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Deep aspheric testing based on phase-shift electronic Moiré patterns

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Abstract: The resolutions of CCD camera and digital computer are limited by Nyquist frequency when deep aspheric wavefronts are tested using phase-shifting technique. A new powerful technique based on parallel generations of three phase-shift patterns through electronic multiplication with computer-generated graftings and low pass filtering, is proposed for measuring wavefronts with large departures from a reference sphere such as those encountered during testing of steep aspheric surfaces. The phase distribution of aspheric surfaces is obtained using a three-step phase-shifting algorithm.

Key words: fringe analysis; moire patterns; compensating testing
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1 Introduction

Fringe analysis has become more and more popular in industry for the evaluation and quantitative analysis of optical components and systems. Traditional automatic fringe analysis is limited in phase-shifting interferometry (PSI)[1-4] and Fourier transformer technology[5]. PSI is the most frequently applied technique for analyzing interferometry, but requires at least three phase-shifted fringe patterns generated sequentially by the appropriate phase shifting of fringes such as piezoelectric transducer driving mirror or wavefront modulation. The testing of steep aspheric wavefronts is limited by the resolution of a CCD camera as well as the aberrations of imaging optics . The frequency beyond Nyquist frequency may produce aliased interferogram that cannot be analyzed by using standard technique PSI. The Fourier transform technique requires high-resolution cameras and much more computation loads for transformation and filtering. In traditional aspheric testing, testing an aspheric surface in null configuration requires use of null lens, i. e. optical compensators, and an auxiliary optical system that can change the wavefronts, so that it is normal to the standard surface. Moreover, a different optical compensator, which usually is expensive and results in aberration misestimation of the system, must be constructed for each aspheric surface. Even the adapting of an optical compensator may lead to be difficult in alignment and fabrication of the system, even delay a project if a component must wait for an optical compensator.

Recently, with the development of manufacturing methods for computer-controlled polishing

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of sphere and asphere, such as CCOS[6-8] (computer-controlled optical surfacing), it is easy to produce aspheric surfaces whose wavefronts are with large departures from a reference sphere, especially those encountered when testing steep aspheric surface. So traditional optical testing is quickly becoming bottlenecks in the application of aspheres to optical design.

In this paper we present a new and powerful techique to avoid the use of optical compensators based on phase-shifting electronic moiré-pattern technology. The pattern is multiplied with computer-generated reference patterns to generate phase-shifted moiré patterns. So we can test deep aspheric surfaces with large departures from a reference sphere by directly testing surface.

2 Principle of the phase-shifting electronic moiré-pattern technique

The principle of this technique is based on the delivery of three phase-shifted moiré patterns in parallel and subsequent computation of phase by computer memory.

Figure 1 shows a schematic diagram of fringe analysis based on the phase-shifting electronic moiré-pattern technique.

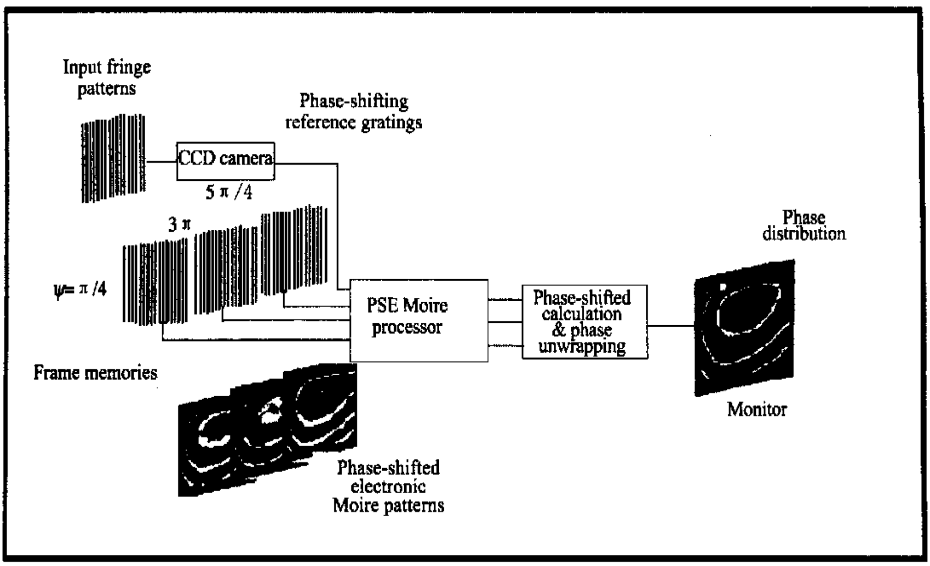


Fig. 1　Conceptual diagram of fringe pattern analysis

The reference fringe patterns generated by digital computer, having a frequency f_r close to the CCD spatial frequency of the carrier fringes f_s, are stored in the frame memory. So we obtained three phase-shifted interferogram stored in the frame memory as reference surface, which are electronic virtual plates named by us. The fringe pattern obtained by CCD camera is multiplied with each of the references by an electronic analog multiplier and low-pass filter to generate three phase shifted moiré patterns. We will illuminate the principle as the example of aspheres.

Aspherical surfaces with rotational symmetry may be defined by means of the following equation, taking the z axis of revolution:

$$Z = \frac{cS^2}{1 + [1-(k+1)c^2 s^2]^{1/2}} + \sum_{i=1}^{n} A_i S^{2(i+1)}, \tag{1}$$

where $S^2 = x^2 + y^2$, $c = 1/R$ radius of curvature, A_i is the aspheric deformation constant, and k is function of the eccentricity of a conic surface ($k = -e^2$);

For clarity, from now on we will take Z-axis, neglect high-order terms, and keep low-order terms in the aspheric equations.

Optical path difference (OPD) between the ideal aspheric wavefront and spherical surface mostly close to the ideal aspheric wavefront in the direction of normal line may be expressed by:

$$X_{opd} = \left[\frac{cx^2}{1+[1-(k+1)c^2x^2]^{1/2}} - \frac{cx^2}{1+[1-kc^2x^2]^{1/2}}\right] \times \left[\frac{1-(k+1)c^2x^2}{1-kc^2x^2}\right]^{1/2}, \quad (2)$$

Therefore, the irradiance of the double-beam interferogram being obtained by CCD camera may be expressed by:

$$Io(x,y) = I(x,y)[1 + \gamma\cos 2\pi f_s X_{opd} + \varphi_0(x,y)], \quad (3)$$

Where f_s, γ, and $I(x, y)$ are the spatial frequency of carrier fringes by CCD cameras, the background bias, and modulation depths of the fringes, respectively.

Based on the ideal aspheric wavefronts as reference surfaces, we will get electronic patterns simulated by digital computer and stored in frame memory.

The irradiance of the ideal aspheric expressed in the following as:

$$I_{R_i}(x,y) = I(x,y)[1 + \gamma\cos(2\pi f_r X_{opd} + \Psi_i)],$$
$$i = 1, 2, 3, \quad (4)$$

Where Ψ_i is the mutual phase shift given initially. So we obtain three phase-shifted patterns stored in the frame memory as reference surfaces.

Multiplying Eq. (3) by Eq. (4), so we obtain:

$$I_0(x,y)I_R(x,y) =$$
$$I_o^2(x,y) + I(x,y)\gamma\cos[2\pi f_s X_{opd} + \phi_0(x,y)] +$$
$$I(x,y)\gamma\cos[2\pi f_r X + \Psi_i] + \frac{1}{2}\gamma^2$$
$$\cos[2\pi(f_r + f_s)X_{opd} + \phi_0(x,y) - \Psi_i] +$$
$$\frac{1}{2}\gamma^2\cos[2\pi(f_s - f_r)X_{opd} + \phi_0(x,y) + \Psi_i], \quad (5)$$

If Eq. (5), 2^{nd}, 3^{rd}, 4^{th} terms have a higher frequency than cutoff of the filter, they can be omitted by low-pass filter. So only 1 stands 5^{th} term controlled by computer will remain. Given the relative phase step equal to $\pi/2$

$$I_i(x,y) = \alpha(x,y) + \beta(x,y) \times$$
$$\cos[2\pi(f_s - f_r)X_{opd} + \phi_0(x,y) + \Psi_i]$$
$$i = 1, 2, 3;\ \phi_i = \pi/4, 3\pi/4, 5\pi/4, \quad (6)$$

α, β are the bias and the modulation-depth factors, respectively. Given $f_s - f_r$ equals to zero, we get three equations as we expected as follows:

$$I_1(x,y) = \alpha(x,y) + \beta(x,y)\cos\left[\varphi_0(x,y) + \frac{\pi}{4}\right], \quad (7)$$

$$I_2(x,y) = \alpha(x,y) + \beta(x,y)\cos\left[\varphi_0(x,y) + \frac{3\pi}{4}\right], \quad (8)$$

$$I_3(x,y) = \alpha(x,y) + \beta(x,y)\cos\left[\varphi(x,y) + \frac{5\pi}{4}\right], \quad (9)$$

From equations (7), (8), and (9), we obtain the expected phase distribution as follows:

$$\varphi(x,y) = \tan^{-1}\left[\frac{I_3(x,y) - I_2(x,y)}{I_1(x,y) - I_2(x,y)}\right], \quad (10)$$

3 Application and implementation of analysis of moiré fringe patterns

In order to implement this technique, we design a fringe analyzer. The fringe analyzer mainly consists of three parts——a phase computation circuit, an electronic moiré pattern generator, and a phase-unwrapping processor[9], as shown in Fig. 2.

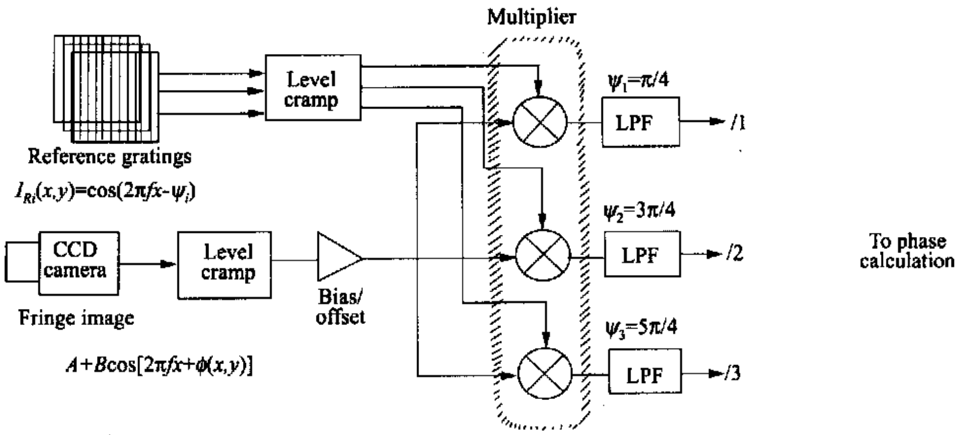
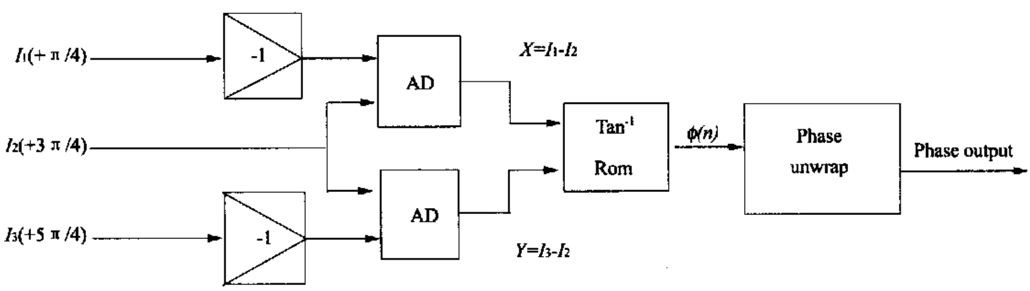


Fig. 2　Conceptual illustration



(If $\varphi(n)-\varphi(n-1)\geqslant\pi$, BIAS= BIAS-2π; If $\varphi(n)-\varphi(n-1)\leqslant\pi$, BIAS= BIAS+ 2π)

Fig. 3　Diagram of parallel signal processor for implementing phase shifting algorithm

The fringe pattern obtained by a CCD camera and three reference patterns stored in the frame memory are inputted into the electronic moiré pattern generator. The fringe pattern obtained by the CCD camera multiplied with three reference each by analog multiplier and low-pass filter to produce three phase-shift moiré patterns. Those patterns are inputted into the parallel signal processor, as shown in Fig. 3. In this system, the CCD camera and the processing operations are synchronized to the same sampling clock. By subtraction of the input moiré patterns, I_2-I_2 and I_3-I_2 are generated and digitized with analog-digital converters. For the testing of aspheric surface with large departures from a reference sphere, such as those encountered when testing steep aspheric surface, we can use this technique so as to avoid the use of optical compensators to analyze the aspheric surface to be tested. Ideal aspheric wavefronts $I_R(x,y)$ generated by the digital computer as reference wavefronts are stored in the frame memory, as shown in Fig. 4 at top left. If the spherical aberration of (x^2+y^2) and coma of $y(x^2+y^2)$ are inputted into ideal aspheric wavefront, we can regard this wavefront $I(x,y)$ as a CCD camera one, as shown in Fig. 3 at down left. Multiplying $I_R(x,y)$ by $I_0(x,y)$ and those frequency , which are higher than the cutoff of the filter , can be removed by a low-pass filter, as shown in Fig. 5 . Clearly, the fringe pattern in Fig. 4 shows the shape of the spherical aberration of $(x^2+y^2)^2$ and coma of $y(x^2+y^2)$.

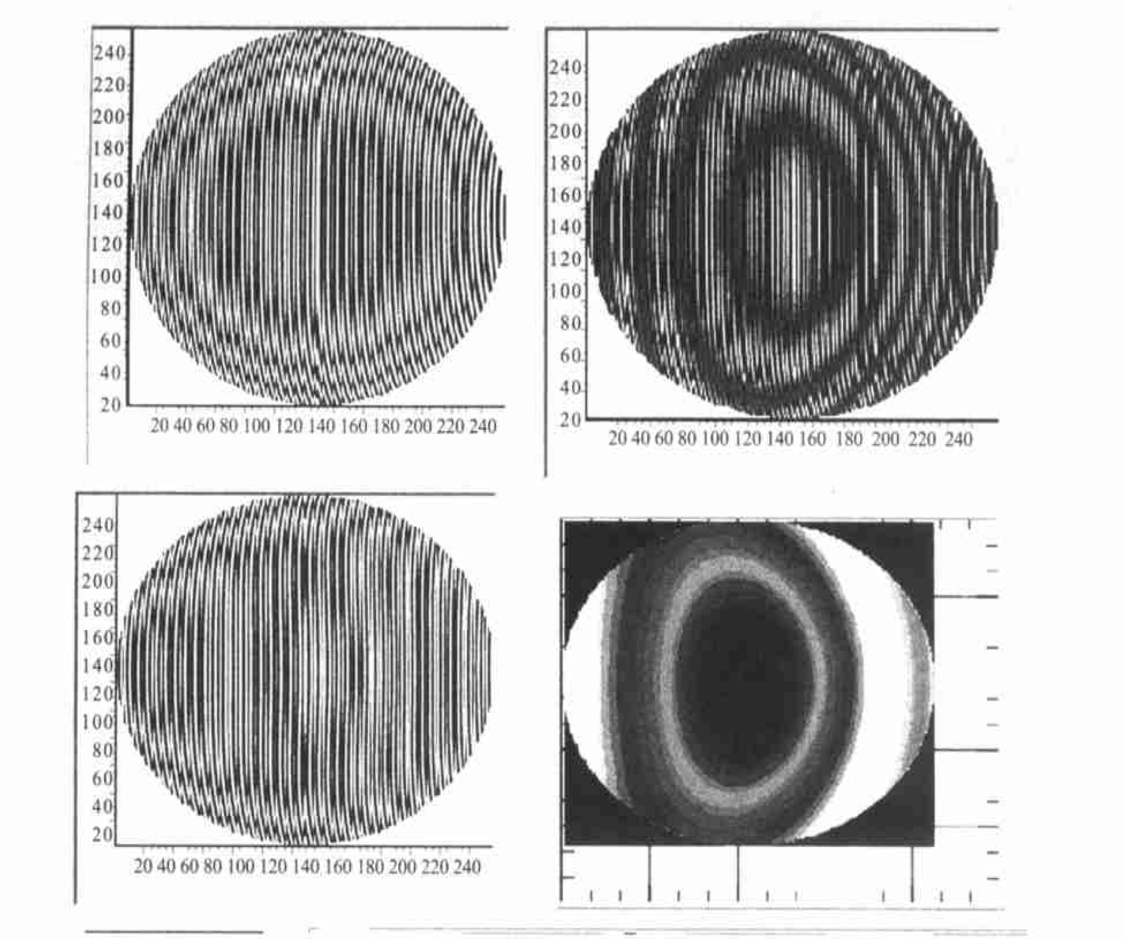


Fig. 4 Aspherical shape based on phase shifting electronic moiré patterns

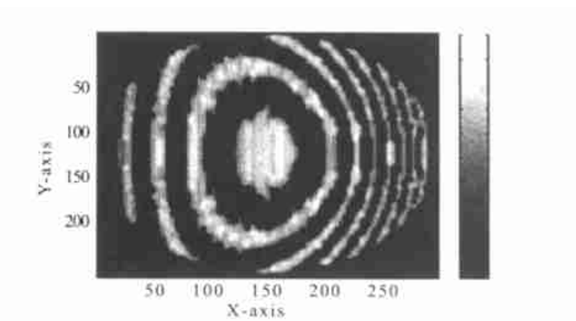


Fig. 5 Phase shifting electronic by low pass filter

4 Conclusion

By means of phase-shifting electronic moiré-pattern technique, we present a simple and powerful technique to test deep aspheric surface with large departures from reference sphere without using an optical compensator. The advantage of this technique is that in this case the compensation is achieved numerically rather than optically. Unfortunately, the present technique is limited to unwrapping only full-field phase maps that have no invalid areas inside them. So we need study of the optimization parameters and the implementation of the experiment.

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基于相移电子莫尔条纹的深度非球面检测

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摘要: 通过相移技术检测深度非球面波前时, CCD 相机和计算机分辨率受到 Nyguist 频率的限制。基于相互平行相移莫尔条纹干涉技术, 我们提出一种新颖有效的检测技术。相互平行的相移电子莫尔条纹是由计算机产生三幅光栅作为参考波前, 分别和输入被检干涉图相叠加, 并通过低通滤波器滤波滤掉高频而得到的。最后, 由三步相移算法, 我们得出非球面的面形分布。

关 键 词: 条纹分析; 莫尔条纹; 补偿检验
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