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Key Techniques in Large-Aperture Phase-Shifting Interferometer Via PZT

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Abstract The key techniques of large-aperture phase-shifting interferometer via PZT are discussed, includings supporting scheme for large-aperture reference mirror, absolute test of large-aperture flat, on-line calibration of piezoelectric (PZT), test of dynamic phase and large-aperture collimated beam wavefront. Theoretical simulation and experimental measurement are done for developing larger-aperture phase-shifting interferometers.

Key words measurement; optical testing; large-aperture interferometer; phase-shifting via piezoelectric; key techniques
OCIS codes 120.3180 120.3940 120.3930 120.5050

大口径 PZT 移相干涉仪的几个关键技术

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摘要 以大口径斐索卧式移相干涉仪为研究对象，研究以压电陶瓷(PZT)实现移相为代表的大口径干涉仪所包含的技术难点和解决方案，主要包括大口径平晶的支撑技术与绝对校准、动态波面测试、大口径波面测试技术、移相器在线测试等关键技术，为更大口径的干涉仪的研制提供理论基础研究和关键技术储备。

关键词 测量；光学测试；大口径干涉仪；PZT 移相；关键技术
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1 Introduction

With the development of science and technology, the large-aperture optical system is more and more widely used in the field of high technology, such as astronomical optics and high power laser system. Such large-aperture optical element has become one of the key parts for developing these high techniques. Wavefront testing of large-aperture optical components, especially in surface finishing, system installation and calibration, on-line test, need to develop the test methods and instruments with suitable precision correspondingly. Therefore, the demand for large-aperture interferometer grows with each passing day.

The accuracy requirements of large-aperture interferometer is very high, manufacturing is very difficult accordingly. At present, taking the Zygo Inc.[1] and WYKO Inc.[2] as representative, the commercial large-aperture interferometer is introduced from abroad. High precision measurement of the plane sample can be achieved, but the price is very expensive; In recent years, Nanjing University of Science and Technology and Chengdu Precision Optical Engineering Research Center have developed 600 mm and 500 mm Fizeau wavelength tunable phase-shifting interferometer, respectively[3-4], but considering the limitations of wavelength tunable phase-shifting technique, such as the re-calibration of phase-shifting before each measurement and the wavelength drift lead by temperature, in this paper, key techniques and solutions of ϕ300 mm vertical Fizeau phase-shifting interferometer via piezoelectric (PZT) are discussed.

Phase-shifting via PZT is realized by driving the reference mirror with piezoelectric ceramics, which is widely applied in the small-caliber (diameter is no more than 150 mm) interferometer. The difficulty for system design increases as the diameter increases, such as the

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deformation correction of reference mirror generated by gravity and absolute test of large-aperture collimator during the process of manufacturing, in-line test of phase shifter nonlinear characteristic. There are many technical difficulties to be solved, which stands as a new challenge to research and development of large aperture phase-shifting interferometer.

2 Key techniques and solutions

2.1 Support and absolute test of large standard flat crystal

The interferometer is a kind of optical testing equipment with high precision, the reference plane is the test datum. Therefore, the surface quality of reference mirror will affect the final measuring result of the interferometer directly, which must be strictly controlled. Because of the manufacturing difficulties of large-aperture reference mirror, in the past, the maximum diameter of common interferometer is usually about $\varphi 150$ mm, the impact, such as gravity and other factors, on small-caliber reference mirror of interferometer can be ignored. With increasing aperture and improving accuracy of interferometer, high standard design and processing technology are put forward to large reference mirror. In order to ensure the physical stability of large-aperture reference mirror, the mirror is usually very thick and often weighs tens kilograms, especially in large-aperture vertical interferometer, the influence of gravity and other factors on the mirror surface must be considered. The traditional support structure of reference mirror with three points is unable to meet the high image quality requirements. The key technology for large-aperture reference mirror is to reduce its deformation induced by self-weight through adopting reasonable support method, which must be controlled strictly so as to ensure high measuring precision.

The finite-element method is used to optimize the design of support structure on $\varphi 300$ mm reference mirror, in order to find an optimal supporting scheme, two horizontal supports are modeled and analyzed in different supporting cases of adhered spots edge support and band-back support (Fig. 1). According to these two supporting methods, the entity model of reference mirror is established and calculated by ANSYS software. Considering the simplicity and economy, the ringy-band support with 10 mm wrap bandwidth is accepted to be the optimum. In this optimal support scheme, the ideal surface deformation of the reference mirror due to self-weight is obtained. According to this result, a certain deformation allowance should be given when the mirror blank is polished. While this reference mirror processed according to the design results is installed in the interferometer, the high accuracy datum needs to be established for the surface test of reference mirror which is tested under practical states.

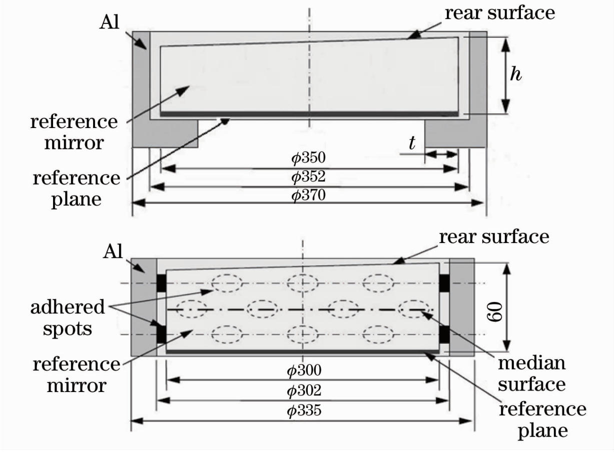


Fig. 1 Back-band support and adhered spots edge support

There are two common methods to establish the optical plane datum: the liquid level reference method and the absolute plane test method (such as the three flat test method and the pseudo shear method)[5]. Because of the increasing diameter, both three flat test method and pseudo shear method have some shortages. For the three flat test method, first of all, three high precision planes are required with same caliber and similar surface accuracy to each other. Especially for large-aperture plane, it is difficult to support and the processing cost of three planes with similar accuracy is high, furthermore, the flat in horizontal mode will generate surface deformation because of gravity; secondly, three planes need interchange and rotation during testing, so the spatial consistency of test wavefront is not easy to guarantee. Each measurement during these three adjustments is required in the complete constant temperature environment, thus the test period is too long. All these points mentioned above increase the difficulty of this method for the reference mirror measurement in large-aperture vertical interferometer, so it is only suitable for manufacturing high precision and medium-caliber plane.

Because of the accumulation errors of original wavefront when the wavefront is unified, pseudo shear method as a method of establishing datum plane is not widely recognized. From the above mentioned, the liquid level is chosen as the reference datum. In order to ensure the test precision of the interferometer, the surface of reference mirror under practical working conditions is measured through building the liquid absolute reference. By comparison with the design results, the differences of peak-valley (P-V) magnitudes and room mean square (RMS) values are only 0.008λ and 0.005λ, respectively. The results show that the structure design of reference mirror and its surface machining accuracy under the guidance of design results meet the technical requirements very well. The feasibility is further verified experimentally. Through analysis of the finite element method, the deformation caused by gravity and supports is far greater than the thermal elastic deformation caused by temperature variation. So by taking some temperature control measures, the influence of thermal turbulence can be effectively reduced by the average algorithms.

2.2 Precise step controlling of phase-shifter

Because of the nonlinear characteristic determined by the piezoelectric ceramic material, the reference mirror should be thick enough to ensure its physical stability when its aperture is larger than 300 mm, so it weighs as much as tens of kilograms. During the process of testing, such heavy mirror should be moved along the optical axis accurately and smoothly at micron level by PZT. Thus the design is more difficulty, higher precision is required for the PZT components. If not handled properly, the system accuracy and final test results will be seriously affected, so the nonlinear error of phase shifter need be corrected under practical working conditions. During the process of phase-shifting, although phase shift error could be minimized through algorithms[6], the nonlinear error of phase shifter cannot be reduced effectively.

There are two different origins of phase shift error as follows: 1) the parallel misalignment of phase shifter: the phase shifter is composed of three PZTs, if the elongation of each PZT is not the same to others during the phase-shifting process at each step, the interference fringe rotates and the fringe spacing changes; 2) the step inaccuracy of phase shifter, that is the nonlinear relationship between reference phase and step number when the reference mirror is drived by phase shifter. The carrier interferogram is introduced and it is a feasible calibration method for phase shifter nonlinear errors. As a way to introduce carrier frequency to interferograms, the fast Fourier transform (FFT) method is often used. Based on the theory of FFT, Zhu *et al.*[7] proposed a calibrating method about phase-shifter error composed of three PZTs. This is a method for global calibration, the sampling number of spatial period and the spatial frequency accuracy are strictly required in order to ensure the phase calibration precision, thus it is suitable for the case of dense fringes. But the wavefront is generally tested when the fringes is adjusted to very sparse, therefore, this method is not suitable for on-line calibration. The calibration is finished just once before testing, and calibration coefficients are kept constant all the time. But due to the influence of the external environment and the phase shifter itself, the phase shifter parameters may change in the process of testing. So we need find a method to calibrate the nonlinear error of phase shifter on-line.

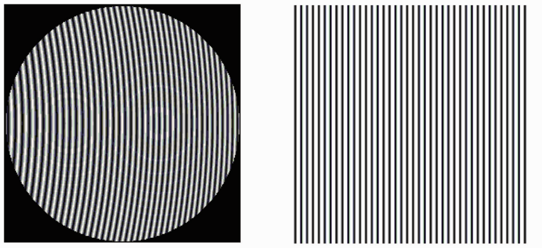
The on-line calibration thought about parallel misalignment of phase shifter is as follows: firstly, the position coordinates of three PZTs should be determined, secondly, the relationship between the threshold of displacement difference and stripes rotation amount is obtained by system modeling. This is the basis of correcting the parallel misalignment error of phase shifter. The displacement data of three PZTs are measured at each step in the experiment, compensation and calibration of parallel misalignment are achieved by comparing experimental data and the threshold which is relevant to the rotation accuracy. So that the displacement difference is controlled in the range of allowable error. For step inaccuracy of phase shift, linear voltage generates nonlinear displacement, on the contrary, if the nonlinear voltage is applied across the PZT, the linear displacement is produced, this is the correction basis of this error. In order to obtain the voltage-displacement (OPD) curve, the mathematical model, matching with the actual voltage-displacement characteristics, is established. The nonlinear error of phase shifter is very small during the actral phase-shifting test, the displacment characteristics is described by a one basic quadratic equation. Then the relationship between intensity and displacement is built from interference equation, the mathematical model between light intensity and displacement and voltage is finally obtained. In the experiment, applying step voltage on PZT, getting N intensity values at same sample point in the interference field, the coefficients of mathematical model are obtained by fitting the voltage-intensity curve through the damped least square method, then the voltage-displacement characteristics of PZT is determined, the voltages corresponding to four interferograms whose phase interval is 90° can be solved.

2.3 Measurement of dynamic phase

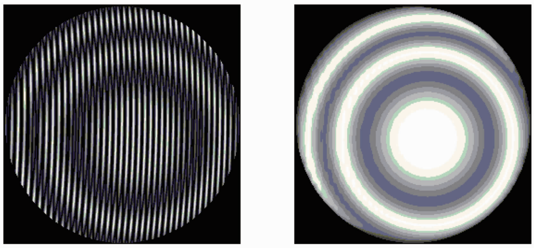
The liquid surface is the test datum of the reference mirror surface. It is very sensitive to vibration and air turbulence in the environment, therefore, the wavefront stability of dynamic liquid surface should be evaluated during the process of liquid datum plane establishment for large-aperture interferometer.

Time domain phase-shifting method and spatial domain phase-shifting method[8] are the common methods to extract the phase information from multiple interferograms based on image processing. For time domain phase-shifting method, each interferogram is captured in the same spacial position at different time. According to the phase-shifting principle, image background, image contrast and the measured phase at the same sample point must be stable in process of phase-shifting, the requirements for the environmental stability is relatively high, so it can only be used to measure the static or quasi-static phase. For spatial domain phase-shifting method, for interferograms are obtained simultaneously in different spatial positions, each phase interval is $\pi/2$. Thus the dynamic phase could be measured, but the optical system is complex, the requirements for detector characteristics is high, each interferogram needs position matching to the next. Fringe tracing method, FFT method and spatial carrier phase-shifting method[9] are the common image processing methods for one interferogram. The early tracing fringe method is rarely used now because of little data quantity and complex image processing, furthermore, the accuracy is low. The FFT method need process interferogram with a carrier frequency through two-dimensional (2D) Fourier transform and complex frequency domain filtering, the number of sampling points is strictly for 2^n, which is large in computing capacity. Spatial carrier phase-shifting method also need process the interferogram with a carrier frequency. Compared with the time domain phase-shifting method and spatial domain phase-shifting method, the phase is solved by processing just one carrier interferogram through phase-shifting algorithm. The carrier frequency can be obtained easily by tilting the reference mirror, but the carrier frequency demands exactly that a stripe with four interval sampling points, so it is very sensitive to the static noise. So the phase extraction method mentioned above is not suitable for processing multi-frame dynamic interferograms, therefore, a new algorithm should be seeked for dynamic phase extraction.

According to the principle of phase-shifting Moire technology, a new method is adopted for phase calculating through processing a static carrier interferogram, named Moire interference technology. As shown in Fig. 2, in order to obtain the carrier frequency value, the tested interferogram with a large linear carrier is analyzed by FFT algorithm, then a virtual sinusoidal grating with this spatial carrier frequency is generated by computer. While the initial phase is set to 0, $\pi/2$, π, $3\pi/2$, four different reference interferograms can be generated. If the measured interferogram is superimposed over four different reference interferograms, four phase shifted moire fringe pattern can be obtained. After that four phase-shifting interferograms can be obtained by image filtering. In the end, as shown in Figs. 3 and 4, the wavefront phase is calculated through four-step phase-shifting method and phase unwrapping method in turn. Because of the phase-shifting process is controlled by computer, the shifted phase is very accurate. Compared with the time domain phase-shifting method, without any phase shifter, the calibration work is avoided and cost is saved accordingly; most of all, dynamic phase can be tested because the results is given by processing only one interferogram; compared with the spatial domain phase-shifting method, the errors caused by multiple detectors can be avoided; Compared with the FFT method, there is no strict requirement for the number of data sampled points, and no demand for 2D FFT transform and frequency filtering, the calculation is relatively simple; compared with the spatial carrier phase-shifting method, the requirements of carrier frequency value is also relaxed.



(a) test interferogram　(b) reference interferogram



(c) moire pattern　(d) filtered moire pattern

Fig. 2　Process of filtered moire pattern

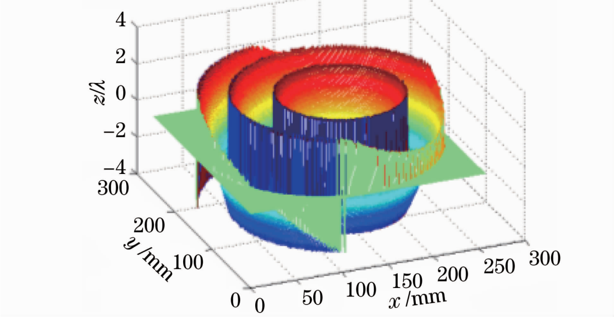


Fig. 3　Wring plane

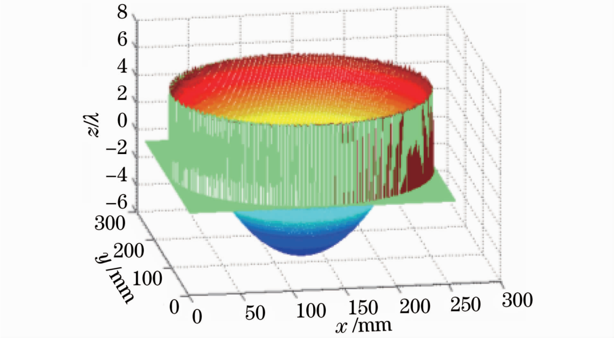


Fig. 4　Retrieved surface

2.4　Wavefront test of lare-aperture collimated beam

Optical plane interferometer is an optical instrument with high precision, and it needs a collimated beam with high quality, especially in large optical path, because of the influence of wavefront propagation errors, the wavefront quality of collimated beam affects the final test result directly, so the wavefront quality must be tested in order to guarantee the interferometer precision.

Wavefront testing of large-aperture collimated beam is often high cost and low spatial resolution. The common methods is self-collimation method, Hartmann method, Shack-Hartmann method, shearing interferometry and sub-aperture stitching method etc. Because of the increasing diameter, the traditional self-collimation method[7] is no longer applicable due to requiring the large-aperture high standard mirror; shearing interferometry[8] must introduce a double shear-plate with uniform materials and same caliber to the test system, and the cost is very high. A matching Hartmann screen should be created in Hartmann method as each system is detected, this screen is very difficult, expensive and time-consuming. In the sub-aperture stitching method commonly used, each sub-aperture wavefront is tested by a small-aperture interferometer, then through splicing these sub-aperture wavefronts to the same reference plane, the full aperture wavefront is reconstructed. The mechanical structure is very complex, both transmission error and accumulated error are large, furthermore, the algorithm is very difficult. Therefore, we should pursue a mean which is simple, high accuracy and easy to realize for the large-aperture wavefront testing.

In this paper, as shown in Fig. 5, the pentaprism scanning scheme is adopted with a small-aperture pentaprism and a horizontal slideway with high accuracy. The test wavefront is divided into several sub-wavefronts by sliding the pentaprism along the slideway accurately, the corresponding spot images are recorded on charge-coupled device (CCD) at same sampling intervals, the relative position of spot centroid of each sub-wavefront can be calculated. Then the wavefront slope at each sampling point can be obtained after calculating the centroid deviations of each sub-wavefront, that is, the first-order derivative value of the tested wavefront at each sampling point. Finally the tested wavefront is reconstructed through intergral algorithm, the collimation wavefront test is realized. Obviously, pentaprism scanning method is essentially a serial Hartmann method. Using the pentaprism properties of one-dimensional (1D) rotation invariant, the longitudinal focusing is converted to the horizontal alignment during the test process. It has the characteristics of simple structure, and can not only guarantee the precision, but also achieve the economic and time-saving. Furthermore, wavefront test with high precision can be realized for the large-aperture collimator, astronomical telescope and other large-aperture optical systems, it cuts down the high cost of conventional test methods, in addition, it is very important to expand the measuring range, improve high spatial resolution and high accuracy.

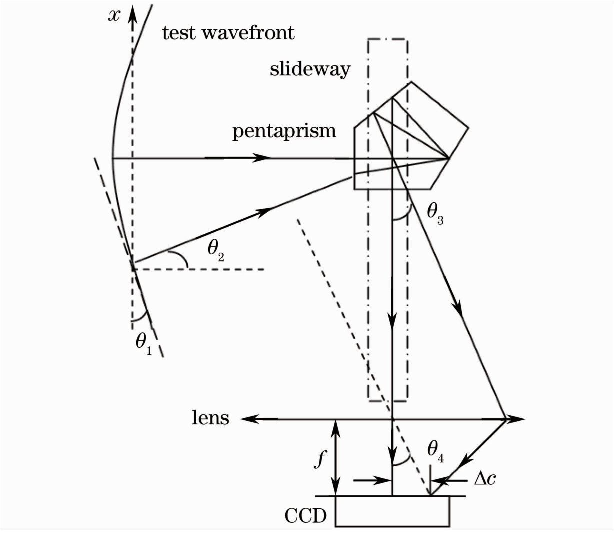


Fig. 5 Schematic of pentaprism scanning method

3 Conclusions

This paper mainly studies the technical difficulties and solutions contained in the large-aperture phase-shifting interferometer via PZT, including the technical support and absolute calibration of large diameter flat crystal, dynamic wavefront testing, large aperture wavefront testing, online testing of phase shifters etc. Key technical reserves for the development of large-aperture interferometer are achieved for the measurement of large-aperture optical systems.

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