DYNAMIC ELECTRONIC SPECKLE PATTERN INTERFEROMETRY IN APPLICATION TO MEASURE OUT-OF-PLANE DISPLACEMENT

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Electronic Speckle Pattern Interferometry is used to measure out-of-plane dynamic deformations of a diffusely scattering object. The fast transient events were excited by an impulsive load caused by focusing high-power laser beam on the surface of a thin steel plate. The fringe pattern representing contours of constant displacement component was revealed by subtraction mode. The object's surface displacements achieved by using ESPI system and a laser vibrometer are compared.

Key words : *ESPI, dynamic deformation, subtraction mode, laser vibrometer, CCD camera*

1. Introduction

Electronic Speckle Pattern Interferometry is a full-field optical method for the measurement of the surface deformation of a scattering object (the surface height variation is greater than one fourth of the wavelength of illuminating light). Displacement fields are obtained from measurements of the phase distribution of speckle patterns recorded before and after object's deformation.

Fast dynamic events are often studied with pulsed ESPI since the short laser pulses (15 ns) are able to 'stop' an object's motion and images are not blurred. Double exposure method was applied to study a rapid non-periodic transient event caused by an impact loading. Two images of a test-object are captured; one image of the reference state and one of the deformed state. By subtracting these two images, the fringe pattern is formed. The lines of the pattern connect points of the object's surface that were subjected to an equal amount of deformation. The double-exposure technique is complicated to use since the laser pulses must be precisely synchronized with the event [1].

2. ESPI arrangement sensitive to out-of-plane measurement

The Michelson-type interferometer, that is sketched in Fig. 1, allows one to measure out-of-plane test-object displacements. The out-coming beam from a double-pulse ruby laser is divided into three beams by the wedge prism WP. The reflected beams serve as a reference and an object beam. The third one is focused to the centre of the test-object to excite an out-of-plane transient motion.

The reference beam is firstly attenuated by a neutral-density filter ND Filter and then is filtered and expanded by a spatial filter SF to remove extraneous optical noise. The object

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beam illuminates the plate and after impinging on, the scattered light is collected by the imaging lens OBJ and added to the reference beam on the charge-coupled device (CCD) array.

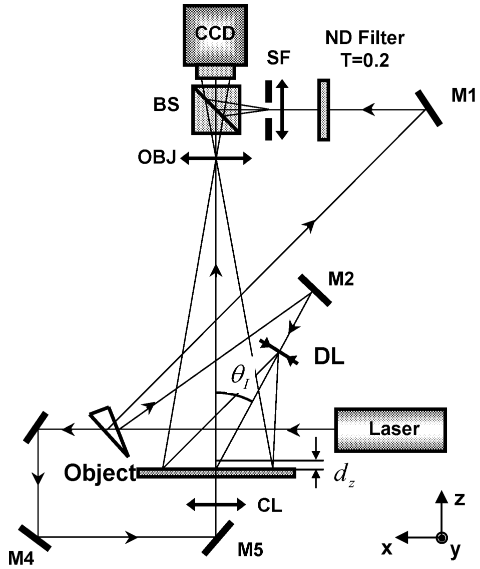

Fig.1: The optical set-up for out-of-plane measurement

The aperture of the imaging lens OBJ directly affects the speckle size that consequently gives the magnitude of the detector areas (sensitive pixel area). As derived in [2] the detectors have to be considerably smaller than the speckle dimension to actually resolve a speckle field. If the aperture is circular, the speckle diameter in the (xy) plane is given by

$$d = 1.22\,\lambda\, f_{\#} \tag{1}$$

where $f_{\#}$ is the ratio of the focal length of the lens to its clear aperture. As mentioned in [3] the size of speckle without the addition of the reference beam corresponds roughly to the spacing of the interference fringes generated by waves coming from the opposite ends of a diameter of the speckle-forming pupil.

2.1. Synchronization of loading and recording part of the interferometer

An electronic set-up was developed to synchronize a camera exposure with laser pulses. The laser pulses were used to both illuminate and excite object's transient motion. By focusing a laser beam on the object surface, high-energy of the laser pulse is transferred to the plate and an out-of-plane transient motion of the plate is excited. A high-energy laser pulse focused at a steel plate is transferring both mechanical impulse and local thermal energy to the plate. The mechanical impulse creates propagating bending waves in the plate. The local heated spot at the plate surface creates thermal stresses which gives rise to an out-of-plane deformation of the plate [4].

The record of the very fast transient event was conditional upon using of charge-coupled device (CCD) camera with asynchronous reset mode. Monochrome camera Sony XC-8500CE in connection with frame-grabber acquisition card Matrox Meteor-II/Multi-Channel enabled us to capture two consequently images with delay a few microseconds (15–50 μs). The XC-8500CE camera operates in asynchronous reset mode. An external trigger signal is provided to the frame grabber. The frame grabber in turn triggers the asynchronously resettable camera to initiate exposure. The trigger signal from the frame grabber to the camera is referred to as the exposure signal (see Fig. 2) and is controlled through the DCF file in Matrox Intellicam. The camera is resynchronized on the arrival of the exposure signal. The delay from the time the frame grabber is triggered to the time it starts exposing is programmable. The camera module outputs EVEN and ODD signals from the VIDEO OUTPUT 1 and VIDEO OUTPUT 2 connectors in a 1/50 sec.

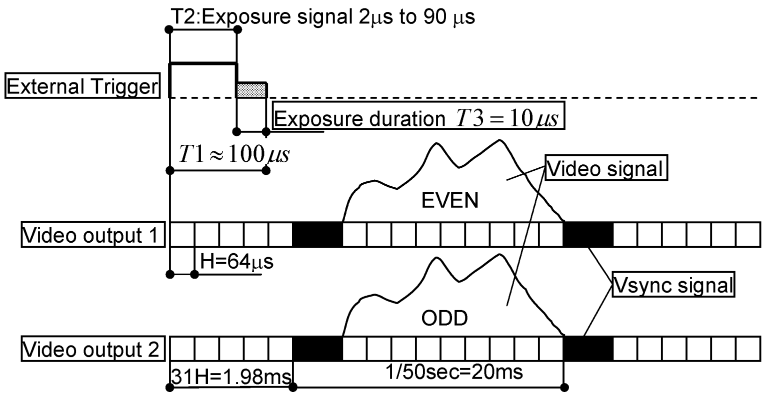

Fig.2: Timing chart for high-speed RESET mode video signal output

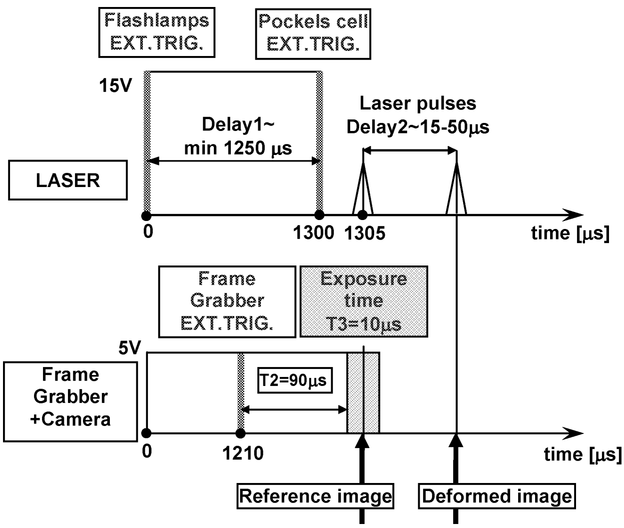

Fig.3: Pulse delay and pulse separation in electronic part of the interferometer

To capture an image at the moment of firing the laser, a few following requirements have to be followed (see Fig. 3). The pockels cell can be triggered 1250 μs after triggering flashlamps. As soon as the first laser pulse fires (5 μs after triggering pockels cell) the reference image can be captured. After finishing the exposure time, which lasts $10\,\mu$s, the image is moved out from the light-sensitive elements of CCD to vertical shift registers. As soon as the reference image transfer from the light-sensitive elements to the vertical shift registers ($4\,\mu$s), the light-sensitive pixels are ready for the next exposure and the second 'deformed' image is recorded.

3. Formation of speckle correlation fringes

An image formed by mixing of an object and a reference beam is recorded digitally to form a reference image. The test-object is deformed and a second 'deformed' image is recorded. Because the surface of the test-object is diffusely reflected, the images take the form of speckle patterns and no fringe pattern is seen. The desirable fringe pattern can be revealed by addition or subtraction of the two frames [2].

We can write the complex amplitude of the object, U_{obj}, and the reference, U_{ref}, beam as follows

$$U_{\mathrm{obj}} = a_{\mathrm{obj}} \exp(\mathrm{i}\,\phi_{\mathrm{obj}}) \,, \tag{2}$$

$$U_{\mathrm{ref}} = a_{\mathrm{ref}} \exp(\mathrm{i}\,\phi_{\mathrm{ref}}) \tag{3}$$

where a_{obj} is the amplitude and ϕ_{obj} is the phase of the light scattered from the test-object surface in its initial state. The amplitude a_{ref} and the phase ϕ_{ref} relate to the reference beam.

The intensity at any point on the image plane before loading the test-object is given by the following

$$\begin{gathered} I_{\mathrm{Unload}} \approx |U_{\mathrm{obj}} + U_{\mathrm{ref}}|^2 = a_{\mathrm{obj}}^2 + a_{\mathrm{ref}}^2 + 2\,a_{\mathrm{obj}}\,a_{\mathrm{ref}} \cos(\phi_{\mathrm{obj}} - \phi_{\mathrm{ref}}) \Rightarrow \\ \Rightarrow I_{\mathrm{Unload}} = I_{\mathrm{obj}} + I_{\mathrm{ref}} + 2\sqrt{I_{\mathrm{obj}}\,I_{\mathrm{ref}}} \cos(\phi) \end{gathered} \tag{4}$$

where $\phi = \phi_{\mathrm{obj}} - \phi_{\mathrm{ref}}$ represents the random phase of the interfering waves.

After deformation of the plate, the relative phase of the two fields will change, thus causing a variation in the irradiance of the speckle pattern. If the object is deformed, the complex amplitude of the object beam becomes

$$U_{\mathrm{obj\_Load}} = a_{\mathrm{obj}} \exp[\mathrm{i}\,(\phi_{\mathrm{obj}} - \Delta\phi)] \tag{5}$$

where $\Delta\phi$ is the phase difference introduced in the original object beam due to normal displacement d_{z} (see Fig. 1) of the test-object.

The irradiance distribution after the object deformation becomes

$$I_{\mathrm{Load}} \approx |U_{\mathrm{obj}} + U_{\mathrm{ref}}|^2 = I_{\mathrm{obj}} + I_{\mathrm{ref}} + 2\sqrt{I_{\mathrm{obj}}\,I_{\mathrm{ref}}} \cos(\phi - \Delta\phi) = I_0 + I_{\mathrm{M}} \cos(\phi - \Delta\phi) \tag{6}$$

where I_0 and I_{M} is referred to as the background and the modulation intensity respectively.

In ESPI, the recorded images do not directly show fringes representing the interferometric measurement, because the phase value, $\phi = \phi_{\mathrm{obj}} - \phi_{\mathrm{ref}}$, varies in a random way.

There is, however, a way to produce speckle correlation fringes corresponding to changes between an initial and a final test- object state. Both an addition and a subtraction mode are used to obtain a correlation fringe pattern that denotes the change in optical path difference.

Addition correlation fringe patterns can be obtained by the accumulation of charge yielded by each laser pulse at the surface of the CCD chip. The corresponding fringe pattern is expressed by

$$I_{\mathrm{Add}} = |I_{\mathrm{Unload}} + I_{\mathrm{Load}}| = 2\,(I_{\mathrm{obj}} + I_{\mathrm{ref}}) + 4\,\sqrt{I_{\mathrm{obj}}\,I_{\mathrm{ref}}}\,\cos\left(\phi + \frac{\Delta\phi}{2}\right)\,\cos\frac{\Delta\phi}{2}\;. \tag{7}$$

The subtraction mode requires the recording of a reference image and 'deformed' image in separate fields. Consequently, the mode introduced more complicated optical arrangements.

The subtraction mode yields a correlation fringe pattern denoted by

$$I_{\mathrm{Sub}} = |I_{\mathrm{Unload}} - I_{\mathrm{Load}}| = 4\,\sqrt{I_{\mathrm{obj}}\,I_{\mathrm{ref}}}\,\sin\left(\phi + \frac{\Delta\phi}{2}\right)\,\sin\frac{\Delta\phi}{2}\;. \tag{8}$$

Equation (7) and (8) describes the modulation of the high-frequency noise $\sin(\phi+\Delta\phi/2)$ by a low-frequency interference pattern $\sin(\Delta\phi/2)$ related to the phase difference term $\Delta\phi$.

The main difference between Egs. (7) and (8) is the presence of the term $2(I_{\mathrm{obj}} + I_{\mathrm{ref}})$, a mean intensity level in the addition fringes that reduces fringe visibility. Hence, the subtraction mode was employed in the experiment.

4. The subtraction fringe pattern interpretation

As it was stated in the previous section, both speckle images are correlated by digitally subtracting the reference and the deformed frame. As a result of subtraction, correlation fringes representing contours of constant $\Delta\phi$ are seen in the form of light and dark bands modulating the object image. These lines connect points on the object's surface that were given an equal amount of deformation, according to certain rules concerning illumination and observation directions.

The intensity of the subtraction fringe pattern becomes minimum when

$$\Delta\phi = 2\,\pi\,n \tag{9}$$

where $n = 0, 1, 2, \dots$ is the fringe order.

The fringe pattern in the Fig. 4 visualizes a propagation of a bending wave in the thin steel (240×240×1.04 mm) plate 15 μs after loading. The approach to fringe interpretation given here follows the formulation in [5].

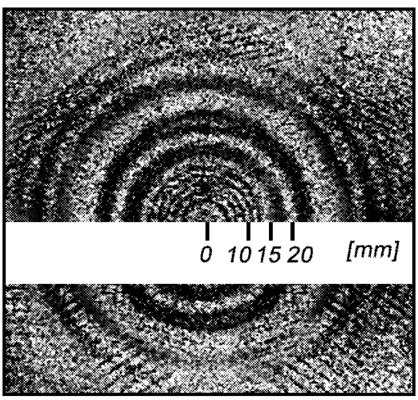

Fig.4: Subtraction fringe pattern representing propagation of the bending wave 15 μs after impact

In Fig. 5 several vectors are defined for use in determining the relation between phase change $\Delta\phi$ and object's displacement $\vec{d}$. After object deformation an object point O is displaced by $\vec{d}$ to the point O'. The object's displacement results in an optical phase shift $\delta\phi$ caused by a path difference ΔL.

$$\Delta\phi = \frac{2\,\pi}{\lambda}\,\Delta L \tag{10}$$

where λ is the wavelength of the laser light.

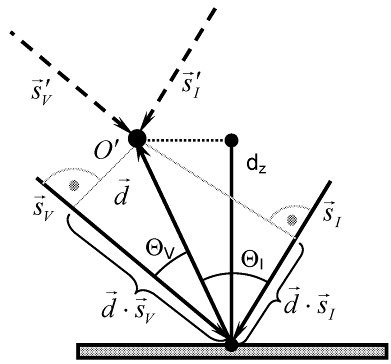

Fig.5: Nomenclature for fringe analysis

The test-object in its reference state is illuminated and viewing in direction of unit vector $\vec{s}_\mathrm{I}$ and $\vec{s}_\mathrm{V}$ respectively (see Fig. 5).

The path difference of the reference wave and object wave ΔL is expressed as

$$\Delta L = \left(\vec{d}\cdot\vec{s}_\mathrm{I}\right) + \left(\vec{d}\cdot\vec{s}_\mathrm{V}\right) = \left(\cos\theta_\mathrm{I} + \cos\theta_\mathrm{V}\right) d_\mathrm{z}\ . \tag{11}$$

The deformation field is determined by the following relation between the phase change and the out-of-plane displacement d_z

$$\Delta\phi = \frac{2\pi}{\lambda}\left(\cos\theta_\mathrm{I} + \cos\theta_\mathrm{V}\right) d_\mathrm{z}\ . \tag{12}$$

The phase jumps of 2π show lines of constant deformation. The change of deformation between two fringes is achieved by

$$d_\mathrm{z} = \frac{\lambda}{\cos\theta_\mathrm{I} + \cos\theta_\mathrm{V}}. \tag{13}$$

On our condition, for $\theta_\mathrm{I} = 12°$, $\theta_\mathrm{V} = 0°$ and $\lambda = 0.6943\,\mu$m (ruby laser), the sensitivity will be $0.35\,\mu$m per fringe.

5. The comparison of ESPI and Laser vibrometer results

The magnitude of displacement component achieved by ESPI system was compared with results of a point-wise laser vibrometer. The laser vibrometer is an opto-electronic high performance instrument for non-contact measurement of surface vibrational velocity. After

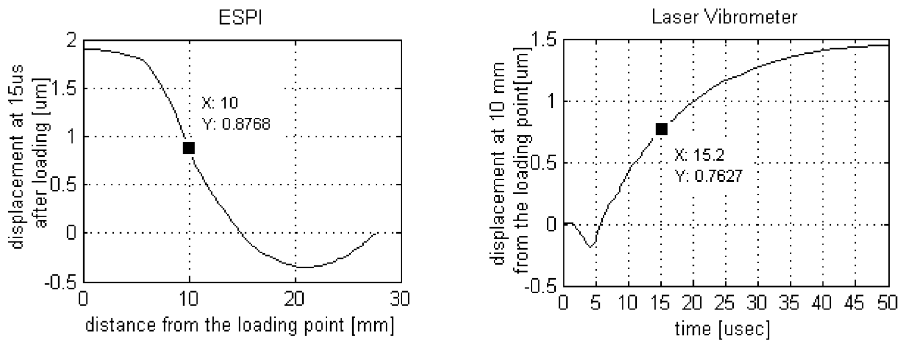

Fig.6: The comparison of ESPI and laser vibrometer results

integrating of the object's surface velocity the magnitudes of the object's surface displacement were compared. The z-axis displacement $d_z = 0.87\,\mu$m at the point 10 mm from the object's centre is depicted in the deformation profile of the steel plate (see Fig. 6). The same quantity $d_z = 0.76\,\mu$m was measured by the laser vibrometer. The maximal difference between both displacement fields makes 13 %.

6. Conclusion

Dynamic Electronic Speckle Pattern Interferometry (ESPI) was used to measure deformation profile of the thin steel plate. The optical arrangement for ESPI was designed to be sensitive to out-of-plane transient motion of the test-object. The transient event is complicated types of motion and therefore introduced the use of a pulsed laser, fast detectors and more complicated optical arrangements.

The fringe pattern obtained by ESPI can provide valuable information to the trained eye, but they have a few drawbacks. Analysis of the fringe pattern was performed by intensity-based technique and fringe tracking were carried out to identify only the centres of fringes that means the whole width of a fringe represents the same magnitude of displacement. Moreover, from the fringe pattern alone it is impossible to determine the sign of the phase change. For improving ESPI system, the phase shifting methods will be employed.

Full-field interferometric measurement [6] of dynamic displacement is well established through the techniques of holography. Interferometric holography produces fringes of quality comparable to those obtained with conventional interferometry from optically smooth surfaces. By comparison, speckle fringe patterns are noisy. However, the operational practical advantages of ESPI (photographic techniques are not required) are usually a decisive factor in the choice of the ESPI technique.

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