ELECTRONIC SHEAROGRAPHY: CURRENT CAPABILITIES, POTENTIAL LIMITATIONS, AND FUTURE POSSIBILITIES FOR INDUSTRIAL NONDESTRUCTIVE INSPECTION

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INTRODUCTION

Image-shearing speckle pattern interferometry, more commonly referred to as 'shearography', is a full-field, laser-based interferometric technique first developed for applications in experimental mechanics [1,2]. Shearography is sensitive to derivatives of the out-of-plane surface displacement of a body under load, as opposed to other full-field methods such as holographic interferometry and conventional speckle pattern interferometry, which typically contour the surface displacement directly [3]. The early shearography experiments used high-resolution photographic film to record images of the laser speckle patterns. In contrast to traditional film-based techniques, electronic shearography uses an electronic camera for image recording [4]. This technology, commercially available for the past several years, has received much interest within the NDE community because of its potential for rapid, non-contacting optical inspection of large areas. While there are advantages and disadvantages specific to either imaging medium, electronic shearography is the clear choice for industrial inspection because image acquisition and processing is accomplished at a video frame rate of 30 Hz to produce shearographic fringe patterns in real time. Real-time inspection is not possible with film-based shearography, which requires time-consuming development of the filmplate and optical high pass filtering for readout of the fringe patterns.

Electronic shearography is a 'self-referencing' common-path interferometric method, as shown in Fig. 1. Beamsplitting is performed by the shearing optics such that a double image of the object is formed on the CCD sensor by the imaging lens (usually a commercial camera lens). The direction and magnitude of the image separation, or 'shear', is determined by the orientation of the shearing optics. The two wavefronts, labeled as 'sheared' and 'unsheared' in Fig. 1, are coherently added in the image plane to produce a speckle interference pattern that represents a unique spatial signature of the topography of the object's surface. Any deformation of the target surface alters the speckle interference pattern accordingly.
The basic strategy for shearographic NDE involves first storing a speckle interference pattern (reference image) from the test object at rest and then applying a controlled load or excitation to the object. The CCD camera records the speckle interference pattern as it changes in response to the applied load, and digital subtraction of each new speckle pattern image from the original reference image produces a shearographic fringe pattern that contours the derivative, with respect to the shearing direction, of the out-of-plane displacement induced by the loading. The digital frame subtraction is performed at the frame rate of the camera by an arithmetic logic unit (ALU) resident on the frame-grabber board. The fringe pattern is updated at 30 Hz and the effect of the applied load may be viewed in real time.

Successful flaw detection hinges on the proper choice of a stressing technique that will generate a distinct artifact in the fringe pattern in the presence of a defect in the sample. Heating, vibration, pressurization (or depressurization), and mechanical point loading have proven useful for NDE with shearography, as well as other full-field interferometric techniques [5]. For simple test structures the choice of an excitation method often is intuitively straightforward. However, for complex geometries, finite element modeling is an invaluable aid in predicting an effective loading strategy, because the extent of the surface deformation in the vicinity of a defect depends on the nature of the applied load as well as the structural geometry and material properties of the test sample.

This paper will examine certain characteristics of the laser, digital imaging and computer systems that are integral to electronic shearography. The objective is to assess how these parameters influence present-day performance of electronic shearography for NDE and deduce what the future might hold in light of potential technological enhancements.

PRACTICAL ADVANTAGES OF ELECTRONIC SHEAROGRAPHY

The option to select the direction and magnitude of the image shear lends considerable versatility to shearography. The orientation of the image shear can be varied by adjustment of the shearing optics to permit contouring the displacement derivative with respect to any direction across the test object. Depending on the nature of the stressing and the sample geometry, the choice of shearing direction may have a dramatic effect on the shearographic response, as illustrated in Fig. 2. The sample was a carbon-carbon composite plate (38 cm wide, 28 cm tall, 3.8 mm thick) that was acoustically excited by a piezoelectric shaker table. The excitation frequency of the shaker table was scanned during the inspection to locate the resonant frequencies of the panel. The modal patterns corresponding to the strongest detected resonance are shown in Fig. 2. Both images...
Figure 2. Shearographic modal patterns of a stiffened C-C composite sheet driven at an excitation frequency of about 7 KHz. Shearing was in the vertical direction in the upper image and the horizontal direction in the lower image. Each image is composed of two frames tiled side-by-side.

Shearography provides additional flexibility in that changing the magnitude of the image shear permits tuning the measurement sensitivity to the application. At each point in the shearographic fringe pattern, the interferometric phase change $\Delta \Phi$ induced by an applied load can be expressed as a function of the derivative of the surface displacement, $W$, with respect to the shearing direction, $x$ [6]:

$$\Delta \Phi = \frac{2\pi}{\lambda} \left( C \frac{\partial W}{\partial x} \right) \Delta x$$

where $\lambda$ is the wavelength of the laser light and $C$ is a geometric constant that depends on the relative positions of the illuminating laser, test sample, and image sensor. Note that the phase change is directly proportional to the magnitude of the shear, $\Delta x$. Accordingly, a larger image shear results in a greater phase change between the same two points in the image and thus a greater fringe density across the image, as shown in Fig. 3. Both images were recorded from the same aluminum sheet (15.3 cm square, 1 mm thick) which was clamped along all four edges. In each case a micrometer was used to apply a center point deflection of 5 $\mu$m to the back side of the plate, resulting in nominally identical displacement profiles. However, the image on the left was recorded with a shearing angle of 0.14° while that on the right was recorded a shearing angle of 0.43°. The greater fringe density in the image on the right is indicative of the higher measurement sensitivity.
Shearographic fringe patterns recorded for a 5 μm center-point displacement of a 1 mm thick aluminum sheet. The measurement sensitivity was proportional to the shearing angle which was 0.14° for the image on the left and 0.43° for the image on the right. Shearing was in the horizontal direction and the field of view was about 15 cm wide.

The common-path interferometer arrangement employed by shearography has considerable practical significance for NDE. This design relaxes the coherence requirements for the laser source because the pathlengths remain well matched independent of the relative positions of the test object and the interferometer head. Most importantly, this configuration provides reasonable immunity to environmental disturbances such as low frequency room vibrations, an advantage for industrial applications where such problems are frequently unavoidable. As a result, a sturdy tripod provides adequate mounting for a shearographic interferometer head. By comparison, ESPI and holographic interferometry techniques usually incorporate separate object and reference beam optical schemes that require cumbersome pneumatic vibration isolation bases to operate reliably.

PRACTICAL LIMITATIONS FOR SHEAROGRAPHIC NDE

In spite of its many advantages, shearography does not permit one to completely ignore all problems associated with demanding testing conditions. In particular, relative motion between the interferometer head and test sample must be eliminated during the inspection to insure reliable performance. This is a potential complication with a tripod-mounted system, because the test object and interferometer head are independently supported. For testing large objects, a more stable arrangement involves fixing the interferometer head to the workpiece with vacuum actuated grippers, an option available on some commercial shearography systems.

Shearography is also sensitive to local refractive index variations resulting from thermal gradients in the beam path. Figure 4 shows the shearographic response to thermal turbulence generated by holding a person's hand beneath the beampath (notice the dual images of a fingertip at the bottom of the figure, indicating that the image shearing was in the horizontal or x-direction). Thermally induced 'noise' of this sort tends to obscure the signal information during shearographic NDE in a high-temperature environment.

Background lighting can hinder shearographic testing because any room light transmitted by the imaging system adds incoherently with the laser light at the CCD detector, reducing the fringe contrast. This problem may be eliminated, for example, by enclosing the interferometer head and beam path in a rigid light-tight hood, as is done in some commercial systems. Alternatively, a laser-line optical bandpass filter placed ahead of the imaging lens will reject light with a wavelength other than that of the illumination laser. This option is particularly useful when using quartz heat lamps to thermally stress...
As with other optical NDE techniques, shearography is sensitive to the surface condition of the test object. An ideal surface for shearographic testing must reflect and also diffusely scatter the incident laser light with high efficiency to ensure that suitable optical power is delivered to the CCD camera. Unfortunately, many industrial applications involve the inspection of surfaces that are far from ideal. Composite materials such as carbon-carbon usually exhibit poor reflectance. Metallic materials can have high reflectance and still be difficult to inspect if the reflectance is of a specular nature. Figure 5 illustrates how the surface condition can affect the shearographic fringe quality. The sample was a graphite-epoxy composite sheet (15 cm wide, 13 cm high, 1.5 mm thick) subjected to a center point displacement of 10 μm. The top half of the sheet was left 'as-received', and the layer of resin at the surface contributed a specular reflectance. The bottom half of the sheet was coated with flat white contact paper to create an ideal diffusely reflecting surface. The boundary between the two surfaces was clearly visible, and as expected, the coated surface yielded superior fringe contrast, particularly around the perimeter of the sample.

In response to the demand for efficient, economical NDE methods for large structures, shearography offers the potential to inspect a large area in a single frame. However, realizing this potential is not simply a matter of using a short focal length imaging lens to yield a wide field of view. Sufficient image brightness at the CCD array is necessary to ensure good fringe contrast, as was shown in Fig. 5. The condition of the target surface and the total available laser power are important factors in determining the maximum field of view that may be practically inspected at one time. When the illumination beam is expanded to cover a wider field of view, the image brightness decreases and the shearographic fringe contrast falls off accordingly. Obviously, surfaces
that offer efficient diffuse reflection will permit the largest possible field of view for a
given laser power.

The most direct solution for the inspection of large areas and/or poorly reflecting
surfaces would be to increase the laser power. The Helium-Neon laser, used in many
shearography systems, is limited to output powers below 50 mW. The traditional higher-
power alternative has been a large-frame Argon ion laser with a single-line output power
on the order of 1 W. Unfortunately, these lasers are expensive, and the added complexity
and bulk will restrict the portability of the shearography system. A mid-range alternative
available in some commercial shearography systems is the air-cooled Argon ion laser,
which can produce single-line output powers on the order of 100-200 mW in a relatively
compact and reasonably priced package. Similar output powers can be obtained from
frequency-doubled diode-pumped Nd:YAG lasers. These YAG lasers are more compact
and offer superior beam quality and longer lifetimes when compared with air-cooled argon
lasers, although they are currently rather expensive. Another promising option for a laser
source is the semiconductor diode laser. These devices are currently available with single-
line output powers of 100-150 mW at wavelengths around 830 nm in the near infra-red
(IR). The invisible IR radiation complicates matters somewhat; however, CCD cameras
are quite sensitive to these wavelengths, so image acquisition would be unaffected. The
most recent development in diode laser technology is the advent of devices that operate at
visible wavelengths in the 650-690 nm range with rather modest output powers up to 30
mW. A diode laser is particularly attractive from the standpoint of portability, because
these devices are by far the most compact laser systems available. Furthermore, it is
encouraging to note that diode laser technology, and hence diode-pumped solid-state laser
technology is far from mature. The current trend of substantial improvements in output
power accompanied by price reductions will likely continue in the next several years.
The critical flaw size that must be detected is perhaps the most important factor in assessing the maximum inspectable field of view for any application. In other words, the minimum detectable flaw size is always proportional to the field of view, as shown in Fig. 6. Both images were recorded from an aluminum face sheet (1 mm thick) that was painted flat white and contained a single manufactured circular disbond of diameter 3.3 cm. In each case, vacuum stressing was used to detect the disbond. The disbond is a prominent feature in the image in Fig. 6-A, which was recorded with the interferometer head positioned at a working distance of 0.64 m, resulting in a relatively small field of view, 18 cm wide by 15 cm high (only a portion of the total field of view is included in each image). A pressure difference of only 0.5 psi was used to locate the defect. The image shearing was in the Y direction, so the image of the circular disbond appears elongated in the vertical dimension by the amount of the image shear. By comparison, for the image in Fig. 6-B, the working distance was increased to 1.88 m, enlarging the total field of view to 46 cm wide by 38 cm high. The disbond was still resolved in the fringe pattern, although with significantly less clarity. The perception that there are two separate disbonds in this image arises because the lateral image shear was slightly larger than the diameter of the disbond (the amount of image shear increased with working distance in this interferometer design). Recall that increasing the image shear also increases the measurement sensitivity, so a pressure difference of only 0.25 psi was required to locate the defect at the longer working distance. It is apparent that enlarging the field of view in this experiment much beyond 0.5 m would have further obscured the presence of the 3.3 cm diameter defect in the shearographic image to the point of being unresolvable.

It is impractical to specify the minimum resolvable flaw size for a given field of view, because factors such as the image brightness are different for each case. However, the shearographic resolution in any application is strongly influenced by the parameters of the CCD array, which divides the image into individual pixels for readout and storage. To be resolved, any feature in the image must be spatially sampled by a sufficient number of pixels, so for a fixed field of view, the detection resolution for shearographic NDE can be enhanced by increasing the total number of pixels in the image. The typical CCD camera operating according to the RS-170 video standard incorporates a small detector

![Figure 6. Shearographic fringe patterns recorded for pressure stressing of a 3.3 cm-diameter manufactured disbond in a 1 mm thick aluminum sheet. The working distance was 0.64 m in image (A) and 1.88 m in image (B). Shearing was in the vertical direction.](image-url)
array with dimensions in the range of 640 pixels wide by 480 pixels high, although the exact dimensions vary among the different manufacturers and camera models. The opportunity to operate with higher resolution is becoming increasingly more practical with continued progress in non-standard CCD cameras. Arrays with 1024 by 1024 (1K x 1K) and greater pixel dimensions are now commercially available, as are compatible frame grabbers. There are still several caveats regarding the potential use of the larger arrays in shearography. These CCD cameras and the corresponding frame grabbers are currently much more expensive than RS-170 systems. More importantly, substantially increasing the number of pixels in the image requires that much more memory per image, so acquisition and processing are performed at slower frame rates.

CONCLUSIONS

Several key factors affecting the general suitability of using electronic shearography for NDE have been discussed. Whether or not electronic shearography is an appropriate solution for a given NDE problem ultimately depends on the nature of the targeted defects, the structural geometry and material properties of the sample, and the availability of an effective stressing technique. The resolution limit, or minimum detectable flaw size for shearographic NDE depends on parameters such as the image brightness and field of view specific to each application. The one general rule to remember is that in any situation, the detection resolution gets poorer as the field of view is expanded.

The future potential for electronic shearography appears to be even brighter than the successes already documented. The laser, electronic imaging, and computer processing technologies from which electronic shearography has emerged continue to register tremendous improvements in performance and economy with each passing year. The diode lasers and diode-pumped solid state lasers that will be developed in the next several years promise to be at least an order of magnitude more powerful than those available today. The enhanced resolution afforded by larger CCD arrays will be exploited as prices of these devices moderate and faster image acquisition hardware is perfected. Finally, sophisticated optical and image processing strategies (which are beyond the scope of this paper) have been and continue to be developed to improve the fringe contrast, reduce the speckle noise, and ultimately increase the detection resolution of shearographic NDE. Implementation of these processing methods in real time will become more practical as personal computers grow increasingly robust and economical.

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REFERENCES