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RESEARCH ARTICLE

Power spectral density measurement for large aspheric surfaces

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Abstract To ensure the safe and normal operation of the whole optical system, it is important to test and evaluate the quality of optical components. The article explores the advantages and disadvantages of general parameters used in aspheric surface testing, the composition of the system, the principle of operation and the design of related power spectral density (PSD) software used in testing large aspheric surfaces with Shack-Hartmann and phase shifting interferometer. The results indicate that PSD can give the spatial frequency distribution of the wavefront aberration when large aperture phase shifting interferometer is used as an instrument to test the wavefront, and this can also be applied as an evaluation standard in testing the quality of optical components. In addition, this paper describes the test results of optical components in the size of 64 mm × 64 mm.

Keywords power spectral density (PSD), optic testing, large aspheric

1 Introduction

Large aspheric optical components have become more common in all kinds of fine optical systems, so it is very important to manufacture high-quality large aspheric optical components and develop corresponding specification and measurement methods [1,2].

By means of quantitative measurements, the interferogram obtained by large aperture phase shifting interferometry can help characterize surface features and provide sufficient description of surface structures. Traditionally, simple statistical measurements such as Zernike polynomials, peak-to-valley wavefront error and root mean square (RMS) roughness are used to obtain an initial quantitative description of the surfaces [3–6]. These measurements are based on height information and, for certain types of surfaces, can serve as a good description of their roughness. However, in many cases roughness cannot be described solely by height—a more sophisticated tool such as power spectral density (PSD) is used to quantify the observed surface. The essence of PSD is Fourier spectral analysis and it can quantificationally supply the spatial frequency distribution of the wavefront error [7,8].

At present, PSD is mainly used to analyze the mid-spatial error of optical components in an inertial confinement fusion (ICF) system. There are a few reports about the mid-spatial error specification of large aspheric optical components, so it is necessary to study the use of PSD as a specification.

2 Measurement system and principles

The essence of the measurement of wavefront PSD is the testing of the transmission or reflection wavefront error, and it is common to use laser interferometer or Hartmann as the measuring instrument. Figure 1 shows the sketch for the experimental system of testing the wavefront of an optical component. The spherical mirror is provided for self-alignment when the interferometer is used as the measuring instrument and the laser is provided as the light source when Hartmann is used as the measuring instrument.

The experimental system layout shows the method of testing the mid and the high spatial error. Based on the rotational symmetric characteristic of circular optical surfaces, it is beneficial to improve the resolving power to test the parts of the optical component surfaces. For example, if the optical component diameter is 100 mm and the CCD pixels of the interferometer is 1024 × 1024, the sample period can reach 0.09 mm, and the high spatial confine will be improved effectively.

Each measuring instrument has its own metrical bandwidth which limits the precision and range of the test

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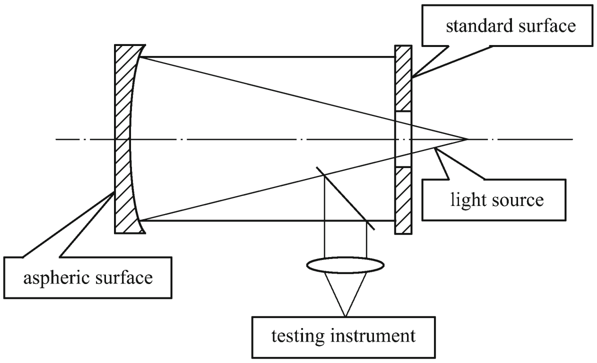


Fig. 1 Sketch of experimental system for testing the wavefront of an optical component

system. Bennett J M and Church E L have studied this widely [9,10].

According to the theory of Church E L [11], the valid and conservative spatial frequency bandwidth is

$$2f_0 \leqslant f \leqslant f_{\max}/2, \tag{1}$$

where f_0 is the minimum spatial frequency, $f_0 = 1/L_0$, L_0 is the sampling length; $f_{\max} = f_s/2$, f_s is half of the Nyquist sampling frequency.

Generally, if the maximum spatial frequency is $f_{\lim}$ and the maximum sampling points is N, then the sampling length will be

$$L_0 = \frac{N}{4f_{\lim}}. \tag{2}$$

The plot of the detectable bandwidth is shown in Fig. 2 according to Eq. (2).

The valid bandwidth is $3f_0 \leqslant f \leqslant f_{\max}/2$ in the National Ignition Facility (NIF), now China has adopted the same range as NIF.

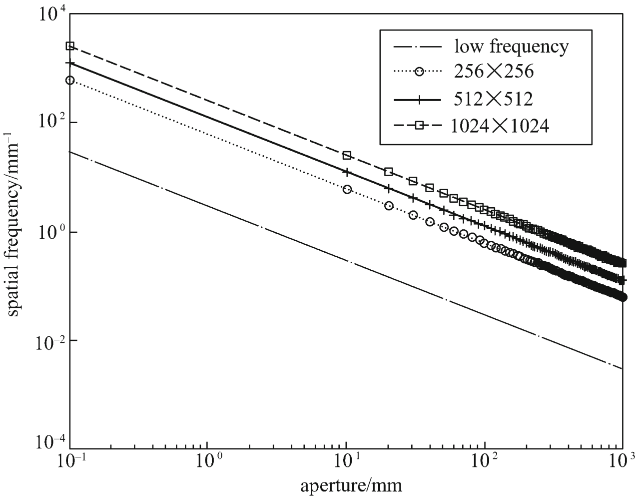


Fig. 2 Detectable bandwidths

3 Data processing

If $z(x)$ is the surface roughness height as a function of distance x, a finite-length Fourier transform could be rewritten as [12–14]

$$Z(k) = \int_0^L z(x)\exp(-\mathrm{i}kx)\mathrm{d}x, \tag{3}$$

where k is the wave number. As the surface profile measurements of $z(x)$ yield digitized data, assuming that the surface roughness data set consists of N values for $z(x)$ that are measured at equally spaced intervals Δx over a total length of $L = N \cdot \Delta x$, Eq. (3) is discrete as

$$Z(m) = \Delta x \sum_{n=0}^{N-1} z(n)\exp(-\mathrm{i}2\pi mn/N), \tag{4}$$

where $k = 2\pi f_m$, $f_m = m/(N \cdot \Delta x)$ is the spatial frequency, $-N/2 \leqslant m \leqslant N/2$.

The calculating formula of one-dimensional PSD is defined as [15–17]

$$P(m) = \frac{|Z(k)|^2}{L} = \frac{\Delta x}{N}\left|\sum_{n=0}^{N-1} z(n)\exp(-\mathrm{i}2\pi f_m n\Delta x)\right|^2. \tag{5}$$

As shown in Fig. 3, we first load the original data gathered from the measuring instrument and apply wavefront pretreatment, and then get rid of the errors from the measurement. However, the frequency leakage cannot be avoided as the computer can only deal with finite discrete data, so it is necessary to correct the obtained data by adding a window, dealing with the results by fast Fourier transform (FFT), and estimating the PSD using a suitable arithmetic. There are no perfect systems in the practical world, so the system error is unavoidable, but it can be reduced or canceled. The PSD of the wavefront error and the system transfer function (STF) of the system have the following connection [18–21] as

$$S = \sqrt{\frac{P_{\text{measured}}}{P_{\text{ideal}}}}. \tag{6}$$

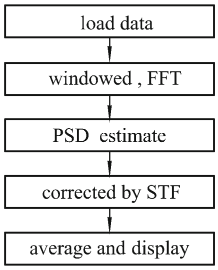


Fig. 3 Flow diagram of PSD calculating

When demarcating, P_{measured} is calculated by a sample whose P_{ideal} is known, and then the STF of the system is obtained. A high quality phase step is tested as it can cover the total spectrum range of the measured system and the precision of the step can be guaranteed by present manufacturing techniques. The STF of the system can then be calculated according to Eq. (6). With the STF of the system thus obtained, its influence on the measured PSD can be removed using the following formula:

$$P_{\text{restored}} = \frac{P_{\text{measured}}}{S^2}. \tag{7}$$

Finally, repetitively appearing P_{restored} value is averaged and used as the evaluation standard in testing the quality of optical components.

4 Experiments

An optical flat with a size of 64 mm × 64 mm corresponding to pixels of 990 × 990 is tested by a WYKO 4100 interferometer. Its valid frequency range is 0.03–3.87 mm^{-1}. Figure 4 shows the interferogram of this optical component. Figure 5(a) shows the one-dimensional horizontal average PSD of the tested component, and Fig. 5(b) shows the one-dimensional vertical average PSD of the tested component.

As shown in Fig. 5, PSD can quantificationally supply the spatial frequency distribution of the wavefront error. It is important to choose an efficient measurement and design a reasonable arithmetic when describing the quality of a large aspheric optic with wavefront PSD in order to eliminate the influences of the range of frequency limited by the measuring instrument.

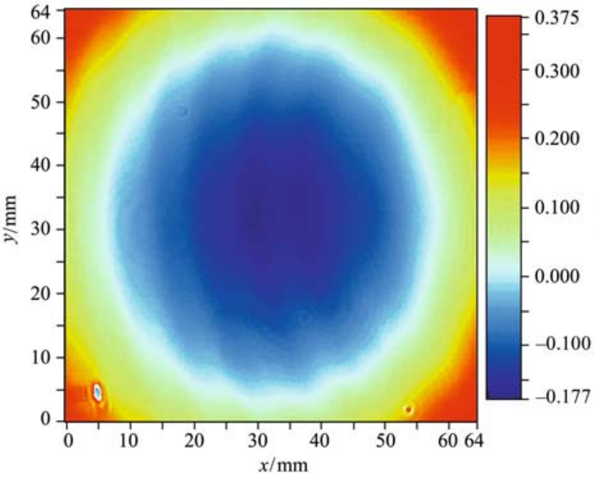
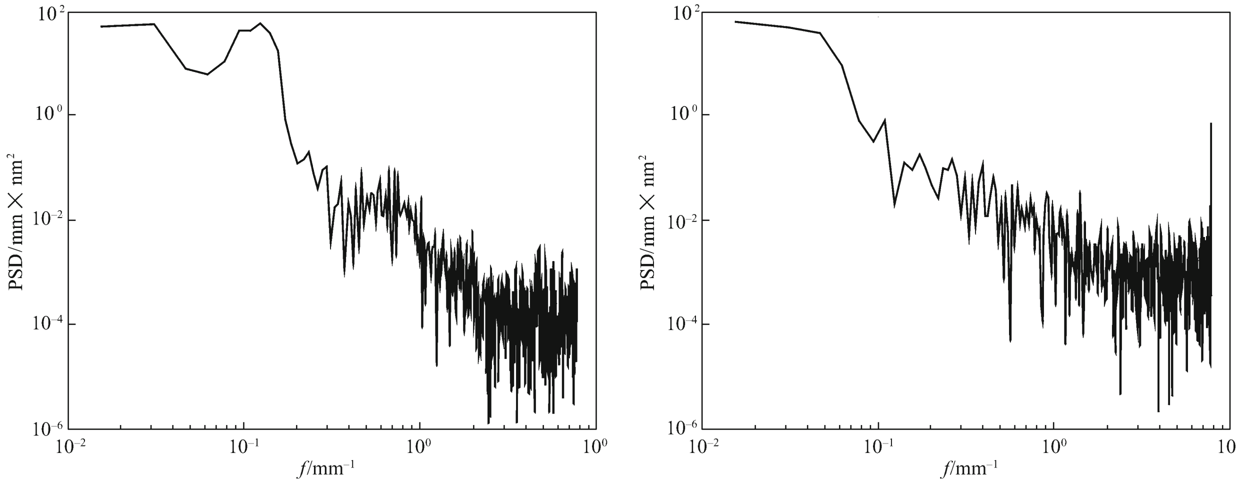


Fig. 4 Interferogram of an optical flat

5 Conclusions

With the study and development of computer-controlled optical surfaces, more mid- and high-spatial frequency errors are generated by the use of small tools than by the use of the classical manufacturing method. It is therefore increasingly important to test and evaluate the quality of optical components. The article explores the advantages and disadvantages of general parameters used in aspheric surface testing, the composition of the system, the principle of operation and the design of related PSD software used in testing large aspheric surfaces with Shack-Hartmann and phase shifting interferometer. The essence of PSD is Fourier spectral analysis and it can quantificationally supply the spatial frequency distribution of wavefront error, which can be applied as the evaluation standard in testing the quality of optical



(a) (b)

Fig. 5 One-dimension average PSD of tested component components and reflects the demands of the quality of optical components roundly.

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