![Fig.7 Shearography image, after heating for 5 seconds.](image1)

![Fig.8 Shearography image, after heating for 10 seconds.](image2)

5 Conclusion

Both stationary and portable laser shearography systems are developed by present authors for the purpose of inspection of composite structures of aircrafts under rough industrial conditions. It could be validated, that if optimized, shearography can be used really under daylight conditions and still can give precise indications of flaws in a wide variety of inspection situations, even under harsh environmental conditions. The systems were demonstrated under real and unusual rough conditions and showed a great potential in future applications. With the described work a new milestone was set for the acceptance of optical testing in real aircraft maintenance.

References


