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Optics and optical instruments — Accuracy of optical transfer function (OTF) measurement

Optique et instruments d'optique — Exactitude du mesurage de la fonction de transfert optique (OTF)

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Contents

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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.

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.

International Standard ISO 11421 was prepared by Technical Committee ISO/TC 172, *Optics and optical instruments*, Subcommittee SC 1 *Fundamental standards*.

Annex A forms an integral part of this International Standard.

Annexes B, C and D are for information only.

Introduction

The optical transfer function (OTF) is one of the main criteria used for objectively evaluating the image-forming capability of optical, electro-optical and photographic systems.

The terms used in the measurement of OTF are defined in ISO 9334, whilst ISO 9335 covers the actual principles and procedures of measurement. A further International Standard, ISO 9336, deals with specific applications in various optical and electro-optical fields and is in several parts, each dealing with a particular application.

Although ISO 9335 lists the main factors which influence the accuracy of OTF measurement and describes procedures which are aimed at achieving accurate and repeatable results, it does not cover in detail the techniques and procedures for evaluating the accuracy of OTF measuring equipment and for estimating the uncertainty in measurements made on specific imaging systems.

The present International Standard lists the main sources of inaccuracy in OTF measuring equipment and provides guidance on how these can be assessed and how the results of these assessments can be used in estimating the error band in any measurement of OTF. One of the aims in preparing this International Standard is to encourage the setting of more realistic uncertainty levels for the results of OTF measurements. Another is to encourage the use of methods of expressing the accuracy of OTF test equipment which recognize the fact that the accuracy of a particular measurement is a function of both the equipment and the test piece.

Optics and optical instruments — Accuracy of optical transfer function (OTF) measurement

1 SCOPE

This International Standard gives general guidance on evaluating the sources of error in optical transfer function (OTF) equipment and in using this information to estimate errors in a measurement of OTF. It also gives guidance on assessing and specifying a general accuracy value for a specific measuring equipment, as well as recommending methods of routine assessment.

The main body of this International Standard deals exclusively with the modulation transfer function (MTF) part of the OTF. The phase transfer function (PTF) is dealt with relatively briefly in annex A.

2 NORMATIVE REFERENCE

The following standard contains provisions which, through reference in this text, constitute provisions of this International Standard. At the time of publication, the edition indicated was valid. All standards are subject to revision, and parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent edition of the standard indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

ISO 9334:1995 *Optics and optical instruments - Optical transfer function - Definitions and mathematical relationships*

3 DEFINITIONS AND SYMBOLS

3.1 DEFINITIONS

For the purposes of this International Standard, the following definitions apply.

3.1.1 standard lens

Single- or multi-element lens which has been constructed with a level of accuracy which is sufficient to ensure that for precisely specified conditions of measurement the MTF will be equal to that predicted from theoretical calculations to an accuracy of better than 0,05 (MTF units).

NOTE - In order to achieve this accuracy, standard lenses are usually of simple construction and therefore of limited performance. An example of a widely used lens is the 50 mm focal length plano-convex lens described in reference [3]. This and several other standard test lenses (including afocal systems and lenses operating in the infrared wavelength bands) are available commercially.

3.1.2 audit lens

Single- or multi-element lens of stable construction whose accuracy of construction is not sufficient to enable the MTF to be predicted by calculation from design data (usually as a result of the complexity of the lens), but whose "accepted" values for the MTF under precisely defined measuring conditions have been obtained by measurements done by a reputable authority (preferably a national standards laboratory, if such a service is available).

3.2 SYMBOLS

Symbol	Meaning	Unit
h	object height	mm, mrad, degree
h'	image height	mm, mrad, degree
$\Delta h'$	error in image height	mm, mrad, degree
l	object conjugate	mm
l'	image conjugate	mm
$\Delta l'$	error in image distance	mm
Δz	departures from straightness of object slide	mm
$\Delta z'$	departures from straightness of image slide	mm
Δa	angular departure of object slide from perpendicularity to reference axis	rad
$\Delta a'$	angular departure of image slide from perpendicularity to reference axis	rad
ΔZ	total departure from ideal object plane	mm
$\Delta Z'$	total departure from ideal image plane	mm
M	magnification	dimensionless
r	spatial frequency	mm^{-1}, $mrad^{-1}$, $degree^{-1}$
Δr	error in spatial frequency	mm^{-1}, $mrad^{-1}$, $degree^{-1}$
$m(r,h)$	rate of change of MTF with object focus (for image intensifier and similar systems)	mm^{-1}
$m'(r,h')$ or $m'(r,\omega)$	rate of change of MTF with image focus	mm^{-1}
$p'(r,h')$ or $p'(r,\omega)$	rate of change of MTF with image height	mm^{-1}, $mrad^{-1}$, $degree^{-1}$
$q'(r,h')$	rate of change of MTF with image distance	mm^{-1}
ω	field angle	mrad, degree
$\Delta\omega$	error in field angle	mrad, degree
f	focal length	mm
ψ	azimuth angle	degree
$\Delta\psi$	error in azimuth angle between slits	degree
R	(test lens focal length)/(collimator focal length) or (decollimator focal length)/(collimator focal length)	dimensionless
g'	width of slit referred to image plane	mm
L'	length of shorter slit referred to image plane	mm
MTF_c	MTF of relay lens	dimensionless
r_o	spatial frequency for zero field angle	mm^{-1}, $mrad^{-1}$, $degree^{-1}$
$n'(r, h')$	rate of change of MTF with spatial frequency	mm, mrad, degree
$\Delta MTF(r)$	error in MTF	dimensionless
$\Delta MTF_c(r)$	MTF error of the relay lens	dimensionless
ΔMTF_{rl}	MTF errors resulting from aberrations of relay lens error	dimensionless
Δl	error in setting collimator focus	mm
ΔMTF(random)	total error in MTF random sources	dimensionless
ΔMTF (systematic)	total error in MTF systematic sources	dimensionless
ΔMTF(total)	total error in MTF from all sources	dimensionless
$\Delta MTF(rand)_n$	error in MTF from nth source of random error	dimensionless
$\Delta MTF(syst)_n$	error in MTF from nth source of systematic errors	dimensionless

NOTE - The notation $m(r,h)$, $m'(r,h')$, $p'(r,h')$ etc. denotes that these parameters are functions of both spatial frequency r and image height h' or h (i.e. the value of the parameter will be different for different frequencies and different image heights).

4 SOURCES OF INACCURACY IN MEASURING EQUIPMENT

In this clause the main sources of inaccuracy in OTF measuring equipment are listed and the effects on a measurement of MTF described (brief comments on the measurement of PTF will be found in annex A).

4.1 GEOMETRY OF OPTICAL BENCH SYSTEM

The function of the optical bench is to provide a means for supporting the "test target unit", the "test specimen" and the "image analyser" in the correct geometrical relationship (i.e. that defined by the chosen I-state, in accordance with ISO 9334). To achieve this one normally relies on such things as the straightness of slideways, their parallelism to each other and/or to the surface to which the test specimen is referenced, the accuracy of angle scales etc. Departures from the assumed geometry result in deviations from the ideal I-state and therefore errors in the measured OTF. The important bench parameters depend on the test arrangement being used (note that for bench arrangements such as "nodal slide benches" which are not covered by this International Standard, the user must make his own assessment of errors). For the arrangements recommended in ISO 9335, the main sources of inaccuracy and the resulting MTF errors are as follows.

4.1.1 Object and image at finite conjugates

Both the test target unit (TTU) and image analyser slideways shall be straight and perpendicular to the "reference axis".

Departures from straightness and perpendicularity will produce departures from the ideal focal planes given by:

$$\Delta Z(h) = \Delta z(h) + h \cdot \Delta a$$

for the TTU and

$$\Delta Z'(h') = \Delta z'(h') + h' \cdot \Delta a'$$

for the image analyser, where h and h' are object and image heights, Δz and $\Delta z'$ are departures from straightness and Δa and $\Delta a'$ angular (radian) departures from perpendicularity to the reference axis, for the TTU and image analyser slideways respectively.

The combined effect is given by:

$$\Delta Z'(h')_{\text{total}} = \Delta Z'(h') + M^2 \cdot \Delta Z\left(\frac{h'}{M}\right)$$

where $M = \dfrac{h'}{h}$ is the magnification.

If $m'(r,h')$ is the rate of change of MTF(r) with focus, then the error in MTF is given by:

$$\Delta \text{MTF}(r) = m'(r,h') \cdot \Delta Z'(h')_{\text{total}}$$

Two further possible sources of error are in the accuracy with which the image height h' is set and the accuracy with which the object and/or image distances are set. The error in MTF is in this case given by (assuming image height and image distance are the parameters set):

$$\Delta \text{MTF}(r) = p'(r,h') \cdot \Delta h' + q'(r,h') \cdot \Delta l'$$

where $\Delta h'$ and $\Delta l'$ are the errors in image height and image distance respectively and p' and q' are the corresponding rates of change in MTF. Usually p' and q' are small and this source of error may be ignored (i.e. errors will be less than 0,01 in MTF units).

4.1.2 Infinite object and finite image conjugates

Similar considerations as for 4.1.1 apply except that there is only a single slideway. Departures from the ideal focal plane are given in this instance by:

$$\Delta Z'(h')_{\text{total}} = \Delta z'(h') + h' \cdot \Delta a'$$

and the corresponding error in MTF is given once again by:

$$\Delta \text{MTF}(r) = m'(r, h') \cdot \Delta Z'(h')_{\text{total}}$$

Errors may also arise from errors in setting image height or field angle (whichever is used in defining the I-state) and in setting the object distance to be infinity. These give MTF errors as previously, i.e.:

$$\Delta \text{MTF}(r) = p'(r, h') \cdot \Delta h' + q'(r, h') \cdot \Delta l'$$

or, if field angle rather than image height is specified:

$$\Delta \text{MTF}(r) = p'(r, \omega) \cdot \Delta \omega + q'(r, h') \cdot \Delta l'$$

In the above equations h', $\Delta l'$, p' and q' are as defined in 4.1.1, ω is the field angle and $\Delta\omega$ is the error in the field angle. The value of $\Delta l'$ shall be determined from the known departure of the object conjugate from infinity. The relevant equation is:

$$\Delta l' = \frac{f^2}{l}$$

where f is the focal length of the lens and l is the actual object conjugate.

Usually errors in MTF from these latter two sources are small and may be ignored except where, instead of using a collimator, a very long object conjugate is used on the assumption that it provides a sufficiently close approximation to an infinite conjugate.

4.1.3 Infinite object and image conjugates

With the recommended bench arrangement for this type of measurement (see ISO 9335) the separation between image analyser and decollimator should not change as the image angle varies. There is therefore no MTF error resulting from a change in focus setting with image angle (or field angle).

If bench arrangements are used where this error can occur, or, if as a result of mechanical flexing of the focal slide which supports the decollimator and image analyser their separation may change, then an error in the MTF may result, given by:

$$\Delta \text{MTF}(r) = m'(r, \omega) \cdot \Delta z'(\omega)$$

where $\Delta z'(\omega)$ is this mechanical error, and $m'(r,\omega)$ is the rate of change of MTF with focus.

Other sources of error are inaccuracies in setting field angle and in setting the object distance to be infinity. The resulting MTF errors are given by the relevant equations of 4.1.2, i.e.:

$$\Delta \text{MTF}(r) = p'(r, \omega) \cdot \Delta \omega + q'(r, h') \cdot \Delta l'$$

whereas before

$$\Delta l' = \frac{f^2}{l}$$

4.1.4 Image intensifiers and other systems with physically defined object and/or image surfaces

An accepted procedure when testing this type of system is to refocus the test target onto the object plane and/or the image plane onto the image analyser, for every test position in the image/object plane. With this procedure, focus errors arising from mechanical bench errors are eliminated. The only other source of error is from incorrectly setting the specified test positions in the object or image surfaces. The resulting MTF errors are usually negligible, and are given as in 4.1.1 by:

$$\Delta\text{MTF}(r) = p'(r,h') \cdot \Delta h'$$

If a test procedure is used where no refocusing is carried out when the object/image position is changed and reliance is placed on the TTU and image analyser slideways being straight and parallel to their respective object/image surfaces, then MTF errors are given by:

$$\Delta\text{MTF}(r) = m(r,h)[\Delta z(h) + h \cdot \Delta a] + m'(r,h')[\Delta z'(h') + h' \cdot \Delta a']$$

4.1.5 Mounting of test piece

The test piece may not always locate exactly as intended on the mount to which it is attached on the equipment. This will introduce some variability in the results of a sequence of measurements where the test piece has been removed from and remounted on the equipment between each measurement. The main effect is likely to be a small tilt of the image plane. The effect on the measured MTF, which can be very significant, is given by the same equations as for angular errors in the slideways (see 4.1.1).

4.2 AZIMUTH CHANGING

With most OTF equipments a change in measurement azimuth is achieved by rotating the TTU and the image analyser. This rotation can result in a movement of the TTU and or the image analyser along the direction of the axis of rotation. This will produce a focus change which will be denoted as:

$\Delta z(\psi)$ and $\Delta z'(\psi)$,

for the TTU and image analyser respectively, where ψ is the azimuth angle. The MTF error resulting from this focus change is given in 4.2.1 to 4.2.4 for each of the bench configurations.

4.2.1 Object and image at finite conjugates

$$\Delta\text{MTF}(r) = m'(r,h')\left[\Delta z'(\psi) + M^2 \cdot \Delta z(\psi)\right]$$

4.2.2 Infinite object and finite image conjugates

$$\Delta\text{MTF}(r) = m'(r,h')\left[\Delta z'(\psi) + R^2 \cdot \Delta z(\psi)\right]$$

where R is the ratio $\dfrac{\text{(test lens focal length)}}{\text{(collimator focal length)}}$.

Usually R^2 will be small and the second term in the brackets may be ignored.

4.2.3 Infinite object and image conjugates

$$\Delta\text{MTF}(r) = m'(r,\omega)[\Delta z'(\psi) + (M \cdot R)^2 \Delta z(\psi)]$$

where R is the ratio $\dfrac{\text{(decollimator focal length)}}{\text{(collimator focal length)}}$) and M is the magnification of the test telescope.

4.2.4 Image intensifiers and other systems with physically defined object and/or image surfaces

If a test procedure is used where the test target is refocused on to the object plane and/or the image plane on to the image analyser, for every test azimuth (see 4.1.4) then no errors will result. If a test procedure is used where no refocusing is carried out when the object/image azimuth is changed, then MTF errors are given by:

$$\Delta \mathrm{MTF}(r) = m(r,h) \cdot \Delta z(\psi) + m'(r,h') \cdot \Delta z'(\psi)$$

4.3 ALIGNMENT (ORIENTATION) OF TTU AND IMAGE ANALYSER

If both the TTU and the image analyser use mask patterns which are not circularly symmetric, then their relative orientation is important. Usually one or both of the masks is in the form of a slit perpendicular to the scan direction. The effect of any angular misalignment $\Delta\psi$ between the two (see figure 1) will result in an effective increase in width of the slit, given by:

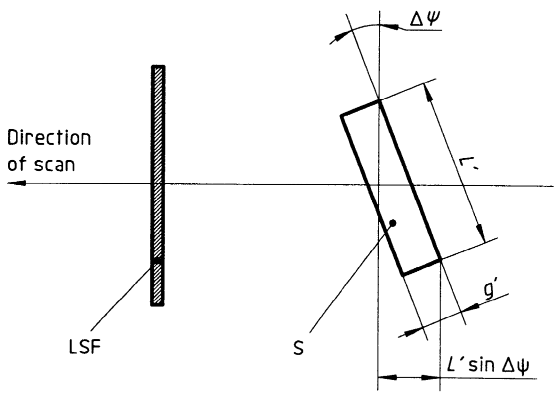
$$\Delta g' = L' \cdot \Delta\psi$$

where L' is the length of the shorter of the two slits, referred to the image plane. The error in MTF resulting from this is given by:

$$\Delta \mathrm{MTF}(r) = \pi \cdot r \cdot L' \cdot \Delta\psi \cdot \mathrm{MTF}(r) \cdot \left(\frac{1}{(\pi \cdot r \cdot g')} - \frac{1}{tan(\pi \cdot r \cdot g')} \right)$$

where g' is the assumed width of the slit, referred to the image plane.

It is important to note that in some types of equipment a combination of a slit and a grating is used to generate a periodic target whose spatial frequency can be altered by changing the orientation of the grating with respect to the slit. Spatial frequency errors will usually result from any errors in the relative orientation of the slit and grating. The user must make his own assessment of the effect of such errors (see 4.6 for the effect of spatial frequency errors on MTF).



$$W = g' + L'\sin\Delta\psi$$

Key

LSF Line spread function
S Image analyser slit
L' Length of slit
g' Width of slit
$\Delta\psi$ Angular misalignment
W Effective slit width

Figure 1 - Errors from alignment of analysing slit with respect to object pattern

4.4 CORRECTION FACTORS

Correction factors are applied to MTF measurements to allow for the effect of equipment constants such as the finite width of target and/or analyser slits, the MTF of incoherently coupled relay lenses and the effect of off-axis measurement geometry on spatial frequency (see ISO 9335). Errors in MTF will occur either if these factors are not applied, or if there is an error in the value of the applied correction factor. Only the most common correction factors are considered here. However, these may be taken as examples of how to deal with other types of correction factor.

4.4.1 Slit width errors

Errors or uncertainties in the widths of slits will introduce errors in the measured MTF, given by:

$$\Delta \mathrm{MTF}(r) = \pi \cdot r \cdot \mathrm{MTF}(r)\left(\frac{1}{(\pi \cdot r \cdot g')} - \frac{1}{\tan(\pi \cdot r \cdot g')}\right) \cdot \Delta g'$$

where g' is the width of the slit, referred to the image plane and $\Delta g'$ is the error or uncertainty in its value.

4.4.2 Correction for MTF of incoherently coupled relay lenses

Incoherently coupled relay lenses are frequently used in equipment for measuring the MTF of electro-optical devices and systems such as image intensifier tubes. The reciprocal of the MTF of these relay lenses is applied to the measured MTF as a correction factor. Any errors in the value of MTF of such relay lenses will therefore introduce errors into the final MTF value for the system under test. If the error in the MTF of such a relay lens is $\Delta \mathrm{MTF}_c(r)$ and the actual value of its MTF is $\mathrm{MTF}_c(r)$, then the error in the MTF of the test system is given by:

$$\Delta \mathrm{MTF}(r) = \mathrm{MTF}(r) \cdot \frac{\Delta \mathrm{MTF}_c(r)}{\mathrm{MTF}_c(r)}$$

where MTF(r) is the MTF of the system.

Similar considerations apply to other measurement situations where a correction is applied for the MTF of a device in the measurement train.

4.4.3 Spatial frequency correction for field angle

In making off-axis measurements with a grating test pattern positioned on the axis and in the focal plane of a collimator, a correction of the frequency scale should be performed (this also applies whenever frequency is measured in this plane). The corrected frequency is given by:

$r = r_o \cdot \cos^2(\omega)$ for the tangential azimuth and

$r = r_o \cdot \cos(\omega)$ for the radial azimuth, where r_o is the on-axis frequency

Errors in the value of r will be produced by errors in the value of ω the field angle. The values of these errors are given by:

$$\Delta r = 2 \cdot r_o \cdot \sin(\omega) \cdot \cos(\omega) \cdot \Delta\omega$$

and

$$\Delta r = r_o \cdot \sin(\omega) \cdot \Delta\omega$$

The effect of such errors on the MTF can be calculated in the manner indicated in 4.6.

4.5 FOCUS ERROR

An error or uncertainty in focus of $\Delta z'$ (referred to the image plane) will result in an MTF error or uncertainty given by:

$$\Delta\mathrm{MTF}(r,h') = m'(r,h') \cdot \Delta z'$$

where $m'(r,h')$ is the rate of change of MTF with focus for a spatial frequency r and an image height h'.

The value of $\Delta z'$ will depend on several factors. The most important of these are: the sensitivity of the focus control, the technique of focusing used, the spatial frequency at which the MTF is maximized (low frequency will generally result in a low focusing accuracy), the numerical aperture (NA) of the test lens, the MTF of the test lens, the signal/noise ratio associated with the particular equipment and test configuration.

Uncertainties in the focus position will normally only lead to small errors in MTF at the field position where the lens is focused (usually on-axis). However large errors may result at other field positions, particularly where astigmatism and/or field curvature are present.

4.6 SPATIAL FREQUENCY ERRORS

An error Δr in the spatial frequency will produce an MTF error given by:

$$\Delta\mathrm{MTF}(r,h) = n'(r,h') \cdot \Delta r$$

where $n'(r,h')$ is the rate of change of MTF with spatial frequency. Some sources of spatial frequency errors are: calibration errors, non-linearity and/or zero offset in transducers or mechanisms generating the spatial frequency reading. Note that the relationship between spatial frequency in image and object space may change with image height in the presence of distortion.

4.7 RESIDUAL ABERRATIONS IN RELAY OPTICS

Any optical system in the MTF measurement chain which is coherently coupled to the system under test (e.g. collimators and image relay lenses) should be aberration-free, since corrections cannot be applied for their effect on the measured MTF.

Accurate assessment of the errors resulting from known residual wavefront aberrations in relay lenses require the aberrations of the test system to also be known. Moreover, complex calculations are required for its determination.

If information is available about the MTF errors $\Delta\mathrm{MTF}_{rl}(r)$ which would result from the aberrations of the relay system when testing a diffraction-limited lens with the same NA and aperture diameter as the test system, then this represents the largest error which will be introduced into the measurements from this source. The value of $\Delta\mathrm{MTF}_{rl}(r)$ can either be measured directly or can be computed from the measured aberrations of the relay lens.

Unfortunately this approach will overestimate the errors when the system under test is poorly corrected.

4.8 SPECTRAL CHARACTERISTICS

The mismatch between the actual and desired spectral response characteristics of the measurement equipment will introduce errors in the measured MTF. The magnitude of the errors will depend on the sensitivity of the MTF of the system under test to the particular mismatch.

If the design data for the system under test is available and the characteristics (or likely characteristics) of the spectral mismatch are known, then the associated MTF errors can be calculated using a computer program for calculating polychromatic MTF. An alternative to this is to estimate the errors from the results