

Shape and Strain Measurement of Rotating Tire by Sampling Moiré Method

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ABSTRACT

Recently, sampling moire method was developed to analyze the phase of a one-dimensional or two-dimensional grating on an object with high accuracy. In the method, several phase-shifted moire patterns are generated from one image of the grating. In order to analyze a shape by a stereoscopic method, it is necessary to find the corresponding points between the two images of the object recorded from different two cameras. It is possible to analyze the phase of the grating using the sampling moiré method and find the corresponding points as points with the same phase. It is also possible to analyze the displacement and strain from the corresponding point before and after deformation. This method is, therefore, suitable for shape and strain distribution measurement of a moving object. In this paper, a dynamic shape and strain measurement method using the sampling moiré method is proposed and a system for the measurement is developed. The principle of the method, the measurement system, and the experimental results applied to a rotating tire running at the speed of 80 km/h are shown.

INTRODUCTION

It is important to analyze the shape and the distributions of displacement and strain of a moving object such as a rotating tire. The results of the shape and the displacement can be applied to computational analysis such as finite element method to analyze the strain and stress distributions of the object.

Takahashi et al. [1] measured the shape of a rotating tire using light cross section method with an ultra high speed image processing camera. They took one picture of a cross line of the rotating tire. It measures only the shape along one line on the tire. The light cross section method can measure only shape. It cannot measure the displacement and strain.

Stereoscopic method is often used for measuring the 3-D coordinates on the surface of an object [2]. The 3-D coordinates are obtained from two images of an object recorded by two cameras from different directions. It is important to find the corresponding points accurately between the two images. Especially, the accuracy of the 3-D coordinates is important in the case of analyzing strain distribution from the 3D coordinates between before and after deformation of the object.

Schmidt et al. [3] and Moser et al. [4] measured dynamic displacement and strain of a tire by 3D digital imaging correlation method. The digital image correlation (DIC) is a popular and famous method to find the corresponding points between two images using random patterns [5, 6]. This is very useful method to measure displacement and strain distributions. However, the analysis speed and the spatial resolution are not so high. In the case of a rotating tire, the measurement methods using Fourier transformation of a grating image were proposed [7, 8, 9]. This measurement method has some problem on analyzing time and measurement accuracy.

Moiré method is usually used to measure the shape and the strain distributions of an object [10, 11, 12]. Conventional geometric moiré method uses a specimen grating and a reference grating. The superposition of the two gratings shows a fringe pattern which provides a moiré fringe pattern showing the information of the deformation of a specimen grating. In order to analyze the moiré fringe pattern, phase analysis method is useful to obtain accurate result. It requires more than three images which have different phase-shifted fringe patterns. However, it is difficult for the moving object to obtain several phase-shifted images simultaneously or in the same condition.

Recently sampling moiré method or scanning moiré method is used to analyze the deformation of an object [13, 14, 15]. It uses scanning lines or sampling pixels instead of a reference grating. The analysis of the phase by the scanning moiré method or sampling moiré method makes it accurate analysis [16, 17, 18, 19, 20]. Arai et al. [16] proposed a method to analyze the phase distribution by four phase-shifted moiré images produced from a grating image using phase-shifting method. This method is very useful and accurate. The authors also applied this method to measure the displacement distribution of a lever under three-point bending [18]. A specimen grating pattern on an object is recorded by a digital camera. Though the digitized image shows only the grating, a moiré fringe pattern appears by thinning-out the pixels, i.e., by sampling the image with a constant pixel pitch. If the sampling pitch is changed, the moiré pattern is changed. If the phase of the sampling i.e., the start point of the sampling is changed, the phase of the moiré pattern is changed [15, 16, 17, 18]. The method can analyze the phase values from one image of a grating pattern. The analyzed phase is very accurate because several phase-shifted moiré fringe patterns are obtained by changing the sampling phase. The accuracy of this method is very high because the phase of the grating pattern is analyzed by a phase-shifting method using many phase-shifted moiré patterns [19]. The phase-shifted moiré patterns are generated in a computer from a one-shot grating image. This method is, therefore, suitable for shape and strain distribution measurement of a moving object such as a rotating tire.

The phase analysis of the grating on an object is also possible to find corresponding points between two images of the grating patterns captured by two cameras from different directions.

In this paper, a dynamic shape and strain measurement system are developed for experimental testing using the sampling moiré method. The deformation of the shape and the strain distribution of the surface of a rotating tire running at 80 km/h speed are analyzed. The principle, the developed system and experimental results applied to a rotating tire are shown.

PRINCIPLE OF SAMPLING MOIRÉ METHOD

GENERATION OF PHASE SHIFTED MOIRÉ PATTERN FROM ONE-SHOT GRATING IMAGE

In sampling moiré method, a specimen grating is captured by a digital camera. Though the digitized image shows only the grating, a moiré fringe pattern appears by thinning-out the pixels, i.e., by sampling the image with a constant pixel pitch. Figure 1 illustrates the appearance of moiré fringe patterns by sampling moiré method. In this figure, only three horizontal lines are shown. Dots show the positions of the sampling points captured by the digital camera. They are corresponding to the pixel positions of the digital camera. Squares show the brightness intensities at the sampling points. Figure 1(a) shows the deformed grating pattern attached on the specimen. The pitch of the grating in this figure is 1.125 times larger than that of the sampling points. Then, the captured image by the digital camera is shown in Fig. 1(b), in which no moiré fringe pattern can be discerned. Figure 1(c) shows the moiré fringe patterns when the sampling distance of a camera is N -pixel (in the figure, $N = 4$). The four images of Fig. 1(c) are obtained by sampling at the first, second, third and fourth pixels of Fig. 1(b) as the sampling start points, respectively. This process is corresponding to the phase-shifting of the moiré fringe pattern. The intensities of the pixels which do not sampled in Fig. 1(c) are interpolated using the intensities of the neighboring sampled pixels. Figures 1(d) are obtained by the linear interpolation from Figs. 1(c), respectively. Then, four phase-shifted moiré images are obtained from a single picture.

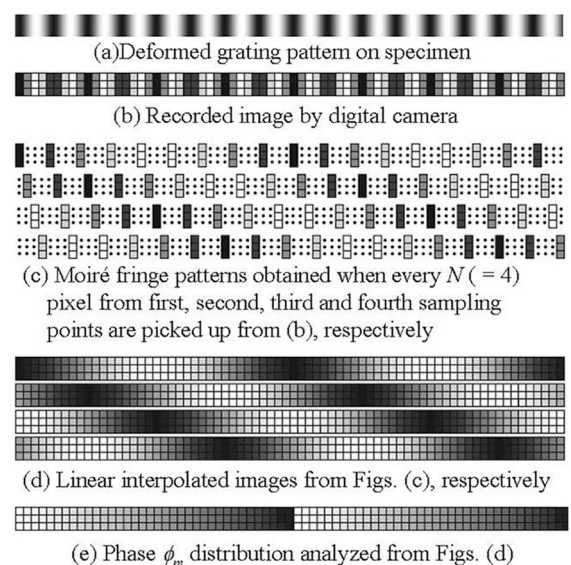


Figure 1. Schematic explanation of principle of phase-shifting by sampling moiré method.

PHASE ANALYSIS OF ONE-DIMENSIONAL GRATING

The k -th phase-shifted images can be expressed approximately as follows:

$$I_k(i, j) = a(i, j) \cos[\phi(i, j) + k \frac{2\pi}{N}] + b(i, j) \quad (k = 0, 1, \dots, N-1) \quad (1)$$

where $a(i, j)$ represents the amplitude of the grating intensity, $\phi(i, j)$ is the initial phase value and $b(i, j)$ represents the background intensity in the image. The phase distribution of the moiré pattern can be obtained by Discrete Fourier transform (DFT) algorithm [19] as follows.

$$\tan \phi(i, j) = - \frac{\sum_{k=0}^{N-1} I_k(i, j) \sin(k \frac{2\pi}{N})}{\sum_{k=0}^{N-1} I_k(i, j) \cos(k \frac{2\pi}{N})} \quad (2)$$

The phase ϕ_m of the moiré pattern is the difference between the grating phase ϕ_s and the phase ϕ_r of the reference grating (the sampling phase) and then,

$$\phi_s = \phi_r - \phi_m \quad (3)$$

The phase ϕ_r of the reference grating is the sampling phase which is a known $(2\pi k/N)$ at each pixel point. Therefore, the phase ϕ_s of the grating pattern can be calculated from the phase ϕ_m of the moiré pattern.

PHASE ANALYSIS OF TWO-DIMENSIONAL GRATING

Figure 2 shows the process of the x -directional phase analysis by the sampling moiré method. In this study, a 2-D grating pattern pasted on an object is analyzed. Figure 2(a) shows the 2-D grating pattern image captured by a CCD camera. Figure 2(b) shows the grating image obtained after the y -directional averaging of the intensities of the pixels for the twice of the y -directional grating pitch. By this process, the y -directional grating is eliminated and only the x -directional grating is extracted. Figure 2(c) shows a phase-shifted moiré patterns produced from Figure 2(b).

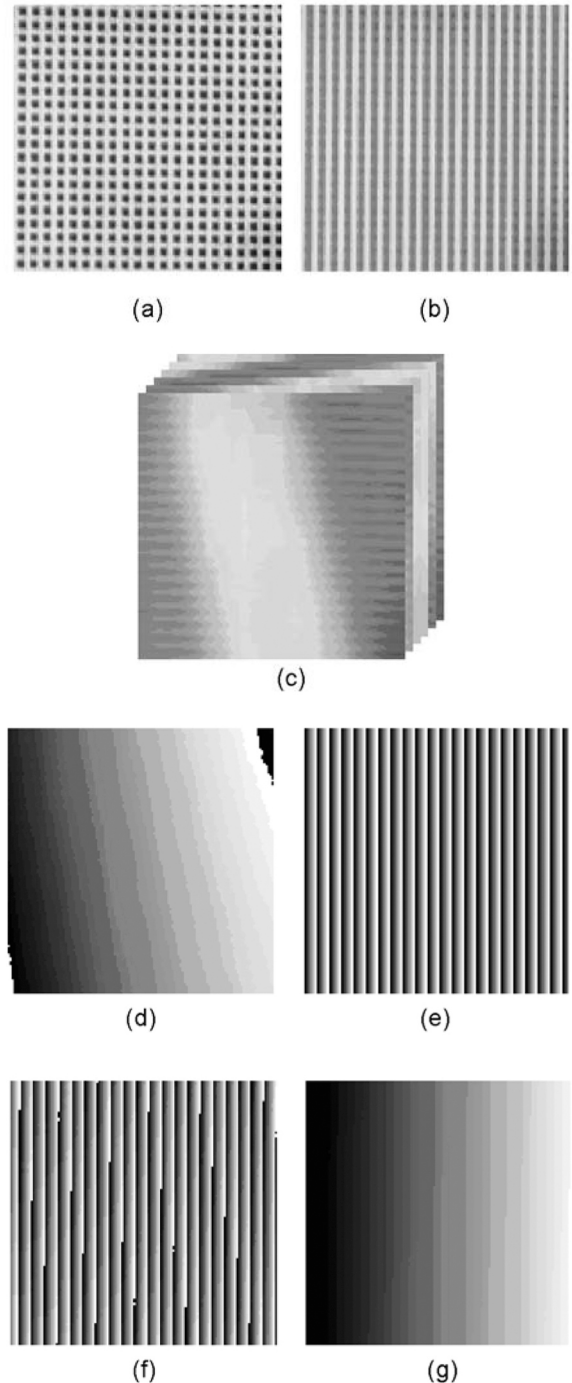


Figure 2. Process for analyzing x -directional phase of two dimensional grating (a) 2-D grating image (b) Extracted x -directional grating (c) x -directional moiré (d) Phase of moiré (e) Phase of reference grating (f) Phase of deformed grating (g) Unwrapped phase

The x -directional grating phase is analyzed by the process of the sampling moiré method shown in Fig. 1. Figure 2(d) shows the phase distribution of the moiré by the sampling moiré method. Figure 2(e) shows the x -directional phase distribution of the reference grating.