Scanning Projection Grating Moiré Topography

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ABSTRACT

One problem with moiré topography for 3D surface metrology is the so called $2\pi$-ambiguity limiting the maximum step height difference between two neighboring sample points to be less than half the equivalent wavelength of moiré fringes. To cope with the ambiguity problem, a special scheme of scanning moiré technique is proposed by resorting to the frequency domain fringe analysis that is in fact originated from white light scanning interferometry. This new moiré principle of 3D measurement allows determining the absolute height of the surface without information on absolute fringe orders so that largely stepped surfaces are measured with a great improvement in accuracy.

Keywords: moiré topography, 3-D profile measurement, grating scanning interferometry, phase–shifting fringe analysis, peak detection of interferograms.

1. INTRODUCTION

Moiré topography for 3-D surface metrology requires a suitable means of fringe analysis to extract height information from generated fringes.$^{1-3}$ In the beginning period until the 1980s, the spatial image processing techniques such as fringe contouring and Fourier transform were mainly investigated$^{4-5}$. Later the phase-shifting technique has being extensively explored since it allows automatic handling of complex fringes with enhanced measuring resolution$^{6,7}$. In recent years the authors have been involved in the grating projection moiré method that incorporates the phase-shifting technique along with a special sliding mechanism of line gratings. With many successful applications, the method has been proved to provide remarkable advantages in handling complex surfaces even with varying reflectance$^{8-10}$. However, still further improvement needs to be made until the method evolves itself into a general tool of 3D surface profiling. One problem to be urgently solved is the so called $2\pi$-ambiguity, which limits the maximum step height difference between two neighboring sample points to be less than half the equivalent wavelength of moiré fringes. With aims of coping with the problem, a new configuration named the scanning projection grating moiré topography is presented.

2. PHASE-SHIFTING PROJECTION MOIRÉ

Figure 1 shows the overall optical configuration to implement the projection moiré arranged in this investigation. A pair of line gratings of identical pitch is used; one is called the projection grating and the other the viewing grating. The line pattern of the projection grating is cast on the target object and its deformed line pattern is imaged back on the viewing grating. Moiré fringes are then observed by a CCD array through a relay lens with an appropriate magnification. The optical axis of the projection lens is aligned in parallel with that of the viewing lens on the same vertical level. This allows contour lines of generated moiré fringes to be in parallel with the x-y plane of the object coordinate system.

Assuming that the projection and viewing gratings have an identical sinusoidal transmittance, the fringe intensity at an arbitrary point $P(x,y)$ is obtained as$^{10}$

$$I_p (x, y) = A(x, y) \left\{ 1 + \cos \left[ \frac{2\pi}{mg} \left( h(x, y) (\tan \theta_1 - \tan \theta_2) \right) + \frac{2\pi s_0}{g} \right] \right\}, \quad (1)$$

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where $A(x,y)$ is the mean intensity; $h(x,y)$ the height of the point $P(x,y)$; $m$ the magnification of the projection and viewing lenses; $g$ the pitch of the gratings; $\theta_1$ the projection angle to the point $P(x,y)$; $\theta_2$ the viewing angle; and $\delta$ is the relative distance between the two gratings as depicted in Figure 1. Adopting phase-shifting technique in fringe analysis requires the fringe intensity be expressed in the form of

$$I(x,y) = A(x,y)[1 + v(x,y)\cos(\phi(x,y) + \Delta)]$$

(2)

In Eq.(2), $v(x,y)$ is referred to as the normalized fringe visibility; $\Delta$ the amount of phase shift; and $\phi(x,y)$ the relative phase of the surface to be measured. Comparing Eq.(1) with Eq.(2), the wavelength $\lambda$ of moiré fringes is derived as

$$h(x,y) = \frac{\lambda}{2\pi}\phi(x,y), \text{ where } \lambda = \frac{mg}{\tan\theta_1 - \tan\theta_2}.$$  

(3)

The geometry of Figure 1 determines the term $(\tan\theta_1 - \tan\theta_2)$ and the magnification $m$ in terms of $h(x,y)$ such as

$$\tan\theta_1 - \tan\theta_2 = \frac{d}{\ell - h(x,y)} \text{ and } m = \frac{\ell - f - h(x,y)}{f},$$

(4)

where $\ell$ denotes the working distance, $d$ the lateral distance between the projection and viewing lenses, and $f$ the focal length. Substituting Eq.(4) into Eq.(3) allows the wavelength $\lambda$ to be described as

$$\lambda = \frac{\ell^2 g}{fd}\left[1 - \left(\frac{h(x,y)}{\ell}\right)^2 - \frac{f}{\ell}\left(1 - \frac{f}{\ell}\right)\right].$$

(5)

This result implies that the wavelength of resulting moiré fringes is not constant but varies with $h(x,y)$ in a nonlinear manner. If the working distance $\ell$ is taken to be much larger than the surface height $h(x,y)$, i.e., $h(x,y)/\ell \ll 1$, then $\lambda$ may be approximated as a constant of

$$\lambda = \frac{\ell^2 g}{fd}\left(1 - \frac{f}{\ell}\right).$$

(6)

3. SCANNING PRINCIPLE

Now, the problem is how to determine $\phi(x,y)$ from the measured intensity distribution of moiré fringes. Eq.(2) indicates that $\phi(x,y)$ is not extracted simply from a single intensity measurement because there are two additional unknowns of $A(x,y)$ and $v(x,y)$. The well-known phase shifting technique takes more than three intensity measurements by varying the amount of $\Delta$. 

Figure 1. Optical configuration of projection moiré
according to a predetermined sequence so that $\phi(x,y)$ can be solved through relatively simple linear algebraic procedures\(^8\)\(^-\)\(^10\). However, the resulting value of $\phi(x,y)$ are constrained to be in the range of $-\pi < \phi(x,y) < +\pi$ due to the arctangent arithmetic computation inevitably encountered in the phase shifting technique. Unwrapping operations should consequently be applied to provide the absolute fringe order to each $\phi(x,y)$. In the process of unwrapping, the so called $2\pi$ ambiguity problem occurs so that step heights larger than the equivalent wavelength $\lambda$ are not accurately measured. Figure 2 illustrates basic principles of the scanning projection grating moiré proposed in this investigation to cope with the $2\pi$ ambiguity problem. The main idea is to impose a sequential variation on the distance between the object surface and the gratings. Then the intensity at a certain surface point is expressed in terms of the scanning distance $z$ as

$$I(z) = I_0 + a(h - z) \cos(2k(h - z) + \Delta)$$

(7)

where $I_0$ is the mean intensity, $k=2\pi/\lambda$, and $a(h-z)$ is referred to as the visibility envelop function. Figure 3 shows a typical interferogram that is obtained from this scheme. Interference fringes are narrowly localized in the spatial domain due to defocus effects of the projection and viewing lenses, being wrapped by the visibility envelop function $a(h-z)$. The analytical expression of $a(h-z)$ usually turns out to be a Gaussian or sinc type function for most practically available light sources and imaging lenses.

### 4. FRINGE PEAK DETECTION

It is interesting to note that the intensity variation of Eq.(7) is identical with that of short coherence interferograms produced by white light interferometry\(^11\). During last two decades, much attention has been paid to the three-dimensional surface mapping using white light interferometry, and as results, quite a few noble different techniques are available in the published literature as faithfully reviewed by Creath\(^12\). The techniques differ from each other in the intricate way of fringe data processing, but just about all of them are based upon the common tactics of locating the fringe peak of interferograms through intensive computation with aids of fast desktop computers. Kino and Chim \(^13\)\(^,\)\(^14\) first used the Fourier and later Hilbert transforms to extract the visibility envelope function in the frequency domain and then inversely transform the result back in the spatial domain to determine the fringe peak. Later de Groot and Deck \(^15\)\(^-\)\(^17\) revisited the Fourier transform as previously but succeeded in locating the peak directly in the frequency domain, easing sampling requirements and computational burden. Now in this investigation, the well-known computational technique of frequency domain analysis is adopted to detect the fringe peak of the measured intensity profiles. Detailed mathematical description of the frequency domain analysis is omitted here since it can be found in the Ref.\(^15\)\(^-\)\(^17\).
Figure 4. Photograph of experimental setup for scanning projection grating moiré: (a) illumination unit, (b) projection & view lens, (c) CCD camera, (d) translational stage and (e) object.

At $Z = 40\ mm$

At $Z = 60\ mm$

Figure 5. Experimental result. The object is tilted plane (a) Images of moire fringe, observed with CCD camera at two different Z-axis position, (b) Interferograms at two different measuring points Point A, Point B shown in (a), (c) Final result of measurement.
5. EXPERIMENTS AND DISCUSSIONS

The following experiment was intended to demonstrate the possibility of scanning projection grating moiré. A prototype system for the scanning projection grating moiré has been built with the proposed hardware schematic shown in Figure 4. Two identical imaging lenses with 25 mm focal length are used for the projection and viewing optics. The grating is made of a single body of glass on which fine line patterns are etched with chrome by the fabrication process of electron beam lithography. Halogen lamp and optical fiber is used to project the gratings on to targets. Resulting moiré fringes are magnified by a relay lens of X1 magnification and captured by a CCD array. Scanning motion is provided by a motion control servo equipped with a stepping motor and a linear displacement sensor. An IBM compatible Pentium-PC processes the sampled fringe data to reconstruct the three-dimensional profiles of the measured surfaces. Figure 5(a)-(c) illustrates the experiment. In Figure 5(a) which is taken by the CCD camera, Moiré fringe with visibility envelope is clearly seen. Figure 5(b), corresponding intensity changes of various measurement points are displayed, while Figure 5(c) present the final measuring result in 3-D plot.

During the experiment, we found out that there were two problems in realization step. The first one is about the variation of fringe wavelength that is assumed as constant value like Eq. (6). This innate defect in conventional moiré topography also influences performance of adopted fringe peak detection algorithm. The other is about relatively broad envelope that is caused by aberrations in each projection and view lens. It deteriorates the measurement accuracy seriously, because the high S/N of this method can be achieved by sharp envelope. By these reasons, the quantitative analysis had not been performed yet. Naturally, solutions to suggested problems will be main objective of future studies.

6. CONCLUSIONS

A special scheme of scanning moiré technique using line grating projection has been proposed to avoid the $2\pi$-ambiguity problem encountered when measuring surface profiles with high step discontinuity. The main idea is resorting to the frequency domain fringe analysis that is in fact originated from white light scanning interferometry. This new moiré principle of 3D measurement allows determining the absolute height of the surface without information on absolute fringe orders so that largely stepped surfaces are measured with a great improvement in accuracy. Test results prove that the proposed scheme is capable of finding absolute fringe orders automatically, so that the $2\pi$-ambiguity problem can be effectively overcome to treat large step discontinuities in measured surfaces.

REFERENCES