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Non-destructive strain determination based on phase measurement and radial basis function

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ABSTRACT

A method of non-destructive strain field determination based on the combination of the temporal phase measurement interferometry (TPMI) with radial basis function (RBF) was proposed in this paper. The quality of unwrapped phase obtained by TPMI was improved after RBF interpolation. Then accurate displacements can be obtained, followed by the strain components calculated by employing point-wise local least-squares fitting technique. Optimal sampling intervals of images with different sizes were given based on numerical experiments. For validation, the normal strain distributions in y direction of an aluminum plate subjected to uniform tensile loading were determined by the proposed technique and compared with values measured by strain gauge. The results are in good agreement with each other. Besides, strain distribution of a three-point bending beam with pre-notch was evaluated by the proposed method and the strain gauge technique. Comparison of the results reveals the effectiveness and feasibility of the proposed method.

1. Introduction

Strain is an important parameter in the mechanical testing. There are two ways to measure strain: fundamental surface touch technique and non-contact measurement method. Electric resistance strain gauge technique is the most widely used method. Although very small strains can be measured, it has some drawbacks. For example, adhesion of strain gauge requires experienced technician and it is tedious and time-consuming. Furthermore, only the discrete data can be obtained, and the measured locations with strain gauges must be decided before testing. Optical techniques, such as moiré, holography, digital image correlation and scanning laser doppler vibrometer, were developed to evaluate strain for the advantages of being accurate, full-field, non-destructive and fast data extraction. For moiré interferometry, it needs to coat gratings on the surface of the test specimen [1]. Moreover, spatial resolution and experimental difficulties with the method are directly linked with the grid step. Projection moiré is another famous technique, a disadvantage of this technique is that the imaging system must be able to resolve the grating as projected onto the specimen; and, to satisfy the paraxial assumption, the imaging must be done from a distance [2]. Holographic interferometry is also well known. This method is possible to apply mainly in laboratories – to ensure the stability of the holographic equipment. Digital image correlation (DIC) is a practical and effective optical technique for surface deformation measurement [3,4]. However, the accuracy and computational efficiency of DIC rely on the algorithm and the natural or artificial speckle pattern on the test object surface. For scanning laser doppler vibrometer, complex and high requested works should be prepared before testing, such as exact 3D alignment and performing a precise measurement of the coordinates of all grid points [5]. Among all optical interferometric techniques, electronic speckle pattern interferometry (ESPI) is frequently applied to determinate the full-field displacement and strain, and it is the most practical and powerful one [6,7]. The accuracy of ESPI can reach 30–50 nm in applications and requires less surface preparation.

Admittedly, most of these optical techniques are based on the principle that the strain distribution can be calculated from the measuring displacement field. That is to say, the accuracy of strain field mainly depends on the quality of the displacement field. For ESPI, the displacement information is encoded in the form of a phase distribution which can be extracted from speckle patterns. However, there are some noises which contaminate the differential of the displacement. Thus, many research works focused on eliminating the noisy data of the pattern or the phase. For example, denoising was done on intensity by spin filters [8] and partial differential equation (PDE) based methods [9]. Windowed Fourier transform (WFT) [10], regularized quadratic cost function

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(RQCF) [11] and sine/cosine average filtering [12] were applied to filter the wrapped phase.

Radial basis function (RBF) method, which is a powerful mathematical tool [13], was performed on temporal phase measurement interferometry (TPMI). And a method of strain field analysis based on the combination of the TPMI with RBF interpolation was proposed. RBF is a famous means used for the purpose of scattered data approximation. Inasmuch as RBFs involve a single independent variable regardless of the dimension of the problem [14], they have been used extensively in the context of multivariate interpolation including image interpolation from scattered data [15,16]. Wang et al. introduced the RBF interpolation to the fringe skeleton method and RBF was used to filter original ESPI fringes [17]. However, sometimes it is difficult to distinguish between signal and noise in the original fringe while contaminations can be identified from the unwrapped phase map [12]. Furthermore, the result calculated from the fringe after RBF interpolation would not be creditable if more noise points were sampled as signals. Consequently, we put the emphasis on improving the quality of the unwrapped phase in this paper.

Theoretically, to achieve a reliable radial basis function, the sampling interval should be small enough so that there are sufficient nodes contained in the function to be close to the actual one. However, more sampling nodes must cost more time. On the other hand, it may lead to larger errors in the approximation in actual applications because more noise nodes may be chosen as the data sources. Obviously, a better sampling interval should meet these conflicting demands. In the research, thirteen different sets of node spacings and seven different test functions were used to study the accuracy and the computing time of thin-plate spline interpolation for two dimensional data. For each set of data points and each test function, the computing time and root mean square (RMS) error between the radial basis interpolation and the test function were computed. Then the better sampling interval can be determined by taking into account time and error.

To obtain the accurate strain field, two aspects should be considered. One is the accuracy of displacement fields, the other is the method of calculation. In mathematical theory, strain components can be computed from numerical differentiation of the estimated displacement field. Unfortunately, the numerical differentiation is an unstable and risky operation, because it can greatly amplify the noises contained in the computed displacement [18]. Many smoothing algorithms have been performed on the computed displacements to suppress the noise of the displacements and subsequently differentiating them to calculate strains [19,20]. However, some of them are quite cumbersome. The more practical technique for strain estimation is point-wise local least-squares (PLS) fitting technique. Since the noises can be largely removed in the process of local fitting, the accuracy of the calculated strains would be greatly improved. It has been widely used in DIC because of simpleness, high accuracy and effectiveness [3,21].

In our work, the unwrapped phase, which was measured by TPMI, was interpolated by means of RBF with optimal node spacing first. Then the strain components can be calculated by PLS after obtaining displacement distributions. In order to verify the feasibility and effectiveness of the proposed method, an experiment was performed on an aluminum plate under uniform tensile loading. Partial derivative of in-plane displacement, which corresponds to the interpolated phase, was compared with the data obtained by strain gauge technique. The results show a good agreement. As an application example, normal strain in x direction of a three-point bending beam with pre-notch was determined. During the test, electric resistance strain gauge technique was also applied at the same time. Comparison of the results reveals the effectiveness and feasibility of the proposed method.

2. Theory

2.1. Temporal phase measurement interferometry (TPMI)

2.1.1. Principle

Phase measurement interferometry (PMI) is the most widely used technique today for the measurement of wavefront phase in interferometers. PMI techniques can be broadly classified into two categories: (1) phase-shifting methods which take the phase data sequentially and (2) spatial methods which take the phase data simultaneously. Generally thinking, the overall accuracy of the spatial techniques is usually expected to be lower than for the temporal methods [22]. So when it comes to static nature, methods of the first type are more popular for phase estimation. Methods of the first type are known as temporal PMI or TPMI.

A general expression for the recorded intensity in an interferogram can be written as

$$I(x, y, n\alpha) = a(x, y) + b(x, y)\cos[\varphi(x, y) + n\alpha],\ \ n = 0, 1, \ldots \tag{1}$$

where $\varphi(x, y)$ is the phase to be determined, $a(x, y)$ is the slowly varying background illumination, and $b(x, y)$ is the contrast of the interference fringes. The parameter α is the phase step among the interferograms obtained by linearly varying the path difference between the test and reference beams. With regard to detector non-linearities, the algorithms with four frames, which is quite insensitive to such error, was used in the research [22]. In this case, let $\alpha = \pi/2$, then the searched phase can be solved by

$$\varphi = \arctan\left(\frac{I(3\alpha) - I(\alpha)}{I(0) - I(2\alpha)}\right) \tag{2}$$

During the test, the object is illuminated by a laser light located at S, as shown in Fig. 1. Light is scattered by an object point P_1 to an observer at point B. When the object is deformed, the surface point P_1 moves to point P_2 by the displacement vector $\vec{d}$, there is a change in the optical path from the point source S to point P_2 and from there to the viewing point B. So, there is a change in phase associated with this change in optical path. This phase difference is due to two reasons: the scatter changes its distance from the source, and it also changes its distance to the detector [23].

The optical path difference (OPD) is expressed as

$$\begin{aligned} \mathrm{OPD} &= SP_1 + P_1B - SP_2 - P_2B \\ &= \vec{s}_1\cdot\overrightarrow{SP_1} + \vec{b}_1\cdot\overrightarrow{P_1B} - \vec{s}_2\cdot\overrightarrow{SP_2} - \vec{b}_2\cdot\overrightarrow{P_2B} \end{aligned} \tag{3}$$

where $\bar{s}_1$ and $\bar{s}_2$ are unit vectors in the illumination direction, $\bar{b}_1$ and $\bar{b}_2$ are unit vectors in the observation direction.

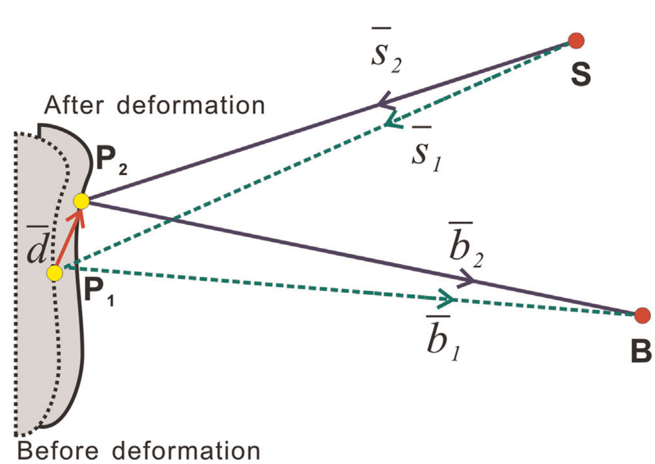

Fig. 1. Scheme of sensitivity vector.