

Comparison of in-plane displacement measurement from circular grating moiré fringes using Fourier transformation and graphical analysis

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ABSTRACT

The analysis of moiré patterns generated by a pair of circular gratings requires complex computation, especially for high resolution in-plane displacement measurements. In this paper, the Fourier transformation method developed by previous researchers for analyzing the moiré patterns was applied to digitally generated and real moiré patterns. The real moiré patterns were formed by low-frequency gratings, typically used in crack growth monitoring. Due to the failure of the Fourier transformation method when applied to moiré patterns generated by low-frequency gratings, the performance of the recently proposed graphical analysis method that determines the displacement values accurately from the moiré patterns was compared with the Fourier transformation approach. In this method, the moiré patterns were spatially transformed from Cartesian-to-polar coordinate system. The morphological grayscale dilation operation was used to eliminate the residual grating in the transformed pattern and preserve only the moiré fringes. The centerline of each moiré fringe was fitted with a sine function, and the eccentricity magnitude and directions between the two gratings were determined directly from the amplitude and the phase shift of the fitted function. The comparison shows that the proposed graphical analysis method is able to give high in-plane displacement accuracy with a mean error of -0.002 mm and 0.451° in the eccentricity magnitude and direction, respectively, without the need for complex computation using Fourier transformation.

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1. Introduction

Moiré methods, such as geometric moiré, shadow moiré, projection moiré, reflection moiré and moiré interferometry, have been used for many decades in the measurement of surface topography, deformation, in-plane displacement, strain and vibrations. A wide range of measurement sensitivity is possible in these methods, depending mainly on the frequency of the gratings used and the optical amplification of the imaging system. In most moiré methods linear gratings have been the most popular type of gratings, especially in shadow and projection moiré [e.g. 1–5]. Non-linear gratings have been applied only by a limited number of researchers for the purpose of measurement. Some of the related published papers are reviewed in the following paragraphs due to their potential for crack monitoring in building structures.

Song et al. [6] determined the displacement and direction of movement using elongated gratings in the form of an athletic track. The technique was applied to measure the refractive indices of several materials as well as the expansion coefficient of aluminum. Park and Kim [7] used Fourier series transformation

method to determine the 2-D displacement components from moiré patterns generated by superimposing two circular gratings of slightly different pitches. Lay and Chen [8] determined the rotation angle of a human head using the circular gratings moiré method. Kim et al. [9] analyzed the self-image of a phase-type elongated circular grating that has a period structure so that it can be used in moiré deflectometry. Zhang et al. [10] introduced a phase-shifting method for circular gratings moiré patterns formed using a Michelson interferometer. The phase shifting was achieved by rolling a polarization foil placed in the path of the reference beam. A set of radial or circular moiré fringes, depending on the direction of the overlapping gratings, was generated by Szwajkowski and Patorski [11]. Li et al. [12] introduced the digital moiré technique with circular and radial gratings for the measurement of in-plane displacement and strain in soft material under tensile load. A computer generated reference grating was superimposed onto the deformed specimen grating to generate the moiré fringes. Using the digitally generated gratings it was possible to introduce phase-shifting and obtain the displacement and strain fields. The authors transformed the moiré pattern into the polar coordinate system to ease the filtering and phase-shifting operations. In a related study, Xiao et al. [13] measured the strain in a mixed-mode fracture problem of large deformation materials using the digital moiré method using circular and radial

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gratings with phase-shifting technique. A method to increase the measurement accuracy of the moiré deflectometry method using circular gratings by measuring the angle between the zeroth and first fringe order was proposed Ng [14].

In a recently published paper [15], the circular grating moiré patterns were applied to measure the in-plane displacement caused by crack growth. In the proposed method, two circular gratings having slightly different pitches were attached to either side of the crack and were superimposed to form a geometric moiré pattern. The changes in the moiré pattern due to the change of the relative displacements between the centers of the gratings reflected the growth of the crack and the direction of the structural movement. The moiré patterns were captured and were compared with a set of reference patterns of known displacements after a series of image processing stages. The displacement components were determined using pattern matching. Although the proposed method is simple, the resolution of the linear displacement (eccentricity magnitude) was limited to about 0.50 mm, while the resolution of angular offset (eccentricity direction) was limited to 15°.

A residual gratings removal algorithm that produced better quality moiré fringes was introduced by Yen and Ratnam [16]. The algorithm enabled the resolution of the previous pattern matching method to be increased. An algorithm that could detect the eccentricity direction was developed to decrease the number of reference patterns as well as increase the resolution of the direction (angle) measurement. Using the approach it was possible to achieve a resolution of 0.02 mm for the eccentricity magnitude and 5° for the eccentricity direction. Since the resolution of this approach relied on the step difference in the reference moiré patterns, it was necessary to generate a large number of reference patterns with very fine steps in order to increase the resolution further. This imposed an upper limit to the resolution that can be achieved due to the need to prepare a large database of reference images and the increase in the computer processing time during pattern matching.

In the method proposed by Park and Kim [7], Fourier series transformation was used to determine the displacement from the moiré patterns generated by overlapping two circular gratings of very high frequencies (very small pitches). Using a pair of circular gratings having pitches of 6 μm and 24 μm the authors achieved a measurement resolution of 0.01 μm. To achieve such a high measurement resolution, however, the authors used special imaging optics to magnify the moiré patterns due to the small size of the gratings, which was about 2.4 mm in diameter. The authors' work provided an alternative to analyzing the circular gratings moiré pattern, which has potential for application in crack growth measurement as presented in previous work [15–17]. However, a detail study of their method is needed to determine its applicability to low frequency circular gratings with grating pitches larger than 0.50 mm.

In another recent publication [17], a graphical analysis method that seeks in-plane displacement directly from the moiré fringe pattern in the polar coordinate system was proposed. Although the displacement values can be determined more easily using this approach, the algorithm was applied to custom-made gratings that produce a single circular moiré fringe when the eccentricity value is zero. Moreover, no detailed comparison with the Fourier transformation method developed by Park and Kim [7] was carried out. This work is aimed at comparing the Fourier transformation method developed in previous research [7] with an improved graphical analysis method.

In the early part of this paper, the method proposed by Park and Kim [7] was applied to moiré patterns obtained by superimposing both high-frequency and low-frequency circular gratings to test the applicability of their approach for such type of gratings. An improved graphical analysis method that can be used to obtain the displacement components using commercially

available gratings that produce multiple moiré fringes at zero eccentricity is presented.

2. Theory and development of algorithm

In the method developed by Park and Kim [7], the moiré patterns were generated by optically overlapping a pair of circular gratings. The fluctuation of the intensity in the radial direction of each grating was assumed sinusoidal. The intensity and the position of each pixel in the digitized moiré pattern were used as inputs to determine the relative displacement of the gratings. The Fourier transformation method and phase-unwrapping were used to determine the relative linear displacement represented by the eccentricity magnitude (ε) and eccentricity direction (φ) of the two gratings. These parameters are illustrated in Fig. 1. Once ε and φ are known the in-plane displacement components can be readily obtained from the following relations:

$$d_x = \varepsilon \sin \varphi \quad (1)$$

and

$$d_y = \varepsilon \cos \varphi \quad (2)$$

The intensity variation in the pure moiré fringes (without the original gratings) is given by [7]

$$I_m(r, \theta) = \cos[2\pi r - \psi_{uw}(\theta)] \quad (3)$$

where

$$\psi_{uw}(\theta) = 2\pi N \varepsilon_{out} \cos(\theta - \varphi_{out}) \quad (4)$$

and N is the number of the circles in the gratings, r and θ are the pixel coordinates in the r - θ plane. The Fourier series transformation method is applied to determine the wrapped radial phase $\psi_w(\theta)$ from the input moiré pattern given by

$$\psi_w(\theta) = \tan^{-1} \left(\frac{\sum_{i=0}^{n-1} [I_m(R(i/n), \theta) \sin 2\pi(i/n)]}{\sum_{i=0}^{n-1} [I_m(R(i/n), \theta) \cos 2\pi(i/n)]} \right) \quad (5)$$

where i is the index of the pixel in the radial direction and n is the total number of pixels in radial direction. Phase unwrapping is then carried out to ensure the continuity of the radial phase distribution so that a continuous sine-wave profile can be obtained. The unwrapping operation is given by

$$\psi_{uw}(\theta) = 2\pi m + \psi_w(\theta), \quad m = 0, \pm 1, \pm 2, \pm 3, \dots \quad (6)$$

A second Fourier transformation after the phase unwrapping operation results in Eqs. (7) and (8) from which the output eccentricity magnitude ε_{out} and output eccentricity direction φ_{out} can be

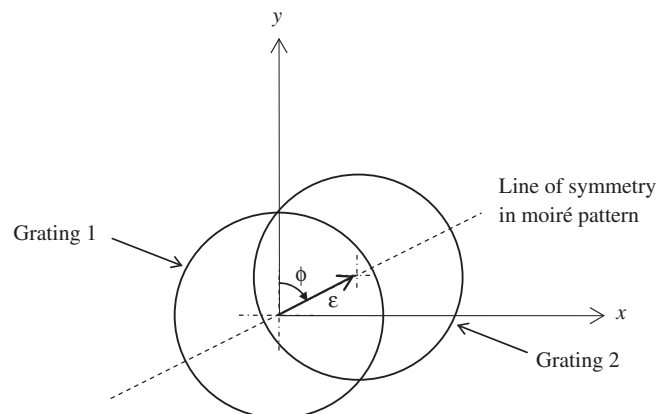


Fig. 1. Eccentricity magnitude ε and eccentricity direction φ of superimposed circular gratings.

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