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VIBRATION ANALYSIS BY DIGITAL SHEAROGRAPHY

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Abstract: Digital Shearography, a laser interferometric technique in conjunction with the digital image processing, has the potential for vibration analysis due to its simple optical system and insensitivy against small rigid body motions. This paper will focus on its recent developments for vibration analysis and for nondestructive testing (NDT) by dynamic (harmonic) excitation. With the introduction of real time observation using automatically refreshing reference frame, both small and large rigid body motions are greatly suppressed. The development of a smaller and more mobile measuring device in conjunction with a user guided comfortable program ***Shearwin*** *enables the digital shearography to be applied easily as an industrial on line testing tool.*
Keywords: Digital speckle pattern shearing interferometry, vibration analysis, NDT, time average.

1 INTRODUCTION

In recent years, holography has been applied in the field of vibration analysis and nondestructive testing. The main limitation of this technique arises from its sensitivity against rigid body movement and rapid increases in fringes depending on the displacement which makes it difficult to interpret the fringe pattern. An approach which is relatively insensitive against such motion is performed by shearography. Shearography has a simple optical setup due to its "self-referencing" optical system. Instead of measuring displacement, shearography measures displacement derivatives directly and obtains thus the strain information. The rigid body movement doesn't generate the displacement derivatives, so such motion does not result in the additional interferometric fringes. Thus this method has the potential for industrial applications [1, 2].

2 MEASURING PRINCIPLE OF DIGITAL SHEAROGRAPHY

Fig. 1 shows the schematic of the digital shearography. The tested object is illuminated by an expanded laser beam. The light reflected from the object surface is focused on the image plane of an image shearing CCD - camera in which a Michelson interferometer is implemented in front of its lens. By turning the mirror 1 in one of the two illumination arms of the interferometer for a very small angle, a pair of sheared images of the object is generated in the image plane of the CCD - camera (cf. Fig. 1). (The mirror 2 is a piezoelectric transducer (PZT) driven mirror. It will be described in the following part). The two sheared wavefronts interfere with each other producing an interferogram, i.e. the so called "speckle pattern". Due to the shearing function, this technique is thus called *shearography*.

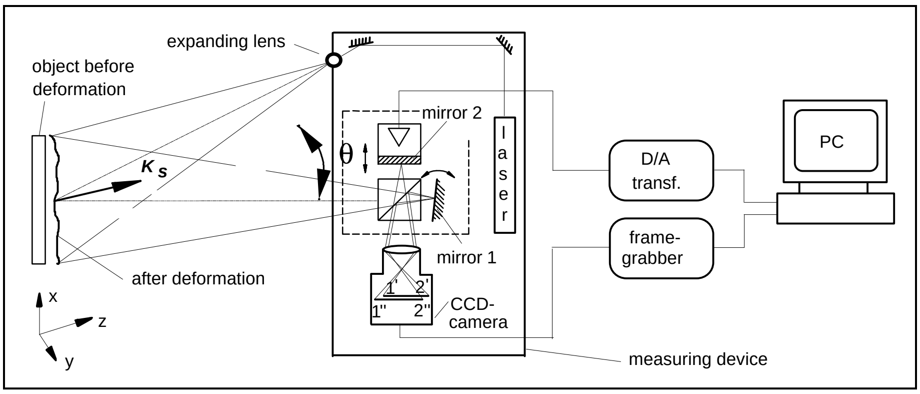

Figure 1. The principle of digital shearography

When measuring, the CCD-camera records first a speckle pattern and stores it in one frame, i.e. the reference frame. After the object is stressed, the second speckle pattern is registered by the CCD-camera again and stored in another frame. Digital subtraction between the two recorded images yields a fringe pattern, i.e. the so called “digital shearogram”. It is displayed on the screen of a computer directly. A commercially available image processing board allows to subtract the arriving image from the reference image at video rate. The digital shearogram is thus observed in real time.

3 VIBRATION ANALYSIS BY DIGITAL SHEAROGRAPHY

In general, vibrations, especially in cases of resonant frequencies occurring, in machines and structures are undesirable because of the increased stresses and the energy losses which accompany them. They should be eliminated or reduced as much as possible by an appropriated design. Therefore, the major task of vibration analysis is to determine the resonant frequencies of the object and to know the vibration form.

Vibration measurement by digital shearography can be performed by time average or stroboscopic method, if the object is excited harmonically. Time average method is by far the most usual technique for qualitative analysis such as for qualitative modal analysis and for NDT by dynamic excitation due to its simple optical setup. In the following parts, we will discuss only the vibration measurement by time average method.

In order to find out the resonant frequencies simply and rapidly, the real time observation of the digital shearogram is usually required. In the conventional technique for real time observation, the real time subtraction with fixed reference frame is usually adopted. The fringe pattern is very sensitive to the ambient disturbances. Moreover, the fringes are modulated by $[1-J_0(\Omega)]$ and the contrast of the fringe pattern is poor.

3.1 Real time subtraction with fixed reference frame

Using real time subtractive method with fixed reference frame, the CCD-camera records first the intensity distribution I(x,y) of the speckle pattern corresponding to the stationary state of the object and stores it in one frame, we call it the reference frame. The recorded intensity distribution I(x,y) is given by:

$$I_R(x,y) = 2\, I_0 + 2\, I_0\, \gamma \cos [\phi(x,y)], \qquad (1)$$

where I_0 is the average intensity of the two sheared images, γ represents the modulation of the interference term, and $\phi(x,y)$ denotes the random relative phase angle between the two sheared images. When the object is excited, the intensity distribution of the speckle pattern is slightly altered and it is represented by:

$$I(x,y,t) = 2I_0+2I_0\, \gamma \cos [\phi(x,y)+\Delta(x,y,t)] \qquad (2)$$

where Δ represents the relative phase change due to the object vibration. If the object is vibrating in the steady state with the frequency f ($\omega = 2\pi f$) much higher than the video frame rate, the image recorded in a frame is an integration of the intensity distribution I(x,y,t) shown in Eq. (2) during the frame period (T_f) and it is a time-average correlogram:

$$I(x,y)_{ave}=\frac{1}{T_f}\int_0^{T_f} I(x,y,t)\, dt \qquad (3)$$

Using normal illuminating and viewing, the relative phase change $\Delta(x,y,t)$ is related to the out-of-plane displacement (amplitude) gradients for the sinusoidal vibration [3].

$$\Delta(x,y,t) = (\delta x \,\frac{4\pi}{\lambda}\, \frac{\partial w}{\partial x}) \sin \omega t \qquad (4)$$

where δx is the shearing amount between the two images, λ is the wavelength of the laser beam, w and ω represent the out-of-plane displacement (amplitude) in z-direction and the angular frequency of the vibrating object, respectively.

Eq. (3) can be thus rewritten as:

$$I(x,y)_{ave} = 2I_0 + 2I_0\gamma\frac{1}{T_f}\int_0^{T_f}\cos[\phi(x,y) + (\delta x\frac{4\pi}{\lambda}\frac{\partial w}{\partial x})\sin\omega t]dt = 2I_0 + 2I_0\gamma\cos[\phi(x,y)J_0(\Omega)] \quad (5)$$

where J_0 is the zero-order Bessel function of the first kind and *W* ***is equal to [dx (4p/l) (¶w/¶x)].***

Theoretically, Equation (5) depicts already a fringe pattern, however, the fringe contrast of the time average correlogram is very low and the fringes are barely visible due to the high level of the selfinterference term ($2I_0$), i.e. the first term of the Eq. (5). In order to make the fringe pattern visible, the current frames corresponding to $I(x,y)_{ave}$ are always subtracted at video rate from the reference frame recorded at the stationary state of the object with respect to $I_R(x,y)$. After the subtraction, the selfinterference term is eliminated and a visible fringe pattern is displayed on the monitor in real time (at video rate);

$$I_S = I_R(x,y) - I(x,y)_{ave} = 2I_0\gamma[1 - J_0(\Omega)]\cos\phi(x,y) \quad (6)$$

Equation (6) shows that the real time subtractive fringe pattern is modulated by $[1-J_0(\Omega)]$ rather than by $J_0(\Omega)$ or $J_0^2(\Omega)$ (cf. Fig. 2). Thus the contrast of this fringe pattern is poor. Furthermore, this kind of fringe pattern is still very sensitive against the ambient disturbances such as the relative large rigid body motion, the thermal noise and low frequency vibration etc. because of the long time interval between the current and the reference frame. Therefore its applications in industry, especially, for industrial on-line testing, are still limited. To solve these problems, the real time subtractive method with refreshed reference frame is here introduced.

3.2 Real time subtraction with permanently refreshed reference frame

The real time subtraction method with the refreshed reference frame has been used in the stroboscopic illumination digital shearography so that a fringe pattern which is insensitive against ambient disturbances can be obtained [4]. If this technique is applied in the time average digital shearography, the complex synchronising system for the camera, the object vibration signal and the stroboscopic signal is not required.

It is a three-step process: If the current frame is the Nth frame, the reference frame is the (N-1)th frame rather than the frame recorded at the stationary state. First, an image is recorded in the (N-1)th frame. It is obvious that this image is a time-average correlogram due to object vibration. It can be represented by:

$$I_{(N-1)}(x,y)_{ave} = 2I_0 + 2I_0\gamma J_0(\Omega)\cos[\phi(x,y)] \quad (7)$$

If the Nth current frame is now subtracted directly from the (N-1)th frame without introducing a phase shift between the two frames, no fringe can be observed because the algebraic expressions for $I_{(N-1)}(x,y)_{ave}$ and $I_N(x,y)_{ave}$ are exactly identical. Therefore, a 180° phase shift after the (N-1)th frame is introduced in the second step (the phase shift could also be another value). This phase shift can be introduced by a piezoelectric transducer (PZT) driven mirror 2 in one of the two illumination arms of the Michelson interferometer (cf. Fig. 1) and controlled by the software ***Shearwin*** developed by the laboratory of photoelasticity, holography and shearography, University of Kassel. Then in a second step, the Nth frame is taken. Now the image recorded in the Nth frame becomes:

$$I_N(x,y)_{ave} = 2I_0 + 2I_0\gamma J_0(\Omega)\cos[\phi(x,y) + 180°] \quad (8)$$

The Nth current frame is then subtracted digitally from the (N-1)th frame. Obviously, the self-interference term in Eq. (7) and (8) is eliminated and thus a visible fringe pattern can be observed:

$$I_S = I_{(N-1)}(x,y)_{ave} - I_N(x,y)_{ave} = 4\, I_0\, \gamma\, J_0\,(\Omega)\, \cos\phi\,(x,y) \qquad (9)$$

Since the intensity of an image can not be negative, the absolute value or the square value of the subtraction should be displayed. Repeating the three step process, a fringe pattern modulated exactly by $|J_0\,(\Omega)|$ or $J^2{}_0(\Omega)$ rather than by $[1- J_0\,(\Omega)]$ is displayed on the monitor in real time. The contrast of this kind of fringe pattern is much better than that of $[1-J_0(\Omega)]$ (cf. Fig. 2). Furthermore, the time interval between current and reference frames is greatly reduced (about 1/25 second). Therefore, ambient disturbances are greatly suppressed. Not only the small rigid body motion, but also the relative large rigid body motion, the low frequency vibration and the thermal air currents etc. are strongly suppressed due to the measuring method of the refreshing reference frame technique. Therefore, this technique is suited well for industrial applications such as for on-line testing.

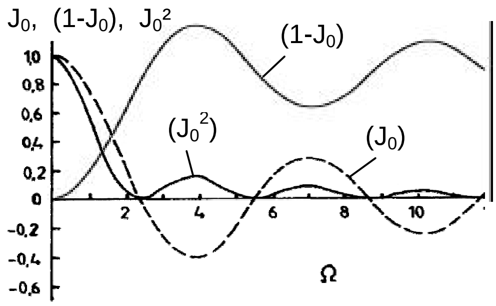

Figure 2. Variation of the real-time fringe function $J_0(\Omega)$,$J^2{}_0(\Omega)$ and $[1 - J_0\,(\Omega)]$ versus Ω, $[\Omega = \delta x\,(4\pi/\lambda)\,(\partial w/\partial x)]$

4 MEASURING DEVICE AND DEVELOPED SOFTWARE

The outstanding advantage of the time average technique lies in its simple optical setup. The complex stroboscopic illumination and synchronising system are not required. In combination with the properties of shearography where the single mode laser is not required, a laser diode can thus be applied in the technique of the time-average-digital-shearography. By introducing the real time subtraction based on the refreshed reference frame, time interval between current and reference frames is greatly reduced (about 1/25 second). Thus a laser diode ***without temperature stabilisation*** can be used in this measuring device, which is inexpensive in price and small in volume. The illumination by this type of laser has been proven to be a practical method [5]. Therefore, this measuring device of the time-average-digital-shearography becomes smaller and more flexible.

Fig. 3 shows the measuring device of digital shearography which is designed according to the principle of Fig. 1. This measuring device includes completely a CCD camera, a Michelson interferometer acting as the shearing unit and two 50 mW laser diodes without temperature stabilisation. The application of two laser diodes which have the same indicated wavelength makes it possible to illuminate a relative large surface of the tested object. This measuring device is only about 200 × 60 × 80 mm³ in size and one kg in weight and can be fixed on a tripod head. Using two 50 mW laser diodes, the measuring area of the object covers 500×500 mm².

A software ***Shearwin*** implemented under Windows has been developed by LSHS to perform the testing and to evaluate the shearogram automatically. This program carries out the real time subtraction, controls the PZT driven mirror 2, transmits the values from the CCD-array to the signal processor. The testing results can be displayed in real time (at video rate).

Figure 3. Measuring device of digital shearography equipped completely with a CCD camera, the shearing unit and two 50 mW laser diodes without temperature stabilisation.

5 APPLICATIONS

Time average method is by far the most usual technique for qualitative analysis such as for qualitative modal analysis and for NDT by dynamic excitation. In this part, the "modal analysis" using time average digital shearography with the technique of the refreshed reference frame will be shown.

5.1 Vibration measurement

By means of real time observation technique, the resonant frequencies of the tested object can be determined simply. The fringe pattern of the time average digital shearogram depicts amplitude derivatives at each point of the object surface. The brightest fringe lines of the time average digital shearogram are those where Ω is zero, i.e. the position of the zero-order fringe. Considering $\Omega = \delta x\,(4\pi/\lambda)\,(\partial w/\partial x)$ and $\delta x\,(4\pi/\lambda) \neq 0$, the brightest fringe lines are those where amplitude derivatives $(\partial w/\partial x)$ are zero, thus these lines show the positions of maximal amplitude.

Fig. 4 shows the digital shearographic experimental investigation of a vibrating aluminium beam (180mm $\times$ 35mm $\times$ 5mm) using the technique of real time subtraction with refreshed reference frame. This beam was clamped at the left end and excited by a very small piezoelectric crystal (m = 2g) on the back right hand side. Fig. 4a to 4c show the time average digital shearograms of the beam from second to fourth bending modes. The brightest fringe lines are the positions where the amplitude is maximum, thus the vibrating shape of these resonance frequencies can be imagined. Fig. 4d to 4f show the corresponding vibrating shapes (after qualitative integration). A comparison between the theoretical and experimental resonant frequencies for this vibrating beam and for a vibrating circular plate can be found in references [6, 7].

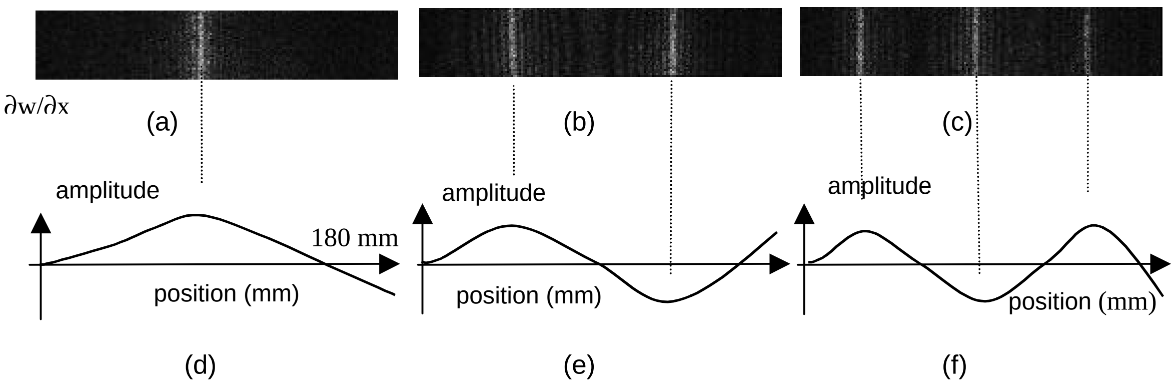

Figure 4. Time average digital shearograms of a vibrating aluminium beam for second (f = 730Hz) (4a), third (f = 2018) (4b) and fourth (f = 3987) (4c) resonant frequency as well as the corresponding vibration mode [from (4d) to (4f)].

5.2 NDT by dynamic excitation

The other application of the time average digital shearography using the permanently refreshed reference frame is the nondestructive testing by dynamic (harmonic) excitation. A drilled GLARE 4/3 (glass fiber metal laminate) panel (195 x 145 x 2 mm^3) is shown in Fig. 5. The plate shows 32 drilled holes: 16 properly drilled holes on the left hand side and 16 improperly drilled holes on the right hand side which are generated by disadvantageous production conditions. The real time time average shearogram vibrating at 65.2 kHz excited by a piezo crystal (m = 3g, glued on the back side) detects the invisible delaminations around the holes on the right hand side; the shearing amount is δy = 3.5 mm. The GLARE-panels will be used for producing the fuselage including stringers and frames of the Super Airbus A3XX [9].

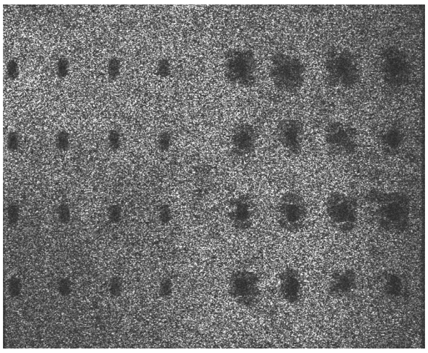

Figure 5. 32 drilled holes: 16 properly drilled holes on the left hand side, 16 improperly drilled holes (delaminations) on the right hand side, real time time average shearogram vibrating at 65,2 kHz, δy = 3,5 mm

6 CONCLUSIONS

As an industrial nondestructive testing tool, digital shearography has special advantages such as small in volume, light in weight and simple in performing. With the introduction of the technique of the permanently refreshed reference frame, not only the small rigid body motion (due to the characteristic of shearography), but also the relative large rigid body motion, the low frequency vibration, and thermal air waves etc. are greatly suppressed. Therefore, this technique can be designed into a robust and compact measuring tool and it is well suited especially for industrial on-line inspection. It is expected that a wide range of applications by means of digital shearography will be seen in the near future.

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