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The Wavefront Power Spectral Density Measurement of Aspheric Lens with Long Focal-Length Using a Computer-Generated Hologram

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Abstract

To ensure the performance of the optical system, the machining accuracy of lens with long focal lengths is required to ensure the image quality. A new method for lens transmission wavefront power spectral density (PSD) in mid-frequency domain measurement using binary phase computer-generated hologram (CGH) is presented. This technique is widely applicable and is particularly useful for measuring large-size lenses with long focal lengths. A comparison experiment of the CGH measurement with results from a Fizeau sphere interferometry method is carried out to verify the accuracy and convenience of the measurement. Furthermore, measurement uncertainty due to CGH fabrication process is analysed. Analysis of the CGH test showed the overall accuracy of less than 1 nm RMS for a sphere lens with over 30 m focal length and Φ410 mm clear aperture. CGH can provide reference spheres with high precision, in the meantime greatly shorten air space, thus reducing the effect of vibration and air turbulence, therefore is of great importance for lens transmission wavefront PSD measurement. The realization of high precision, high efficiency and nondestructive testing of long focal-lens wavefront PSD ensure the ultra-precision and certainty level of machining, hence improving the comprehensive performance of the optical system.

Keywords

Power Spectral Density Measurement, Interferometry, CGH

1. Introduction

There is a growing demand for lenses and mirrors with high image quality, good optical performance, and high laser damage thresholds in the optics industry, such as information, communication technology and high-power density laser system, to realize high precision, high efficiency and nondestructive testing of large aperture long focal-lens wavefront PSD, therefore ensure the ultra-precision and machining certainty level of machining, hence improving the comprehensive performance of the optical system.

Different from traditional imaging optical system, the high-power laser system has strict requirements of wavefront quality in the whole spatial frequency band, as wavefront distortion in low-frequency band affects laser beam focal spot distribution, mid- and high-frequency band distortion is one of the main reasons for self-focusing destructive effect, thereby reduce laser damage threshold. Wavefront power spectral density (PSD) is used to evaluate the optics quality in mid frequency band [1], thus should be strictly measured and controlled.

However, transmission wavefront PSD measurement of lens with long focal lengths is still a great difficulty nowadays. As it is almost impossible to measure the wavefront of lens with tens of meters focal length by the usual Fizeau interferometry method, for the effect of air turbulence and vibration caused by the long optical path cannot be neglected.

Considering the special optical property of computer-generated hologram (CGH), the CGH method is introduced to measure lens transmission wavefront (TWF) power spectral density (PSD). As it is well-known, computer-generated holograms (CGHs) are diffractive optical elements synthesized with the aid of computers. CGHs use diffraction to create wavefronts of light with desired amplitudes and phases. This high degree of flexibility in generating complex wavefronts has made CGHs extremely useful. In the field of optical testing and metrology, CGHs are commonly used in optical interferometric systems [2]-[7]. Nowadays, CGH with both high accuracy and high resolution can be fabricated with e-beam writing, ion-beam writing or laser direct writing [8] [9] [10].

In previous work [11], we have studied the low-spatial frequency errors of long focal length lens and the experimental results show that this method is feasible and of high precision. In this paper, an optical test system using CGH method is built to measure lens transmission wavefront (TWF) power spectral density (PSD), and the precision of this method is quantitatively analysed. Compared with Fizeau interferometry method, the configuration of the CGH method is very simple and compact, which is very easy to adjust, thus enabling high precision. Moreover, experiment results and theoretical analysis show that the overall accuracy of less than 1 nm RMS for a sphere lens with over 30 m focal length and Φ410 mm clear aperture.

2. Metrology

2.1. System Construction

Traditionally, the compensation method is used to measure the transmission wavefront PSD of lens with astigmation, as shown in Figure 1 (left). Spherical wave from an interferometer is transmitted through a compensation lens and the test lens successively, the output parallel light is retroreflected by a reference flat. For an interferometric test a suitable reference wavefront has to be provided, which impinges perpendicular everywhere on the surface.

However, the null tests require the use of some auxiliary optics to match the f-# and compensation system aberration, which therefore introduces unwanted error into the test. Furthermore, reflective optics with long focal length creates laboratory space problems, not to mention potential wavefront errors from air turbulence by large airspace traversed.

By using the CGH method, all these potential problems can be alleviated. The setup is shown in Figure 1 (right), the testing optical system is composed of a phase-shifting interferometer (PSI), lens under test and a reflective CGH.

When performing a lens TWF PSD test, CGH is equivalent to a diffraction grating. The slope of the diffraction varies according to the interval between grating pattern. Part of the collimated light from the PSI is reflected from the transmission flat (TF), forming the reference beam; the rest transmits through the TF, lens afterwards and is retroreflected from the hologram, which carries the information of deviations from its ideal figure, and then returns into the interferometer forming the test beam.

2.2. Design and Fabrication of a CGH

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For a general form, such as lens aberration cannot be neglected, hologram should be designed in accordance with the aplanatic principle. The geometric diagram for the design of a hologram is shown in Figure 2. All the parallel light coming from the TF transmits through the lens to the hologram with the same optical path, *i.e.*,

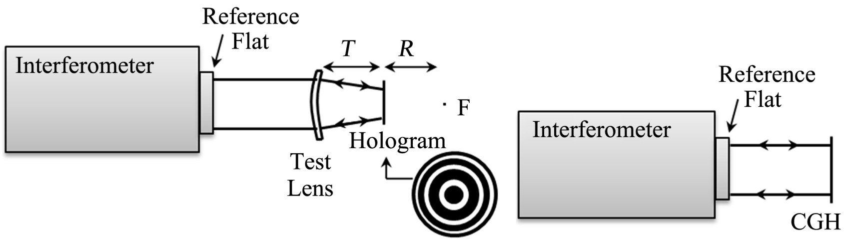

Figure 1. Experimental setup for measuring the wavefront of a test convex lens using compensation method (left) and CGH method (right).

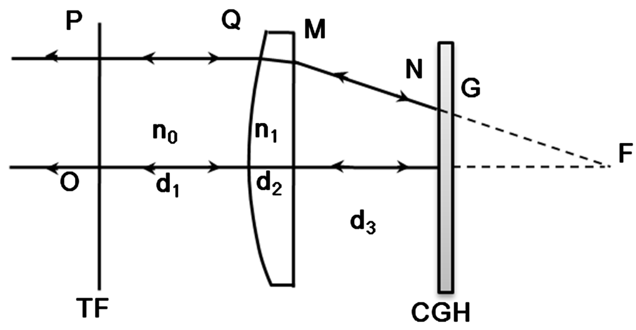

Figure 2. Geometric diagram for the design of CGH.

$$n_0|PQ|+n_1|QM|+n_0|MN|+\phi(r)=C \quad (1)$$

where C is constant. Thus,

$$\phi(r)=n_0d_1+n_1d_2+n_0d_3-\left(n_0|PQ|+n_1|QM|+n_0|MN|\right) \quad (2)$$

The radius of hologram can be derived by this phase function, and thus can be manufactured by method of laser writing, ion-beam writing, etc. Lithography puts spatial information into a substrate, and it is this information that determines the lens-like effect functionality.

2.3. Calculation of PSD

The power spectral density (PSD) is the power spectrum per unit frequency, which describes the wavefront error in terms of spatial frequency. In this section, we will briefly describe the mathematical calculations of obtaining PSD from a two-dimensional (2D) wavefront map.

Considering a wavefront map $U(x, y)$ of transmissive optic over an area $L_x \times L_y$, the finite-length Fourier transform and 2D PSD are defined as [12]

$$U(\nu_x,\nu_y)=\int_0^{L_Y}\int_0^{L_x}u(x,y)\mathrm{e}^{-i2\pi(\nu_x x+\nu_y y)}\mathrm{d}x\mathrm{d}y \quad (3)$$

$$\mathrm{PSD}(\nu_x,\nu_y)=\frac{|U(\nu_x,\nu_y)|^2}{L_xL_y} \quad (4)$$

where x and y are wavefront position variables in horizontal and vertical directions, ν_x and ν_y are spatial frequency variables in the corresponding directions, respectively.

3. Experiment

3.1. Comparison with Fizeau Interferometry Method

In order to verify the CGH method, a comparison experiment was carried out. The focal length of the lens under test is 1500 mm, with a diameter of 80 mm. For the Fizeau interferometry method, the optical setup is shown in **Figure 3**. A Dynamic sphere interferometer with matched f-# sphere lens and a reference flat were used, and the total optical path length is over 3000 mm. While for the

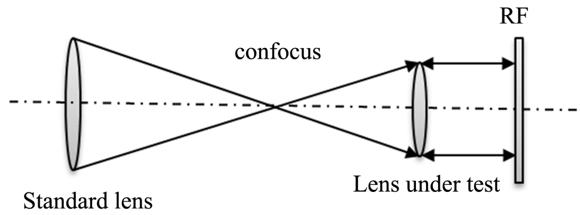

Figure 3. Fizeau interferometry method for measuring lens transmission wavefront.

CGH method, the first-order radius of curvature value of the hologram is designed to be 1200 mm, thus the lens-to-CGH spacing $\tau = 300$ mm, and the total optical path length is less than 500 mm.

The measured reflective wavefront PSD of the CGH method and that of the Fizeau interferometry method are shown in **Figure 4**. From which we can see that the RMS value of PSD both are quite consistent. The clear aperture is Φ50 mm.

3.2. Large-Size Long Focal Length Lens Measurement

In order to measure large size lens with long focal length, large size zone hologram was manufactured. The wavelength of the PSI is 632.8 nm, the diameter and focal length of the lens are Φ410 mm and 30.5 m, respectively. The first-order radius of curvature of zone hologram is 30 m, with a diameter of Φ410 mm. The lens-to-CGH spacing is 0.5 m.

The transmitted wavefront PSD of the hologram is represented in **Figure 5**. The clear aperture is Φ410 mm.

The transmitted wavefront PSD of the lens is represented in **Figure 6**, the right graph shows the wavefront PSD removed the substrate. The clear aperture is Φ410 mm, power is removed from the graph.

As shown in **Figure 6**, the substrate error can be effectively reduced by subtracting the zero-order wave front of the CGH, which is carried out by interpolation in order to avoid the lateral difference with direct subtraction. On condition that the substrate shape is very smooth, and the machining precision is very high, this background error can be neglected.

4. Error Analysis

The CGH test errors include design error, fabrication error and alignment error. In this section, the wavefront error in PSD1 frequency band is analyzed.

4.1. Binary Linear Grating Model

CGH fabrication errors may be classified into two basic types: substrate figure errors and pattern errors. Pattern errors may further be classified as fringe position errors, duty-cycle errors, and etching depth errors.

Based on Fraunhofer diffraction theory, the far field diffraction wavefront may be related to the original wavefront by a simple Fourier transform relationship. The displacement of the recorded fringe in a hologram from its ideal position

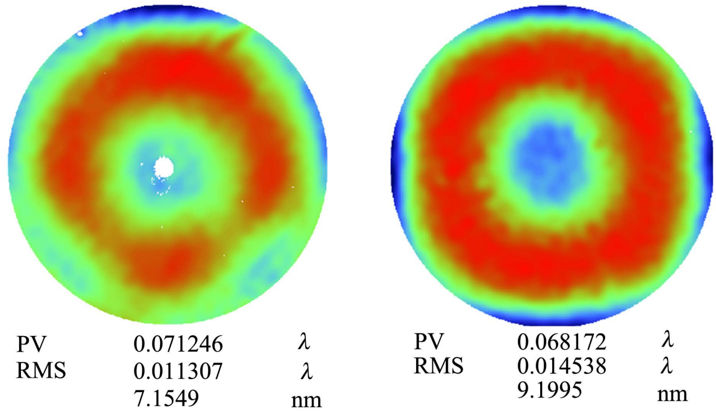

Figure 4. The reflective wavefront and PSD of a lens tested by CGH method (left) and Fizeau interferometry method (right).

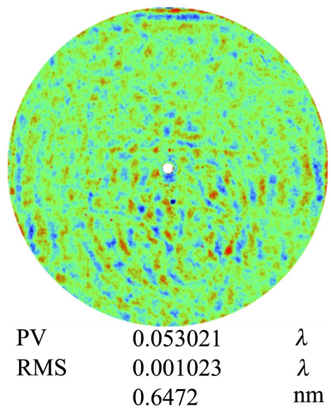

Figure 5. The reflective wavefront PSD of the hologram.

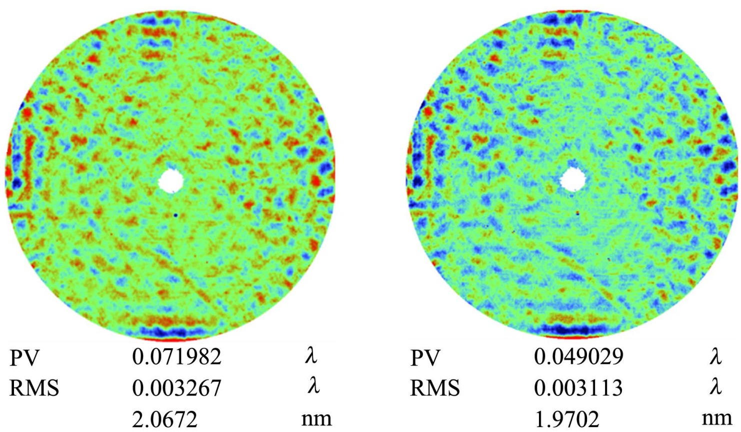

Figure 6. The reflective wavefront PSD of the lens under test.

is commonly referred to as pattern distortion. The amount of wavefront phase errors produced by the hologram pattern distortions can be expressed as a product of the gradient of the diffracted wavefront function and the pattern distortion vector. For a linear grating, reflective wavefront phase errors produced by grating pattern distortions in the m-th order beam can be calculated as [13]:

$$W = -2m\lambda \frac{\varepsilon}{p} \tag{5}$$

where W is the wavefront phase, ε is the grating position error in direction perpendicular to the fringes, and p is the localized fringe spacing, and m is the diffraction order.

Combined the wavefront phase sensitivity function and the PSD theory, the PSD 1 band-passed wavefront error caused by the CGH fabrication can be evaluated. The PSD1 band-passed wavefront errors σ_{PSD1} can be calculated by

$$\sigma_{\text{PSD1}}^2 = \frac{S_{\text{PSD1}}}{S_N}\sigma_{\Delta W}^2 = \frac{\pi \nu_h^2 - \pi \nu_l^2}{4\nu_x \nu_y}\sigma_{\Delta W}^2 \tag{6}$$

where S_{PSD1} is the "area" covered by the PSD1 frequency band and S_N is the "area" covered by the frequency below Nyquist frequency, $\sigma_{\Delta W}^2$ is the variance of the introduced CGH fabrication wavefront error, ν_h and ν_l are the high and low cut-off frequency for the PSD1 band, respectively.

4.2. Evaluation of Each Error Source

The wavefront errors from each error source for the CGH test in PSD1 frequency band are given in **Table 1**.

The design residual of CGH is 0.0000 nm RMS, which can be ignored. The substrate error is the main error source during the CGH manufacturing process, which is 0.6472 nm RMS. The period of the pattern has a minimum value of 34 μm, thus the wavefront error caused by 0.5 μm (3σ) pattern distortion is 0.3359 nm RMS. The phase CGH used in our experiment, $A_0 = A_1 = 1$, the duty-cycle is 0.5 with a 5% variation (3σ), and the etching depth variation is 5% (3σ), the wavefront error introduced by etching depth is 0.5711 nm RMS, duty cycle error has no effect on higher order wavefront. During the measurement process, the "spurious fringe" and "ghost spot" method are used to align the lens under test. The wavefront error caused by 0.2 mm decenter is 0.0031 nm RMS, and the wavefront error caused by 0.04' tilt is 0.0012 nm RMS.

Table 1. Information on video and audio files that can accompany a manuscript submission.

Source of Errors		PSD1 band-passed error (RMS)
Design error		0.0000 nm
Fabrication error	Substrate error	0.6472 nm
	Pattern distortion error	0.3359 nm
	Duty-cycle error	0.0000 nm
	Etching depth error	0.5711 nm
Alignment error	decenter	0.0031 nm
	tilt	0.0012 nm
RSS Errors		**0.9262 nm**

Assuming the calculated wavefront errors induced by pattern distortion and etching depth are un-correlated to each other [2], the composite error can be estimated as the root-sum-square (RSS), the total wavefront PSD errors for the phase hologram can be calculated as the RSS of these errors, which is approximately 0. 9262 nm RMS.

5. Conclusions

In this paper, the use of a diffractive element, a so-called null-CGH, offers a practical solution to generate the reference wavefront for lens PSD measurement. Thus, the 3-dimensional fabrication and measurement problem is converted into a 2-dimensional problem. A phase CGH was fabricated to carry out lens wavefront PSD measurement, a comparison of the CGH measurement with results from a Fizeau interferometry method test shows excellent agreement. Finally, measurement uncertainty due to CGH fabrication process is analyzed. Thanks to that the continuous progress in microlithography high precision lateral pattern can be fabricated, experiment result shows that wavefront PSD error induced by CGH etching process is less than 1 nm for a sphere lens over 30 m focal length and Φ410 mm clear aperture. Hence, the measurement accuracy using the proposed CGH is proved to be very high, CGH can therefore be used to measure lens transmission wavefront PSD accurately.

In order to improve the measurement uncertainty, the analysis of image error aberration analysis would be researched further, so as to ensure the precision and certainty level of machining, hence improving the comprehensive performance of the optical system.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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