Asphere testing with a Fizeau interferometer based on a combined computer-generated hologram

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Fizeau interferometers with an additional diffractive optical element are frequently used for measuring spherical and aspherical surfaces. We present a new (to our knowledge) optical test method, in which the Fizeau principle is now perfectly fulfilled by generating reference and measuring wavefront on the last optical surface, which carries a diffractive optical element. This method has been examined experimentally by testing a reference $f/0.68$ spherical mirror and can be applied identically for testing aspheres. Several advantages of this method are discussed and proved experimentally. © 2006 Optical Society of America

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1. INTRODUCTION

Diffractive optical elements (DOEs), or computer-generated holograms (CGHs), are very powerful instruments for interferometric measurements of aspherical surfaces because they can transform an incoming wavefront into nearly any arbitrary numerically or mathematically defined shape. Such CGHs, which consist of patterns of lines or rings, are now easily manufactured by using equipment from the microelectronics industry or precision task-oriented circular laser writing systems optimized for CGH fabrication.[1] The precision of the CGH fabrication affects the accuracy and validation of the measured results. However, errors and uncertainties during the CGH fabrication process result in errors in the diffracted wavefront created by the hologram. Consequently when the final hologram is used for optical testing, the precision of the measurement will be affected. The accuracy of the fabrication of the hologram structure with present-day equipment reaches several nanometers, which allows formation of steep enough wavefronts with a peak-to-valley (PV) error of ~1/20 waves and even less.[2] The certification of the writing process of the CGH fabrication, which can reveal random errors of the writing process, has been demonstrated.[3] The application of these innovations has allowed creation of precision CGHs for interferometric measurements of large aspherical optics, e.g., 6.5-m $f/1.25$ and 8.4-m $f/1.14$ paraboloidal primary mirrors.[4] In the past few years new types of diffractive elements, such as combined (or split, cellular, multiplexed, dual-wave, for example) CGHs,[5] which represent the alternate encoding of two or more wavefronts on the CGH aperture split into regular strips or rings, have been presented. CGHs of this kind can transform one input wavefront into several independent output wavefronts. These new kinds of elements have been widely investigated for testing optical surfaces and certification of wavefronts generated by the CGHs.[5–7] However, these diffractive elements also have properties of splitting wavefronts and can be used as the basic component of an interferometer, splitting the measuring and reference beams. This paper presents a new (as far as we know) design, in which the principle of a Fizeau interferometer is now perfectly fulfilled, namely, by generating reference and measuring wavefronts on the last optical surface, which carries a DOE. Several advantages of this design are discussed. We present a simple and general method of aspheric figure metrology using a combined CGH placed in the output beam of a conventional Fizeau interferometer. We examine this method experimentally by testing a reference $f/0.68$ spherical mirror. The experimental results that we have obtained by the proposed method agree well with those obtained by using a Fizeau interferometer with a standard transmission sphere.

2. OPTICAL TESTING WITH A COMPUTER-GENERATED HOLOGRAM

Interferometers operate by generating two laser beams, one as a reference and one as a test beam. The test beam interacts with the optics under test, and the reference beam is reflected by a reference surface. Test and reference beams overlap each other inside the interferometer in the plane of the CCD camera. Usually the reference surfaces are flat or spherical; hence only plane and spherical surfaces can be measured.

For testing aspherical surfaces, a CGH is added to the test arm, acting as a null lens. The CGH null operates in double path, first producing an aspheric test wavefront

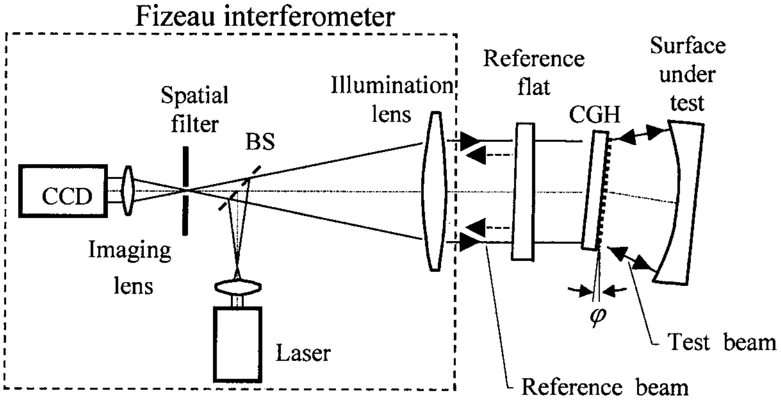


Fig. 1. Layout of a null CGH test of an asphere. BS, beam splitter.

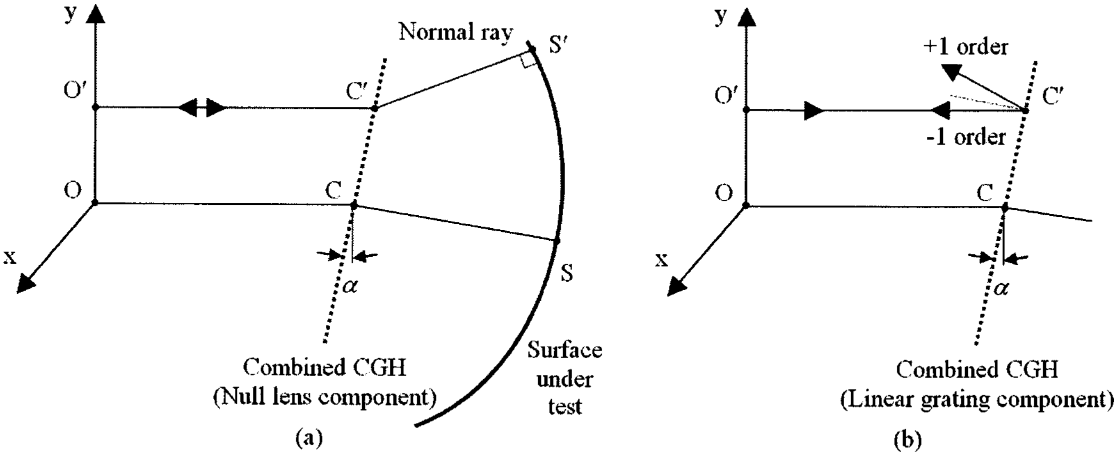


Fig. 2. Configuration of a combined off-axis CGH optical test: (a) null lens component, (b) linear grating component.

and then recollimating the wavefront reflected from the tested surface. This technique is used for measuring aspheres with existing Fizeau interferometers.[8] A common configuration for using a CGH for optical testing with Fizeau interferometer is shown in Fig. 1. In this configuration, either on-axis or off-axis CGH nulls can be used. If the interferometer operates with a plane output wavefront, the CGH null is tilted by a small angle (less than 1°) with respect to the optical axis, so that the various diffraction orders will be separated. The tilt of the CGH null is necessary for elimination of the direct reflection (zero order) from the CGH surface as well.

In this configuration, the interferometer measures the combination of the CGH null *and* the asphere, so the accuracy of the test depends on the quality of the CGH null. In the presented case, the major source of error is the surface of the reference flat of the Fizeau interferometer and the transmitted wavefront distortion (TWD) of the CGH substrate.[8,9] In practice, the TWD of the CGH substrate limits the precision of this type of interferometric measurement. Typical CGH substrate errors show low spatial frequencies, and these errors show the low-spatial-frequency wavefront aberrations in the diffracted wavefront.[9] One method of eliminating the substrate error is to measure its flatness first. The CGH substrate errors can be measured by using the zero-order diffraction beam. However, the zero-order diffracted wavefront is extremely sensitive to duty-cycle variations of the phase CGH pattern.[9] This phase error overwhelms the effects of the CGH substrate error in the zero diffraction order and prevents substrate figure measurement. Thus, eliminating the TWD of the CGH substrate leads directly to significantly improved measurement accuracy.

3. DESIGN CONCEPT

Our basic idea to increase the accuracy of the interferometric measurement consists of eliminating the influence of the CGH substrate figure error. For this purpose, we propose to use an off-axis combined CGH, where the substrate plane carrying the diffractive structure is facing outside with respect to the interferometer. The combined CGH consists of two independent CGHs: One component of the hologram is generating a plane wave (reference beam), while the other component (null CGH) is generating a test wavefront (test beam). This CGH can be composed of for example, a linear grating and a null CGH. The geometry for defining the CGH functions of both components is shown in Fig. 2. The phase function of the null CGH component is derived by use of a geometrical model of rays normal to the surface under test (aspheric surface), as shown in Fig. 2(a). The null CGH function is the optical path difference (OPD) between $O'C'S'$ and OCS.

Choosing the reference point as the center yields the following function across the CGH[10]:

$$\phi_1(x,y) = O'(x,y)C'S' - O(x_0,y_0)CS. \qquad (1)$$

The reference beam function is the OPD between $O'C'$ and OC, as shown in Fig. 2(b). The grating spacing S is determined in a way such that the angle of diffraction φ is equal to the double of the angle of inclination of the CGH plane (Littrow angle):

$$\varphi = \lambda/\mathrm{S} = 2\alpha, \qquad (2)$$

where λ is the wavelength.

In this case, the diffracted light beam is exactly returned back. The OPD for the reference beam is given by

$$\phi_2(x,y) = O'(x,y)C' - O(x_0,y_0)C = x\tan(\alpha). \qquad (3)$$

From Eqs. (1) and (3) we can see that the final OPD for the null CGH, taking into account the reference beam OPD, is given by

$$\phi(x,y) = C'(x,y)S' - C(x_0,y_0)S. \qquad (4)$$

Figure 3 shows the layout of the null test on the basis of the combined CGH. In this optical scheme, both test and reference wavefronts are formed by means of diffraction and by one single CGH. This makes it possible to eliminate the substrate heterogeneity and increases the test accuracy. Only one side of the substrate (the CGH plane) has to be fabricated with high quality. This combined CGH can be designed as an amplitude-only CGH or as a mixed amplitude–phase CGH.

The formation of a combined amplitude–phase CGH is shown in Fig. 4. The first component [Fig. 4(a)] is built as a phase CGH in order to achieve maximum diffraction efficiency. The second component [Fig. 4(b)] is a reflective amplitude grating. The combination of these two elements leads to an amplitude–phase CGH [Fig. 4(c)].

The proposed test method is a hybrid of the two optical measurement methods: Fizeau test plate interferometry and the use of CGHs. The accuracy of the proposed test is limited by the quality of the single flat optical surface, by the accuracy of the CGH structure location, and by the etching process. Structuring and etching can be produced with sufficiently high accuracy. This method is close to the CGH test plate technique developed by Burge and Anderson.[11]

It is interesting to compare the classical Fizeau interferometry with the developed test. The Fizeau principle is perfectly fulfilled if the combined CGH is an amplitude-only element. For the case of a combined amplitude–phase CGH there might be a nonuniform etching depth, leading to a degradation of the test wavefront but without

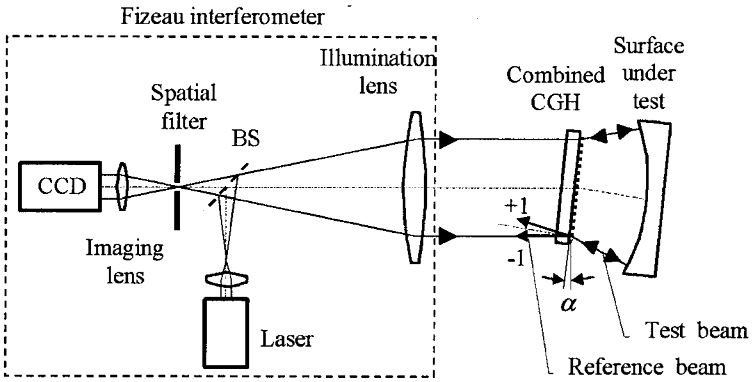


Fig. 3. Layout of a null CGH test of an aspherical surface, using one single CGH working in a collimated interferometer beam without reference flat.

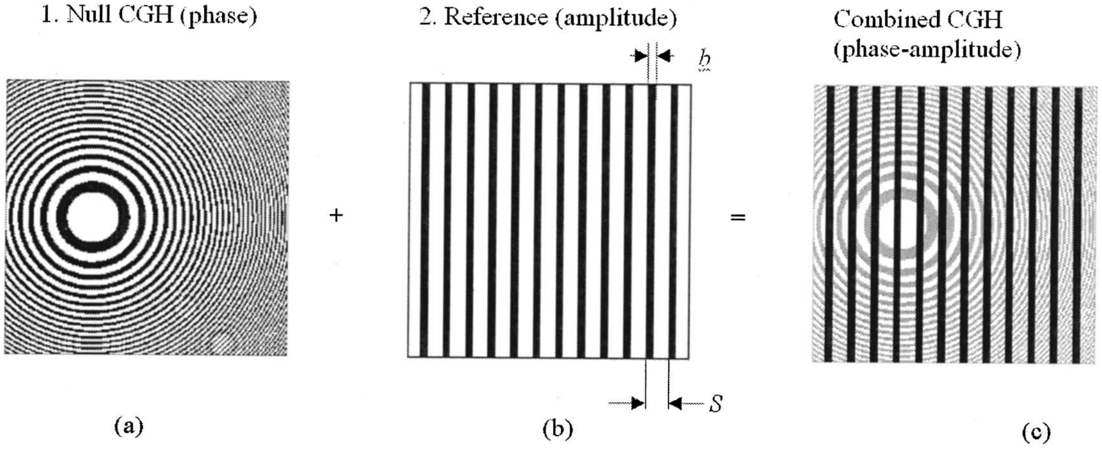


Fig. 4. Formation of a combined CGH.

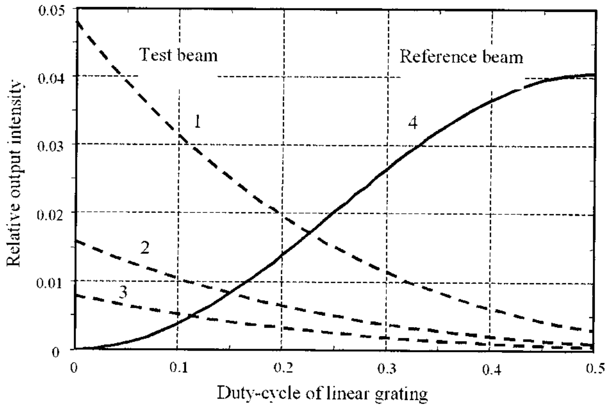


Fig. 5. Relative output intensities of the test beam (curves 1, 2, 3) and reference beam (curve 4) as a function of the duty cycle of the linear grating. The reflectance of the tested surface is (1) $\rho_{test}=40\%$, (2) $\rho_{test}=10\%$, (3) $\rho_{test}=5\%$.

influencing the reference wavefront. There is a similar situation with use of standard transmission spheres (TSs) in Fizeau interferometers. Here the reference wavefront is formed by reflection on the last surface acting as the "master surface," commonly referred to as an aplanatic surface. The quality of the reference wavefront depends on the figure quality of this master surface, although the quality of the transmitted test wavefront depends on the TS lens design and the quality of all the lenses.

The test beam with intensity I_2 passes the null CGH twice at the first order of diffraction. The reference beam with intensity I_1 is formed by diffraction (in reflection) on the linear grating with the spacing S calculated from Eq. (2). The CGH is designed to diffract this reference beam to match an ideal test wavefront. The combined CGH should be designed in a way such that its diffraction orders are spatially separated in the plane of the pinhole (spatial filter). If θ is the full angular size of the pinhole, the spacing S is derived by $S<\lambda/\theta$.

The duty cycle of the linear grating is defined on the basis of the parity condition for the test and reference beams' intensities. The intensity of the diffracted reference beam is defined by the diffraction amplitude of the linear grating,

$$I_1 = I_0 \rho_{grat} D^2 \operatorname{sinc}(mD)^2, \tag{5}$$

where ρ_{grat} is the reflectivity of the linear grating material, m is the diffraction order, and D is the grating duty cycle defined by $D=b/S$. The intensity of the test beam (after double pass through the CGH) is defined by the zero-order diffraction efficiency,[12]

$$I_2 = I_0 \eta_1{}^2 \rho_{test} D^4, \tag{6}$$

where η_1 is the diffractive efficiency of CGH 1 (null CGH) in +1st order and ρ_{test} is the reflectance of the surface under test. The relative intensities of the test and reference beam as a function of the duty cycle of the linear grating are shown in Fig. 5, based on the parameters $\eta_1=0.4$, $\eta_2=0.1$, $R=0.8$ and $\rho_{test}=0.4$ (curve 1), $\rho_{test}=0.1$ (curve 2), and $\rho_{test}=0.05$ (curve 3). For these given values, the optimal duty cycle is $D=0.16$. In this case, the light transmission of the test and reference arms of the interferometer is approximately $I_2/I_0=I_1/I_0=1\%$. One can see that by changing the duty cycle of the grating, it is possible to reach an optimal contrast of the final interferogram for a variety of materials with different reflectance (e.g., glass, silicon, germanium, metallic mirrors, optical ceramics).

4. FABRICATION PROCESS OF THE COMPUTER-GENERATED HOLOGRAM AND EXPERIMENTAL RESULTS

The aim of the experiments was the verification of the proposed CGH design. The test was performed by using a phase-shifting Fizeau-type interferometer manufactured by Zygo (GPI). The CGH has been designed and fabricated with the following parameters: diameter $D=50$ mm, focal length $f=150$ mm, and tilt angle $\varphi=0.25°$. As a surface under test we used a standard reference sphere $f/0.68$ (from the GPI toolkit).

A. Fabrication of the Computer-Generated Hologram

The CGH was written by using the circular laser writing system (CLWS), built by the Institute of Automation and Electrometry in Novosibirsk, Russia.[1] The CLWS is capable of writing up to 300-mm diameter CGHs with an absolute accuracy of 100 nm across the full diameter. The machine rotates the substrate at 600–800 rpm and uses an interferometrically controlled linear air bearing writing head, with a positioning precision of several nanometers. This machine also writes arbitrary patterns that do not have a circular symmetry, by using a coordinate transformation software and a high-quality angular encoder with rapid-writing beam switching. We could calibrate the writing system in a way such that nonrotationally symmetric patterns, especially the mentioned linear grating that generates the reference wavefront, are recorded with the same precision as the circular patterns of the object wave hologram.

In fact, due to the 0.25° tilted off-axis design, the described combined CGH has slightly elliptical zones with a minimum spacing of $T_{min}=3.9$ μm. The 0.25° tilt angle leads to a corresponding spacing of the linear grating equal to $S=72$ μm. This linear grating and the elliptical zones of the CGH are written simultaneously. The accuracy of the resulting wavefronts formed by the combined CGH is defined by the writing pitch, which has been set to 0.2 μm in our case. The value of the writing pitch is a compromise between the accuracy of the CGH structure and the velocity of the writing. The accuracy of the writing in the angular direction is defined by the angular encoder of the CLWS, which has approximately 2×10^6 positions per revolution, corresponding to a spacing of $\sim$0.1 μm at 25-mm radius.

The wavefront error produced by the CGH pattern at the mth order of diffraction can be calculated by[9]

$$\Delta W(x,y) = -m\lambda \frac{\varepsilon(x,y)}{S(x,y)}, \tag{7}$$

where $\varepsilon(x,y)$ is the positioning error perpendicular to the zones and $S(x,y)$ is the spacing of the zones. Thus, with

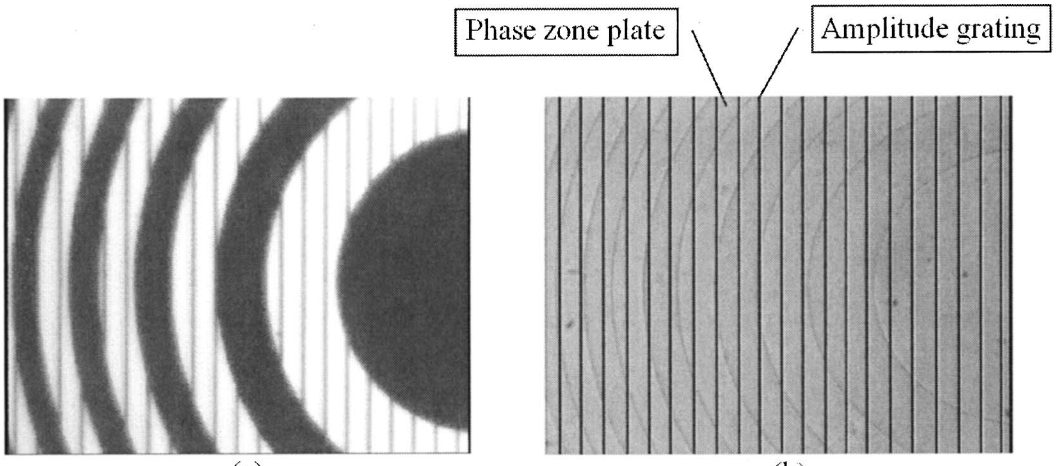
$m=1$, the maximum error of the test wavefront of the fabricated CGH is less than 0.05λ (PV), and the error of the reference wavefront is less than 0.003λ (PV).

The CGH had been fabricated on a 60-mm fused silica substrate with 1/20-wave PV surface quality. The second surface had approximately 1–2 waves PV quality. The substrate wedge was approximately 4–5 min. A chromium layer was deposited onto the high-quality surface and was structured using a resistless technology by direct laser writing onto chromium films.[2] Figure 6(a) shows a photograph of the chromium pattern of the CGH null fabricated by direct writing with the CLWS. The linear grating has approximately $S=72\ \mu$m spacing and $b=18\ \mu$m line width. The CGH null component as chrome on glass pattern diffracts approximately 10% into the first order in transmission, and the linear grating diffracts 1% into the first order in reflection. This amplitude CGH can be used for testing surfaces with high reflectivity ($\rho_{test} > 40\%$).

For testing glass surfaces with a low reflectivity ($\rho_{test} \sim 5\%$) we need to achieve a high diffraction efficiency for the transmitted object wavefront and a low efficiency for the linear grating, thus obtaining similar amplitudes for the reference and the test wave. Therfore the CGH has been processed in the following way: First, we transferred the CGH structures into the substrate by ion etching. In order to keep the chromium pattern of the linear grating, we covered each single line of the linear grating with a photoresist masking process. Then the uncoated chromium was removed, and, finally the photoresist, which had protected the linear grating, was removed.

One should add that for the case of a combined amplitude to phase CGH used for testing low-reflective glass surfaces, the geometrical plane of origin of the object wavefront is no longer well defined. Thus the Fizeau principle might be affected in theory. But it is still valid that a highly accurate flatness is required only on the last substrate plane. With this precision flatness, the binary phase step level inside the substrate is then generated by ion etching.

Figure 6(b) shows a photograph of the resulting combined amplitude–phase CGH after ion etching and after removal of the chromium layer from the phase CGH area. Figure 7 shows an image of the central part of the fabri-



(a) (b)

Fig. 6. Microscope images with transmission illumination: (a) central part of the chromium mask fabricated with the CLWS, (b) final amplitude–phase CGH.

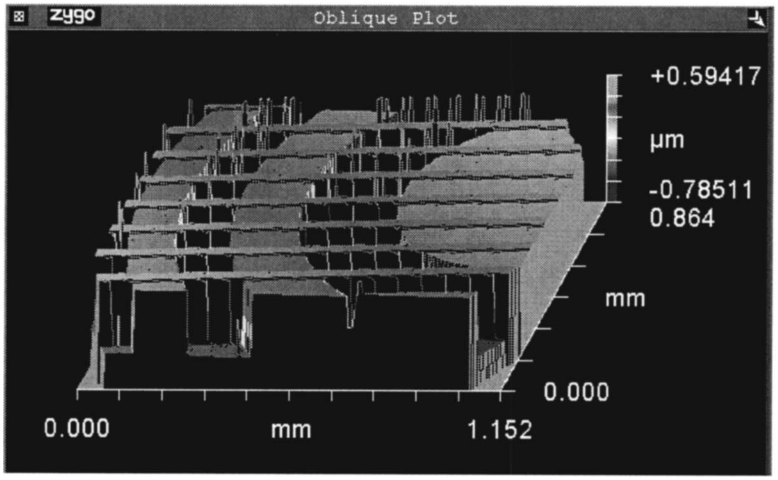


Fig. 7. 3D image of the central part of the fabricated combined CGH.

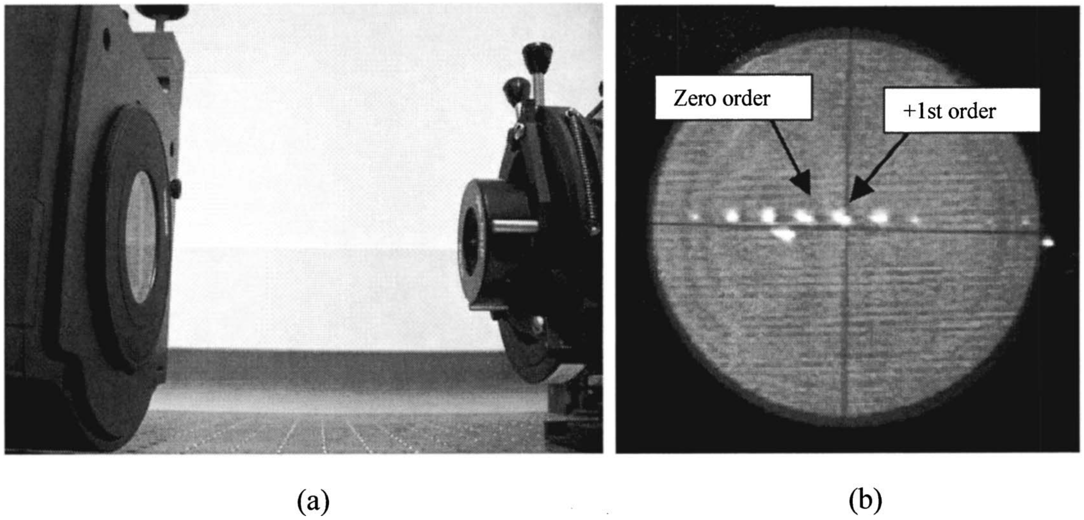


Fig. 8. (a) CGH (left), mounted directly into a Zygo Fizeau interferometer, and lens surface (right) under test. (b) Alignment pattern with CGH null.

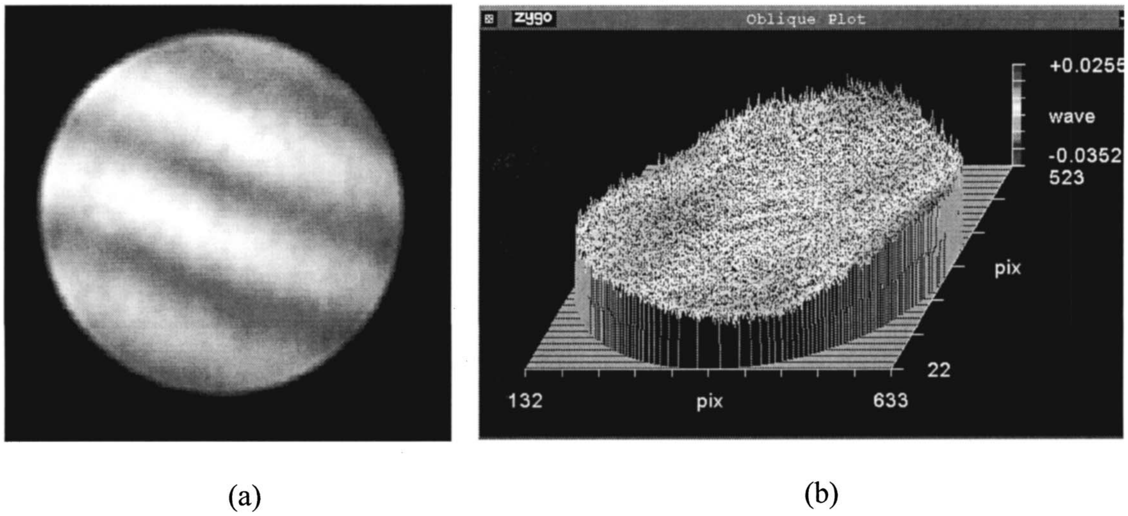


Fig. 9. (a) Interferogram and (b) phase map of a reference spherical mirror with $f/0.68$, measured with the combined CGH null.

cated combined CGH taken with a white-light interferometric microscope and processed in a three-dimensional (3D) representation. Hence, an amplitude-phase CGH has been fabricated with approximately 40% diffraction efficiency into the first order of diffraction and 1% efficiency in reflection. This CGH can be used for testing surfaces with low reflectivity.

B. Characterization of the Computer-Generated Hologram Null

To prove the feasibility of the concept, the fabricated CGH null was mounted into a standard Zygo-type bayonet housing and was fixed at the place of the transmission sphere in the Zygo interferometer [Fig. 8(a)]. The optical test layout was chosen according to Fig. 3. As a first step, the alignment procedure (tilt of CGH at 0.25.) was made. Figure 8(b) shows the "view" mode of the alignment pattern. One can see several orders of diffraction caused by the linear grating of the CGH.

The first order of diffraction indicated in Fig. 8(b) has to be aligned into the center of the crosshair. The alignment of this kind of CGH is comparable with the well-known procedure used in alignment of commonly used refractive reference lenses. As this hologram is working in a collimated beam, there is no need to align it transversally. Principally one could think about a reference wavefront that is reflecting back an incoming *spherical* wave. But in this case, the compatibility with standard interferometers is lost for two reasons: First, the incoming beam needs to be spherical instead of parallel; and second, the bayonet holder would require additional adjustments in the X and Y directions.

A typical interferogram produced by testing a $f/0.68$ spherical reference mirror is shown in Fig. 9(a). The intensity distribution of the reference beam shows very good uniformity, and the contrast of the fringes is good enough. A 3D plot of the phase map is shown in Fig. 9(b). The resulting precision of the measurement is P-V=0.06 waves and rms=0.01 waves.

5. CONCLUSIONS

A hybrid optical measurement method was developed in which the test plate of a Fizeau interferometer is combined with a computer-generated hologram (CGH). This method meets the extreme challenges of high-precision measurements of aspherical optics. The technique can be used with standard commercial interferometers. The CGH test plate can be used to measure any spherical or aspherical surfaces with convex or concave shape.

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