Reflection Shearography for Non-Destructive Evaluation
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ABSTRACT
Conventional nondestructive evaluation (NDE) techniques include visual inspection, eddy current scanning, ultrasonics, and fluorescent dye penetration. These techniques are limited to local evaluation, often miss small buried defects, and are useful on polished surfaces only. Advanced NDE techniques include laser ultrasonics, holographic interferometry, structural integrity monitoring, shearography, and thermography. A variation of shearography, employing reflective shearographic interferometry, has been developed. This new shearographic interferometer is presented, together with models to optimize its performance and experiments demonstrating its use in NDE.

1. INTRODUCTION
Engineering structures such as engines, nuclear reactors, automotive engines, piping and pressure vessels, and building support structures inherently have stresses, usually produced by material processing or joining operations (welding, rolling, etc.) or during use. Some types of stresses, such as high cycle fatigue (HCF) and fretting fatigue in aircraft engines, can cause fatal crashes. The current techniques for nondestructive testing and evaluation (NDE) of aircraft on-wing components and many other aircraft structures require disassembling these systems and subsystems. These procedures are labor and time intensive, requiring high budgets for maintenance and operation and support (O&S) plus a long period of downtime for testing. Conventional NDE techniques for detecting structural and surface damage include visual inspection, eddy current scanning, ultrasonics, and fluorescent dye penetration. These techniques are limited to local evaluation, and often miss small, buried defects. Advanced NDE techniques, including laser ultrasonics, digital holographic interferometry, shearography, and thermography can be applied for real-time, high-resolution inspection. However, their usefulness is limited by their bulkiness, sensitivity to external vibrations – and by their low dynamic range, measurement sensitivity, and spatial resolution. We present a technology founded on the principles of shearographic interferometry, employing the shearing element in the reflective mode.

2. THEORY
NDE by reflective shearography depends on three areas: applications of shearography to NDE, detailed analysis of the shearing element, and image processing.

2.1. Shearography for NDE
Shearography is a type of interferometry in which the two interfering wavefronts are virtually identical except for a slight difference in their angle of propagation (the shear angle). For reflective shearography, the shear is induced by reflection from a wedge (Figure 1). The beam with intensity $I_1$, then, has a slightly different angle (which can appear as a position-dependent phase shift) and a slight position shift with respect to the beam with intensity $I_2$. If the wedge angle is designed to shift the beam only in the x-direction, the interference between these two beams can be written...
\[ \Gamma_{\text{ref}}(x,y) = I_1(x,y) + I_2(x + \Delta x, y) + 2\sqrt{I_1(x,y)I_2(x + \Delta x, y)} \cos[\varphi(x,y) - \varphi(x + \Delta x, y) - 2\pi f_0 x] , \]  
\text{(1)}

where \( f_0 = \sin \theta_\lambda / \lambda \), \( \theta_\lambda \) is the shear angle between the two beams, and \( \lambda \) is the wavelength of the illumination laser. Eq. (1) represents an interference pattern varying in the x-direction with fringe spacing \( 1/f_0 \).

Shearography depends on the difference between two interferograms, one taken under reference conditions and the other when stress is applied to the target. This stress affects the phase of the light reflected from the target to the wedge. So the interference pattern under stressed conditions is

\[ \Gamma_{\text{stress}}(x,y) = I_1(x,y) + I_2(x + \Delta x, y) + 2\sqrt{I_1(x,y)I_2(x + \Delta x, y)} \cos[\varphi'(x,y) - \varphi'(x + \Delta x, y) - 2\pi f_0 x] , \]  
\text{(2)}

where the primed phases indicate that the measurements are taken in the stressed condition. The patterns of Eqs. (1) and (2) are captured and digitized, so that the difference image (a “shearogram” – the difference image between two shearographic interferograms) can be created. This image’s overall intensity is

\[ \Delta \Gamma(x,y) = \Gamma_{\text{stress}}(x,y) - \Gamma_{\text{ref}}(x,y) = 4\sqrt{I_1 I_2} \sin \frac{\varphi(x,y)}{2} \sin \frac{\varphi'(x,y)}{2} , \]  
\text{(3)}

where \( \varphi \) is the sum of the phases of the stressed and reference interferograms and \( \varphi' \) is their difference. The sum term includes \( \sin(4\pi f_0 x) \), and is a rapidly-varying term that effectively adds to the speckle noise, but the difference term is

\[ \varphi'(x,y) = [\varphi'(x,y) - \varphi(x,y)] - [\varphi'(x + \Delta x, y) - \varphi(x + \Delta x, y)] . \]  
\text{(4)}

This includes the useful term

\[ \delta = \frac{\varphi'(x,y) - \varphi(x,y)}{2\pi} u \cdot K , \]  
\text{(5)}

where \( u \) is the displacement vector and \( K \) is the sensitivity vector of the shearographic measurement. For the case described above, with shear in the x-direction, we also have

\[ \delta = \delta_x = \left( \frac{\partial u}{\partial x} k_x e_x + \frac{\partial v}{\partial x} k_y e_y + \frac{\partial w}{\partial x} k_z e_z \right) \Delta x , \]  
\text{(6)}

where \( u, v, \) and \( w \) are the components of the displacement vector in the x, y, and z directions, respectively, and \( e_x, e_y, \) and \( e_z \) are the direction cosines of \( K \). Thus, the result described by eq. (3), over distances much larger than \( 1/f_0 \), is the gradient of the deformation. The gradient of the deformation also defines the strain tensor, so shearography can be used to measure stress-induced strain. Additionally, eq. (4) tells us that the large (spacing \( \gg 1/f_0 \)) fringes visible in a shearogram line up along the gradient of the strain tensor, providing a very sensitive measurement of surface strain.
whether caused by surface or subsurface defects. The shearogram can also provide a quantitative measurement of strain with image processing, as described in Section 2.3.

2.2. The shearing element

For reflection shearography, the shearing element is a wedge as shown in Fig. 1. This wedge has the following characteristics: thickness $t_w$, front- and rear-surface reflectivities $R_1$ and $R_2$ respectively, wedge angle $\theta_w$, and refractive index $n_w$ (we assume it is non-absorbing). For near-normal incidence, the shear angle between the first- and second-surface reflections is

$$\theta_s = 2\theta_w + \sin^{-1}\left\{ n_w \sin \left[ \theta_w - 2\sin^{-1}\left( \frac{\sin \theta_w}{n_w} \right) \right]\right\}.$$  

(7)

This value enables calculation of the spacing between interference fringes in the surface reflection. For digital shearography, the fringe pattern must be visible, indicating that the spacing between fringes must be several pixels. This is complicated by the speckle introduced when a scattering surface (typical of targets of interest) is illuminated by a laser (generally needed for interferometry). There must be at least two complete fringe cycles in every speckle. Thus, the speckle size is controlled as well as the spacing between fringes. The average speckle diameter is

$$d_s = \frac{\lambda x}{D_a},$$  

(8)

where $D_a$ is the diameter of an aperture placed in the expanding beam a distance $x$ from the wedge, $\lambda$ is the illumination wavelength, and $M$ is the image magnification of any optics between the aperture and the wedge. Due to the random nature of speckle, it is generally prudent to design the speckle size to be at least three times the interferometric fringe spacing.

For near-normal incidence, the image shift due to shear is

$$\Delta x = \frac{2t_w}{n} \frac{\sin \theta_w}{\sqrt{1 - \sin^2 \frac{\theta_w}{n^2}}} = \frac{2t_w}{n} \theta_w$$  

(9)

for small wedge angles. For wedge angles typically used in reflection shearography, this is less than the fringe spacing.

The reflectivity of the front and rear surfaces must be optimized. To do so, we refer again to Fig. 1. All useful information is contained in the interference pattern formed by the beams whose intensities are $I_1$ and $I_2$. It is easy to calculate their intensities:

$$I_1 = R_1 I_0$$  

(10)

and

$$I_2 = R_2 \left[ 1 + 6R_1 + R_1^2 - 4\sqrt{R_1 (1 + R_1)} \right] I_0.$$  

(11)

All other reflections show up as noise:

$$I_{\text{noise}} = \sum_{i=3}^{\infty} I_i = \frac{R_1 R_2^2}{1 - R_1 R_2} \left[ 1 + 6R_1 + R_1^2 - 4\sqrt{R_1 (1 + R_1)} \right] I_0.$$  

(12)

The interferometric fringe contrast is

$$C_F = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}}.$$  

(13)

where $I_{\text{max}}$ and $I_{\text{min}}$ are the maximum and minimum intensities, respectively, in the interference pattern. If noise is neglected, $I_{\text{max}} = I_1 + I_2$ and $I_{\text{min}} = I_1 - I_2$, so the contrast is optimized for $I_1 = I_2$. The brightest reflection that satisfies
this condition obtains when $R_1 = 38.1\%$ and $R_2 = 100\%$. Unfortunately, these reflectivities result in unacceptably high noise (~25% of the maximum signal). When noise is included, $I_{\text{max}} = I_1 + I_2 - I_{\text{noise}}$ and $I_{\text{min}} = I_1 - I_2 + I_{\text{noise}}$. Since the peak value of the \textit{useful} signal is $I_1 + I_2$, we can define a signal-to-noise ratio as

$$\text{SNR} = \frac{I_1 + I_2}{I_{\text{noise}}} = \frac{1}{R_1 R_2} + \frac{1}{R_2^2 (1 - \sqrt{R_1})^2}.$$ (14)

This equation is plotted in Fig. 2.

![Fig. 2. Shearographic signal-to-noise ratio as a function of front- and rear-surface wedge reflectivity (R1 and R2, respectively). For visibility, SNR was clipped at 100.](image)

SNR is large for low reflectivities, since $I_{\text{noise}}$ contains an extra factor of $R_1 R_2$ compared to $I_2$. But at low reflectivities little of the light reaching the wedge is reflected to the detector, reducing or even eliminating any capability of measuring the interferometric signal. The peak reflectivity, the brightest signal reflected (at a point of constructive interference) divided by the incoming intensity, is

$$R_{\text{eff}} = \frac{I_{\text{sig}}}{I_0} = R_1 + R_2 \left(1 - \sqrt{R_1}\right)^4 + 2 \sqrt{R_1 R_2 \left(1 - \sqrt{R_1}\right)^4}. \quad (15)$$

In eq. (15), $I_{\text{sig}}$ is the maximum signal intensity ($I_{\text{max}} - I_{\text{noise}}$). Effective reflectivity is greatest for high front surface reflectivity $R_1$, although low values of $R_1$ can result in high effective reflectivity if $R_2$ is large. This is shown in Fig. 3.
Since the SNR can, theoretically, reach \( \infty \), a more useful measurement is the contrast. This is defined by eq. (13), with the values of \( I_{\text{max}} \) and \( I_{\text{min}} \) that include noise. Just as the peak reflectivity is constrained to \( 0 < R_{\text{eff}} < 1 \), contrast must be between 0 and 1. The contrast of the shearographic interference pattern, including noise, is

\[
C_{\text{EFF}} = \frac{4 \sqrt{R_1 R_2 (1 - \sqrt{R_1})^4 - R_1 R_2 (1 - \sqrt{R_1})^4}}{2 R_1 + R_2 (1 - \sqrt{R_1})^4 + R_1 R_2 (1 - \sqrt{R_1})^4}.
\]  

(16)

As shown in Fig. 4, the contrast has similar dependence on \( R_1 \) and \( R_2 \) as the SNR at low \( R_1 \), but is reduced at high \( R_1 \). This is due to the reduction in \( I_{\text{max}} \) and increase in \( I_{\text{min}} \) caused by the noise.
The wedge design figure of merit is presented in Fig. 5.

Fig. 5. Wedge design figure of merit.

2.3. Image processing to quantify strain

It is possible to detect phase differences in the shearographic signal through the use of Fourier transforms. To do so, eq. (1) is first rewritten in terms of the electric field instead of the intensity:

\[ x, y(\mathbf{u}) = u_1 x, y(\mathbf{u}) + u_2 x, y(\mathbf{u}) + u_{12} x, y(\mathbf{u}) + u_{11} x, y(\mathbf{u}) , \]  

(18)

where \( u_j \) is the electric field of wave \( j \), \( u^* \) is the complex conjugate of \( u \), and the intensity at each point is

\[ I_j = u_j u_j^* . \]

We take the Fourier transform of Eq. (18), which converts it from the space domain to the spatial frequency domain,

\[ \mathcal{F} (\mathcal{I}) = U_1 \otimes U_1^* + U_2 \otimes U_2^* + U_1 \otimes U_2^* + U_2 \otimes U_1^* , \]

(20)

where the convolution operator \( \otimes \) has replaced multiplication because multiplication in the space domain is convolution in the spatial frequency domain, and \( U_j \) is the Fourier transform of \( u_j \).

In a real system, the signal of eq. (18) is captured by a CCD camera, resulting in a digitized signal. This is then Fourier transformed by the fast Fourier transform routine, FFT. The first two convolution terms in eq. (20) are centered on zero frequency, while the cross terms, which contain the phase information, are complex conjugates of each other. The computer applies a mask to select only the first cross term and set the others to zero. The inverse Fourier transform then yields

\[ \mathcal{F}^{-1} (U_1 \otimes U_2^*) = u_1(x, y) u_2^*(x, y) , \]

(21)

which is a complex function. Then, from Eqs. (1), (4), and (18) we find
\[
\varphi(x,y) - \varphi(x + \Delta x, y) - 2\pi \times f_0 = \tan^{-1}\left( \frac{\text{Im}\left[ u_1(x,y)u_1^*(x,y) \right]}{\text{Re}\left[ u_1(x,y)u_1^*(x,y) \right]} \right),
\]

where \(\text{Im}[\ ]\) is the imaginary part and \(\text{Re}[\ ]\) is the real part. A similar equation obtains for the deformed shearogram, and the strain related phase change \(\varphi_\perp(x,y)\) can be calculated easily. The magnitude of the strain gradient can then be calculated from eq. \(6\).

3. EXPERIMENT

We performed an experiment to demonstrate the use of reflection shearography in NDE. A thin piece of aluminum with a scratch on the back was placed in a holder and tested. Stress was applied by heating the aluminum with a CO₂ laser. The unstressed image and its associated phase are shown in Fig. 6.

![Fig. 6. Speckle pattern from illuminated area (a) and wrapped phase (b) for an unstressed aluminum plate.](image)

The interference pattern is visible within the speckles in Fig. 6(a). There was no visible difference in the speckle pattern or the wrapped phase between the stressed and unstressed images. In each case, the phase was calculated by the Fourier transform method described in Section 2.3. This process appears in Fig. 7.
Fig. 7. The Fourier transform method of calculating phase. First, the image (Fig. 6(a)) is transformed (a). Then the area of interest, offset from the center by the fringe frequency $f_0$, is selected (b). When this selection is inverse transformed, the argument of the resulting complex array is the “wrapped” phase – the phase modulo $2\pi$ (Fig. 6(b)).

After obtaining the phase of the images taken under reference and stressed conditions, the derivative of the strain tensor can be determined. It is the difference between the phases of these images (eqs. (5) and (6)). The unwrapped phase (continuous, without the $2\pi$ jumps) looks the same in the stressed and unstressed cases, but the difference shows a stress location near the bottom of the image (Fig. 8).

4. CONCLUSIONS

Reflection shearography has been shown to be a useful technique for measuring strain in objects. It relies on applying stress to an object and determining the difference between the phase of the reflected light in the unstressed (reference) and stressed cases. This method is capable not only of qualitatively locating stress, but also of quantifying the gradient of the strain tensor for the object under test.
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