

Spatial Phase-Shift Digital Shearography for Out-of-Plane Deformation Measurement

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ABSTRACT

Measuring deformation under dynamic loading is still a key problem in the automobile industry. The first spatial phase-shift shearography system for relative deformation measurement is reported. Traditional temporal phase-shift technique-based shearography systems are capable of measuring relative deformation by using a reference object. However, due to its low acquisition rate, the existing temporal phase-shift shearography system can be only used under static loading situations. This paper introduces a digital shearography system which utilizes the spatial phase-shift technique to obtain an extremely high acquisition rate. The newly developed spatial phase-shift shearography system uses a Michelson-Interferometer as the shearing device. A high power laser at 532nm wavelength is used as the light source. A one mega pixels high speed CCD camera is used to record the speckle pattern interference. The spatial frequency carrier is introduced by tilting one of the mirrors in the Michelson-Interferometer. The Fourier Transform method (FT) is used to separate the spectra on spatial frequency domain. The Windowed Inverse Fourier Transform (WIFT) method is then used to evaluate the phase information of the recorded speckle pattern interference. The newly developed spatial phase-shift shearography system is used to measure an impact on a square metal plate clamped along its entire perimeter. The theory and experiment are shown in detail in this paper.

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INTRODUCTION

Deformation under dynamic loading is a key factor for automobile structural design. Digital shearography is a non-contact, whole field, coherent optical measurement method which has the capability to measure relative deformation [1, 2, 3]. The use of the phase shift technique improves the sensitivity of the measurement [4, 5, 6]. Most shearography systems use the temporal phase shift technique, which requires a stable speckle pattern distribution between the phase shifting steps and, thus, limits its usage to static situations only [6-7]. A spatial phase shift technique should be introduced into the digital shearography setup to improve its applicability for dynamic measurements [6].

The most common method used in industry for dynamic deformation measurements are displacement transducers based on strain gages. However, it only provides data for one point, and the measured data represents average data on the strain gage area. For localized deformation measurement, a big error will exist [4]. Digital image correlation is a computer vision based method. It can provide a full field deformation measurement by tracking the gray value distribution on the surface. However, the measurement sensitivity is usually limited to the micrometer level [5]. For smaller deformation measurements, laser based techniques are needed. Spatial phase-shift digital holography can measure the dynamic deformation at measurement sensitivity of tens of nanometer [8, 9, 10]. However, digital holography technique has too high of a requirement on environment conditions such as vibration, isolation, temperature, and air flow, limiting its application to lab

conditions only. The digital shearography technique takes advantage of the high measurement sensitivity of laser techniques, but has much higher resistance to the environment disturbance, making it suitable for use in industry in-field measurement. However, most digital shearography system existing now is only suitable for static measurements, due to the limitation of the temporal phase-shift technique [11, 12, 13]. By introducing the spatial phase-shift technique to digital shearography systems, it is possible to achieve dynamic deformation measurement.

This paper reports the first spatial phase-shift shearography system for relative out-of-plane deformation measurement. Theoretical derivation and experimental results are presented in detail.

THEORY AND DERIVATION

Fig. 1 shows the schematic of the shearography system for relative deformation measurement. A Helium-Neon laser, with a wavelength of 632.8nm, is expanded by a beam expander (BE) to illuminate the testing object and the reference object. The diffused light reflected from both objects goes through the shearing devices and is imaged on the CCD plane. One mirror of the Michelson Interferometer (M1) is tilted with a big angle, and the two images recorded on the CCD camera are completely separated by this big shearing. In this case, the light reflected by M1 contains only information from the testing object, while the light reflected by M2 contains only information from the reference object. A 4f system which consists of three lenses (image lens, L1 and L2) is added to the interferometer to enlarge the field of view.

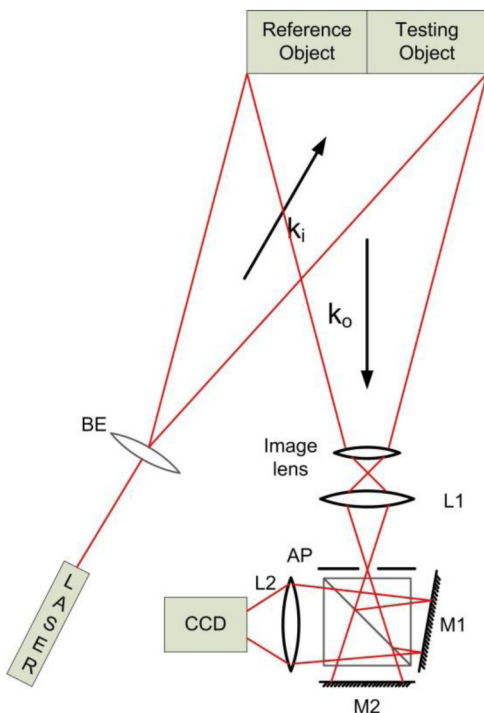


Figure 1. Schematic of 4f system embedded shearography setup for big shearing

By analyzing the phase difference of the light before and after loading, the relative deformation of the testing object due to the loading can be evaluated. As the optical path difference of these two lights is much smaller than the coherent length of the laser, a hologram between the testing object and reference object can be recorded on the CCD camera.

The CCD camera captures two shared wave fronts from the reference object and testing object. For this experiment, the shearing direction is in the x-direction. These two wave fronts can be represented by the following equations:

$$u_1(x, y) = |u_1(x, y)| \exp[i\varphi(x, y)]$$

Reference Beam)

(1)

$$u_2(x, y) = |u_2(x + \Delta x, y + \Delta y)| \exp\{i\varphi(x + \Delta x, y + \Delta y) - 2\pi f_0 \cdot x\}$$

(Sheared Beam)

(2)

Where u_1 , u_2 are the two components of the reference object and the testing object. The value f_0 represents the component of the spatial frequency introduced by shearing angle and can be expressed as:

$$f_0 = (\sin \theta / \lambda)$$

(3)

θ represents the shearing angle of the two mirrors (M1 and M2). Δx and Δy are the shearing distances in the x and y directions, respectively, and λ is the laser wavelength.

The intensity recorded on the CCD camera can be expressed as:

$$I = (u_1 + u_2)(u_1^* + u_2^*) = u_1 u_1^* + u_2 u_2^* + u_1 u_2^* + u_2 u_1^*$$

(4)

The * denotes the complex conjugate of u . A Fourier Transform is used to transmit the image from the spatial domain to the Fourier domain. After Fourier Transform, Eq. 4.11 transforms into the following form:

$$FI = U_1^2 + U_2^2 + U_1(f_x, f_y) \otimes U_2(f_0, 0)^* + U_2(f_0, 0) \otimes U_1(f_x, f_y)^*$$

(5)

Here $\otimes$ is the convolution operation, $U_1(f_x, f_y) = FT(u_1)$, $U_2(f_x + f_0, f_y) = FT(u_2)$.

Fig. 2 shows the spectrum after use of the Fourier Transform.

There are three spectra showing on the spatial frequency domain. The center spectrum is the $U_1^2 + U_2^2$, which is the low frequency term, and contains the information from the