Invited Paper

Current state of optical testing

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Introduction

Basic interferometry and holographic interferometry are becoming useful tools for precision measurements. The use of electronic solid state detector arrays, together with small computers for extracting the information from the interferograms improve their applications. Computer analysis is becoming increasingly important. A lot of information can be extracted from the interferograms leading to higher sensitivities and accuracies.[1]

New technologies to generate optical surfaces have been introduced. Progress has been made in manufacturing of metallic spherical and aspherical surfaces using diamond turning techniques, for instance. The improved production techniques will motivate the optical designer to use aspheric surfaces more frequently especially for IR applications. Using replica techniques, aspheric surfaces will be used more often in serial production of components used for the visible or near IR. In consumer products the cost of precision optics is relatively high. Using inexpensive aspheric lenses could cut the cost considerably. The application of aspherical optical surfaces could be helpful to reduce the number of optical elements reducing the total weight of the optical system and possibly the cost, in addition, the quality may be improved. Replication of an aspheric surface on a thin film onto a spherical glass body using photocurable la cquer is very cost effective.[2]

The aspheric mold as well as the resulting aspheric optical elements need to be tested. Optical contactless testing techniques using computer generated holograms can be very useful for industrial applications for micro- and macro structure analysis of aspheric surfaces.[3]

Phase measurement in interferometry

Measurements of the profil, shape as well as deformation by interferometry or holographic interferometry requires the determination of the wavefront from interference fringe pattern.[3,8,9]

Automated interference fringe evaluation uses digital image-processing methods. The intensities of the fringe patterns are recorded by a vidicon or charge coupled-device camera along a rectangular array of pixels and are quantized to discrete values normally ranging from 0 to 255, corresponding to 8 bits.

Digital extraction of the phase in interferometry provides means for obtaining very precise measurements at rapid rates. For the fringe analysis in interferometry and holographic interferometry the different techniques can be classified into static and dynamic methods.

For static methods where the fringes are frozen, closed fringes should be avoided which means that an additional tilt may be introduced. The centers of dark and bright fringes are located using video techniques and image processing. In addition, phase detection in the spatial domain can be obtaind by Fourier-transformation methods and by Fourier analysis of the digitized fringes.[5,6]

Dynamic techniques are:

- phase shifting in three or four steps or continously
- heterodyne technique
- phase locked technique.

Precise results are obtained by the evaluation of three or four interferograms with mutual phase shifts introduced into the reference wave for instance. Although three interferograms with two phase shifts of $\pi/2$ between are required the processing of four interferograms with three phase shifts offer advantages in error reduction capabilities.

In holographic interferometry the phase shifts may be performed during real time reconstruction or by double exposure technique with the application of the two reference beam holographic techniques.[9,10]

The measured intensities of the interference patterns with a phase shift Δ can be written as

$$I(x,y) = a(x,y)+b(x,y)\cos[\phi(x,y)+\Delta]$$

where a(x,y) describes the background variation and b(x,y) is related to the local contrast of pattern. The phase $\phi(x,y)$ needs to be determined and Δ is the phase shift to be introduced. If one assumes a monotonically increasing phase distribution $\phi(x,y)$, the sampling theorem demands at least two pixels per fringe. Therefore, the phase difference between two adjacent pixels must be less than π.

In <u>heterodyne</u> interferometry the two light fields are assumed to be

$$A_1 = a_1\cos[\omega t+\phi_1(x,y)] \text{ and } A_2 = a_2\cos[\omega t+\Delta\omega t+\phi_2(x,y)+\phi(x,y,t)]$$

where $\Delta\omega$ is proportional to the frequency shift f_2-f_1 and $\phi(t)$ is the time varying phase shift leading to a frequency shift by interference of the two wave-fields namely

$$I(x,y) = a(x,y)+b(x,y)\cos[\Delta\omega t+\phi(x,y,t)+\Phi_2(x,y)-\phi_1(x,y)].$$

The frequency shift is

$$\Delta f = \frac{\phi(x,y,t)}{2\pi t} = \frac{2}{\lambda}\cdot\frac{dz}{dt}$$

where z is the displacement parallel to the line of sight.

For a harmonically oscillating object, $\phi(x,y,t) = \frac{4\pi}{\lambda}\rho\cos(\Omega t)$ producing a frequency modulated output signal at the detector with carrier frequency of $\frac{\Delta\omega}{2\pi}$ and amplitude and frequency of oscillation of ρ and Ω respectively. The signal can be evaluated by well known frequency analysis techniques.[7]

The resolution to be obtained with the phase shifting technique is of the order of $\frac{\lambda}{100}$ and with the heterodyne-technique $\frac{\lambda}{1000}$.

Phase locked techniques are capable of detecting phase differences in two beam arrangements of $\lambda/100$ and may be used for measuring surface topography.[8] The interferometer incorporates, as part of a zero system, a piezoelectrically driven mirror that is capable of applying a known optical phase offset and a periodic optical modulation. The ac signal is processed to generate an error signal for the servo system. A signal proportional to the phase difference between two beams occurs.

Some applications of interference and fringe analysis

Phase shifting techniques for fringe analysis are used for testing spherical surfaces[3,4] as well as for microstructure analysis for relatively flat surfaces (in a small area).[11] In addition, the technique can be used for fringe analysis in two reference holographic interferometry.[9,10]

Heterodyne interferometry is used for distance measurement as well as for microsurface analysis based on scanning the object point by point. The technique can also be applied for fringe analysis in holographic interferometry.[7]

For nondestructive material analysis, photoacoustic and photothermal methods can be applied. In photothermal interferometry the thermal expansion of the specimen is measured rather than the thermal wave itself.[13] Figure 1a. shows an experimental arrangement where a modulated Ar^+ laser heats the object under test leading to a heat wave that propagates through the material and deforms the surface a few nanometers. An interference arrangement detects the deformation using a phase locked technique, where the piezo shifts the phase appropriately. Figure 1a. shows the result of a subsurface defect (3 holes diameter 0.8 mm each) in the specimen for different modulation frequencies of the heating laser.

Komponent and system analysis from interference fringes

Twyman-Green and Fizeau interference arrangements are frequently used for testing flat and spherical surfaces. By testing aspheric surfaces using computer generated holograms (CGH) the asphericity as well as the adjustment errors or the test surface and the hologram need to be determined. Adjustment errors can be evaluated from the interferogram and compensated.

In an application for fringe interpretation, refractive index, lens separation and radius of curvature of components of an optical system can be determined by combining fringe analysis with ray tracing.

Figure 2. shows an example for the analysis of the parameters of a single lens: the four autocollimation points. The autocollimation points 2 and 3 are used when measuring the radius and surface quality and the refractive index respectively using 3 autocollimation points 3 and 4 together both, the refractive index and the thickness can be found. Figure 3. shows an experimental arrangement for testing spherical and aspherical surfaces. Figure 4a. shows a procedure to measure the refractive index. To study the focus dependence 3 different focus positions with different fringe patterns were analysed. Figure 4(b-d) show the interference fringes for the 3 focus positions. The corresponding wavefronts are shown in Figure 4e. and the residual wavefronts after fitting the data by iteration are shown in Figure 4d. A remaining adjustment error is not compensated. The refractive index was determined for each of the 3 interference patterns leading to Δn of $\pm 2 \cdot 10^{-4}$. Therefore focusing is not critical as long as it compensated by the fringe analysis. To measure the refractive index n of lens elements of an optical system using immersion liquid its temperature dependence needs to be considered for precision measurements.

In the same way optical systems can be analysed and manufacturing errors found. They can be partly compensated by changing the air separations of the lenses, for instance.

Surface parameter and excentricity analysis of aspheric surfaces

Computer generated holograms (CGH) are very useful for testing aspheric surfaces.[3] From the fringe analysis, shape errors as well as aspheric parameters or adjustment errors can be evaluated. Contactlenses, for instance, wil be selected and specified by the vertex curvature and the excentricity of the back surface. The determination of such parameters from the fringe pattern is obtained by a modification of the latter in an optimisation program in order to obtain agreement between the computed and measured wavefronts. For this purpose, the wavefront will be described by Zernike polynomials up to the order 10. Zernike polynomials[14] are chosen because of their orthogonal properties (Figure 6.). For special applications Zernike-Tatian (for central abstruction) or Tschebyscheff polynomials can be used. The coefficients are the goals envisaged for the parameter variation. At first vertex radius and excentricity are varied.

Figure 5a. shows a part of the test beam of the experimental arrangement shown in Figure 3. The interference fringes obtained for three different focus positions are shown in Figure 5b. The corresponding wavefronts for the three focus positions are shown in Figure 5c. Figure 5(d-f). show the wavefronts for the iteration steps to obtain the best fit for the excentricities and vertex curvature. The remaining residual aberrations are very small as shown by curve A in Figure 5f. for the best fit of excentricity and vertex curvature by best simulated adjustment.

Adjustment errors occuring by the test procedure modify the fringe pattern. It should be noticed that by testing aspheric surfaces with CGH, 7 degrees of freedom need to be considered. From the analysis of the fringe pattern the contributions of adjustment errors like centring errors can be calculated and subtracted from the wavefront. For an estimation of the microprofile, for instance, the shape error can be subtracted from the wavefront.[3]

Holographic interferometry for testing optical components

Holographic interferometry can be used for testing optical surfaces and components. A hologram of the master surface or system is stored. The reconstructed wavefront is compared with the test object in real time. The storage material can be a photothermoplastic material, or a photorefractive crystal or a thin film storage device. An automatic fringe analysis is very useful for many applications in holographic interferometry for the analysis of the shape of optical components. A modified Twyman Green or Mach Zehnder arrangement is very useful for such applications. In addition, contour line holography in real time could become a very powerful technique for future methods.[15]

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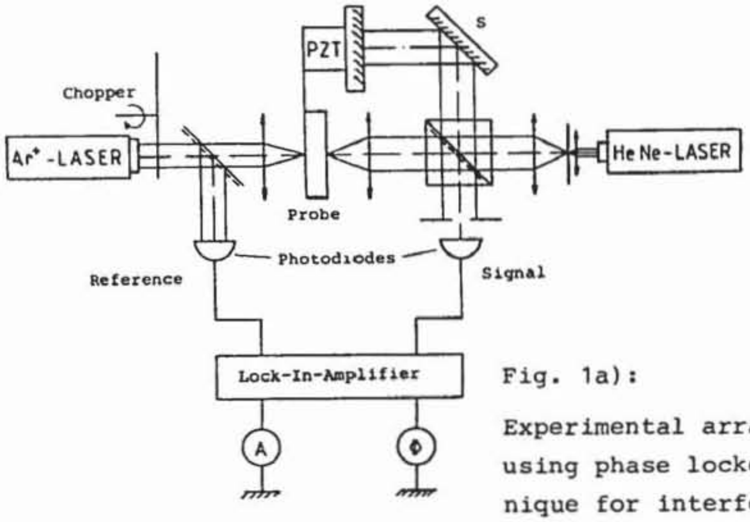


Fig. 1a):

Experimental arrangement using phase locked technique for interferometric detection of subsurface defects.

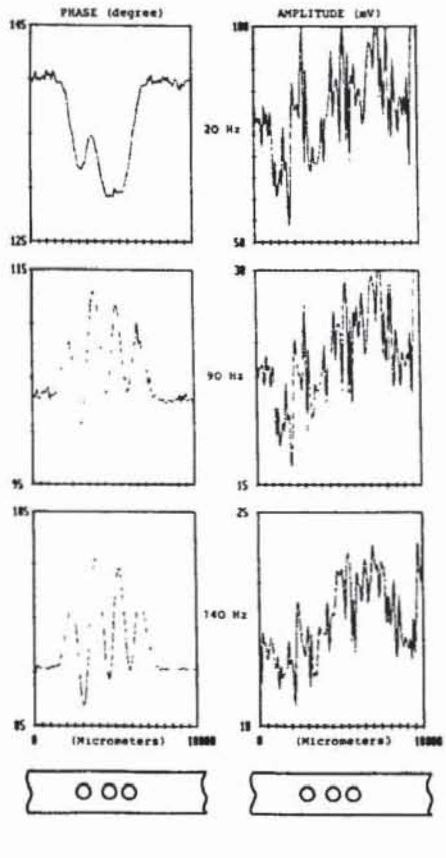


Fig. 1b):

Subsurface defects obtained from holes of 0.8 mm diameter in a 3 mm thick Al plate. The modulation frequencies were 20, 90, 140 Hz.

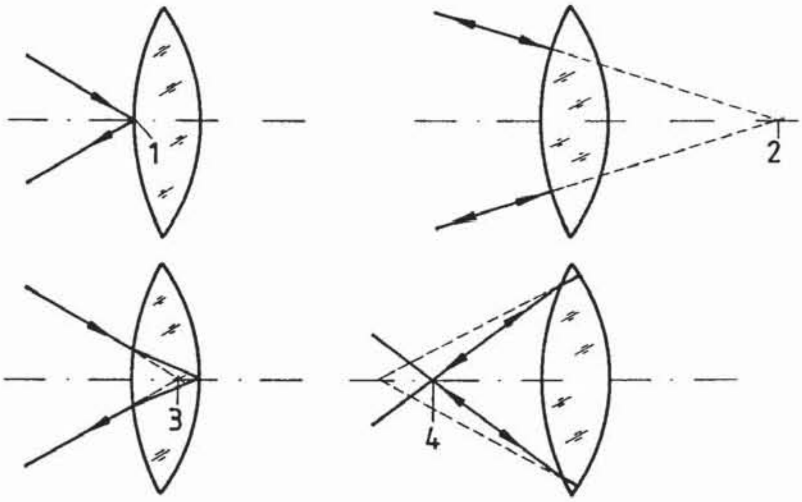


Fig. 2):

Autocollimation points of a single lens.

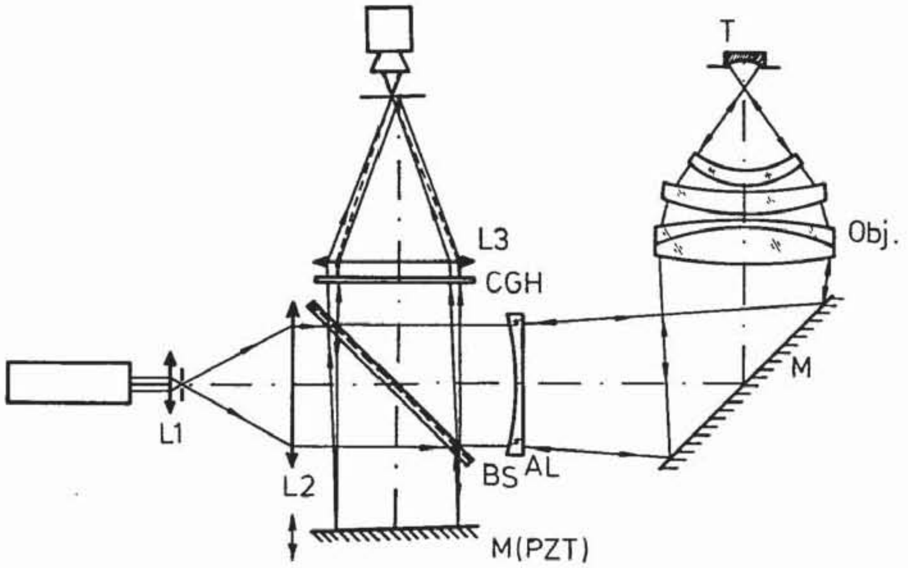


Fig. 3):

Experimental arrangement for testing spherical and aspherical surfaces.

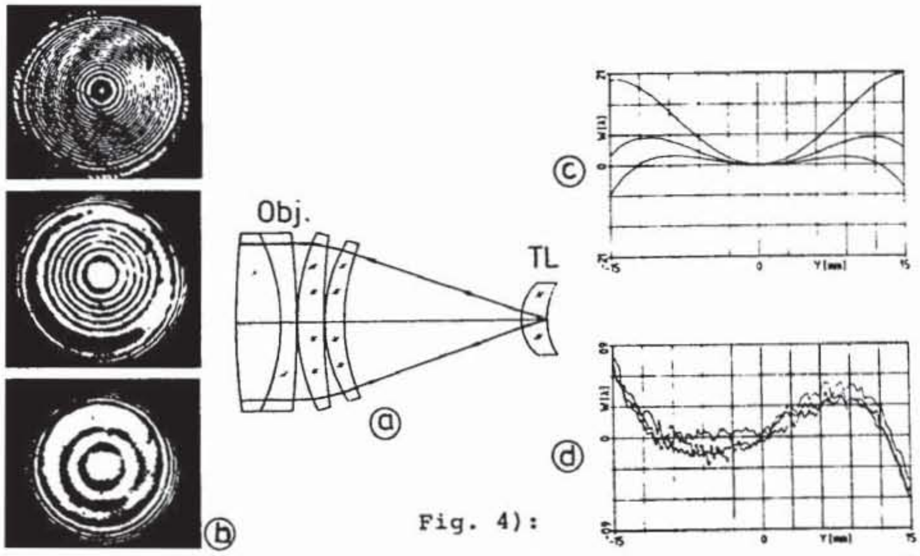
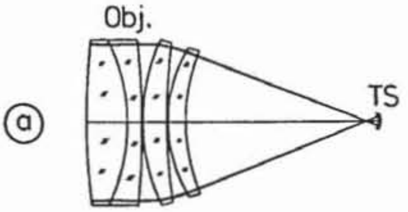


Fig. 4):

Refractive index measurement with the equipment of fig.3 and fringe analysis.

a) Autocollimation arrangement.
b) Interferograms for three defocusing positions.
c) Wavefront of the interferograms.
d) Residual wavefront after iteration.



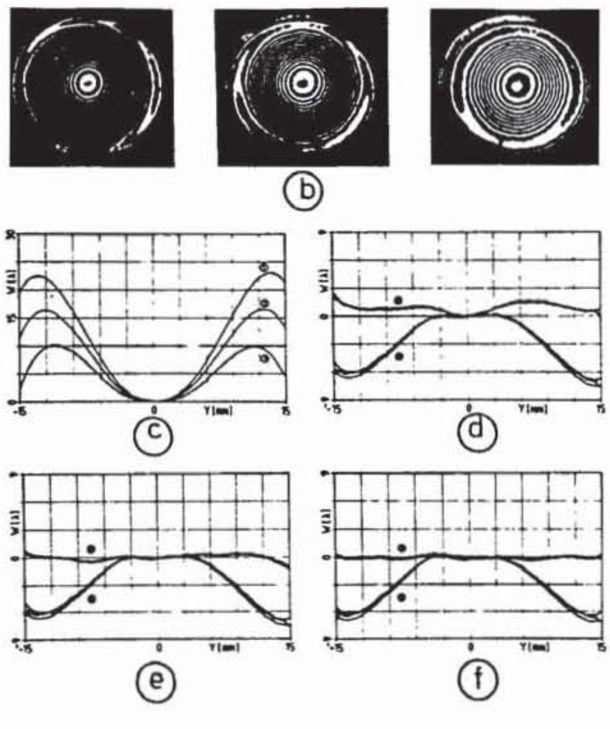


Fig. 5):

Arrangement for the evaluation of the surface parameter and excentricity of contact lenses.

a) Test beam of fig.3.
b) Interference patterns for different focusing positions.
c) Wavefronts of b).
d)-f) Iterations to obtain the surface parameters and excentricity.

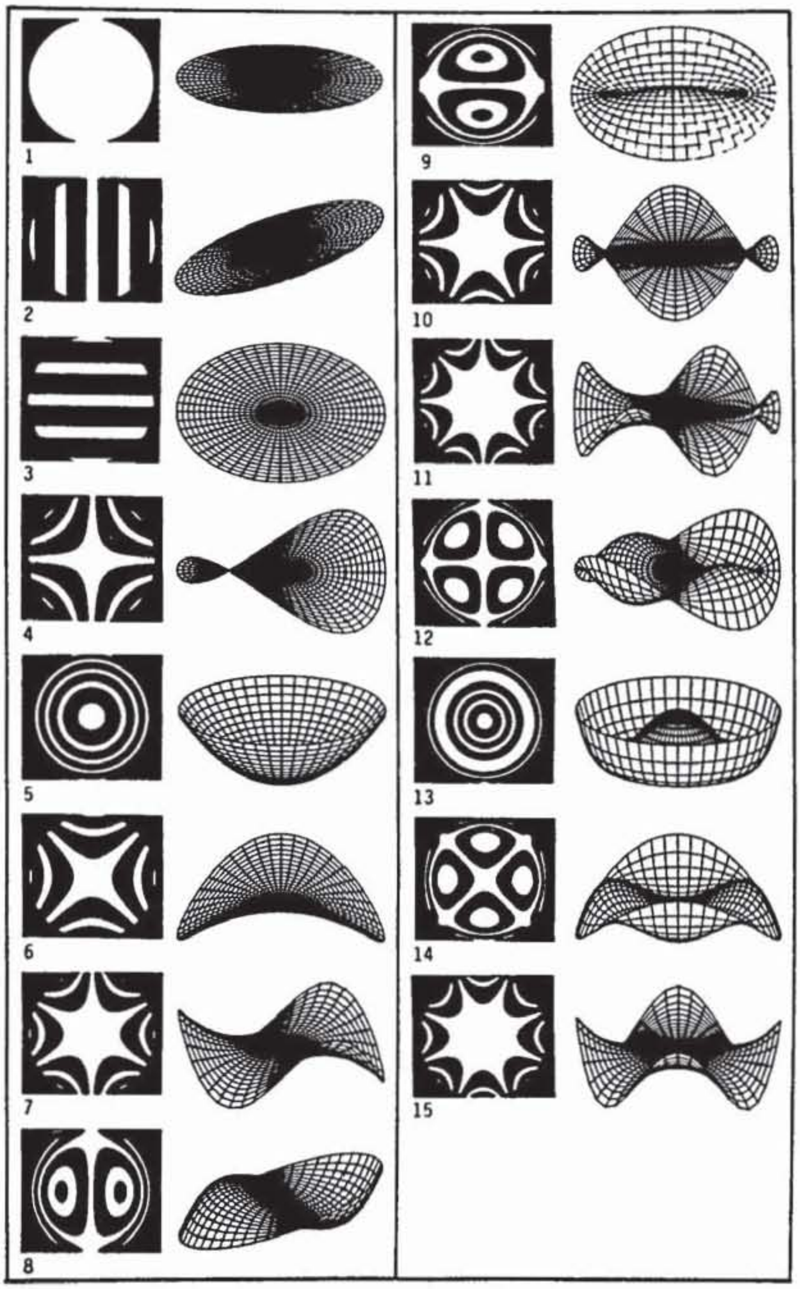


Fig. 6):

Zernike polynomials.