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Digital ultrasonic speckle phase-shifting method

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ABSTRACT

The digital ultrasonic speckle phase-shifting method (USPM), which is introduced in this paper, can be applied to the measurement of small displacement that is smaller than speckle size at the test point compared to traditional ultrasonic speckle correlation method (USCM). Using USPM, a digital ultrasonic reference signal is introduced to interfere with the ultrasonic speckle signal, which is picked up at the test point on an object surface and is referred to as the object signal. As the phase of the reference signal is shifted several times using the software and then they superimpose with the object signal respectively, the phase of the object signal can be calculated according to the intensities of the superimposed signals. If the object surface moves a small distance, the phase variation of the object speckle can be detected by the same process. As a result, the displacement of the object surface can be measured. Based on the feature of ultrasonic speckles, inner surface displacement of an object can be measured using this proposed method. In this case, the effect of outer surface roughness to the measurement accuracy of USPM is examined experimentally. The experimental results show that the measurement is successful when the displacement is smaller than half of the speckle size at the test point and the roughness parameter R_a of the outer surface of the specimen is less than about 5.47 μm.

1. Introduction

When the laser beam is incident upon a rough interface, waves are scattered and then speckles with random amplitude and phase are formed in the space. Since 1970s researchers have paid a lot of attention to this phenomena [1,2]. As a result, various kinds of laser speckle detecting methods, including laser speckle pattern interferometry, have been set up and widely applied to fundamental scientific research and engineering [3,4]. Alternatively, there is also interest in the fact that when ultrasound waves are incident upon an interface between dissimilar media, speckles are also formed in the media. Ultrasonic speckles cannot be directly viewed by eyes as laser speckles, but they can be detected by a focus probe. Ultrasonic speckle signals can be converted to form a gray scale image too, as shown in Fig. 1, though it is not a necessary process. By comparison to laser speckles, ultrasonic speckles are still treated as noises to be compressed in most situations, e.g. in medical B-scan imaging, etc. However, ultrasonic speckles carry information about the surface characters and deformation as laser speckles do, moreover, ultrasonic speckles exist not only in air and liquid but also the inside of solid. These outstanding features gradually attracted attentions. In 1997 ultrasonic speckle pattern interferometry was proposed by Hong [5]. Nevertheless, this assumption does not come true due to lack of related theory and equipment support. Later, the first order and second order statistics of backscattered ultrasonic speckles were studied by Zhu et al. [6,7]. Moreover, the properties of ultrasonic speckles which were formed on two typical kinds of weak scattering surfaces were investigated [8,9]. Further, the statistical properties of P-SV mode converted ultrasonic speckles were also examined [10]. The results of these researches consist of the foundation of the application of ultrasonic speckle techniques to object deformation measurement. In 2006, ultrasonic speckle correlation method (USCM) was proposed [11], with which in-plane and out-of-plane displacement of an object immersed in water were measured in a non-contact way. Besides, USCM was applied to measure the underwater vibration [12] and strain based on adaptive genetic algorithm [13]. But USCM has its limitation, which requires the displacement of the object to be greater than the size of the ultrasonic speckle. In order to break through this limitation, we propose a digital ultrasound speckle phase-shifting method (USPM) in this paper. When using this method, ultrasonic probe does not need to scan in the space as in USCM. Instead, a standing focus probe is used to pick up the ultrasonic speckle on the object surface. Further, different with the laser

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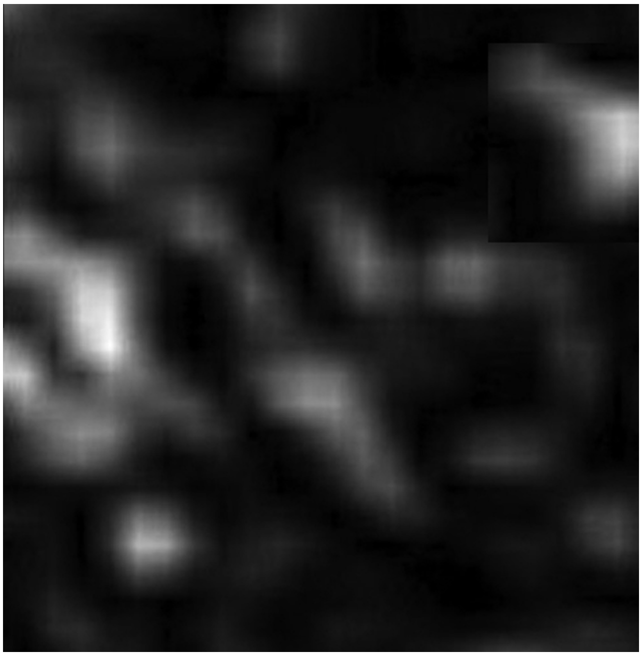

Fig. 1. A gray scale image converted from ultrasonic speckles.

speckle interferometry, the reference signal is not picked up from a reference object surface but produced by a signal generator. And the interference from the reference signal to the object signal does not take place in the media space but in the computer instead.

2. Principle of USPM

The principle of USPM is similar to that of the laser speckle phase-shifting interferometry [14]. As a rough surface is radiated by ultrasound, the complex amplitude of the speckle located at point $P_1(x_1, y_1)$ on O—XY plane, which is referred to as object signal, can be expressed as

$$\boldsymbol{A}(x_1, y_1) = a(x_1, y_1)\exp[j\varphi(x_1, y_1)], \tag{1}$$

where $a(x_1, y_1)$ is its amplitude and $\varphi(x_1, y_1)$ is its phase. Assuming there is another speckle located at point $P_2(x_2, y_2)$ on O—XY plane, which is referred to as reference signal, its complex amplitude is expressed as

$$\boldsymbol{B}(x_2, y_2) = b(x_2, y_2)\exp[j\psi(x_2, y_2)], \tag{2}$$

where $b(x_2, y_2)$ is the amplitude and $\psi(x_2, y_2)$ is the phase. As mentioned above, actually the reference signal is produced by a wave generator. Let the object signal interfere with the reference signal, the intensity of the superimposed signal is

$$\begin{aligned} I_0(x_1, y_1;\ x_2, y_2) &= (\boldsymbol{A} + \boldsymbol{B})(\boldsymbol{A} + \boldsymbol{B})^* \\ &= a^2(x_1, y_1) + b^2(x_2, y_2) + 2a(x_1, y_1)b(x_2, y_2) \\ &\quad \times \cos[\varphi(x_1, y_1) - \psi(x_2, y_2)] \end{aligned} \tag{3}$$

where * denotes the conjugate operation. Now, with the phase of the reference signal shifted by $\pi/2$, π and $3\pi/2$ in sequence, their complex amplitude becomes

$$\boldsymbol{B}_i(x_2;\ y_2) = b(x_2, y_2)\exp[j(\psi(x_2, y_2) + i\pi/2)] \quad (i = 1, 2, 3). \tag{4}$$

Then, they interfere with the object speckle signal in sequence and the intensities of these superimposed signals are

$$I_i(x_1, y_1;\ x_2, y_2) = a^2 + b^2 + 2ab\cos[\varphi(x_1, y_1) - \psi(x_2, y_2) - i\pi/2] \quad (i = 1, 2, 3). \tag{5}$$

Let

$$\alpha(x_1, y_1;\ x_2, y_2) = \varphi(x_1, y_1) - \psi(x_2, y_2), \tag{6}$$

where $\alpha(x_1, y_1;\ x_2, y_2)$ means the phase difference between the object signal and the reference signal before object displaces. According to Eqs. (3), (5) and (6), $\alpha(x_1, y_1;\ x_2, y_2)$ is given by

$$\alpha(x_1, y_1;\ x_2, y_2) = \tan^{-1}\frac{I_1 - I_3}{I_0 - I_2}. \tag{7}$$

Now, the object moves a distance smaller than the size of speckle at $P_1(x_1, y_1)$. In this case, the amplitude of the object signal picked up at $P_1(x_1, y_1)$ is assumed to be unchanged, whereas its phase has a variation $\Delta\varphi(x_1, y_1)$. Thus, after the displacement the complex amplitude of the object signal becomes

$$\boldsymbol{A}^d(x_1, y_1) = a(x_1, y_1)\exp[i(\varphi(x_1, y_1) + \Delta\varphi(x_1, y_1))]. \tag{8}$$

As it interferes with the original reference signal, the intensity of the superimposed signal is

$$\begin{aligned} I_0^d(x_1, y_1;\ x_2, y_2) = a^2 + b^2 + 2ab\cos[&\alpha(x_1, y_1;\ x_2, y_2) \\ &+ \Delta\varphi(x_1, y_1)]. \end{aligned} \tag{9}$$

Now consider the interference from the object signal to the reference signal, whose phase has been shifted by $\pi/2$, π and $3\pi/2$ in sequence. As a result, the intensities of these superimposed signals are

$$\begin{aligned} I_i^d(x_1, y_1;\ x_2, y_2) = a^2 + b^2 + 2ab\cos[&\alpha(x_1, y_1;\ x_2, y_2) + \Delta\varphi(x_1, y_1) \\ &- i\pi/2] \quad (i = 1, 2, 3). \end{aligned} \tag{10}$$

Similarly, $\alpha(x_1, y_1;\ x_2, y_2) + \Delta\varphi(x_1, y_1)$ is given by

$$\alpha(x_1, y_1;\ x_2, y_2) + \Delta\varphi(x_1, y_1) = \tan^{-1}\frac{I_1^d - I_3^d}{I_0^d - I_2^d}, \tag{11}$$

which is the phase difference between the object signal and the reference speckle after displacement. Thus, according to Eqs. (7) and (11), $\Delta\varphi(x_1, y_1)$, the phase change of the object signal due to the displacement, is obtained by

$$\Delta\varphi(x_1, y_1) = \tan^{-1}\frac{I_1^d - I_3^d}{I_0^d - I_2^d} - \tan^{-1}\frac{I_1 - I_3}{I_0 - I_2}. \tag{12}$$

For either laser speckle or ultrasonic speckle, the size of a speckle is defined as the following. If the speckle's intensity or amplitude between two neighboring points in a speckle field is changed by a period, i.e. the phase is changed by 2π, the distance between these two points is defined as the size of the speckle. In ultrasonic speckle experiment, a focus probe is used to pick up the speckle signal. When the surface translated, the speckles in the space will be translated synchronously. If the focus probe remains motionless, its received signal changes continuously. If the phase of the signal received by the focus probe at the receiving point changes by 2π, the distance of the surface translation is equal to the size of the speckle. Similarly, if the phase of the signal at the receiving point changes by π, the distance of the surface translation is equal to the half of the speckle's size. So the out-of-plane displacement and the in-plane displacement of the test point $P_1(x_1, y_1)$ are given by

$$\begin{cases} d_{out}(x_1, y_1) = \delta_L\frac{\Delta\varphi(x_1, y_1)}{2\pi} \\ d_{in}(x_1, y_1) = \delta_T\frac{\Delta\varphi(x_1, y_1)}{2\pi} \end{cases}, \tag{13}$$

where δ_L and δ_T are the longitudinal size and the transverse size of the speckle at $P_1(x_1, y_1)$ respectively.