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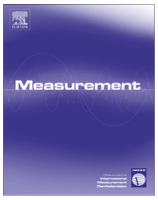

Displacement measurement using digital speckle multi-frequency harmonic wave correlation method

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ABSTRACT

In the displacement measurement using digital speckle correlation method, significant measuring error due to the multi-peak nature of the correlation coefficient function is a critical issue as sometimes the secondary peak can be wrongly determined as the maximum instead of the highest peak. In the multi-frequency harmonic wave correlation method (MHCM) as proposed in this work, for speckle patterns before and after the displacement, correlation calculations were performed on corresponding sets of data matrices assembled by amplitudes/intensities obtained from harmonic waves with different frequencies. The calculated maximum correlation coefficients were compared with each other to locate the maximum in order to measure the displacement. Both ultrasonic speckle MHCM and laser speckle MHCM were applied to the displacement measurement respectively. Measured results indicated that MHCM effectively helps to ensure the correct determination of the maximum correlation coefficient, to avoid random errors caused by other factors and improves the measurement accuracy in the meanwhile.

1. Introduction

In early 1980s, Yamaguchi in Japan and Peters and Rason in the US proposed the idea of Digital Speckle Correlation Method (DSCM) [1,2]. It utilizes digital computational technique to replace the traditional calculation method based on laser speckle interference fringes, and was successfully applied to rigid body displacement measurements [3]. After that, DSCM was intensively studied and improved to be a widely accepted engineering measuring method [4,5]. Similarly, speckle patterns can also be generated at the interface (or inside the media) by the interference of scattered waves when an ultrasonic wave is incident onto a rough interface or is propagating in an inhomogeneous media. Compared with laser light, ultrasound can propagate not only in gases and liquids, but also in solids, which enables underwater displacement measurements and inner surface deformation measurements in nontransparent objects. Based on this advantage, the ultrasonic speckle measurement method may open up a new field for underwater engineering measurement as well as the study of the interior deformation in solids. Earlier works on ultrasonic speckles mainly focus on medical imaging [6,7]. Engineering based applications have attracted much attention in recent years. Experimental and analytical studies have been performed on the statistical characteristics of the first and the second order ultrasonic speckle field reflected at rough surfaces [8,9], and the ultrasonic DSCM was used to measure the underwater displacement, underwater strain and vibration coefficients [10–12].

The correlation coefficient in laser or ultrasonic DSCM is a multi-peak function. Because of the multi-peak nature when searching for the position of the maximum correlation coefficient, from time to time the secondary peak

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was wrongly determined as the highest peak and resulting in significant measurement errors. To avoid such misjudgments, a digital speckle multi-frequency harmonic correlation method (MHCM) is proposed in this work, that a spectrum analysis is performed on the collected ultrasonic speckle patterns. Data matrices consisting of harmonic wave amplitudes at different frequencies are assembled, and correlation calculations are performed respectively on set of data matrices before and after the displacement to obtain comparable results. By taking average of results from multiple groups of measurements, the measurement accuracy can be improved. For laser speckle MHCM on the other hand, different monochromatic speckle patterns can be obtained when laser light with different wavelengths are used, correlation calculations can be performed respectively before and after the displacement with each color. Comparing different groups of results helps to minimize the possibility of significant measurement error and improves the accuracy in the meantime.

In this way, significant measuring error can be avoided from both the misjudgment of the highest peak of correlation coefficient function and other random factors, including the electrical noise and the mechanical error (error from the stepping size and from the stepping motor in fixing the position of the sampling point). Besides, for underwater applications, the influence of the water fluctuation is a very important issue. Water is incompressible most of the time, so the fluctuation of water will not change the density of water. Therefore the index of refraction in water can be treated as a constant. Ultrasonic waves travel in water at a speed around 1500 m/s, so the refraction index of ultrasonic waves in water can be hardly influenced by a water speed less than 10 m/s. In this way, the water fluctuation is considered a minor influence for underwater applications for MHCM.

2. Theories

In MHCM, speckle patterns are recorded on the object surface before and after deformation. Information including displacement and strain at different positions can be extracted based on the probability statistical correlation on the amplitude/intensity distributions of speckles in small regions.

Ultrasonic and laser speckle MHCM shares similar calculation criteria but with discrepancies. In laser speckle MHCM, laser as an excellent monochromatic light source is adopted. A CCD camera records speckle patterns. Speckle intensity is represented by the gray scale of pixels, with which data matrices can be determined. In ultrasonic speckle MHCM, a string of short pulses with poor monochromaticity is used instead. The speckle intensity is resulted from the superposition of interference waves with all different frequencies within the bandwidth. As a result, the intensity difference at different positions is not high enough to define a data matrix suitable for correlation calculation. On the other hand, receiving ultrasonic speckle signals simultaneously over the entire measuring surface is not currently possible due to instrument limitations. Therefore in ultrasonic speckle MHCM for the time being, 2D step by step scan of the testing surface is conducted using a focusing probe to collect the speckle signal at different positions. Then a discrete fast Fourier transform (DFFT) is performed on the collected speckle signals to obtain the amplitude spectrum. Amplitude at specific frequencies at different positions were extracted as the amplitude spectrum of that very frequency. As shown in the example in Fig. 1 that the amplitude at frequency F_1 is determined as the characteristic value of the signal, and a data matrix can be assembled after interpolation.

Correlation calculations can be performed on matrices before and after the displacement using standard correlation coefficient $C_1(u, v)$ as the following:

$$C_1(u,v)=\frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\left[f_1(x_i,y_j)-\bar{f}_1\right]\cdot\left[g_1(x_i',y_j')-\overline{g_1}\right]}{\sqrt{\sum_{i=1}^{n}\sum_{j=1}^{n}\left[f_1(x_i,y_j)-\overline{f_1}\right]^2}\cdot\sqrt{\sum_{i=1}^{n}\sum_{j=1}^{n}\left[g_1(x_i',y_j')-\bar{g}_1\right]^2}} \tag{1}$$

in which, $f_1(x_i, y_j)$ $(i, j = 1,2,\ldots,n)$ is the amplitude distribution matrix m_1 at a subdivision with harmonic frequency F_1 before the displacement; $g_1(x_i{}', y_j{}')$ $(i,\ j = 1,2,\ldots,n)$ is the amplitude distribution matrix M_1 at the corresponding subdivision with harmonic frequency F_1 after the displacement; $\bar{f}$ and $\bar{g}$ are the average amplitude of the subdivision before and after the displacement, with $\overline{f_1}=\sum_{i=1}^{n}\sum_{j=1}^{n}f_1(x_i,y_j)/n^2$, $\overline{g_1}=\sum_{i=1}^{n}\sum_{j=1}^{n}g_1(x_i',y_j')/n^2$; $x_i'=x_i+u$, $y_i'=y_i+v$, with u and v the displacement in x and y directions in the corresponding subdivision respectively; correlation coefficient C_1 is in the range $[-1,\ 1]$. When matrices m_1 and M_1 are so similar to each other, $C_1(u, v)$ is very close to or equals to 1, indicating the overlap of the center of m_1 with the center of M_1 after the displacement. In application of MHCM, it is very important that the subdivision M_1 associated with m_1 needs to be located after the displacement. Therefore the position of the highest peak needs to be located, which involves the proper searching protocol and the determination of the highest peak.

The correlation coefficient $C_1(u, v)$ is usually a multi-peak function as shown in the spacial distribution in

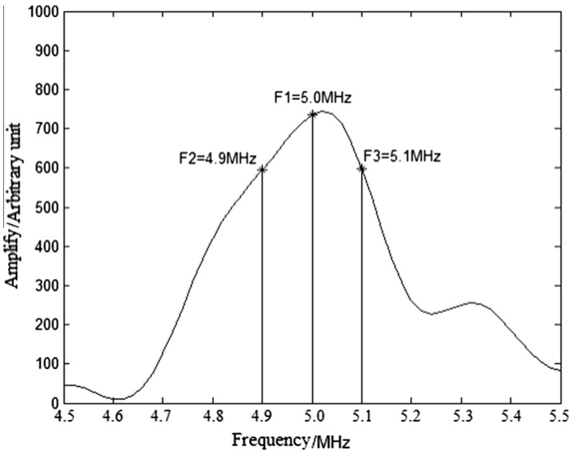

Fig. 1. Spectrum diagram of ultrasonic speckle signal.