Prospects of testing aspheric surfaces with computer-generated holograms

Hans J. Tiziani
Institute of Applied Optics, University of Stuttgart
Pfaffenwaldring 9, D-7000 Stuttgart 80, Germany

Abstract

For testing aspheric surfaces, computer generated holograms are frequently used. Some methods of generating the holograms as well as a comparison of in-line and off-axis computer generated holograms will be discussed. Furthermore, examples tested will be analysed from the stand point of an industrial testing procedure.

1. Introduction

The application of aspheric surfaces is increasing especially in infrared optical systems. Aspheric surfaces could be used more frequently when time and price for its generation and testing would be comparable with that of spherical surfaces. Manufacturing and testing procedures have been improved lately and further work is on the way.

The present paper is concerned with testing aspheric surfaces; there are different methods:

1. Testing the performance of the complete optical system.
2. Using a null corrector in the test arm of a two beam interferometer in order to compensate the aspherical wavefront deviation of the aspherical surface under test.
3. Using a computer generated hologram in a two beam interferometer either to transform the aspheric wavefront of the test surface to a stigmatic one or to generate an "ideal" aspheric wavefront for comparison in the reference beam.
4. A point by point analysis, normally with a mechanical taster; this possibility is not a subject of the present paper.

Computer generated holograms are applicable advantageously for a widespread range of test surfaces. A number of papers on testing aspheric surfaces by means of computer generated holograms (CGH) have been written, only a few will be mentioned.[2-9] From a practical point of view a two beam interferometric arrangement in which both beams pass through the CGH is desirable. Corresponding rays in the reference and the beam under test pass nearly through the same region, hence, some of the inhomogenity of the device storing the CGH (usual high quality photographic plates) is nearly compensated. For testing aspheric surfaces with CGH, different holographic configuration can be used. For symmetrical optical systems to be tested, in-line (Gabor-type) and off-axis CGH can be applied; their differences and applications will be discussed. Methods for generating CGH will be discussed as well as some experimental results.

2. Methods for writing computer generated holograms

Different methods for generating CGH have been devised, new methods are in the process of being developed. The principal to be adopted depends on the objective as well as on the shape of the aspheric surfaces and the test arrangement to be used. For plotting CGH, a large computer with a CalComp plotter is often used. In some recent works other possibilities were considered. Some of the techniques will be discussed briefly. A very fast method was introduced in our work in Zürich[2] where a Lohmann type hologram was generated in a few minutes by using a cathode ray-tube. Fig. 1 shows the principle of the Lohmann type hologram.

The principle of the hologram recording is shown in fig. 2. The position accuracy of the beam of the cathode ray-tube, although specially stabilized, is not adequate for high quality CGH. Therefore, an amplitude-grating G is placed close to the emulsion. The grating period corresponds to a cell width of the Lohmann type hologram[1]. The holograms were written by projecting light dots larger than the slit width but smaller than the grating period from the fast cathode-ray tube. In this way, the accurate positioning of the dots depends on the mechanical positioning of the grating having a slit width smaller than half the grating period. For the next phase step, the photographic plate was translated by a step and repeat motor. All the dots for one particular phase step were recorded before displacing the photographic plate to the next phase position. 126 by 126 cells were chosen and 25 phase steps for each hologram. The photographic plate was positioned by a step and repeat motor driven by means of a computer tape. The writing time for one hologram turned out to be less than 15 minutes. With the arrangement chosen, the position accuracy was given by the mechanical positioning of the grating and the speed of writing of the CGH by the cathode ray-tube. Fig. 3 shows a typical result where the spherical aberration of a single lens was compen-

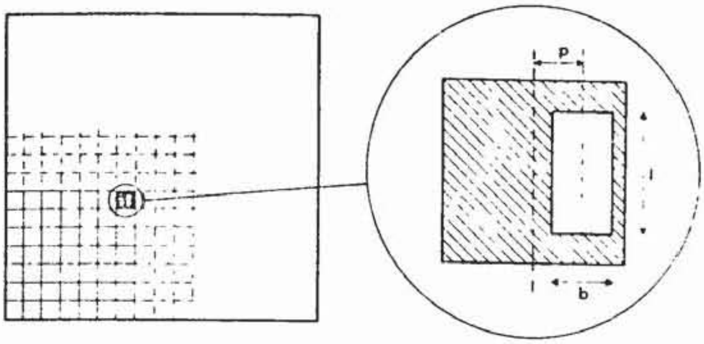


Fig. 1 Principle of a Lohmann type hologram

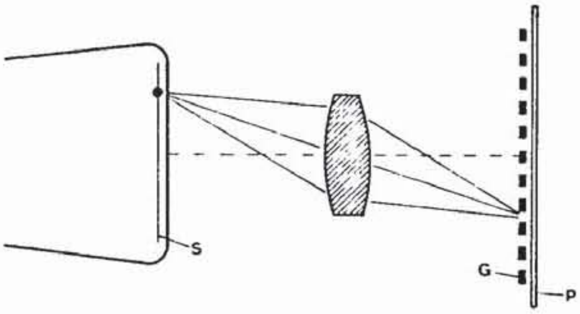


Fig. 2 Principle of writing a Lohmann type hologram with the beam of a cathode-ray tube

Fig. 3 Example of a complete compensation of spherical aberrations of a single plane-convex lens

sated completely. The limitation of the method occured for large wavefront deviations. For very large wavefront variations, another techniques was adopted at the Institute of Applied Optics in Stuttgart. For generating the CGH, the Optronics drum plotter P-1700 was used. The P-1700 is controlled by a PDP 11/34 computer, where the computations for the wavefront is carried out. The spatial resolution obtained in this way is 20000 x 20000 pixels. The following examples shown in the report were plotted with the Optronics plotter. The reduction ratio for the holograms copied on high contrast photographic plates was 1:6.

For writing in-line holograms, to be discussed for testing symmetrical optical systems, an alternative technique could also be considered. Concentric fringes can be drawn with a light pencil on photographic material, mounted on an accurately rotating turn-table. The positioning of the writing-arm can be interferometrically controlled[8].

3. A comparison of in-line and off-axis holograms

For testing aspheric surfaces off-axis CGH were mostly used[2-6]. In-line holograms were used by the authors in references[7-9]. Mercier and Lowenthal[9] studied the filtering properties of in-line holograms used for testing aspheric surfaces carefully. The use of rotational symmetric holograms (RSH) for testing rotational symmetric optical surfaces and systems can be bery useful:

1) for symmetric optical systems the centring of the RSH is simpler and the RSH can be centred with respect to the optical axis of the whole system and is not sensitive to rotation;
2) it allows the compensation of stronger aspheric contributions!
3) the computation and manufacturing of the RSH holograms could be simpler if compensation for distortion and centring error, for instance, are not necessary.

Testing with RSH will be shown schematically in fig. 4. The filtering of the spurious diffraction orders and optimizing the system is more difficult as will be discussed.

Filtering procedure by RSH

Among all the diffraction orders that appear after the hologram, two are stigmatic, namely

- the reference wave is theoretically perfect, when crossing the hologram in the zero order (Σ_0 in fig. 5a),
- the aspherical wavefront to be tested is transformed, idealy, in a plane wave by crossing the hologram (Σp_1 in fig. 5b).

The point image in the focal plane of the lens L_3 (fig. 4) is the diffraction pattern of the plane wave with it's diameter limited by the hologram. It is referred to as the diffraction limited spread function.

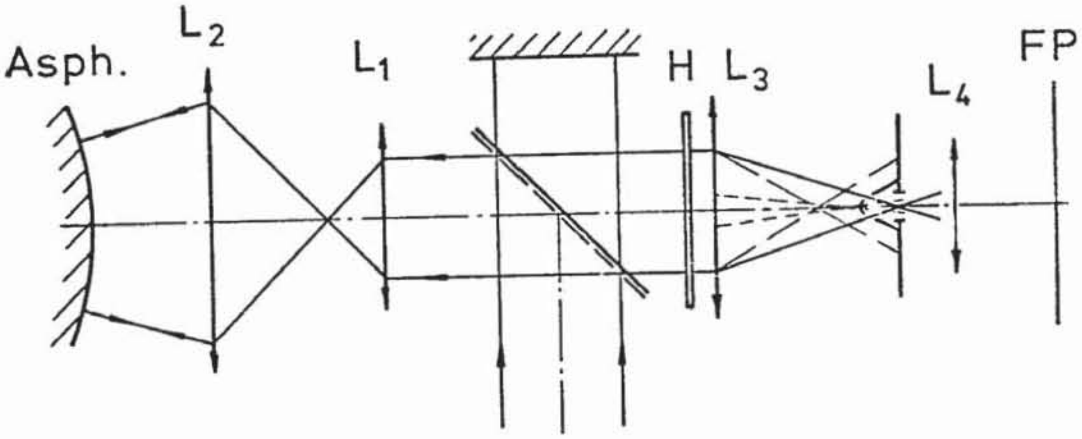
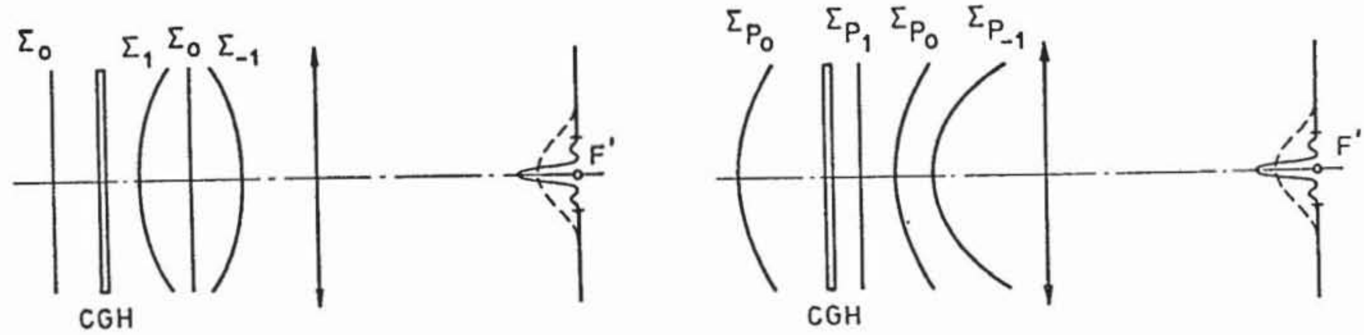


Fig. 4 Holographic one-line arrangement for testing aspheric surfaces



a)

b)

Fig. 5 Masking wavefronts from different diffraction orders
a) reference wave passing through the CGH
b) wavefront from the aspheric surface passing through the CGH

In fig. 5 the wavefronts and diffraction patterns in the filter-plane are drawn for an ideal system where the aspheric surface is perfect and the optical elements such as the hologram plate and gelatine do not introduce disturbances. If no stop or filter is placed in the filter-plane, different wavefronts diffracted will contribute to the interference pattern to be obtained. The filter is, however, essential to avoid spurious light. Furthermore, the filter should be such that disturbances such as deviations from the perfect wavefront of the aspheric surface to be tested are accepted as well as some high frequency variations introduced by the holographic plate or gelatine. The filter is therefore a compromise, it's maximum diameter is found to be

$$2|\Delta\rho'| = \frac{\partial W(r)}{\partial r} f' ,$$

where $\frac{\partial W(r)}{\partial r}$ is the variation (slope) of the expected maximum wavefront-error to be measured and f' = focal length of L_3. The equation of the wavefront for symmetrical systems used was

$$W(r) = W_{00} + W_{20} r^2 + W_{40} r^4 + W_{60} r^6 + W_{80} r^8 + W_{10} r^{10}$$

Where:

W_{20} = coefficient for defocussing

$W_{40}, W_{60}, W_{80}, W_{10}$ = coefficients for spherical aberration.

In fig. 5 it is shown schematically that Σ_0 of the reference wave, fig. 5a), and Σp_{+1} of the wavefront under test, fig. 5b), should contribute to the interferogram only. Of course,

Σp_{+1} is usually not perfect, the deviation from the perfect wavefront is to be measured. Furthermore, it is found appropriate to introduce a focussing error into the system to be tested; the latter will be compensated by the hologram. The central part of the lens under test can, however, not be tested in this way. Therefore, 2 to 10 per cent of the aspheric surface is not tested, a disadvantage not always to be accepted. The center part can, however, directly be viewed near the hologram (moiré techniques) where no special requirements on the shape of the wavefront is to be imposed, because filtering of unwanted diffraction orders is avoided. For convenience, however, the hologram should be drawn with some grey-levels, because wide hard-clipped hologram lines - for instance in the centerpart of the hologram - have the same spatial frequency range as the moiré fringes, but with higher contrast. The filter, a hole, stops most of the spurious light but can limit the resolution.

Off-axis holograms are chosen especially when small wavefront compensation is required, only, or by complicated wavefronts where the sign of the slope changes. The filtering for off-axis holograms is very much simpler. The carrier frequency of the hologram can be chosen to have no overlap between the zero, first and second diffraction orders. Fig. 6 shows an arrangement for off-axis holographic testing of aspherical surfaces.

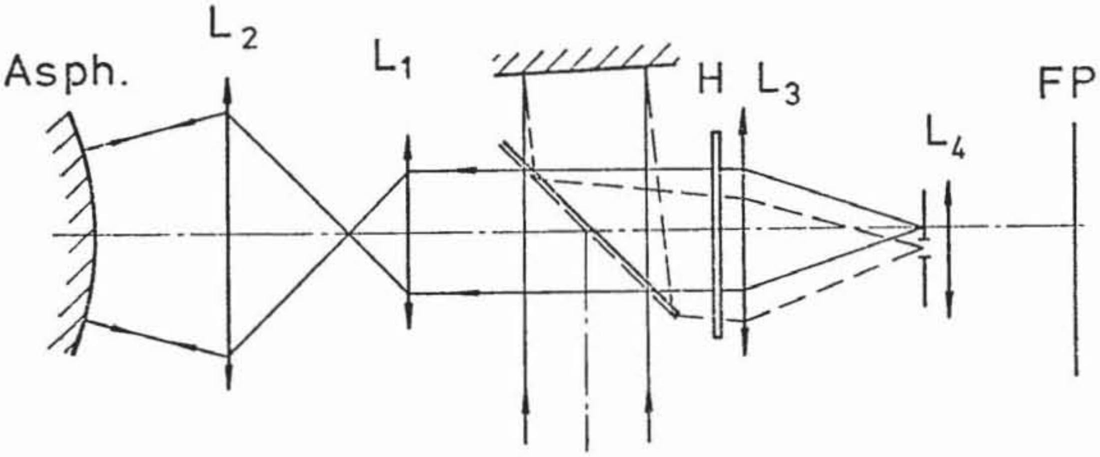


Fig. 6 Principle of off-axis holographic testing of aspherical surfaces

In fig. 7 results of in-line and off-axis holography for a high aperture, single plane-convex lens are shown using basically the same experimental arrangement and two focussing positions. It shows a zonal error of the lens under test in addition, the central portion not to be tested is clearly seen by the in-line hologram; the diameter of the filtering hole was 0.5 mm by a focal length of the focussing lens of f'_3 = 500 mm and a hologram diameter of 32 mm. The Gaussian image of the wavefront under test was 124.5 mm before, respectively 248 mm behind the filter plane, hence, 4.7% of the diameter of the test surface can not be tested. No doubt, the main advantage of in-line holograms is the centring facilities; no centring in the azimuth is required.

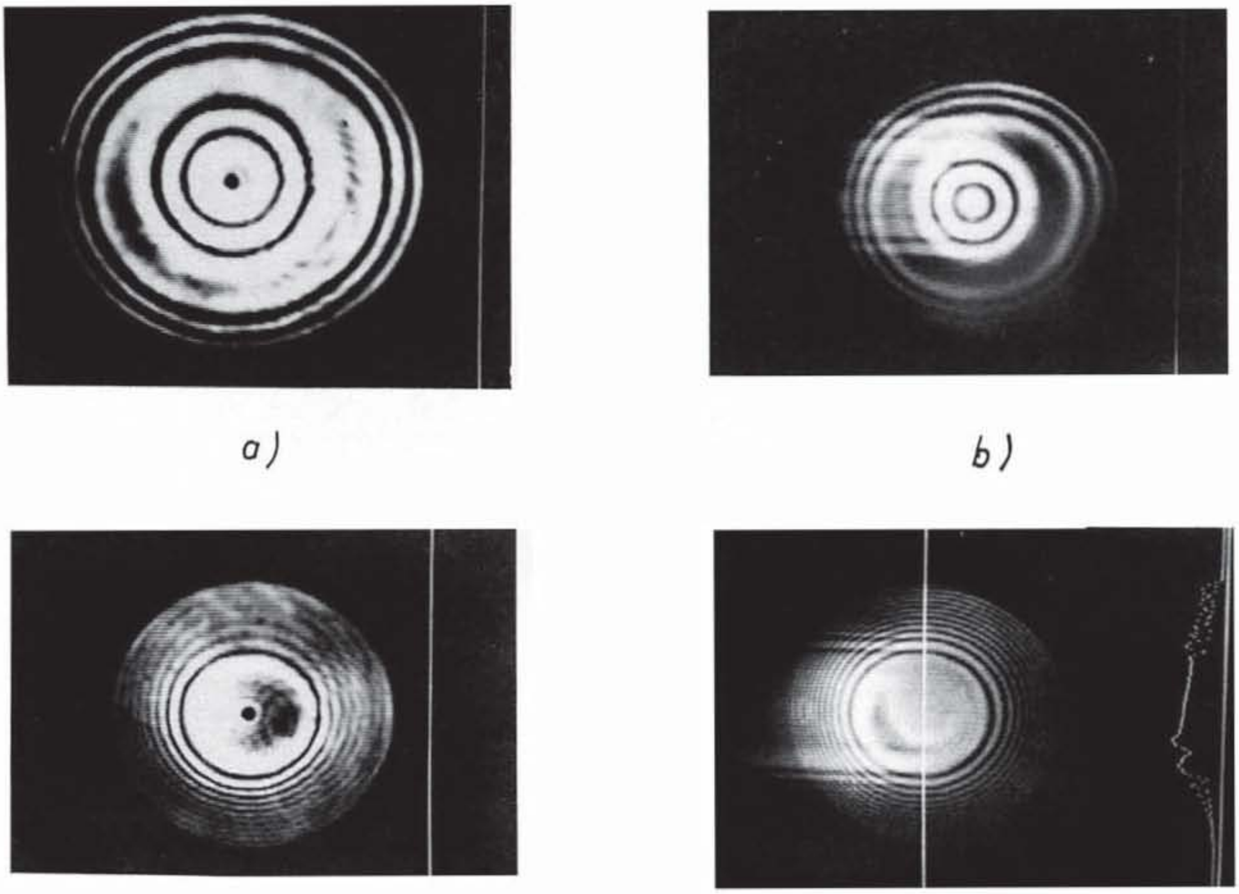

a) b) c) d)

Fig. 7 Comparison of the results obtained from a high aperture single plano-convex lens under test in transmission using a
- a) in-line hologram
- b) off-axis hologram
- c) in-line hologram with defocussing
- d) off-axis hologram with defocussing

4. Computation of the wavefront and design of the refractive corrector

The wavefront at the hologram is obtained by computing the optical path difference along a number of rays. The ray-aberrations obtained along the rays are inverted at the exit pupil of the whole system. For the ray tracing,a plane wave is usually considered to be incident on the first lens (L_1 in fig. 1).

The auxiliary lens system (L_1, L_2 in fig. 4 and 6) is arranged to optimize the aberration of the whole system including the aspheric surface to be tested. Furthermore, it illuminates the whole aperture of the lens under test. It is, however, not always easy to form the image of the aspheric surface to be tested onto the hologram, but L_4 is imaging the surface under test onto the fringe plane. To have the hologram plane conjugate to the aspheric surface would very often require additional lens elements especially by testing convex surfaces which is not desirable. The equation for the aspheric surface was chosen in the form

$$W(r_1) = \frac{c}{1+\sqrt{(1-\varepsilon c^2 r_1^2)}} + W_{20}\, r_1^2 + W_{40}\, r_1^4 + W_{60}\, r_1^6 + W_{80}\, r_1^8 + \ldots$$

where

$\varepsilon = 1-e^2$, e = excentricity
$\varepsilon = 0$ for paraboloid
$\varepsilon = 1$ for sphere
$\varepsilon < 1$ for ellipsoid
$\varepsilon > 1$ for hyperboloid
c = base curvature of conics

$r_1 = \sqrt{(x_1^2 + y_1^2)}$

x_1, y_1 = rectangular coordinates on the aspheric surface

W_{20}, W_{40}, W_{60}, W_{80} are the aspheric figuring terms. A parabola, for instance, can be represented either by an W_{20} term, or by a curvature with $\varepsilon = 0$. In the latter representation, the ray is traced more quickly. To obtain the highest accuracy from the plotter the plotted size of the hologram was kept roughly the same. In addition, the reduction ratio was also kept constant ($M = -1/6$) to obtain very small and constant distortion to be compensated during the computation of the hologram. For the adaptation of different test lenses to the test equipment, auxiliary lenses or lens systems are required. They are designed to illuminate the test lens appropriately and to compensate some of the aberrations but they are not used as null correctors designed to circumvent testing with holograms. For practical reasons, the beam diameter of the reference beam and the beam illuminating the auxiliary lens was kept small.

A null corrector is a lens designed to have spherical aberration such that the emerging wavefront at some position along its optical axis will match the aspherical surface to be tested. In the arrangement to be discussed the compensating lens system will reduce the spherical aberration and is designed to illuminate the aperture of the lens under test. Some corrector lens systems are shown in fig. 8 for convex and concave aspheric surfaces[10].

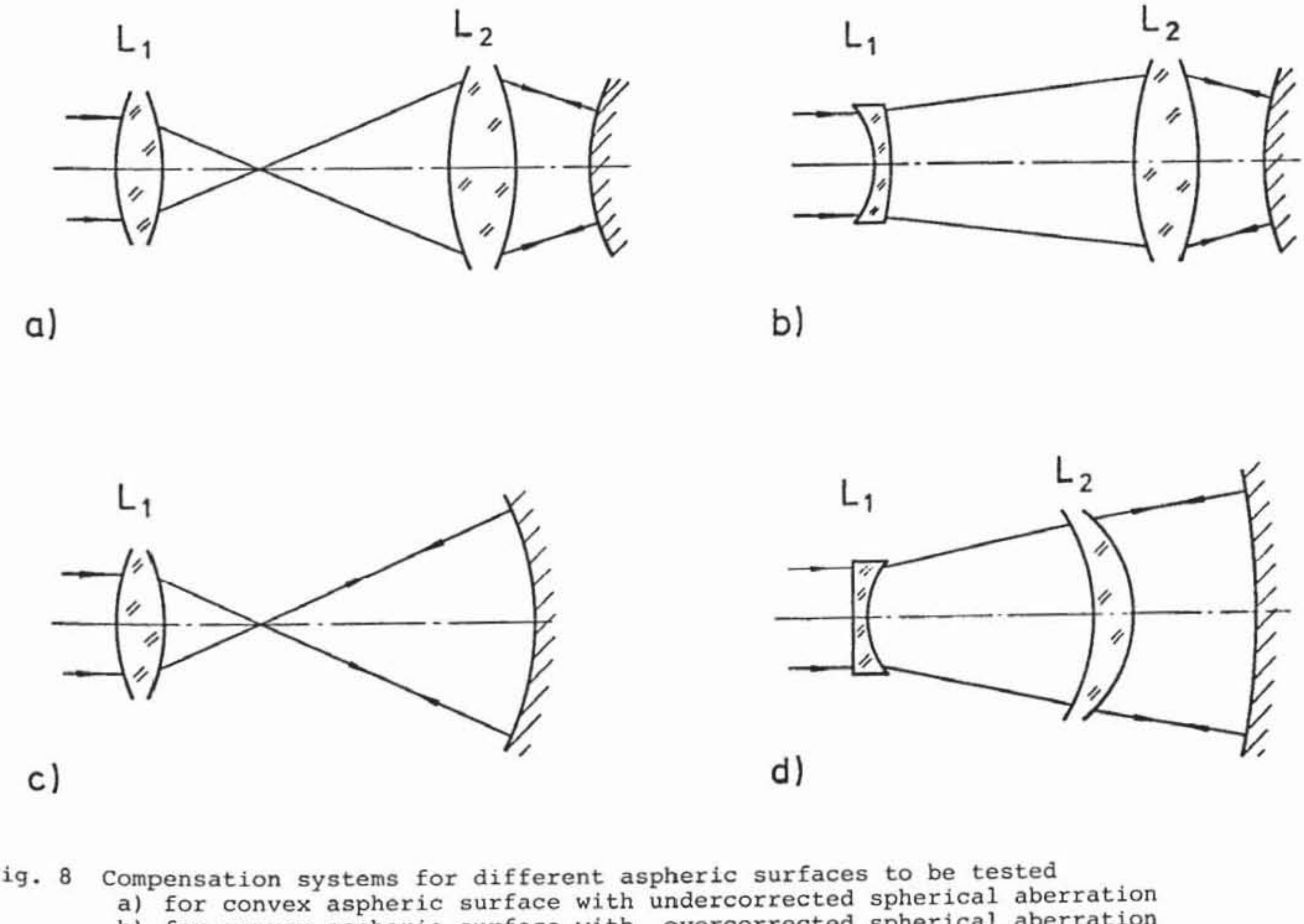


Fig. 8 Compensation systems for different aspheric surfaces to be tested
- a) for convex aspheric surface with undercorrected spherical aberration
- b) for convex aspheric surface with overcorrected spherical aberration
- c) for concave aspheric surface with undercorrected spherical aberration
- d) for concave aspheric surface with overcorrected spherical aberration

Designing the compensating system is not difficult. Fabrication of a null corrector, however, becomes an iterative process between the designer and shop personnel to insure proper performance. The refractive index of the specific glass melt needs to be measured. After the optics fabrication, the lens data are measured and substituted instead of the

original values (radii, thickness), the air spaces are adjusted for compensation. Therefore, fabrication of the corrector takes time and is expensive. We designed the compensating systems using existing lenses with refractive,index thickness and radii known approximately from lens data. The correctors were designed with the lens data available (obtained from manufactures). Since the lens data are not known to the required accuracy a CGH hologram together with an appropriate spherical mirror was designed in order to compensate different disturbances introduced by the auxiliary lens system as well as by other sources.
Some of the errors to be compensated result from
1) departure from the lens data and separation used for the computation,
2) centring of the components,
3) magnification error and distortion by photo-reduction,
4) error in generating the hologram.

The convex aspheric surface is usually positioned close to the last lens of the corrector. A result of a specimen tested off-axis in reflexion is shown in fig. 9.

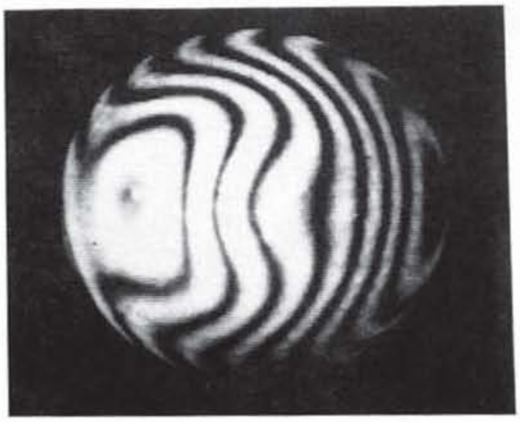


Fig. 9 A typical result of a test-object in reflexion with an off-axis CGH.

5. Some remarks on testing aspheric surfaces under industrial environments

For industrial testing of aspherical surfaces. Centring of the hologram and the test surface as well as focussing need to be easy. Usually, aspheric surfaces will be tested in reflection to be sure that deviations of the aspheric surface are measured only. Automatic fringe analysis is another aspect to be looked at for industrial testing of aspheric surface. The decision whether in-line ore off-axis holography is appropriate for the testing procedure depends on the aspheric surface and compensation system. In our arrangement both methods can be used with minor modification of the test equipment.

I would like to thank my co-workers M. Küchel and W. Krause for supplying some of the experimental results and the BMFT No. NT 2008 for the financial support.

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