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Optics and optical instruments — Preparation of drawings for optical elements and systems —

Part 14: Wavefront deformation tolerance

Optique et instruments d'optique — Indication sur les dessins pour éléments et systèmes optiques —

Partie 14: Tolérance de déformation des fronts d'onde

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Foreword

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The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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ISO 10110-14 was prepared by Technical Committee ISO/TC 172, *Optics and optical instruments*, Subcommittee SC 1, *Fundamental standards*.

ISO 10110 consists of the following parts, under the general title *Optics and optical instruments — Preparation of drawings for optical elements and systems*:

— *Part 1: General*

— *Part 2: Material imperfections — Stress birefringence*

— *Part 3: Material imperfections — Bubbles and inclusions*

— *Part 4: Material imperfections — Inhomogeneity and striae*

— *Part 5: Surface form tolerances*

— *Part 6: Centring tolerances*

— *Part 7: Surface imperfection tolerances*

— *Part 8: Surface texture*

— *Part 9: Surface treatment and coating*

— *Part 10: Table representing data of optical elements and cemented assemblies*

— *Part 11: Non-toleranced data*

— *Part 12: Aspheric surfaces*

— *Part 14: Wavefront deformation tolerance*

— *Part 16: Aspheric diffractive surfaces*

— *Part 17: Laser irradiation damage threshold*

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Introduction

This part of ISO 10110 makes it possible to specify a functional tolerance for the performance (expressed in wavelengths of single-pass wavefront deformation) for an optical system. This tolerance therefore includes the effect of surface deformations, inhomogeneities, and possible interactions among the various individual errors.

The quality of an optical system depends not only on the quality of the surfaces, but also on several other factors, such as the homogeneity of the optical material and how the optical surfaces of the system interact with each other. Because of this effect, the selection of tolerances for individual degradations (such as surfaces and inhomogeneity) may be difficult. For instance, the effect of glass inhomogeneities upon the optical quality of a prism depends greatly upon the form and orientation of the inhomogeneities; this is particularly true when light passes through the glass in more than one direction, as in the case of a pentaprism. In the case of a thin optical element, it often happens that the deformations of the rear surface correspond closely to those of the front surface, due to bending of the system during fabrication. Unfortunately, it is usually not known in advance that this will be the case, and for this reason, in the absence of a wavefront deformation tolerance, the tolerances for the individual surfaces of a system must often be very tight to guard against the possibility that the deformations might add to each other rather than cancel one another.

It should be noted that it is possible to specify a tolerance on the wavefront deformation only, without specifying tolerances on the individual surfaces. In this case, the manufacturer must ensure that the wavefront satisfies the specified tolerance, but is not bound by tolerances on the individual surfaces of the element, and is free, for instance, to allow the surface deformations to be large provided they cancel each other.

It is also possible to supply a tolerance for the wavefront deformation, according to this part of ISO 10110, in addition to tolerances on the individual surfaces and/or inhomogeneity (according to ISO 10110-5 and ISO 10110-4, respectively). In this case, the manufacturer must ensure that all of the individual tolerances (surface deformations and inhomogeneity) are upheld, as well as ensuring that the wavefront is of the specified quality.

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Optics and optical instruments — Preparation of drawings for optical elements and systems —

Part 14: Wavefront deformation tolerance

1 Scope

International Standard ISO 10110 applies to the presentation of design and functional requirements for optical elements and assemblies in technical drawings used for manufacturing and inspection.

This part of ISO 10110 provides rules for the indication of the allowable deformation of a wavefront transmitted through or, in the case of reflective optics, reflected from an optical element or assembly.

The deformation of the wavefront refers to its departure from the desired shape ("Nominal theoretical wavefront"). The tilt of the wavefront with respect to a given reference surface is excluded from the scope of this part of ISO 10110.

There is no requirement that a tolerance for wavefront deformation be indicated. If such a tolerance is specified, it does not take precedence over a tolerance for the surface deformation according to ISO 10110-5. If tolerances for both the surface deformation and the wavefront deformation are given, they must both be upheld.

NOTE In this part of ISO 10110, the term "wavefront" used alone stands for either "transmitted wavefront" or "reflected wavefront", according to the type of system to be specified.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 7944:1998, *Optics and optical instruments — Reference wavelengths*

ISO 10110-1:1996, *Optics and optical instruments — Preparation of drawings for optical elements and systems — Part 1: General*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1
wavefront deformation
distance between a wavefront transmitted and/or reflected once through, or in the case of reflective optics, reflected once from, the optical element or assembly under test and the nominal theoretical wavefront, measured normal to the nominal theoretical wavefront

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NOTE 1 See also 3.13.

NOTE 2 The illuminating wavefront may be specified to be planar, convergent or divergent. See 7.5 and 7.6.

3.2
peak-to-valley difference between two wavefronts
PV difference between two wavefronts
maximum distance minus the minimum distance between the wavefronts

NOTE It is possible that the wavefronts cross, in which case the minimum distance between the wavefronts is a negative number; the sign must be taken into account in computing the PV difference.

3.3
total wavefront deformation function
theoretical surface defined by the difference between the wavefront transmitted and/or reflected once through the optical system under test and the nominal theoretical wavefront, measured normal to the nominal theoretical wavefront

See Figure 1a).

3.4
approximating spherical wavefront
theoretical spherical wavefront tangent to the exit pupil of the system under test for which the root-mean-square difference to the wavefront transmitted and/or reflected once through the optical system under test is a minimum

See Figure 1b).

NOTE 1 For the purpose of this definition, "spherical wavefronts" include the "planar wavefront". (The planar wavefront is considered to be a particular case of the spherical wavefront.)

NOTE 2 See Clause 5 in the case of non-circular test areas.

3.5
wavefront sagitta error
peak-to-valley difference between the approximating spherical wavefront and the reference sphere

NOTE 1 The wavefront sagitta error represents the extent to which the radius of curvature of the approximating wavefront departs from that of the nominal theoretical wavefront.

NOTE 2 If no restrictions are specified on the location of the image of the optical system under test, the reference sphere is identical to the approximating spherical wavefront, and the wavefront sagitta error is defined to be zero.

3.6
wavefront irregularity function
theoretical surface defined by the difference between the total wavefront deformation function and the approximating spherical wavefront

See Figure 1c).

3.7
wavefront irregularity
peak-to-valley difference between the wavefront irregularity function and the plane which best approximates it

NOTE The wavefront irregularity represents the departure of the wavefront from sphericity.

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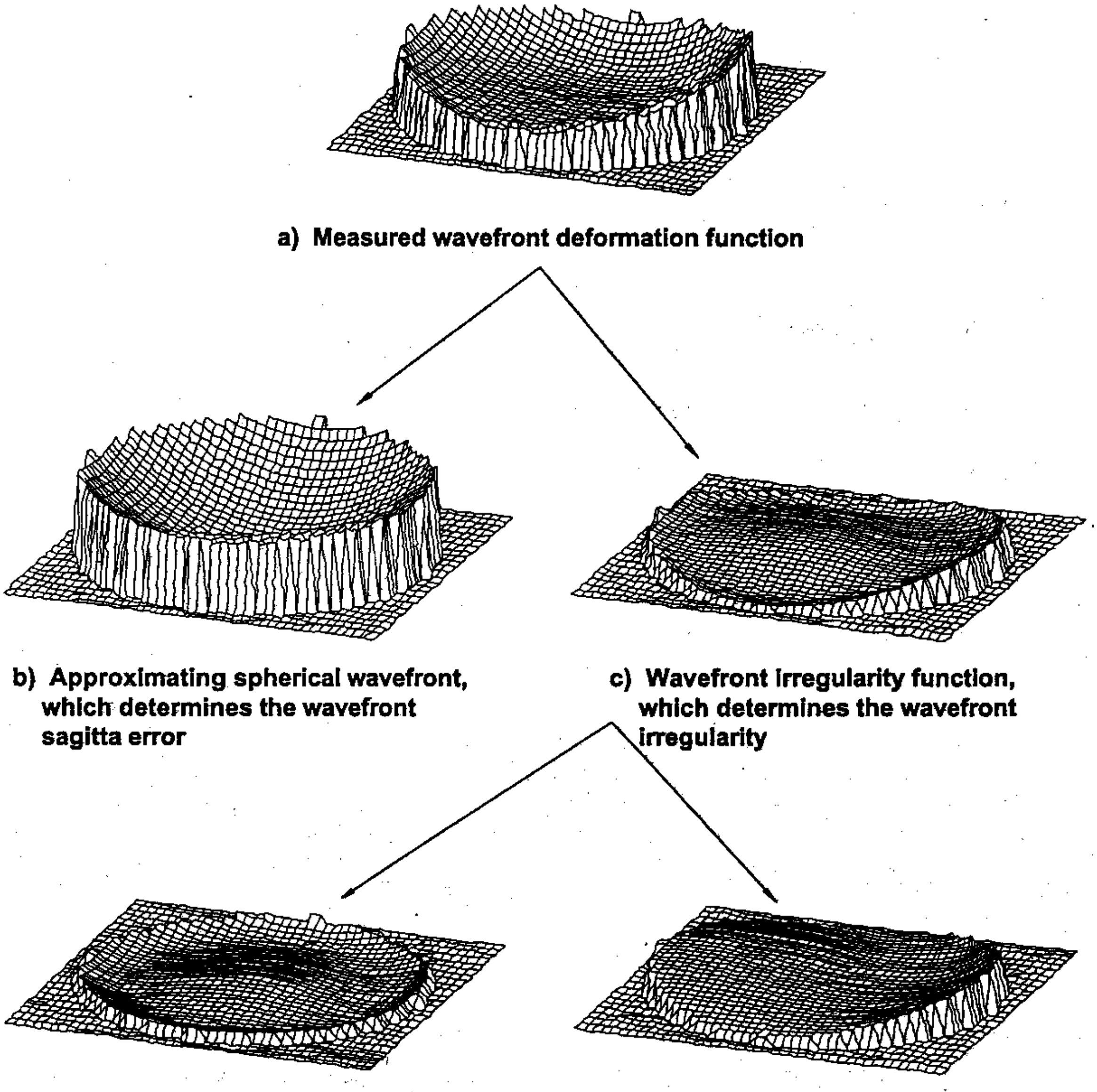
3.8
approximating aspheric wavefront
rotationally symmetric aspheric wavefront for which the root-mean-square difference to the wavefront irregularity function is a minimum

See Figure 1d).

NOTE See Clause 5 in the case of non-circular test areas.



a) Measured wavefront deformation function

b) Approximating spherical wavefront, which determines the wavefront sagitta error

c) Wavefront irregularity function, which determines the wavefront irregularity

d) The (rotationally symmetric) approximating aspheric wavefront, which determines the rotationally symmetric wavefront irregularity

e) The wavefront remaining after removal of b) and d), which determines the root-mean-square (rms) wavefront asymmetry

Figure 1 — Example of a measured wavefront and its decomposition into wavefront deformation types

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3.9
rotationally symmetric wavefront irregularity
peak-to-valley difference between the approximating aspheric wavefront and the plane which best approximates it

NOTE The rotationally symmetric wavefront irregularity is the rotationally symmetric irregularity of the wavefront irregularity function. Its value cannot exceed that of the wavefront irregularity function.

3.10
total rms wavefront deformation
RMSt
root-mean-square difference between the wavefront transmitted once through, and/or reflected once from, the optical system under test and the nominal theoretical wavefront, which includes any specified target aberrations

3.11
rms wavefront irregularity
RMSi
root-mean-square value of the wavefront irregularity function defined in 3.6

3.12
rms wavefront asymmetry
RMSa
root-mean-square value of the difference between the wavefront irregularity function and the approximating aspheric wavefront

See Figure 1e).

3.13
single-pass
testing arrangement in which the light beam passes once through, or in the case of reflective optics, is reflected once by, the element under test

NOTE 1 For corner-cubes, roof prisms, "cat's eyes", and other types of retroreflectors, a single retroreflection from the element constitutes a "single-pass" configuration, even though the light actually passes through much of the element twice.

NOTE 2 Although the wavefront deformation as defined in 3.1 refers to a "single-pass" measurement, many types of optical systems are commonly tested in a "double-pass" configuration, in which the light passes through or reflects from the element twice. In many cases, when an element is tested in a double-pass configuration, the observed deformation of the wavefront is approximately twice the wavefront deformation as defined in 3.1. Regardless of how the system is actually to be tested or used, the tolerance for wavefront deformation always refers to the "wavefront deformation" as defined in 3.1, that is, as if used in a single-pass configuration.

NOTE 3 When an element of poor optical quality is tested in a double-pass configuration, it is possible that the rays of the test beam are disturbed sufficiently (for example, made divergent or convergent) so that they do not pass through the same positions of the test element on the second transmission. In this case, the wavefront deformation is not equal to one-half the observed deformation, and a precise determination of the (single-pass) wavefront deformation is difficult.

NOTE 4 In some cases, the double-pass wavefront deformation is not even approximately equal to twice the single-pass wavefront deformation. For instance, an optical system containing a wedged prism will convert a test beam of circular cross-section into one having an elliptical cross-section. When converting between single-pass and double-pass results, it is necessary to take such effects into account.

3.14
target aberrations
aspheric deformations of the wavefront which have been specified for inclusion in the nominal theoretical wavefront

3.15
nominal theoretical wavefront
theoretical wavefront equal to the reference sphere plus any target aberrations which may be specified

NOTE This is the "Desired shape" of the wavefront mentioned in Clause 1.

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3.16
reference sphere
the theoretical spherical wavefront tangent to the exit pupil of the system under test, for which the root-mean-square difference to the wavefront transmitted once through and/or reflected once from the optical system under test is a minimum, and consistent with any restrictions which may be specified for the location of the image of the system

NOTE 1 See Clause 5 in the case of non-circular test areas.

NOTE 2 If no restrictions are specified on the image position, the reference sphere is identical to the approximating spherical surface.

4 Tolerances for wavefront deformation

The tolerances for wavefront deformation are indicated by specifying the maximum permissible values of the wavefront sagitta error (3.5), wavefront irregularity (3.7), and/or rotationally symmetric wavefront irregularity (3.9). In addition, tolerances for three root-mean-square (rms) measures of wavefront deformation may be specified (see 3.10, 3.11 and 3.12). These rms measures of the wavefront deformation represent the rms value of the function remaining after the subtraction of various types of wavefront deformation.

The wavefront sagitta error is meaningful only when the location of the image is specified. If the location of the image is left unspecified, the wavefront sagitta error, as defined in 3.5, is defined to be zero, and shall not be specified.

NOTE 1 A method for determining the amount of wavefront sagitta error, wavefront irregularity, and rotationally symmetric wavefront irregularity of a given wavefront using digital interferogram analysis is described in Annex A. Methods by which these quantities can be estimated using visual interpretation of interferograms are described in Annex B.

NOTE 2 A method for calculating the total rms wavefront deformation, the rms wavefront irregularity, and the rms wavefront asymmetry is described in Annex A. These rms measures of wavefront deformation cannot be estimated visually.

5 Non-circular test areas

The peak-to-valley (PV) and root-mean-square (RMS) wavefront deformation types given in Clause 3 refer to values calculated within the actual test area. In the case of non-circular test areas, these error types shall be calculated only over the actual test area.

The approximating spherical wavefront (3.4) is the spherical wavefront which best approximates the wavefront. If the test area is non-circular, it is important that this approximation be made by a wavefront that is spherical. In particular, the spherical part of an aspheric approximating function shall not be substituted for the approximating spherical wavefront.

The approximating aspheric wavefront (see 3.8) is the rotationally symmetric wavefront which best approximates the wavefront irregularity function. If the test area is non-circular, it is important that this approximation be made by a wavefront that is rotationally symmetric. In particular, the rotationally symmetric part of a non-symmetric approximating wavefront shall not be substituted for the approximating aspheric wavefront (see 3.8).

NOTE 1 If the test area is non-circular, the various wavefront deformation types defined in Clause 3 are not mathematically orthogonal. Nevertheless, these wavefront deformation types are well-defined (not ambiguous) provided the above restrictions are upheld.

NOTE 2 Annex A describes a method for calculating the amounts of the various types of wavefront deformation, regardless of whether or not the test area is circular.

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6 Specification of tolerances for wavefront deformation

6.1 General

For the specification of tolerances for wavefront deformation, the stipulations given in 6.2 to 6.5 apply.

NOTE It is not necessary that tolerances be specified for all types of wavefront deformation.

6.2 Units

The maximum permissible values for wavefront sagitta error, wavefront irregularity, rotationally symmetric wavefront irregularity and, if applicable, any target aberrations (3.14) shall be specified in units of wavelengths.

These quantities are defined with reference to a wavefront passing once through the element under test (single-pass). See the appropriate definitions given in Clause 3.

If a specification is to be given for one or more rms wavefront deformation types, the specification shall also be in units of wavelengths (single-pass).

6.3 Wavelength

Unless otherwise specified, the wavelength is that of the green spectral line of mercury (e-line), $\lambda = 546{,}07$ nm, according to ISO 7944.

If other than $\lambda = 546{,}07$ nm, the wavelength in which the wavefront deformation is specified shall be indicated on the drawing. See Example 2 in Figure 2. See Clause 7.

6.4 Target aberrations

Frequently, the nominal theoretical wavefront is spherical or planar. In some cases, to allow for the presence of small amounts of residual aberration in the design of an optical system, non-zero target values may be specified for the polynomial aberration types defined in Annex A.

6.5 Cemented (or optically contacted) elements

If two or more optical elements are to be cemented (or optically contacted), the wavefront deformation tolerances given for the individual elements also apply for the elements after assembly, i.e. after cementing (or optically contacting), unless otherwise specified. See ISO 10110-1:1996, 4.8.3.

7 Indication in drawings

7.1 General

In all cases in which a tolerance for wavefront deformation is to be indicated, the optical axis of the element shall be indicated on the drawing according to ISO 10110-1:1996, 4.2.

The location of the stop surface or pupil shall be indicated according to ISO 10110-1:1996, 5.3. See Figure 2.

The tolerance for wavefront deformation shall be indicated by a code number (see 7.2) and the indications of the tolerances for wavefront sagitta error, wavefront irregularity, rotationally symmetric wavefront irregularity and rms deformation types, as appropriate (see 7.3).

For any type of wavefront deformation indicated on the drawing, the specified wavelength shall be indicated in accordance with 6.3.

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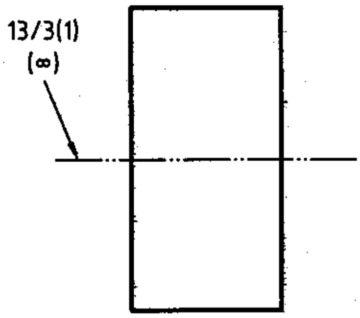
No provision is given for the specification of a PV-tolerance for the total wavefront deformation (that is, including both the wavefront sagitta error and the wavefront irregularity). If such a specification is necessary, this information shall be given in a note on the drawing, for example: "Total wavefront deformation shall not exceed 0,25 wavelength."

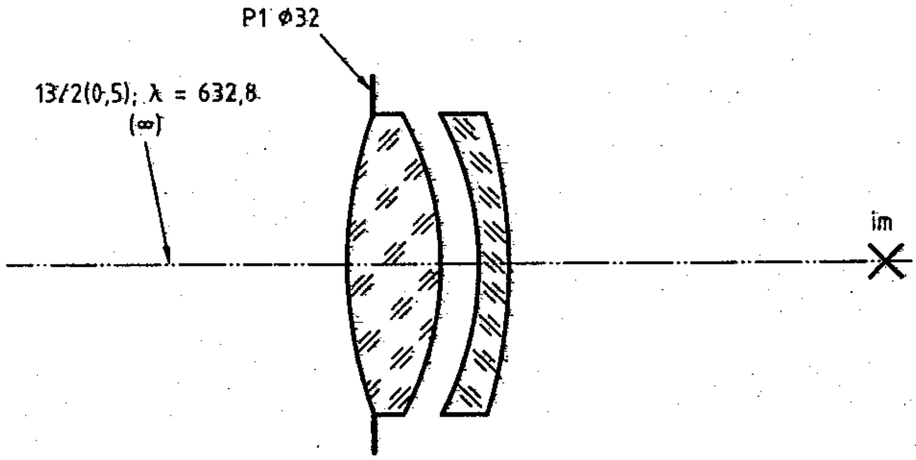
See Clause 8 for examples of tolerance indications.

7.2 Code number

The code number for wavefront deformation is 13/.



a) Example 1



b) Example 2

Figure 2 — Examples of an indication of a tolerance for wavefront deformation, with planar illumination

7.3 Form of the indication

The indication shall have one of the following three forms:

13/*A* (*B*/*C*); $\lambda = E$

or

13/*A* (*B*/*C*) RMSx < *D*; $\lambda = E$ (where x is one of the letters t, i or a)

or

13/ — RMSx < *D*; $\lambda = E$ (where x is one of the letters t, i, or a).

The indication "; $\lambda = E$" (last element of the three forms of indication specified above) may be omitted provided the specified wavelength is λ = 546,07 nm (see 7.1).

NOTE More than one RMSx value may be specified.

The quantity *A* is either

— the maximum permissible (single-pass) wavefront sagitta error, as defined in 3.5, expressed in wavelengths, or

— a dash (—) indicating that no explicit tolerance for wavefront sagitta error is given.

The quantity *B* is either

— the permissible PV value of (single-pass) wavefront irregularity, as defined in 3.7, expressed in wavelengths, or

— a dash (—) indicating that no explicit tolerance for wavefront irregularity is given.

The quantity *C* is the permissible value of the (single-pass) rotationally symmetric wavefront irregularity, as defined in 3.9, expressed in wavelengths. If no tolerance is given, the slash (/) is replaced by the final parenthesis, i.e. 13/*A*(*B*).

If no tolerance is given for the all three deformation types, then *A*, *B*, *C*, the divisor line (/) and the parenthesis are replaced by a single dash (—), i.e. 13/—.

The quantity *D* is the maximum permissible value of the rms quantity of the type specified by x, where x is one of the letters t, i or a. These quantities are defined in 3.10 to 3.12. The specification of more than one type of rms deviation is allowed. These specifications shall be separated by a semicolon, as shown in Clause 8, Example 7.

The quantity *E* is the wavelength, in nanometres, in which the wavefront deformation is specified.

The wavefront deformation tolerance indicated applies to the optically effective area, except when the indication is to apply to a smaller test field for all possible positions within the optically effective area. In this case, the diameter of the test field shall be appended to the tolerance indication as follows:

13/*A* (*B*/*C*) RMSx < *D* (all ∅...); $\lambda = E$

See Clause 8, Examples 4a) and 4b).

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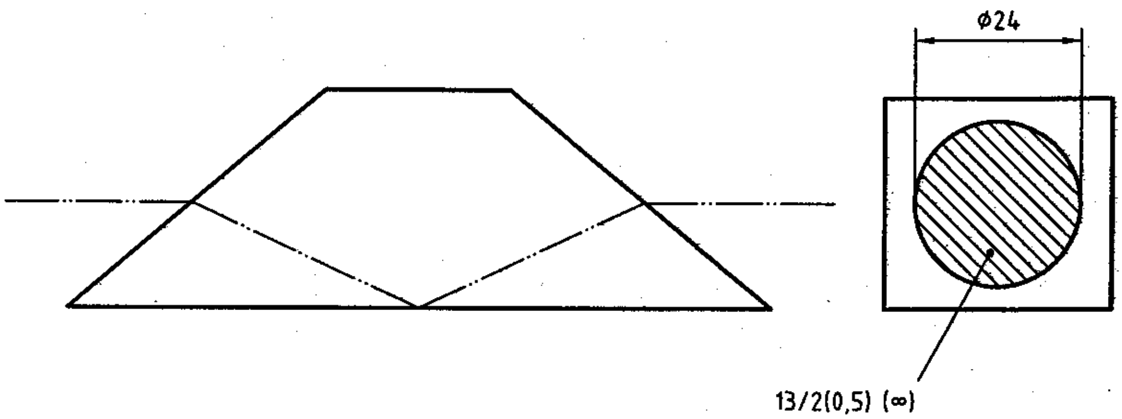
7.4 Location

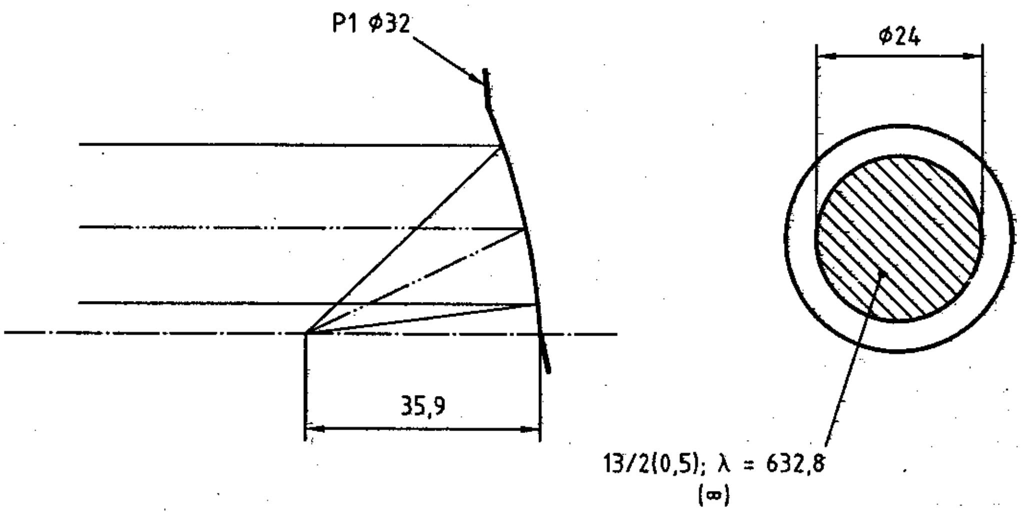
The indication shall be entered near the optical element to which it refers. If necessary, the indication may be connected to the optical axis by a leader, as shown in Figure 2.

In cases where the optical axis is not normal to the surfaces of the element, it may be necessary to indicate the test area for wavefront deformation in a cross-section perpendicular to the optical axis. In this case, the indication of wavefront deformation shall be associated with the test area (see Figure 3).

For elements requiring indications for wavefront deformation along multiple test paths, the various test paths shall be indicated with reference letters, as shown in Figure 4. The indications for wavefront deformation shall be associated with the letters of the input and output test paths, as shown in Figure 4.

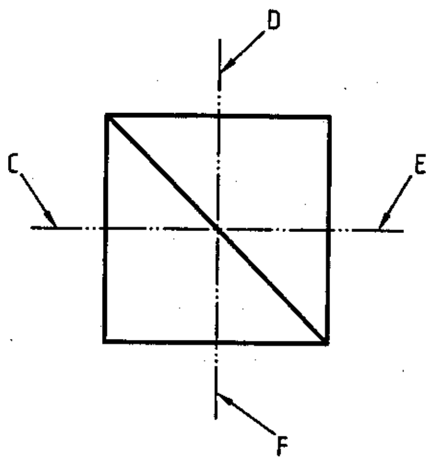


a) **Example 1**



b) **Example 2**

Figure 3 — Examples of indication of the wavefront quality specification referencing an indicated test area



CE: 13/3 (1) (∞)
CF: 13/1 (0,2) (∞)
DE: 13/3 (1) (∞)
DF: 13/1 (0,2) (∞)

Figure 4 — Indication of the wavefront quality specification for an element having multiple test paths

7.5 Indication of type of illumination

For collimated (planar wavefront) illumination, the infinity symbol (∞) shall be appended between parentheses to the indication for wavefront deformation, as shown in Figure 2. For diverging or converging illumination, the position of the object point (ob) shall be indicated on the drawing. See Figure 5.

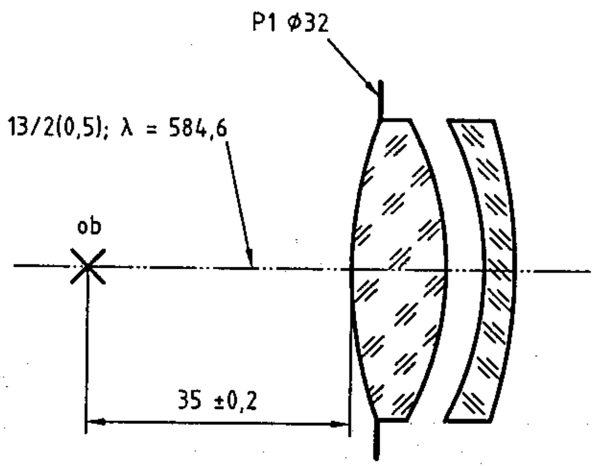


Figure 5 — Example showing the indication of the object point (ob) on the drawing

7.6 Specification of the image-point location

Optionally, the location of the image point may be given with a dimensional tolerance. If the image location is given, it shall be distinguished from the object location by the letters "im" associated with the indicated position. See Figure 6.

NOTE The wavefront sagitta error, which is a measure of the extent to which this tolerance is upheld, is not meaningful unless the object and image position are indicated. See 3.5.

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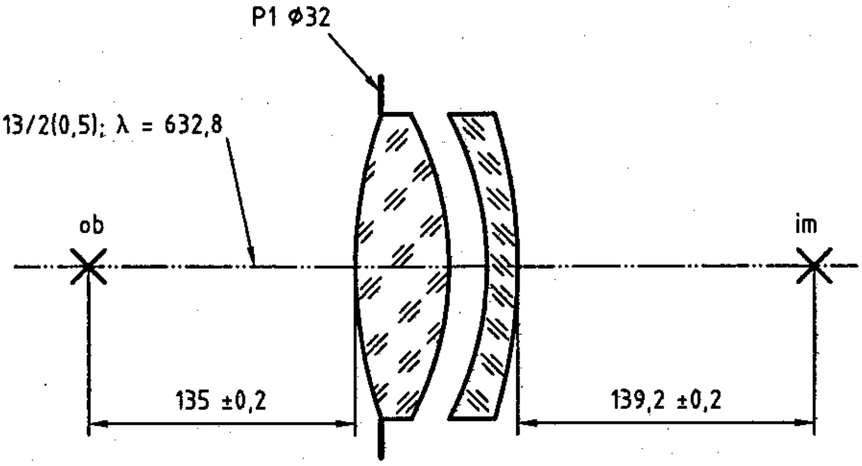

[a] P indicates the pupil.

Figure 6 — Example showing the indication of the object and image positions

7.7 Indication of target aberrations

Target values for one or more of the polynomial aberrations defined in Annex A may be specified following the word "Target". The form for the indication of a target aberration is as follows:

$C_i = x$

where

i is the identifying index of the desired polynomial term;

x is the numerical value of the target.

See Clause 8, Example 8.

8 Examples of tolerance indications

The following examples are designed to illustrate the indications in drawings in accordance with this part of ISO 10110.

EXAMPLE 1 13/— (1); λ = 632,8
The wavefront irregularity shall not exceed 1 wavelength (at λ = 632,8 nm) of single-pass wavefront deformation. No tolerance for wavefront sagitta error is given.

EXAMPLE 2 13/5 (—) RMSi < 0,05; λ = 632,8
The tolerance for the wavefront sagitta error (in addition to the amount corresponding to the dimensional tolerance given in the indication of the image position) is 5 wavelengths of single-pass wavefront deformation. No specific tolerance is given for wavefront irregularity or rotationally symmetric wavefront irregularity, but the rms-value of the wavefront irregularity shall be less than 0,05 wavelength of single-pass wavefront deformation. The wavelength for all wavefront deformation specifications is λ = 632,8 nm.

EXAMPLE 3 13/3 (1/0,5)
The tolerance for the wavefront sagitta error is 3 wavelengths of single-pass wavefront deformation. The total wavefront irregularity shall not exceed 1 wavelength of single-pass wavefront deformation. The rotationally symmetric wavefront irregularity shall not exceed 0,5 wavelength of single-pass wavefront deformation. The wavelength for all wavefront deformation specifications is λ = 546,07 nm.

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EXAMPLE 4a 13/3 (1/0,5); (All ∅ 30)
The wavefront deformation tolerances apply to all possible locations of a 30 mm diameter test area within the optically effective test area. The tolerance for the wavefront sagitta error is 3 wavelengths of single-pass wavefront deformation. The total wavefront irregularity shall not exceed 1 wavelength of single-pass wavefront deformation. The rotationally symmetric wavefront irregularity shall not exceed 0,5 wavelength of single-pass wavefront deformation. The wavelength for all wavefront deformation specifications is λ = 546,07 nm.

EXAMPLE 4b 13/0,5 — RMSi < 0,05 (all ∅ 12)
For all possible positions of a 12 mm diameter test region within the optically effective test area of the element, the (single-pass) wavefront sagitta error shall not exceed 0,5 wavelength, and the rms wavefront irregularity shall be less than 0,05 wavelength of single-pass wavefront deformation. The wavelength for all wavefront deformation specifications is λ = 546,07 nm.

EXAMPLE 5 13/3 (1); λ = 632,8
The tolerance for the wavefront sagitta error is 3 wavelengths in single-pass; the total wavefront irregularity shall not exceed 1 wavelength of single-pass wavefront deformation. The wavelength for all wavefront deformation specifications is λ = 632,8 nm.

EXAMPLE 6 13/— RMSt < 0,07; λ = 632,8
No specific tolerance for the wavefront sagitta error, wavefront irregularity or rotationally symmetric wavefront irregularity is given; however, the total rms difference between the experimental wavefront and the theoretical wavefront shall be less than 0,07 wavelength of single-pass wavefront deformation. The wavelength for all wavefront deformation specifications is λ = 632,8 nm.

EXAMPLE 7a 13/— RMSi < 0,07; RMSa < 0,03; λ = 632,8
No specific tolerance for the wavefront sagitta error, wavefront irregularity or rotationally symmetric wavefront irregularity is given; however, the rms wavefront irregularity shall be less than 0,07 wavelength of single-pass wavefront deformation, and the rms wavefront asymmetry shall be less than 0,03 wavelength of single-pass wavefront deformation. The wavelength for all wavefront deformation specifications is λ = 632,8 nm.

EXAMPLE 7b 13/— RMSt < 0,07; RMSi < 0,04
No specific tolerance for the wavefront sagitta error, wavefront irregularity, or rotationally symmetric wavefront irregularity is given; however, the total rms wavefront deformation shall be less than 0,07 wavelength of single-pass wavefront deformation, and the rms wavefront irregularity shall be less than 0,04 wavelength of single-pass wavefront deformation. The wavelength for all wavefront-deformation specifications is λ = 546,07 nm.

EXAMPLE 8 13/— (0,1); λ = 632,8
Target:
C_8 = 1,24;
C_{15} = − 0,44

No specific tolerance is given for the wavefront sagitta error or the rotationally symmetric wavefront irregularity. The nominal theoretical wavefront consists of the reference sphere plus the following polynomial:

polynomial = 1,24 Z_8 − 0,44 Z_{15}

The tolerance for the wavefront irregularity (compared to this aspheric wavefront) is 0,1 wavelength of single-pass wavefront deformation. The wavelength for all wavefront deformation specifications (including the target aberrations) is λ = 632,8 nm.

EXAMPLE 9 CE: 13/3 (1)
CF: 13/1 (0,2)
DE: 13/3 (1)
DF: 13/1 (0,2)

The tolerance for the single-pass ray paths from C to E and from D to E is 3 wavelengths for wavefront sagitta error and 1 wavelength for wavefront irregularity. The tolerance for the single-pass ray paths from C to F and from D to F is 1 wavelength for wavefront sagitta error and 0,2 wavelength for wavefront irregularity. The wavelength for all wavefront deformation specifications is λ = 546,07 nm.

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Annex A
(informative)

Method for the analysis of wavefronts using digital interferogram analysis

A.1 General

A.1.1 Introduction

The contents of this annex are important for users of digital interferometers, as well as for developers of software for interferometry.

The method described in this annex for the analysis of wavefronts is restricted in its applicability to wavefronts which can be described in terms of polynomials.

Examples of wavefronts to which this method does not apply are those which are coneshaped and those with spatially localized deformations.

The amounts of the various types of wavefront deformation are determined through a process of successive fitting and removal of wavefront deformation types. At each stage, the removal of one type of wavefront deformation exposes the next type of deformation.

The procedure by which a function of a certain type which "best fits" a certain original function is determined is the well-known method of least squares, which minimizes the rms difference between the original function and the approximation to it. The rms value of a function is defined in A.4.

Various approximations to the wavefront are represented as linear combinations of the Zernike polynomials defined in A.3. These combinations are given by corresponding coefficients. The coordinates r and θ are as defined in A.1.3.

A.1.2 Interferometric reference wavefront

The interferometric reference wavefront is a physically existing wavefront generated by the interferometer, to represent the nominal theoretical wavefront. Typically, the interferometric reference wavefront consists of a planar or spherical wavefront corresponding to the reference sphere defined in 3.16. If the nominal theoretical wavefront is weakly aspheric, it may be possible to use a planar or spherical reference wavefront and account for the asphericity through software. If the nominal theoretical wavefront is strongly aspheric, the interferometer shall have a physical means, such as a "null lens" or a computer-generated hologram, of modifying the asphericity of a wavefront. In principle, it would be possible to create an aspheric interferometric reference wavefront to match the desired asphericity of the test wavefront. It is more common, however, to use a null lens or computer-generated hologram to remove the desired amount of asphericity of the test beam, so that it may be compared with a spherical reference beam.

A.1.3 Coordinate system

The wavefront under test is described in polar coordinates by the variables r and θ; the origin of the coordinate system is the centre of the test area, and r is normalised to 1 at the edge of the test area. For non-circular test areas, the "centre" of the test area refers to its centroid, and the radius of the test area refers to the distance from the centre to the most distant point. The parameter r ranges therefore between zero and 1.

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Various approximations to the wavefront are represented as linear combinations of the polynomials – commonly called Zernike polynomials – $Z_0(r,\theta)$, $Z_1(r,\theta)$ ..., given in A.3.2. These linear combinations are given by corresponding coefficients C_0, C_1, ...

A.1.4 Single-pass and double-pass measurements

Wavefront deformation is defined in 3.1 in reference to a wavefront which passes through or, in the case of reflective optics, reflects from the optical element once (single-pass). If the element is tested in this manner, the equations given in this annex may be used directly. (Figure B.1 gives an example of a single-pass interferometer).

Very often optical elements are tested in a double-pass arrangement, an example of which is shown in Figure B.2. If the element is tested in double-pass, the results of all the equations given in this annex will have to be adjusted appropriately to yield single-pass results. In many cases, this adjustment is simply to divide the results by two; however, this is not always true. See Notes 1 and 2 of 3.1.

A.2 Procedure

A.2.1 General

The procedure for finding the amounts of the various wavefront deformation types is given in A.2.2 to A.2.8. Although this procedure is described in terms of the Zernike polynomials, any mathematically equivalent procedure based on another set of functions may be used. However, since the order of operations is important when using non-orthogonal polynomials, the equivalence between the procedure used and that given here shall be maintained at each step of the entire procedure. This is of particular importance when the test region is not circular (see A.3.3).

A.2.2 Total wavefront deformation

The total-optical-path-difference function, $\mathrm{OPD}(r,\theta)$, refers to the difference between the test and reference wavefronts, as measured by the interferometer, including any tilt between the test wavefront and the interferometric reference wavefront. The total-wavefront-deformation function, $\mathrm{TWD}(r,\theta)$, refers to the optical path difference after subtraction of the best-fitting plane, $\mathrm{P}(r,\theta)$.

Specifically, $\mathrm{P}(r,\theta)$ is given by the linear function

$$\mathrm{P}(r,\theta) = C_0 Z_0(r,\theta) + C_1 Z_1(r,\theta) + C_2 Z_2(r,\theta)$$

where the coefficients C_0, C_1 and C_2 are found by the least-squares procedure. From this, the total wavefront deformation function $\mathrm{TWD}(r,\theta)$ is found by subtracting the best-fitting plane and any target aberrations specified according to 7.7 from the measured wavefront deformation $\mathrm{W}(r,\theta)$:

$$\mathrm{TWD}(r,\theta) = \mathrm{W}(r,\theta) - \mathrm{P}(r,\theta) - \sum_i C_i Z_i(r,\theta)$$

where the coefficients C_i are the indicated amounts of the target aberrations (see 7.7).

A.2.3 Total rms wavefront deformation RMSt

The total rms wavefront deviation, RMSt (3.10), is equal to the rms value of the total-wavefront-deformation function, $\mathrm{TWD}(r,\theta)$.

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A.2.4 Approximating spherical wavefront and wavefront sagitta error

The best approximating spherical wavefront is found from the total wavefront deformation function. For reasonable amounts of wavefront deformation, this can be approximated by the parabolic deformation defined by the Zernike term number 3:

Approximating sphere = $C_3 Z_3(r,\theta)$,

where the coefficient C_3 is determined by the least-squares method. (For non-circular test areas, the restrictions of Clause 5 and of A.3.3 apply.) The wavefront sagitta error (3.5) is then determined from the coefficient C_3:

Wavefront sagitta error = $2C_3$

A.2.5 Wavefront irregularity function

The wavefront irregularity function IRR(r,θ) is the difference between the total wavefront deformation function TWD(r,θ) and the approximating sphere. This corresponds to the function remaining after the approximating sphere has been subtracted from the wavefront.

$$\mathrm{IRR}(r,\theta) = \mathrm{TWD}(r,\theta) - C_3 Z_3(r,\theta)$$

A.2.6 Wavefront irregularity and rms wavefront irregularity, RMSi

The rms wavefront irregularity RMSi (3.11) is equal to the rms value of the wavefront irregularity function. The wavefront irregularity (3.7) is equal to the peak-to-valley value of the wavefront irregularity function.

Some form of smoothing (e.g. convolution or replacement of the function with a polynomial of sufficient order) is usually required to remove the effects of isolated surface defects (scratches, local material defects, etc.) scattering of light from dust particles and measurement "noise", which are not part of the surface-form deviation. The nature of the smoothing should be reported as part of the test report for the optical element.

A.2.7 Approximating aspheric wavefront and rotationally symmetric wavefront irregularity

The approximating aspheric wavefront AAW(r,θ) is obtained by a least-squares fit of a series of rotationally symmetric Zernike polynomials to the irregularity function IRR(r,θ):

$$\mathrm{AAW}(r,\theta) = C_8\, Z_8(r,\theta) + C_{15}\, Z_{15}(r,\theta) + C_{24}\, Z_{24}(r,\theta) + C_{35}\, Z_{35}(r,\theta) + \ldots$$

(For non-circular test areas, the restrictions of Clause 5 and of A.3.3 apply.)

In most cases, the approximation is sufficiently accurate using the four terms given above. Higher-order terms may be used if necessary. In cases where spatially localized wavefront deformations are present, a polynomial representation of the wavefront deformation is inappropriate.

The rotationally symmetric wavefront irregularity (3.9) is equal to the peak-to-valley value of the approximating aspheric wavefront AAW(r,θ). This may be determined in practice by calculating the value of AAW(r,θ) at discrete points located on a sufficiently fine grid and taking the difference between the highest and lowest values.

NOTE The topic of this subclause is part of a more general problem which will be addressed in an International Standard which will be published in the future.

A.2.8 The rms wavefront asymmetry RMSa

The approximating aspheric wavefront AAW(r,θ) is subtracted from the irregularity function IRR(r,θ). The rms wavefront asymmetry RMSa (3.12) is the rms value of the function which remains.

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A.3 Zernike polynomials

A.3.1 General

The set of polynomials identified by Zernike and Nijboer[1)] as being orthogonal in the sense of rms integration over a circular area, are commonly used for interferogram analysis. For circular test areas, the analysis may be simplified by the orthogonality properties of these polynomials. For non-circular pupils, these polynomials are no longer orthogonal and no longer offer any advantage over other sets of functions; however, they may still be used, provided that the analysis techniques given in Clause A.2 are used. See A.3.3.

A.3.2 List of Zernike polynomials

$Z_0(r,\theta) = 1$

$Z_1(r,\theta) = r\cos\theta$

$Z_2(r,\theta) = r\sin\theta$

$Z_3(r,\theta) = 2r^2 - 1$

$Z_4(r,\theta) = r^2\cos 2\theta$

$Z_5(r,\theta) = r^2\sin 2\theta$

$Z_6(r,\theta) = (3r^2 - 2)\cdot r\cos\theta$

$Z_7(r,\theta) = (3r^2 - 2)\cdot r\sin\theta$

$Z_8(r,\theta) = 6r^4 - 6r^2 + 1$

$Z_9(r,\theta) = r^3\cos 3\theta$

$Z_{10}(r,\theta) = r^3\sin 3\theta$

$Z_{11}(r,\theta) = (4r^2 - 3)\cdot r^2\cos 2\theta$

$Z_{12}(r,\theta) = (4r^2 - 3)\cdot r^2\sin 2\theta$

$Z_{13}(r,\theta) = (10r^4 - 12r^2 + 3)\cdot r\cos\theta$

$Z_{14}(r,\theta) = (10r^4 - 12r^2 + 3)\cdot r\sin\theta$

$Z_{15}(r,\theta) = 20r^6 - 30r^4 + 12r^2 - 1$

$Z_{16}(r,\theta) = r^4\cos 4\theta$

$Z_{17}(r,\theta) = r^4\sin 4\theta$

$Z_{18}(r,\theta) = (5r^2 - 4)\cdot r^3\cos 3\theta$

$Z_{19}(r,\theta) = (5r^2 - 4)\cdot r^3\sin 3\theta$

$Z_{20}(r,\theta) = (15r^4 - 20r^2 + 6)\cdot r^2\cos 2\theta$

$Z_{21}(r,\theta) = (15r^4 - 20r^2 + 6)\cdot r^2\sin 2\theta$

$Z_{22}(r,\theta) = (35r^6 - 60r^4 + 30r^2 - 4)\cdot r\cos\theta$

1) A discussion of these polynomials and their properties is given in M. BORN and E. WOLF, *Principles of Optics*, Pergamon press, New York, 7th edition, 1999.

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$$Z_{23}(r,\theta) = (35r^6 - 60r^4 + 30r^2 - 4) \cdot r\sin\theta$$

$$Z_{24}(r,\theta) = 70r^8 - 140r^6 + 90r^4 - 20r^2 + 1$$

$$Z_{25}(r,\theta) = r^5\cos 5\theta$$

$$Z_{26}(r,\theta) = r^5\sin 5\theta$$

$$Z_{27}(r,\theta) = (6r^2 - 5) \cdot r^4\cos 4\theta$$

$$Z_{28}(r,\theta) = (6r^2 - 5) \cdot r^4\sin 4\theta$$

$$Z_{29}(r,\theta) = (21r^4 - 30r^2 + 10) \cdot r^3\cos 3\theta$$

$$Z_{30}(r,\theta) = (21r^4 - 30r^2 + 10) \cdot r^3\sin 3\theta$$

$$Z_{31}(r,\theta) = (56r^6 - 105r^4 + 60r^2 - 10) \cdot r^2\cos 2\theta$$

$$Z_{32}(r,\theta) = (56r^6 - 105r^4 + 60r^2 - 10) \cdot r^2\sin 2\theta$$

$$Z_{33}(r,\theta) = (126r^8 - 280r^6 + 210r^4 - 60r^2 + 5) \cdot r\cos\theta$$

$$Z_{34}(r,\theta) = (126r^8 - 280r^6 + 210r^4 - 60r^2 + 5) \cdot r\sin\theta$$

$$Z_{35}(r,\theta) = 252r^{10} - 630r^8 + 560r^6 - 210r^4 + 30r^2 - 1$$

A.3.3 Non-circular test areas

A.3.3.1 General

The Zernike polynomials are only orthogonal if the test area is circular and enough sample points are taken so that an integral is approximated well by summation over the points. If this condition is met, the polynomials are orthogonal, and as a consequence, their coefficients may be determined through the least-squares method, and the results are the same regardless of the grouping of the terms. For example, the coefficient C_3 may be determined by fitting the single term C_3Z_3 to the wavefront, or by fitting the more complex expression $C_3Z_3 + C_8Z_8 + C_{15}Z_{15} + C_{24}Z_{24}$, and the values of C_3 will be the same in both cases.

If the test area is non-circular, the Zernike polynomials are not orthogonal, and the values obtained for C_3 in the two cases described above will not necessarily be the same.

In spite of this, the Zernike polynomials may still be used for the analysis of the wavefront deformation, provided that the procedure described in A.2 is followed. A.2 reflects the stipulations of Clause 5, and prescribes a particular order for fitting the terms and subtracting them; this procedure ensures that the correct values for the wavefront deformation types are obtained.

In accordance with Clause 5, A.2 states that the polynomial terms shall be fit to and subtracted from the wavefront in a particular order; it is not acceptable to fit several terms at once. In particular, it is not permissible to mix the term C_3Z_3 with the aspheric terms, and it is not permissible to mix terms with rotational symmetry with terms that do not have symmetry.

A.3.3.2 Commercially available programs

In some commercially available programs, the polynomials are fit in groups of terms. For example, a polynomial consisting of the first nine terms might be fit to the wavefront. According to Clause 5, the coefficient C_3 obtained in this manner shall not be used in the determination of the approximating spherical wavefront. Furthermore, the coefficient C_8 obtained in this manner shall not be used in the determination of the approximating aspheric wavefront. Instead, the coefficient C_3 is to be determined by fitting only the term C_3Z_3 to the wavefront, after the best-fitting plane $P(r,\theta)$ has been removed. Similarly, in determining the coefficient C_8 for the approximating aspheric wavefront, only terms of the type shown in A.2.7 are allowed. Specifically,

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Clause 5 states that terms that are not rotationally symmetric shall not be included in the fit, and the parabolic term C_3Z_3 shall not be included in the fit.

A.4 Root-mean-square value of a function

The root mean square of a function f over a given area A is given by either of the following integral expressions:

a) Cartesian variables x and y:

$$\text{RMS value} = \left[\frac{\int\limits_x \int\limits_y \left[f(x,y) \right]^2 \, \mathrm{d}x \, \mathrm{d}y}{\int\limits_x \int\limits_y \mathrm{d}x \, \mathrm{d}y} \right]^{\frac{1}{2}}$$

where $(x, y) \in A$

b) Polar variables r and θ:

$$\text{RMS value} = \left[\frac{\int\limits_\theta \int\limits_r \left[f(r,\theta) \right]^2 r \, \mathrm{d}r \, \mathrm{d}\theta}{\int\limits_\theta \int\limits_r r \, \mathrm{d}r \, \mathrm{d}\theta} \right]^{\frac{1}{2}}$$

where $(r, \theta) \in A$

This integral may be approximated by a corresponding summation, provided that a sufficient number of data points is used.

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Annex B
(informative)

Visual interferogram analysis

B.1 General

B.1.1 Information

This annex is intended as an aid to understanding this part of ISO 10110. It is useful for the interpretation of interferograms, but the guidelines given for the estimation of the amounts of the various types of wavefront deformations do not serve to define those wavefront-deformation types.

The purpose of this annex is to demonstrate the visual appearance of interferograms for the different types of wavefront deformation. The appearance of the fringes depends on whether the optical element is tested in single-pass or in double-pass. See B.1.6.

This annex deals exclusively with the following types of wavefront deformation: wavefront sagitta error, wavefront irregularity and rotationally symmetric wavefront irregularity. The rms residual wavefront deformation types (defined in 3.10 to 3.12) cannot be determined by visual inspection.

B.2 and B.3 describe the analysis of circular test areas. Special considerations for non-circular test areas are given in B.2.5.

The analysis of fringe patterns is treated more fully in many textbooks[2].

B.1.2 Test and reference wavefronts, test and reference arms of the interferometer

When the wavefront deformation of an optical element is tested interferometrically, a high-quality wavefront (known as the "reference wavefront") is allowed to interact with a wavefront which has been transmitted through or, in the case of reflective optics, reflected from, the element under test. This latter wavefront will be referred to as the "test wavefront". The two optical sub-systems of the interferometer which produce the reference and test wavefronts will be referred to as the "reference arm" and the "test arm" of the interferometer, respectively.

B.1.3 Fringes, fringe spacings

The interaction of the reference and test wavefronts produces areas of high and low light intensity, known as "fringes". The number of spacings between such fringes is a measure of the deformation of the wavefront. If the test wavefront is tilted relative to the reference wavefront, then the curvature of the fringes, measured relative to the fringe spacing, is a measure of the deformation of the wavefront. The scale factor relating the number of fringe spacings to the wavefront deformation, as defined in 3.1, depends on the number of times the test wavefront is transmitted through or reflected from the element under test. See B.1.6.

B.1.4 Interferometric tilt

Two methods are used for estimating the amounts of wavefront sagitta error and wavefront irregularity, depending on the amount of relative tilt between the test and reference wavefronts. The method without tilt is applied chiefly when the wavefront deformation is large. The method employing tilt is generally more accurate.

The relative tilt between the two wavefronts is not a measure of the wavefront deformation.

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2) For example: MALACARA, D. ed., *Optical shop testing*, Wiley, New York, 2nd edition, 1992.

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B.1.5 Determination of the sign of the deformation

In order to determine the sign of the deformation of the wavefront or regions of the wavefront, it is sometimes necessary to slightly shorten or lengthen the test arm of the interferometer, in order to note the behaviour of the interferometric fringes when this is done. This may be accomplished by pushing very gently on one of the mirrors in the test arm of the interferometer. See B.1.6.

B.1.6 Interferometric arrangements for testing optical elements

B.1.6.1 General

There are many possible arrangements for testing optical elements interferometrically. Because the various testing geometries have different sensitivities to the quality of the element under test, the interpretation of the test results depends on the arrangement used.

Interferometric arrangements in which the light beam passes through (or reflects from) the element under test only once, known as "single-pass" methods, correspond to direct measurements of wavefront deformation.

More commonly, an arrangement is used in which the light beam passes through (or reflects from) the element under test twice. Such arrangements are known as "double-pass" methods and, in such cases, the measured results must be adjusted to account for the second transmission of the light through the element.

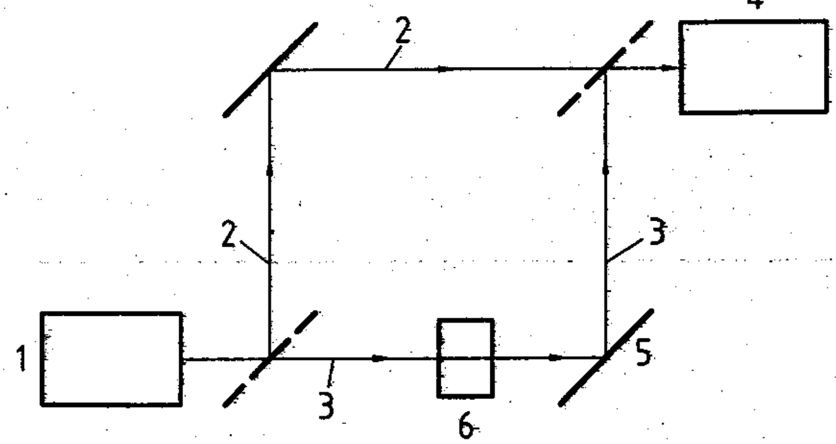
In many cases, the single-pass wavefront deformation may be obtained by dividing the results of a double-pass measurement by two. In the examples given in this annex, it is assumed that this is the case. However, there are cases in which this is not true. See 3.13.

B.1.6.2 Testing elements in single-pass

The definition of wavefront deformation (3.1) makes reference to a wavefront transmitted once through, or reflected once from, the optical system. Optical testing methods in which the light beam travels once through the optical element under test will be referred to as "single-pass" methods.

Figure B.1 shows one possible interferometric method for testing optical elements in this way.

In the case of single-pass optical testing, one fringe spacing visible in the interferogram corresponds to one wavelength of wavefront deformation as defined in 3.1.



a) Optical element without power

Figure B.1 — Testing an optical element in single-pass

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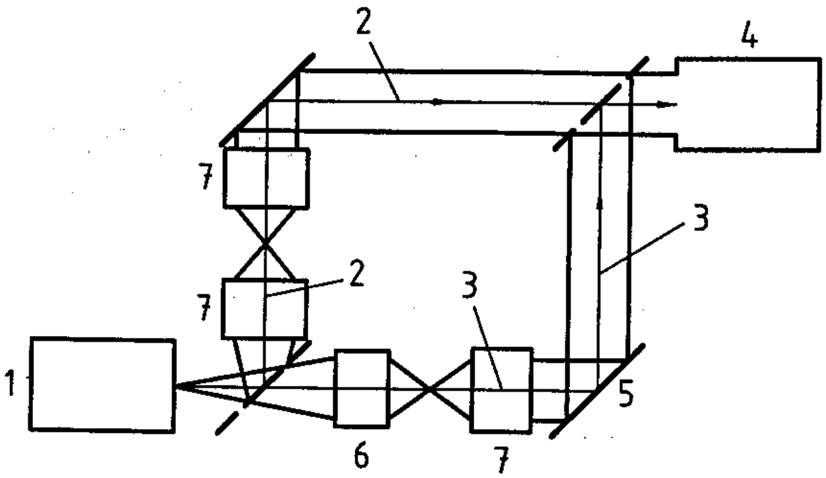

b) Optical element with power

Key

1 source
2 reference arm
3 test arm
4 detector
5 push to shorten test arm
6 element under test
7 auxiliary lens

Figure B.1 (*continued*)

B.1.6.3 Testing elements in double-pass

Optical elements are often tested in a "double-pass" configuration, in which the wavefront passes through or, in the case of reflective optics, reflects from the element under test twice, as shown in Figure B.2.

In the case of double-pass testing, the additional wavefront deformation caused by the second transmission through the element will have to be accounted for when comparing the measurement results with the specified tolerances. If the wavefront is not severely deformed by passing once through the element under test, and reflects from a high-quality mirror, it returns through the identical portion of the test element to the interferometer. In this case, the observed deformation of the wavefront is twice the (single-pass) wavefront deformation as defined in 3.1, that is, the wavefront deformation (as defined by 3.1) is one-half the observed wavefront deformation.

If the wavefront is severely deformed by the element under test, the individual rays do not pass through the same positions in the element under test on their return path, and the wavefront deformation is not exactly twice that of the single path case. Also, if the cross-section of the test beam is distorted in passing once through the optical system, the relationship between double-pass measurements and the single-pass wavefront deformation is more complex than simply a factor of 2. See Notes 3 and 4 to 3.13.

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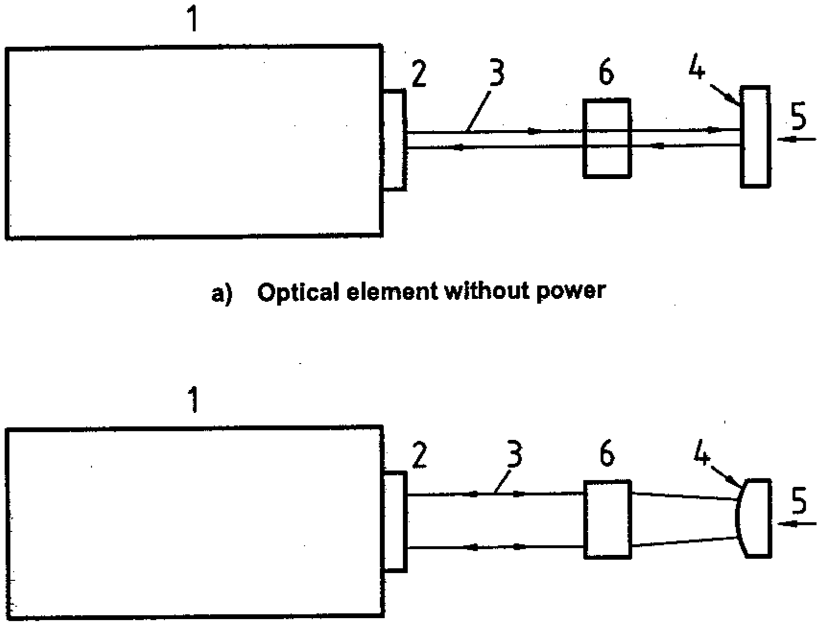

a) Optical element without power

b) Optical element with power

Key

1 fizeau interferometer (reference arm inside)
2 reference surface
3 test arm
4 auxiliary reflecting surface
5 push to shorten test arm
6 element under test

Figure B.2 — Testing an optical element in double-pass

B.2 Estimation of wavefront sagitta error and wavefront irregularity

B.2.1 General

The wavefront sagitta error can only be determined if the positions of both the object point and the image point are specified. Often, when testing optical elements and systems interferometrically, only one of these two positions is specified, and the sagitta error cannot be determined; however, the irregularity can still be determined.

The determination of the wavefront sagitta error is simplest if the point source of the interferometer is placed at the indicated object point, and the mirror which reflects the beam back toward the interferometer is placed concentric with the indicated image point. In the following, it is assumed that this is the case. (If this is not the case, the distances between the indicated and actual object points and the indicated and actual image points must be taken into account.) If dimensional tolerances are associated with the indications of the positions of the object and image points, the source and the reflecting surface may be moved within these tolerances to minimize the sagitta error.

Usually, the wavefront deformation is dominated by wavefront sagitta error and/or by a kind of asymmetry in the sagitta error. In the case of asymmetry, cross-sections of the wavefront in different directions show different amounts of sagitta error. Other kinds of wavefront irregularity are possible; the estimation of their amounts is more difficult. The estimation of the amounts of wavefront sagitta error and wavefront irregularity for the commonly occurring cases is described in B.2.2 and B.2.3, and a more general procedure for unusual types of irregularity is described in B.2.4. The reference given in Footnote 2 (see B.1.1) contains a more thorough discussion of interferogram analysis.

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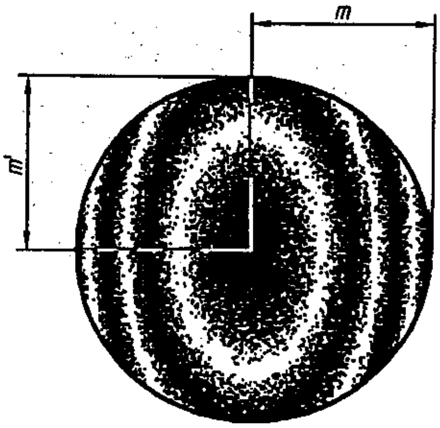
B.2.2 Analysis of interferograms without tilt

In the absence of all other types of wavefront deformation, wavefront sagitta error causes an interference pattern having concentric, circular fringes. The radii of the fringes increase with the square root of the fringe number, counting from the centre of the fringe pattern.

If a small amount of asymmetric deformation is present, the circles distort into ellipses, as shown in Figure B.3. If the test wavefront is concave with respect to the reference wavefront, the fringes will move toward the centre of the fringe pattern when the test arm of the interferometer is shortened. If the reverse is true, the test wavefront is convex with respect to the reference wavefront.



m = 3 fringe spacings

m' = 1 fringe spacing

Figure B.3 — Example of a double-pass interferogram of an optical element with 1 wavelength of wavefront sagitta error and 1 wavelength of wavefront irregularity

To estimate the amount of wavefront sagitta error and wavefront irregularity, let m and m' be the numbers of fringe spacings seen in the fringe pattern, counted from the centre to the edge, in the directions which give the largest and smallest numbers of fringes, respectively[3]. In the case of elliptical fringes, the sagitta error is given by the average of m and m', that is:

$$\text{Wavefront sagitta error (elliptical fringes, single-pass)} = \frac{m+m'}{2} \qquad \text{(B.1)}$$

If the element is tested in double-pass, the results of Equation (B.1) shall be divided by 2, if the assumptions in B.1.6.3 are met.

In the case of elliptical fringes, the wavefront irregularity is equal to the absolute value of the difference of the fringe counts m and m':

$$\text{Wavefront irregularity (elliptical fringes, single-pass)} = |m - m'| \qquad \text{(B.2)}$$

If the element is tested in double-pass, the results of Equation (B.2) shall be divided by 2, if the assumptions in B.1.6.3 are met.

EXAMPLE Figure B.3 shows the double-pass interferogram of an optical element tested as shown in Figure B.2. In Figure B.3, the values of m and m' are 3 and 1 double-pass fringe spacings, respectively. Therefore, the immediate result of Equation (B.1) is (3 + 1)/2 = 2 wavelengths; however, this is a double-pass interferogram, so the wavefront sagitta error

3) Usually, these two directions are oriented at 90° to one another, but this need not be the case.

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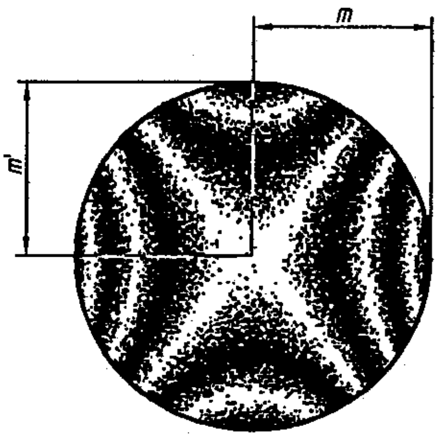
is one-half this, or 1 wavelength. Similarly, the wavefront irregularity appears to be $|3-1| = 2$ wavelengths, but since this is a double-pass interferogram, the wavefront irregularity is 1 wavelength.

If a large amount of asymmetric deformation is present, the elliptical fringes may be broken into approximately hyperbolic fringes, as shown in Figure B.4. In this case, when the test wavefront is moved slightly toward the interferometric reference wavefront, some of the fringes will move toward the centre of the fringe pattern and some will move away from the centre.



m = 2,5 fringe spacings

m' = 1,5 fringe spacings

Figure B.4 — Example of a single-pass interferogram showing 0,5 wavelength of wavefront sagitta error and 4 wavelengths of wavefront irregularity

In the case of hyperbolic fringes, the wavefront sagitta error is equal to half the difference between the numbers of fringe spacings:

$$\text{Wavefront sagitta error (hyperbolic fringes, single-pass)} = \left|\frac{m-m'}{2}\right| \quad \text{(B.3)}$$

If the element is tested in double-pass, the results of Equation (B.3) shall be divided by 2, if the assumptions in B.1.6.3 are met.

The wavefront irregularity, in the case of hyperbolic fringes, is given by the sum of the numbers of the fringe counts:

$$\text{Wavefront irregularity (hyperbolic fringes, single-pass)} = m + m' \quad \text{(B.4)}$$

If the element is tested in double-pass, the results of Equation (B.4) shall be divided by 2, if the assumptions in B.1.6.3 are met.

EXAMPLE Figure B.4 shows the single-pass interferogram of an optical element tested according to the arrangement shown in Figure B.1. In Figure B.4, the values of m and m' are 2,5 and 1,5 wavelengths, respectively, so the wavefront sagitta error is $|2{,}5-1{,}5|/2 = 0{,}5$ wavelength, and the wavefront irregularity is 2,5 + 1,5 = 4 wavelengths. (Since this is a single-pass interferogram, the results are not divided by 2.)

B.2.3 Analysis of fringe pattern with tilt

This method requires the fringes to be observed twice, with the tilt between the test and reference wavefronts adjusted so that the fringes are oriented in two different directions.

When the reference wavefront is tilted with respect to the test wavefront, the fringes appear as in Figure B.5. If only the wavefront sagitta error is present, the fringes appear as parts of concentric circles, with the radii of

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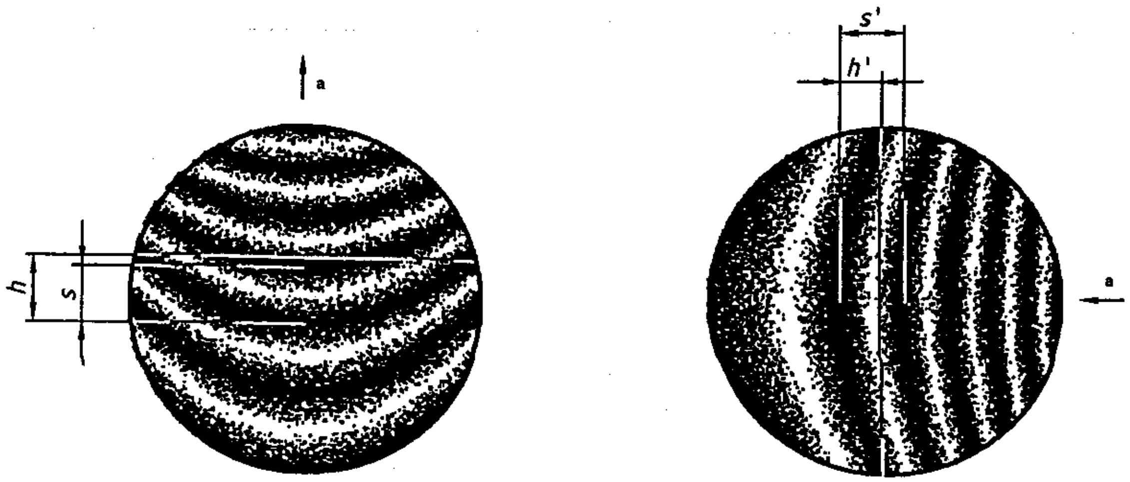
the fringes increasing with the square root of the fringe number, counting from the apparent centre of the fringe pattern. If other wavefront deformation types are also present, the fringes are not parts of concentric circles.



a) Orientation 1 b) Orientation 2

h (h') curvature of fringe closest to centre of interferogram

s (s') spacing of the fringes

$m = h/s$

$m' = h'/s'$

[a] The arrows indicate the direction of motion of fringes when the test arm is shortened.

Figure B.5 — Example showing double-pass interferograms of an optical element with 0,15 wavelength of wavefront sagitta error and 0,9 wavelengths of irregularity, with the interferometric tilt oriented in two directions

To estimate the wavefront sagitta error and the wavefront irregularity, the curvature of the test wavefront in the cross-section parallel to the fringes is estimated, for the two directions of tilt which give the maximum and minimum amounts of curvature. (See Figure B.5). In each case, the number of fringe spacings m is equal to the curvature h of the fringe closest to the centre of the interferogram, divided by the spacing s of the fringes, which is also measured as close as possible to the centre of the test area.

In addition, it is necessary to note (for both directions of the tilt) the direction of motion of the fringes when the test arm of the interferometer is shortened.

If the fringes for both directions of tilt move toward the apparent centre of curvature of the fringes, or if the fringes for both directions of tilt move away from the apparent centre, then the sagitta error exceeds the irregularity. Equations (B.1) and (B.2) are used to estimate the wavefront sagitta error and the wavefront irregularity, respectively. (In the case of double-pass measurement, the results of Equations (B.1) and (B.2) are to be divided by 2, if the assumptions in B.1.6.3 are met.)

If one set of fringes moves toward its apparent centre, and the other fringe pattern moves away from its apparent centre when the test arm is shortened, then the irregularity exceeds the sagitta error, and Equations (B.3) and (B.4) are used to estimate the amounts of wavefront sagitta error and wavefront irregularity. (In the case of double-pass measurement, it is appropriate to divide the result of Equations (B.3) and (B.4) by 2, if the assumptions in B.1.6.3 are met.)

EXAMPLE Figure B.5 shows double-pass interferograms of an optical element tested with tilt. In Figure B.5a), the fringes move toward the apparent centre when the test arm is shortened, and in Figure B.5b), the fringes move away from the apparent centre, so Equations (B.3) and (B.4) apply, with the results divided by two, according to B.1.6.3. In Figure B.5a), the curvature h is approximately 1,2 times the fringe spacing s, so $m = 1{,}2$. In Figure B.5 b), the curvature h' is 60 % the fringe spacing s', so $m' = 0{,}6$. The initial result of Equation (B.3) is 0,3 wavelength; after dividing by 2 to

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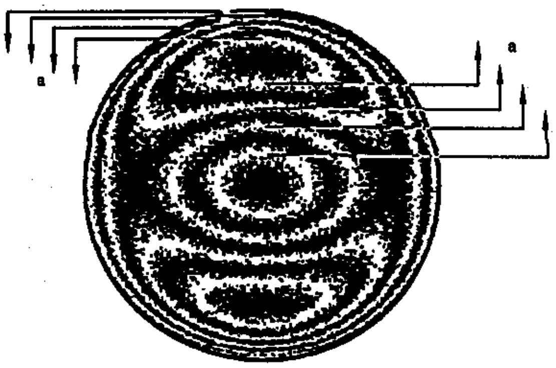
account for the double-pass measurement, one finds that the wavefront sagitta error is 0,15 wavelength. Similarly, Equation (B.4) yields a value of 1,8 wavelengths; after accounting for the double-pass measurement, it yields a value for the wavefront irregularity of 0,9 wavelength.

B.2.4 Unusual forms of irregularity

It is possible that the wavefront deformation be a maximum at some point inside the test area, rather than at the edge. When testing wavefronts with no tilt between the test and reference wavefronts, this leads to closed fringes which may not be concentric with the centre of the test area, as shown in Figure B.6. In cases such as this, it is necessary to note which fringes move away from the centre and which toward the centre when the test arm of the interferometer is shortened. Those which move toward the centre may be regarded as "positive", and the others as "negative".



a Motion

Figure B.6 — Example of an unusual double-pass interferogram, showing the direction of motion of the fringes when the test arm of the interferometer is shortened

The wavefront sagitta error is determined according to Equation (B.1), where m and m' represent the cumulative numbers of fringes measured in two representative directions. In the vertical cross-section of Figure B.6, there are 4 fringe spacings in the negative direction, followed by 4 fringe spacings in the positive direction, giving a value of zero for m. In the horizontal direction, there are 2 negative and 2 positive wavelengths, again giving $m' = 0$. According to Equation (B.1), the wavefront sagitta error is $(0 + 0)/2 = 0$.

The wavefront irregularity is determined by finding the highest and lowest departures from the theoretical expected fringe pattern, which is that the fringes are concentric circles with radii increasing as the square root of the fringe number. The irregularity is the sum of the absolute values of the highest and lowest departures from the pattern. For the pattern of Figure B.6, the sagitta error is zero, so the theoretical expected fringe pattern has no fringes. The lowest departure from this is -4 fringe spacings (at the centres of the two outer oval patterns), and the highest departure from this is zero. Therefore, the wavefront irregularity appears to be $|0| + |-4| = 4$ wavelengths; however, because this is a double-pass interferogram, the wavefront irregularity is half the observed deformation, that is, 2 wavelengths.

B.2.5 Non-circular test areas

According to the definition of wavefront sagitta error (3.5) the wavefront sagitta error is based on the spherical wavefront which best approximates the test wavefront. When using visual analysis methods, the approximating spherical wavefront may be chosen so that the irregularity (which is the difference between the approximating spherical wavefront and the test wavefront) is evenly distributed around the boundary of the test area. This requires that wavefront sagitta error and wavefront irregularity be evaluated by a method similar to that described in B.2.2, except that the calculations must take into account the dimensions of the test area in the two cross-sections in which m and m' are measured.

This method is reasonably accurate for simple forms of wavefront deformation (that is, those which are second-order in x and y); for an accurate evaluation of more complex forms, digital methods are necessary.

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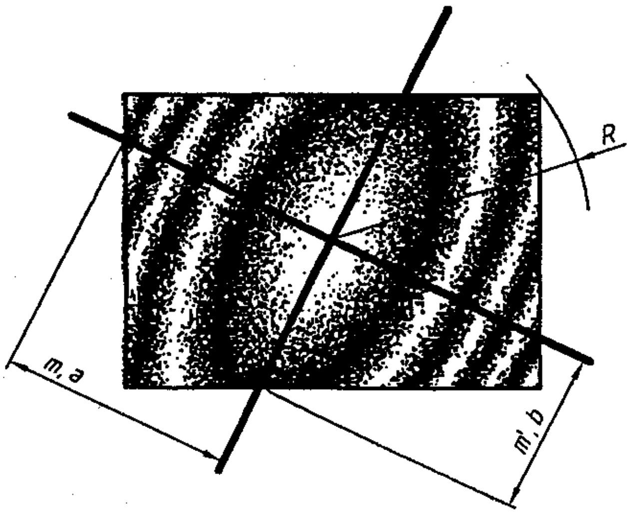
For non-circular test areas, the "centre" of the test area refers to its centroid ("centre-of-gravity"), and its "radius" is equal to the distance from the centre to the most distant point in the test area.

The cross-sectional curvatures m and m' are determined in the same way as in B.2.2, using the description of the case with or without tilt, as appropriate. The directions along which m and m' are determined are given by the symmetry of the wavefront deformation; these directions are not necessarily related to the shape of the test area.

Let m and m' be the cross-sectional curvatures in the two directions of symmetry, from the centre to the edge of the test area, as shown in Figure B.7. Let a be the distance from the centre to the edge of the test area in the direction along which the curvature m is measured. Similarly, let b be the distance along which the curvature m' is measured. Let R be the radius of the test area, as defined above.



R = 36 mm

m = 3,6 fringe spacings; a = 33 mm

m' = 0,4 fringe spacings; b = 23 mm

Figure B.7 — Example of a double-pass interferogram with a non-circular test area, showing 1,6 wavelengths of sagitta error and 1,1 wavelengths of irregularity

In the case of elliptical fringes and a non-circular test area, the sagitta error is determined by

$$\text{Wavefront sagitta error (elliptical fringes, single-pass)} = \frac{R^2(m+m')}{a^2+b^2} \qquad \text{(B.5)}$$

If the element is tested in double-pass, the results of Equation (B.5) shall be divided by 2, if the assumptions in B.1.6.3 are met.

In the case of elliptical fringes and a non-circular test area, the irregularity is determined by

$$\text{Wavefront irregularity (elliptical fringes, single-pass)} = \left| \frac{2R^2\left(a^2m'-b^2m\right)}{a^2\left(a^2+b^2\right)} \right| \qquad \text{(B.6)}$$

If the element is tested in double-pass, the results of Equation (B.6) shall be divided by 2, if the assumptions in B.1.6.3 are met.

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EXAMPLE In Figure B.7, the values of m and m' are 3,6 and 0,4 wavelengths, measured over distances of 33 mm and 23 mm respectively. The radius of the test area is 36 mm. The immediate results of Equation (B.5) and (B.6) are 3,2 wavelengths and 2,16 wavelengths, respectively. Because this element was tested in double-pass, these results are to be divided by 2 according to B.1.6.3. Thus, the wavefront sagitta error according to 3.5 is 3,2/2 = 1,6 wavelengths and the wavefront irregularity according to 3.7 is 2,16/2 ≈ 1,1 wavelengths.

In the case of hyperbolic fringes, the sagitta error is found by the equation:

$$\text{Wavefront sagitta error (hyperbolic fringes, single-pass)} = \left|\frac{R^2(m-m')}{a^2+b^2}\right| \tag{B.7}$$

If the element is tested in double-pass, the results of Equation (B.7) shall be divided by 2, if the assumptions in B.1.6.3 are met.

The irregularity is found in the case of hyperbolic fringes by the equation:

$$\text{Wavefront irregularity (hyperbolic fringes, single-pass)} = \frac{2R^2\left(a^2m'+b^2m\right)}{a^2\left(a^2+b^2\right)} \tag{B.8}$$

If the element is tested in double-pass, the results of Equation (B.8) shall be divided by 2, if the assumptions in B.1.6.3 are met.

If there is tilt between the interferometric reference wavefront and the wavefront under test, it is necessary to note (for both directions of the tilt) the direction of motion of the fringes when the test arm of the interferometer is shortened.

If the fringes, in both cases, move toward the apparent centre of the fringe pattern or if the fringes, in both cases, move away from the apparent centre of the fringe pattern, then the sagitta error exceeds the irregularity, and Equations (B.5) and (B.6) shall be used to estimate the sagitta error and the irregularity, respectively. (In the case of double-pass testing, the results are to be divided by 2, according to B.1.6.3.)

If one set of fringes moves toward its apparent centre, and the other fringe pattern moves away from its apparent centre, then the irregularity exceeds the sagitta error, and Equations (B.7) and (B.8) shall be used to estimate the amounts of sagitta error and irregularity, respectively. (In the case of double-pass testing, the results are to be divided by 2, according to B.1.6.3.)

B.3 Rotationally symmetric wavefront irregularity

The estimation of this deviation by visual methods is difficult if large amounts of other types of wavefront deformation are present. For this reason, digital methods of interferogram analysis are preferred.

If no tilt is present between the test wavefront and the reference wavefront, the fringes appear as concentric circles, but their radii do not increase with the square root of the fringe number, as would be the case with sagitta error. Visual observation of this property is difficult and becomes inaccurate for small deviations. Therefore, the assessment of this type of wavefront deformation is practical only in the presence of tilt.

In the presence of tilt, the fringes are W- or M-shaped, depending on the direction of tilt. In the absence of sagitta error, the two ends and the centre of the fringe nearest the centre of the fringe pattern can be joined by a straight line. In this case, the wavefront irregularity is represented by the deviation of the fringes from straightness. If sagitta error is present in the wavefront, the fringes are curved, as shown in Figure B.8. In this case, the wavefront irregularity may be estimated by the deviation of the fringe nearest the centre from a circular arc joining the two ends and the centre of the fringe, as indicated in Figure B.8.

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The wavefront irregularity is equal to the maximum deviation h of the fringe from a circular arc, divided by the fringe spacing s. The deviation h is measured perpendicular to the circular arc at the point of maximum departure.

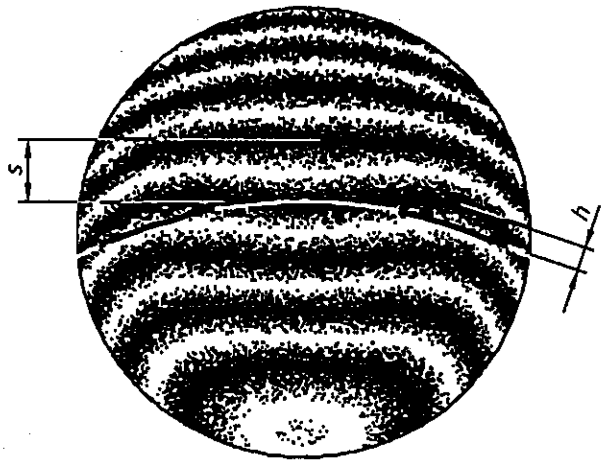

Figure B.8 — Example of a double-pass interferogram showing 0,15 wavelength of rotationally symmetric wavefront irregularity

For single-pass testing, the rotationally symmetric irregularity is given by

$$\text{Rotationally symmetric wavefront irregularity (single-pass testing)} = \frac{h}{s} \qquad \text{(B.9)}$$

If the element is tested in double-pass, the results of Equation (B.9) shall be divided by 2, if the assumptions in B.1.6.3 are met.

EXAMPLE In Figure B.8, the deviation h of the central fringe from straightness is 30 % of the fringe spacing s, so the rotationally symmetric wavefront irregularity as measured in double-pass is 0,3 fringe spacing (the immediate result of Equation (B.9)). According to B.1.6.3, this result is to be divided by 2, giving a value for the rotationally symmetric wavefront irregularity (as defined in 3.9) of 0,15 wavelength.

The degree to which the wavefront deformation is rotationally symmetric is observed by repeating the above test with the tilt adjusted so that the fringes are oriented in another direction. The wavefront deformation is rotationally symmetric if the appearance of the fringes is the same for all orientations of the fringes. The rotationally symmetric wavefront irregularity is that part of the deformation which remains the same for all orientations of the fringes.

B.4 Target aberrations

The visual analysis of interferograms when target aberrations are specified is difficult and not recommended. In principle, it is possible to draw or otherwise generate the interference pattern corresponding to the target aberrations, and examine the difference between this and the actual interferogram. However, the visual appearance of the actual interferogram depends on the amount and orientation of tilt present. Similarly, the exact choice of the radius of the reference sphere (which often has a generous tolerance) influences the visual appearance of the interference pattern. For these reasons, the precise generation of the theoretical interference pattern with which the actual interferogram should be compared is generally not possible, in which case an accurate evaluation can be obtained only through the use of digital analysis techniques.

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