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Optics and photonics — Interferometric measurement of optical elements and optical systems —

Part 2: Measurement and evaluation techniques

Optique et photonique — Mesurage interférométrique de composants et systèmes optiques —

Partie 2: Mesurage et techniques d'évaluation

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

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.

In exceptional circumstances, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example), it may decide by a simple majority vote of its participating members to publish a Technical Report. A Technical Report is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO/TR 14999-2 was prepared by Technical Committee ISO/TC 172, *Optics and photonics*, Subcommittee SC 1, *Fundamental standards*.

ISO 14999 consists of the following parts, under the general title *Optics and photonics — Interferometric measurement of optical elements and optical systems*:

— *Part 1: Terms, definitions and fundamental relationships* (Technical Report)

— *Part 2: Measurement and evaluation techniques* (Technical Report)

— *Part 3: Calibration and validation of interferometric test equipment* (Technical Report)

— *Part 4: Interpretation and evaluation of tolerances specified by ISO 10110*

Introduction

A series of International Standards on *Indications in technical drawings for the representation of optical elements and optical systems* has been prepared by ISO/TC 172/SC 1, and published as ISO 10110 under the title *Optics and photonics — Preparation of drawings for optical elements and systems*. When drafting this standards series and especially its Part 5, *Surface form tolerances* and Part 14, *Wavefront deformation tolerance*, it became evident to the experts involved that additional complementary documentation is required to describe how the necessary information on the conformance of the fabricated parts with the stated tolerances can be demonstrated. Therefore, the responsible ISO Committee ISO/TC 172/SC 1 decided to prepare an ISO Technical Report on *Interferometric measurement of optical wavefronts and surface form of optical elements*.

When discussing the topics which had to be included into or excluded from such a Technical Report, it was envisaged that it might be the first time, where an ISO Technical Report or Standard is prepared which deals with wave-optics, i.e. that is based more in the field of physical optics than in the field of geometrical optics. As a consequence only fewer references than usual were available, which made the task more difficult.

Envisaging the situation, that the topic of interferometry has so far been left blank in ISO, it was the natural wish to now be as comprehensive as possible. Therefore there was discussion, whether important techniques such as interference microscopy (for characterizing the micro-roughness of optical parts), shearing interferometry (e.g. for characterizing corrected optical systems), multiple beam interferometry, coherence sensing techniques or phase conjugation techniques should be included or not. Other techniques, which are related to the classical two beam interferometry, like holographic interferometry, Moiré techniques and profilometry were also mentioned as well as Fourier transform spectroscopy or the polarization techniques, which are mainly for microscopic interferometry.

In order to complement ISO 10110 the guideline adopted was to include what presently are common techniques used for the purpose of characterizing the quality of optical parts. Decision was made to complete a first Technical Report, and to then up-date it by supplementing new parts, as required. It is very likely that more material will be added in the near future as more stringent tolerances (two orders of magnitude) for optical parts and optical systems become mandatory when dealing with optics for the EUV range (wavelength range 6 nm to 13 nm) for microlithography. Also, testing optics with EUV radiation (the same wavelength as they are later used, e.g. at-wavelength testing) can be a new challenge, and is not covered by any current standards.

This part of ISO 14999 should cover the need for qualifying optical parts and complete systems regarding the wavefront error produced by them. Such errors have a distribution over the spatial frequency scale; in this part of ISO 14999 only the low- and mid-frequency parts of this error-spectrum are covered, not the very high end of the spectrum. These high-frequency errors can be measured only by microscopy, measurement of the scattered light or by non-optical probing of the surface.

A similar statement can be made regarding the wavelength range of the radiation used for testing. ISO 14999 considers test methods with visible light as the typical case. In some cases, infrared radiation from CO_2-lasers in the range of 10,6 µm is used for testing rough surfaces after grinding or ultraviolet radiation from excimer-lasers in the range of 193 nm or 248 nm is used for at-wavelength testing of microlithography optics. However, these are still rare cases, which are included in standards, that will not be dealt with in detail. The wavelength range outside these borders is not covered.

Optics and photonics — Interferometric measurement of optical elements and optical systems —

Part 2: Measurement and evaluation techniques

1 Scope

This part of ISO 14999 gives fundamental explanations to interferometric measurement objects, describes hardware aspects of interferometers and evaluation methods, and gives recommendations for test reports and calibration certificates.

2 Measurement objects

2.1 Surfaces

2.1.1 Mirrors: boundary surfaces of optical components in transmission

A common task in interferometry is measurement of the shape of a surface. This can be accomplished in two different ways. Either reflected light or the light transmitted through the surface could be used for the measurement.

Interferometric measurement is achieved by comparing the difference of two optical path lengths $\int nd$. Usually one path is called the reference path, the other the measurement path.

The resulting wave aberration, ΔW, for a displacement d of the surface, if measured in reflection, is $\Delta W = 2nd$. The same displacement measured in transmission results in the wave aberration $\Delta W = (n_2 - n_1)d$.

2.1.2 Reflection degree

The Fresnel reflection from the boundary between two different media, R, can be calculated from the refractive index n_1 and n_2 at the boundary surface.

$$R = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2 \quad (1)$$

For most optical glasses this value is between 4 % and 6 %, so an average of 5 % is usually a good estimate.

This reflection causes a loss of light from the transmitted wavefront at every surface. On the other hand, this reflection is often used for the measurement itself. To obtain maximum fringe visibility, or contrast, the two interfering beams should have approximately the same intensity. Changing the reflectivity of the beam splitter within an interferometer only changes the amount of light in the interference pattern and does not change the beam intensity ratio of the two beams because the light in both arms is transmitted through and reflected by the beam splitter once. If the measurement path and reference path are separated, as in a Mach-Zehnder or Twyman-Green set-up, it is usually possible to adjust the intensities of the light in both arms.

A major problem arises in a Fizeau interferometer. If the reference surface has high reflectance, the result will be multiple beam interference fringes resulting in narrow fringes as in a Fabry-Perot interferometer. If sinusoidal fringes are required as for the evaluation by phase shift interferometry, the reference surface shall have low reflection and an element has to be introduced between the reference and the measurement surface that will absorb light without distorting the wave aberration.

2.1.3 Roughness

For interferometric measurement the roughness of the measured surface should not exceed a certain limit that is a fraction of the wavelength and of the difference of indices of refraction, if used in transmission.

2.1.4 Topology of the regions

Difficulties may arise with interferometer software when the wavefront area has breaks in it (e.g. because it is split into segments by the mechanical supports of the secondary mirror of a mirror telescope). Problems are most severe with static fringe analysis software that depends strongly on using neighbouring points to determine the position and continuity of fringes. Phase shift software is not affected to the same extent as it is a point-by-point evaluation of wave aberrations.

Similar problems may occur if the wavefront area has a complicated outline.

2.1.5 Continuity of the surface; gradient of the surface

Due to the inherent ambiguity of $\pm n \cdot 2\pi$ it is not possible to measure any arbitrary surface shape uniquely. The evaluation of a surface is usually correct, if the wave aberration between two resolvable points is less than π.

The gradient of the surface under test relative to the reference surface results in a gradient of the measured wave aberration and in high-density or closely spaced fringes. Interferograms cannot be evaluated, if the fringe separation is less then twice the distance of two resolvable points. If this condition is not possible by adjustment, or by changing the measurement set-up, compensating optics may be required in some cases.

Some of the problems caused by the ambiguity can be solved by multiple wavelength interferometry.

2.1.6 Stiffness of mirrors; finite-element-calculations

During measurement the method of supporting the optics being tested should not deform them other than when used as intended. It is sometimes difficult to notice whether an object is deformed during the measurement. As a first indication of the influence of the support, the object can be measured by supporting it in two completely different ways. In the case of any doubt, a finite-element-calculation is recommended.

2.1.7 Temperature homogeneity of mirrors

During measurement the object shall have a homogeneous temperature. Inhomogeneous temperatures can cause deformations as the expansion coefficient of optical materials is rather high and the thermal conductivity is very low. Stabilization can take some minutes but may sometimes require several hours.

2.1.8 Examples of measurement objects

Items that can be measured by interferometry include optical flats, windows, raw glass, convex and concave mirrors, lenses, prisms, and optical systems.

2.2 Optical components in transmission

2.2.1 Single-pass versus double-pass testing

Transmitting optical components can be measured in single-pass or double-pass, depending on the interferometric set-up. Double-pass measurement increases the sensitivity by a factor of two but may also include the effect of the reflecting surface. In double-pass measurements consideration shall also be given to the possibility that the returning light passes back through the component at different locations.

2.2.2 Windows (wavefront aberrations in transmission)

For windows the shape error of the surfaces is usually not important. Also, the measured transmitted wavefront will include the homogeneity of the material. Depending on the application, a certain amount of power may be tolerated separate from the other wave aberrations. Also, a tolerated wedge can be measured by interferometry. However, it can be more convenient to measure angular errors by different equipment.

2.2.3 Prisms (wavefront aberrations and angle error)

As in the case for windows, the wave aberrations and angular errors of prisms can be measured by different equipment. However, if the angular tolerances are in the interferometric region, and many parts are to be measured, it can be more convenient to measure both features by interferometry. In this case a fixed set-up, or a master specimen, is used as a reference.

2.2.4 Influence of temperature on the refractive index

For measurement of an optical component in transmission, it shall be noted that not only the objects might be deformed by the thermal expansion but, also, that the refractive index of the material changes with temperature. Therefore, thermal setting of the test piece before testing is even more important.

2.3 Optical systems

2.3.1 Single-pass versus double-pass testing

Complete optical systems can be measured by interferometry in a manner similar to the testing of single components. It is, however, important that systems be measured in the same geometry as they were designed to be used. This can lead to a complicated set-up in single or double pass. For long systems tested in double pass and in the presence of severe aberrations, it is necessary to take into account that the light path on the way back can be considerably different to that in the forward direction.

2.3.2 Examination in the pupil

Interferometric measurements should be made in the exit pupil of the optical system.

2.3.3 Chromatic aberrations

If systems are measured at wavelengths different than those they are designed for, the effects caused by chromatic aberrations shall be computed. There will be some systems, where the wave aberrations can be simply scaled by the ratio of the test and design wavelengths, whereas other systems are so different that a measurement is not possible.

2.4 Indirect examination of the function of optical elements

2.4.1 Examination with different wavelength

Usually the measurement of windows is possible and can be scaled to the correct wavelength. It shall be noted, however, that inhomogeneities of optical materials may to some degree depend on the wavelength range. Because of the presence of chromatic aberrations no universal recommendation is possible.

2.4.2 Examination with different beam path

Usually the measurement set-up should be as similar as possible to the application. In some cases, however, it is more convenient to measure optical elements in a way that is different from their use. In this case, it may be difficult to find a correlation between the measured wave aberration and the tolerances and, therefore, not possible to evaluate how the application is affected.

2.4.3 Tolerance range

Sometimes the relationship between the interferometric measurement and the tolerances of the measured objects is not clear. Usually the complete test set-up shall be considered.

3 Hardware aspects of an interferometer and test environment

3.1 General

The purpose of this clause is to acquaint the user of an interferometer set-up to possible influences on the accuracy of measurements. It is a matter of fact that two different persons using the same hardware and doing their measurements in the same laboratory, will not necessarily achieve identical results with their measurements. The skilled user might achieve a highly accurate result, whereas the unskilled user might have severe errors in his result that he might not be aware of. It is important to keep in mind that good reproducibility of measurement is no guarantee for a correct result, because systematic sources of errors might have influenced the measured results. Knowledge about such possible influences, and how to avoid them, is what experimental skill is about.

Such sources of errors can be, for example:

— improper use of the measuring instrument, because the optical principles are not well understood, e.g. failure to image the surface under test onto the CCD camera of the interferometer;

— use of unsuitable fixtures to hold the test piece, inducing strain which causes bending;

— influence of gravity on the test piece;

— vibrations of the test set-up, which might induce phase-measuring errors;

— unsuitable use of polynomial fits with respect to the given shape of the aperture (for example due to some obscured parts of the circular shape) and adjacent subtraction of error terms like tilt and focus terms, due to an violation of the orthogonality assumption;

— presence of stable layers of air with different temperatures in the interferometer cavity, causing coma and astigmatism;

— flipping (mirroring), or some other mismatch, of a calibration error map with respect to the actual orientation, shape or magnification of the measured field;

— influence of different temperature or different focus settings between calibration and measurement;

— use of test pieces which are not homogeneous in temperature and have a considerable coefficient of temperature expansion.

These are only examples; although there are a much greater number of “typical” sources of error. The only way to overcome such types of error, which depend very much on the actual test situation and the demands for the final accuracy, is that the operator planning and assembling the test should be aware of possible influences on the accuracy of the measurement, which might be of optical or mechanical nature.

Conceptually, it is very important not to believe blindly the results which the instrument shows. At the same time, it is equally important not to blame the instrument, or the principle of the interferometric measurement, if there are inexplicable results. Note that in the majority of cases the instrument shows the “correct” readings from what is presented to it, even if that is not the measurement task in question. If, for example, the measured error map does not rotate by 72° when the test piece is rotated physically by 72°, this might indicate that the reference surface may contribute a considerable amount to the total error. The support of the test piece can also influence the measurement, etc.

Another test might be, to repeat the measurement after 1 h without touching anything in the meantime. If the results deviate from each other the reason might be that the temperature of the supports of the surface under test, may have had an uneven temperature distribution in the first test. Normally, it may take more than 30 min before the temperature has homogenized after handling a part. Also, the temperature in the laboratory might have changed, the instrument might have warmed up, etc.

Such tests are imperative in order to exclude at least the most common sources of error. It is strongly recommended to repeat a measurement at least three times and compare the results; this repetition should include the demounting and remounting of the part in the test set-up, as well as all the adjustments of the set-up and the settings of the interferometer. It is even better to repeat the whole test procedure on another day, and, even by another operator.

All measurement conditions and settings have to be documented and the final data sets should be stored in the computer in an organized way. Ideally, the documentation should be stored together with the measured data sets. Any further treatment like subtraction of tilt or even higher order (Zernike) functions, number of averages, any filtering like smoothing with a spatial low pass or median filter to remove “spikes”, shall be documented and stored together with the data set. Such information is part of the result and when not given together with the measured surface map, the result is useless and cannot be used for proof of quality for the part under test.

3.2 Construction principles and influences on the quality of measurements

3.2.1 General

When the wavefront deviation of a test piece is measured by an interferometer, the test piece becomes part of the optics of the instrument. The auto-collimation condition shall be met, as well as the condition to image the surface under test onto the detector. In order to achieve high flexibility of possible locations for the surface under test and for different test configurations, there will be stringent requirements on the spatial and temporal coherence of the light source which need to be fulfilled. These can easily be attained by use of a laser and, together with a very high intensity compared to other light sources, are the reason that the laser is the standard light source for interferometers.

One of the consequences of the very high coherence of lasers is that all kinds of defects, such as impurities of substrates, optical cements and coatings, tiny scratches, bubbles, holes, dust particles, micro-roughness of surfaces, which can occur at any part of the light path through the interferometer, are “collected” and are superimposed as an uncleanliness, i.e. unwanted amplitude and phase modulations of the wavefronts which finally show clearly on the interferogram. The further away the disturbing defects are from an image plane of the detector, the more the defects are altered in their phase distributions due to Fresnel diffraction and in spatial frequency. A very narrow defect located on a surface near an image of the light source might spread out to a big size in the detector plane. The specification of optical parts used in an interferometer set-up therefore have to be much more stringent than in conventional optical instruments and depend on the position of the part in the ray-path. For surfaces which are at a position near the image of the light source, where the diameters of the ray bundles are small, ultra-high surface quality requirements shall be fulfilled. Generally speaking, the higher the test accuracy has to be, the more severe are the demands for the quality of all parts.

As discussed in ISO/TR 14999-1, it is very important to image the wavefront under test onto the detector plane. If the location of this wavefront relative to the instrument changes from one test set-up to another, a possibility of refocusing the detector to this new location shall be provided. In some instruments, provision is made to alter the magnification with which the wavefront under test is imaged onto the detector. In some cases, this is done in fixed steps, in other cases this is done continuously over a certain range. On the other hand, it is necessary to attain a good optical wavefront-correction when “tailoring” the wavefronts in the instrument to the desired shape and at the same time realizing a good optical transfer function for the amplitude and phase when imaging the wavefront under test at the detector plane.

All such possibilities and demands cause a certain amount of complexity of the optical layout of such an instrument, leading to optical systems with multiple surfaces. It is obvious that it is more difficult to keep the unwanted additional disturbances by the optical parts small when more optical parts are necessary to achieve the desired functionality. The skill of the designer of an instrument lies in finding the best compromise between the degree of aberration correction (keeping the wavefront errors with low spatial frequency small) and the degree of noise (i.e. high spatial frequency errors). The noise increases with every additional surface which might be necessary for aberration correction. Since the complexity of the optical layout grows with the universality of the use of the instrument, it is much easier to construct a high-quality single-purpose instrument.

Due to higher cost of production, and the deterioration in the appearance of the interferograms obvious to any customer, companies tend to minimize the number of optical elements and seek to achieve the best correction for wavefront aberrations. This might have consequences for the handling of the instrument. If, for example, the transmission sphere, used for spherical testing, is not aligned properly when attached to the instrument, coma and astigmatism might be introduced into the measured wavefront. If deviations in the alignment of the focus setting between calibration measurements and final measurements for the parts under test exist, this again might cause wavefront errors in the final results. On the other hand, a highly corrected instrument might be much more “robust” against such higher order errors, but at the cost of a higher number of surfaces and therefore a higher amount of coherent noise.

The opposing criteria for the way to design a laser interferometer require a compromise between wavefront quality, field correction, versatility on the one hand and number and location of surfaces on the other hand.

3.2.2 Intrinsic instrument errors and the principle of common path

The task gets more and more difficult when the errors, which have to be measured accurately, become smaller and smaller. It might be concluded from this that it would be nearly impossible to get reliable measuring results. Needless to say, it is necessary that the “intrinsic errors” caused by the instrument itself should be at least not higher than the errors caused by the test piece. Example: suppose the test piece is a very well polished spherical surface of a lens. The interferometer itself might include in total 12 lens surfaces and another 10 surfaces of plane plates. Therefore, it would be necessary to fabricate the 22 surfaces within the instrument to a degree of perfection that is at least 22 times better than that of the test piece in order to attain the same disturbance from the instrument (i.e. “intrinsic errors”) and from the test piece. Or, if argued with statistically distributed errors, it might be concluded that already a factor 4 to 5 would be sufficient. Even in the latter case, it would be nearly impossible to fabricate and maintain an instrument with such a degree of perfection.

This argument is both right and wrong. It is the principle of interference that errors common to both waves, i.e. the test wave and the reference wave, cancel out. The ultimate use of this principle is apparent in the Fizeau type interferometer, where all but the last surface before the surface to be tested and the air between these two surfaces are common to both waves. The quantity that is measured by a Fizeau interferometer is the optical path difference between the two surfaces facing each other (the “optical thickness-distribution” of the air-gap; this includes the distribution of the refractive index of the air). So far the argument is wrong; but it is right for very small-scale errors. It is never possible for the rays to travel exactly the same path, so the principle of “common path” with cancellation of common errors is always violated, if high spatial frequency noise is in demand. So, even if Fizeau interferometers are more robust for errors with low spatial frequencies, this is not the case for coherent noise.

In order to check the sensitivity of an instrument to alignment errors as well as for intrinsic high frequency noise, the following two tests can be useful.

a) The following simple test should be repeated with different orientations of the fringes and also with the highest number of fringes the instrument is capable of measuring. This test is one measure for the robustness of the instrument against misalignments of all kinds. Proceed as follows.

    1) Place a reference flat in front of the transmission flat of the instrument and adjust for about 25 fringes of tilt.

    2) Perform a measurement and store the result.

    3) Adjust for zero-fringes and perform another measurement.

4) Subtract both data sets and compute the Zernike terms for the resulting difference-data set; besides other errors, the induced wavefront tilt with respect to the optical axis make visible the optical wavefront aberrations which go along with the small angle of the test wave.

b) The second test checks the intrinsic high frequency noise and therefore the ability to detect small-scale errors which normally go along with very small amplitudes. Proceed as follows.

1) Take the data of the difference from the measurement on-axis and the measurement with the 25 fringes of tilt.

2) Subtract the first 36 Zernike terms. The remaining surface map shows mainly the intrinsic coherent noise of the instrument.

3) When “spikes”, which occur at the boundary of measured part, are removed, the r.m.s. value is a quality number for the intrinsic noise. This noise should be uncorrelated when the experiment is repeated with different orientations of the fringes and therefore reduce with the square root law, if measurements with different fringe orientations are averaged and the difference of those averages are calculated instead of the difference of only two measurements.

Together with these tests, it is recommended that two other simple checks be performed to assess the proper alignment of the instrument:

The collimation of the plane-wave leaving the system can be checked with the help of a thick (> 30 mm) plane-parallel plate of known good optical quality by inserting the plane parallel plate with an incident angle of 45° into the beam and projecting the lateral shearing interferogram onto a screen. If the plate has no wedge-angle, no fringes should be visible, but they will be present if the wavefront from the interferometer converges or diverges.

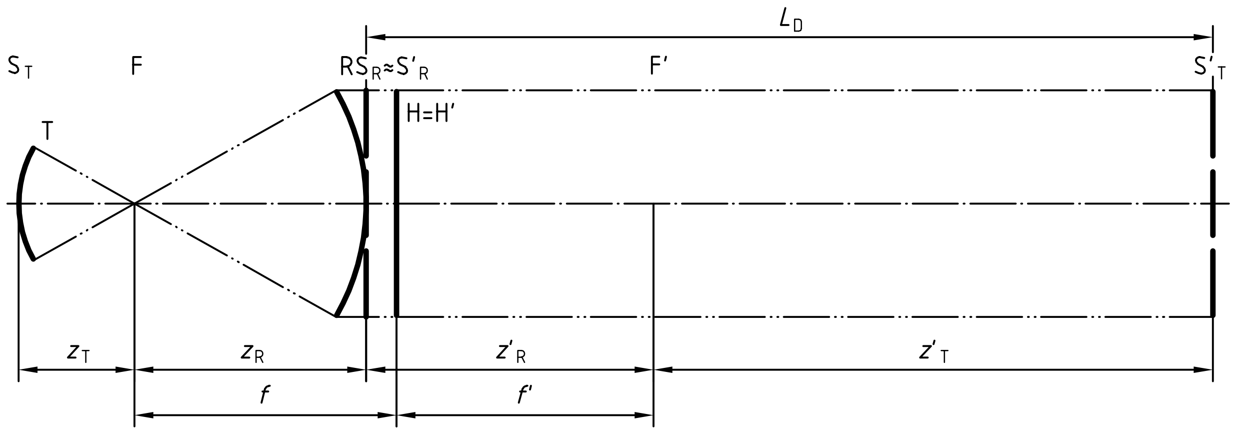
The adjustment for the alignment reticle, or other means for the alignment of the beam, can also be checked using a corner-cube mirror or prism of known good quality. The returning beam should be incident precisely at the centre of the alignment device. This is also a method for adjusting the reference surface perpendicular to the beam. By tilting the reference surface, the interference fringes formed by the reference wave and a wave reflected by the triple-mirror (having three surfaces with angles of 90° between them) should be made as broad as possible.

3.2.3 Optical compensation of errors

It is a very useful property of two-beam interference that the physical principle can help to suppress the errors caused by component parts of the interferometer. If the two interfering beams experience the same disturbances when passing through the optical parts, the wavefront errors impressed on them are identical and cancel out in the final wavefront difference. Therefore, the two wavefronts should travel almost the same path through the instrument so ensuring that “optical compensation” of errors takes place. This is achieved best by the arrangement of a Fizeau test set-up, where the test surface and the reference surface face each other without any component in between. This cancellation is not necessarily perfect, if there are deviations in the optical path when the beams are tilted with respect to each other.

Another deviation from perfect symmetry of the interfering waves is due to the imaging conditions of the two surfaces in question onto the detector. The two surfaces in a Fizeau configuration, the test surface and the reference surface, cannot both be imaged exactly onto the detector surface at the same time. Normally, the reference surface is larger than necessary, so that the surface under test defines the final aperture for the size of the interferogram. In this case, no errors are introduced to a first order by Fresnel diffraction at the boundary of the reference surface, when this boundary is larger than the diameter used. Nevertheless, there remains an error influence, but it is so small, that it will not be visible in most cases. There is another higher-order error, which will be explained in conjunction with the testing of spherical surfaces with a so-called “Fizeau transmission sphere”.

Figure 1 shows the optical conditions when testing a spherical surface T with respect to a reference surface R. In this example, it is assumed that the reference surface R (this is the last surface of the transmission sphere) as well as the test-surface T are both concave. The apexes of the surfaces are called S_R and S_T. The Fizeau cavity is set up correctly when both surfaces are arranged so that they have a common centre of curvature. If the Fizeau lens is calculated and manufactured properly, this centre point coincides with the focal point F of the spherical wave, illuminating the reference surface R. It is supposed that this is the case.



Key

L_D defocus

Figure 1 — The images S_R' and S_T' of the apexes of the reference surface S_R and the test surface S_T are defocused with respect to each other

As can be seen from Figure 1, both surfaces in question are imaged by the transmission sphere (which is optically represented by the principal plane H=H′ and the focal points F and F′) into different locations at the optical axis. The sizes of the images match, but the axial distance between the images, L_D (the "defocus") is shown in Figure 1. Now, it is supposed that there might be aberrations already present in the wavefront illuminating the transmission sphere as well as additional aberrations added by the transmission sphere itself. The transmission sphere should image an infinite object into the focus point F without introducing additional spherical aberration, as well as the test surface T into its image T′ and the reference surface R into R′ without adding different phase-terms into these images.

As was explained in ISO/TR 14999-1:2005, 2.11, only ideal plain waves do not alter their shape when they spread out. So, even if we suppose that the two wavefronts at the locations S_R' and S_T' might still have the same shape, i.e. the same aberrations, the fact that one of them has to travel the distance "defocus" will cause them to deviate from each other when they meet to interfere on the detector. This effect is the more pronounced the larger the distance "defocus" is compared to the diameter of the wavefront. As a rule of thumb, the radius of the test surface should not be smaller than 10 % of the focal length of the transmission sphere. Also, the transmission sphere should not introduce an error greater than $\lambda/2$ in double pass. For high-precision measurements, these tolerances shall even be more stringent.

It is important to keep in mind that any wavefront error, which is already present in the plane wavefront entering the transmission sphere, will be made visible also by this effect of defocused images. There is no way to overcome this problem with Fizeau interferometers other than to keep the defocus as small as possible by using a transmission sphere with the smallest possible air gap. The influence of this error can be minimized by appropriate calibration measurements.

3.2.4 Mathematical compensation of errors

The great advantage of "optical compensation" of errors due to the principle of "common path through the optics" is that this compensation takes place in "real time", i.e. continuously during the measurement.

In contrast to that approach, an even better effect can be gained when two measurements are performed, including all the errors of a test set-up "left over" by the optical compensation scheme (Fizeau or Twyman-Green or others). The first measurement is with a "calibration master" and the second with the test piece. The resulting error maps are stored in computer memory. Suppose that nothing but the master and test pieces have changed between the measurements, the difference of the two measurements should show only the difference in the shape of the master piece and the test piece. All other errors should cancel out by this “mathematical compensation for the intrinsic errors” of the test set-up. Therefore the master plays a similar role as the reference wavefront, but this time some higher order errors, like “defocus” discussed in the context with Figure 1, also cancel out due to the higher degree of “symmetry” compared to the normal Fizeau test.

The drawback with this method is that, in principle, two measurements are necessary to get the result which increases the statistical errors by a factor of $\sqrt{2}$, and that the two measurements cannot be performed both at the same time. In order that this mathematical compensation of errors be effective, it shall be assured that the calibration measurement is still valid for the actual measurement of the test piece. It is therefore highly recommended to take the calibration measurement at a time immediately before or after (or both) the measurement of the test surface.

This “mathematical compensation” can have some important advantages compared to the “optical compensation”:

— Master piece and test piece may have the same radius of curvature, e.g. the imaging properties onto the detector are identical both times.

— Influences of gravitational deformations, quasi-stationary temperature gradients, etc., are cancelled out to some extent.

— The reference piece may be made much thicker than the transmission sphere will normally be. If it is made more stable than the test piece, this might be helpful in some situations. For example, the “bending” of the test piece by the support will show in the result. In other cases, it may be possible to produce an almost identical master (but with a known error map) for calibration purposes.

— A greater flexibility exists for the design of the test configuration. Especially, the reference surface does not have to be the last surface of a transmission sphere any longer, but it could be a plane surface in front of the lens. In this way, “tilt” can be introduced into the test configuration, without causing uncompensated errors.

This last point is an important one, and will be explained later in greater detail.

3.2.5 Contrast as a function of the irradiance in test and reference arm: methods to attain equilibrium in both arms

It is well known (see ISO/TR 14999-1:2005, 3.2.1), that the intensity of two beam interference $I(x)$ is described by the formula

$$I(x) = I_1(x) + I_2(x) + 2\sqrt{I_1(x) I_2(x)}\,|\gamma| \cos\left[\frac{2\pi}{\lambda} \Delta l_{\mathrm{OPD}}(x)\right] \quad (2)$$

where

x is a vector describing the spatial coordinates, which may be on the detector or the surface under test;

Δl_{OPD} is the complete “optical path difference” of the two interfering beams, in principle from the light source all the way down to the detector (practically, in Fizeau interferometers, it is twice the “optical thickness” of the cavity, because of the (quasi) identical paths of the two beams through most parts of the interferometer, as was discussed before);

$|\gamma|$ is the magnitude of the complex degree of coherence; this quantity is close to unity in most cases when using a laser as the light source;

$I_1(x)$ and $I_2(x)$ are the intensities of the interfering wavefronts when measured separately.