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Optics and optical instruments — Optical transfer function — Principles of measurement of modulation transfer function (MTF) of sampled imaging systems

Optique et instruments d'optique — Fonction de transfert optique — Principes de mesurage de la fonction de transfert de modulation (MTF) des systèmes de formation d'image échantillonnés

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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.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 3.

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 15529 was prepared by Technical Committee ISO/TC 172, *Optics and optical instruments*, Subcommittee SC 1, *Fundamental standards*.

Annex A of this International Standard is for information only.

Introduction

One of the most important criteria for describing the performance of an imaging system or device is its modulation transfer function (MTF). The conditions that must be satisfied by an imaging system for the MTF concept to apply are specified in ISO 9334. They are that the imaging system must be linear and isoplanatic.

For a system to be isoplanatic, the image of a point object (i.e. the point spread function) must be independent of its position in the object plane to within a specified accuracy. There are types of imaging systems where this condition does not strictly apply. These are systems in which the image is generated by sampling the intensity distribution in the object at a number of discrete points or lines, rather than at a continuum of points.

Examples of such devices or systems are: fibre-optic faceplates, coherent fibre bundles, cameras that use detector arrays such as CCD arrays, line scan systems such as thermal imagers (for the direction perpendicular to the lines), etc.

If one attempts to determine the MTF of this type of system by measuring the line spread function (LSF) of a static narrow line object and calculating the modulus of the Fourier transform, one finds that the resulting MTF curve depends critically on the exact position and orientation of the line object relative to the array of sampling points (see annex A).

The present International Standard specifies an "MTF" for such systems and outlines a number of suitable measurement techniques. The specified MTF satisfies the following important criteria:

— The MTF is descriptive of the quality of the system as an image-forming device.

— It has a unique value which is independent of the measuring equipment (i.e. the effect of object slit widths, etc. can be deconvolved from the measured value).

— The MTF can in principle be used to calculate the intensity distribution in the image of a given object, although the procedure does not follow the same rules as it does for a nonsampled imaging system.

This International Standard also specifies MTFs for the subunits, or imaging stages, which make up such a system. These also satisfy the above criteria.

Optics and optical instruments — Optical transfer function — Principles of measurement of modulation transfer function (MTF) of sampled imaging systems

1 Scope

This International Standard specifies the principal modulation transfer function (MTF) associated with a sampled imaging system, together with related terms. It also outlines a number of suitable techniques for measuring these MTFs.

This International Standard is particularly relevant to electronic imaging devices, such as CCD cameras and the CCD arrays themselves.

Although a number of measurement techniques are described, the intention is not to exclude other techniques, provided they measure the correct parameter and satisfy the general definitions and guidelines for MTF measurement as set out in ISO 9334 and ISO 9335. The use of a measurement of the edge spread function (ESF), rather than the line spread function (LSF), is noted in particular as an alternative starting point for determining the OTF/MTF of an imaging system.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this International Standard. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of ISO and IEC maintain registers of currently valid International Standards.

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

ISO 9335:1995, *Optics and optical instruments — Optical transfer function — Principles and procedures of measurement*

ISO 11421:1997, *Optics and optical instruments — Accuracy of optical transfer function (OTF) measurement*

3 Terms, definitions and symbols

3.1 Terms and definitions

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

3.1.1
sampled imaging system
imaging system or device with which the image is generated by sampling the object at an array of discrete points, or along a set of discrete lines, rather than a continuum of points

NOTE 1 The sampling at each point is done using a sampling aperture or area of finite size.

NOTE 2 For many devices, the "object" is actually an image produced by a lens or other imaging system (e.g. when the device is a detector array).

3.1.2
sampling period
a
physical distance between sampling points or sampling lines

NOTE Sampling is usually by means of a uniform array of points or lines. The sampling period may be different in two orthogonal directions.

3.1.3
Nyquist limit
spatial frequency equal to $1/(2 \cdot a)$

cf. 3.1.9.

NOTE It is the maximum spatial frequency of sinewave that the system can generate in the image.

3.1.4
line spread function of the sampling aperture of a sampled imaging system
$\mathrm{LSF}_{\mathrm{ap}}(u)$
variation in sampled intensity, or signal, for a single sampling aperture or line of the sampling array, as a narrow-line object is traversed across that aperture or line and adjacent apertures or lines

NOTE 1 The direction of traverse is perpendicular to the length of the narrow-line object and, in the case of systems which sample over discrete lines, it is also perpendicular to these lines.

NOTE 2 $\mathrm{LSF}_{\mathrm{ap}}(u)$ is a one-dimensional function of position u in the object plane, or equivalent position in the image.

3.1.5
optical transfer function of a sampling aperture
$\mathrm{OTF}_{\mathrm{ap}}(r)$
Fourier transform of the line spread function, $\mathrm{LSF}_{\mathrm{ap}}(u)$, of the sampling aperture

$$\mathrm{OTF}_{\mathrm{ap}}(r) = \int_{-\infty}^{\infty} \mathrm{LSF}_{\mathrm{ap}}(u) \cdot \exp(-\mathrm{i} \cdot 2 \cdot \pi \cdot u \cdot r)\, \mathrm{d}u$$

where r is the spatial frequency.

3.1.6
modulation transfer function of a sampling aperture
$\mathrm{MTF}_{\mathrm{ap}}(r)$
modulus of $\mathrm{OTF}_{\mathrm{ap}}(r)$

3.1.7
reconstruction function
function used to convert the output from each sampled point, aperture or line, to an intensity distribution in the image

NOTE The reconstruction function has an OTF and an MTF associated with it, denoted by $\mathrm{OTF}_{\mathrm{rf}}(r)$ and $\mathrm{MTF}_{\mathrm{rf}}(r)$ respectively.

3.1.8
MTF of a sampled imaging system
$\mathrm{MTF}_{\mathrm{sys}}(r)$
product of $\mathrm{MTF}_{\mathrm{ap}}(r)$ and $\mathrm{MTF}_{\mathrm{rf}}(r)$ with the MTF of any additional input device (e.g. a lens) and output device (e.g. a CRT monitor) which are regarded as part of the imaging system

NOTE When quoting a value for MTF_{sys} it should be made clear what constitutes the system. The system could, for example, be just a CCD detector array and associated drive/output electronics, or could be a complete CCD camera and CRT display.

3.1.9
aliasing function of a sampled imaging system
$AF_{sys}(r)$
difference between the highest and lowest values of $MTF_{sys}(r)$ as the image of the MTF test slit is moved over a distance equal to, or greater, than one period of the array

NOTE 1 It is the limiting value of this difference as the width of the test slit approaches zero (i.e. as its Fourier transform approaches unity).

NOTE 2 $AF_{sys}(r)$ is a measure of the degree to which the system will respond to spatial frequencies higher than the Nyquist frequency and as a result generate spurious low frequencies in the image.

3.2 Symbols

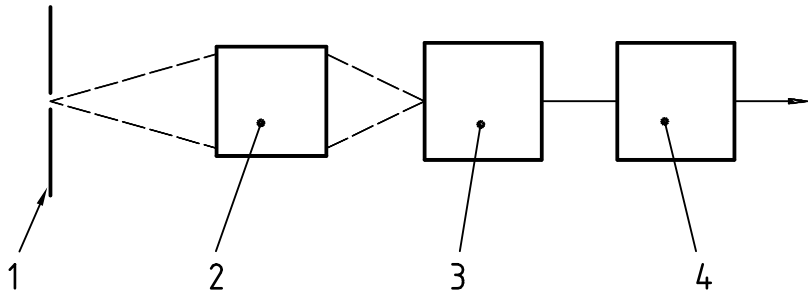
Symbol	Parameter	Units
a	Sampling period	mm, mrad, degrees
$1/(2 \cdot a)$	Nyquist spatial frequency limit	mm^{-1}, $mrad^{-1}$, $degree^{-1}$
u	Local image field coordinate	mm, mrad, degrees
r	Spatial frequency	mm^{-1}, $mrad^{-1}$, $degree^{-1}$
$LSF_{ap}(u)$	Line spread function of a sampling aperture	dimensionless
$OTF_{ap}(r)$	Optical transfer function of a sampling aperture	dimensionless
$MTF_{ap}(r)$	Modulation transfer function of a sampling aperture	dimensionless
$OTF_{rf}(r)$	Optical transfer function of the reconstruction function	dimensionless
$MTF_{rf}(r)$	Modulation transfer function of the reconstruction function	dimensionless
$MTF_{sys}(r)$	Modulation transfer function of a sampled imaging system	dimensionless
$FT_{slt}(r)$	Fourier transform of the slit object	dimensionless
$OTF_{lns}(r)$	Optical transfer function of the relay lens	dimensionless
$MTF_{lns}(r)$	Modulation transfer function of the relay lens	dimensionless
$FT_{img}(r)$	Fourier transform of the final image of the slit object	dimensionless
$AF_{sys}(r)$	Aliasing function of the system under test	dimensionless
$LSF_{in}(u)$	Line spread function of the combination of slit object, relay lens and sampling aperture	dimensionless
$FT_{in}(r)$	Fourier transform of $LSF_{in}(u)$	dimensionless
$LSF_{av}(u)$	Line spread function obtained by averaging the LSF associated with different positions of the object slit relative to the sampling array	dimensionless
$FT_{av}(r)$	Fourier transform of $LSF_{av}(u)$	dimensionless

4 Theoretical relationships

4.1 Fourier transform of the image of a (static) slit object

4.1.1 General case

The stages of image formation in a generalized sampled imaging system are illustrated in Figure 1. The values of the relevant parameters used here are specified in clause 3.



Key

1 Object slit $FT_{slt}(r)$

2 Lens $OTF_{lns}(r)$ / $MTF_{lns}(r)$

3 Sampling apertures $OTF_{ap}(r)$ / $MTF_{ap}(r)$

4 Reconstruction function $OTF_{rf}(r)$ / $MTF_{rf}(r)$

Figure 1 — Image formation by a sampled imaging system

For a sampled imaging system we have:

$$FT_{img}(r) = \{\Sigma_k\, [FT_{in}\,(r - k/a)\cdot \exp\,(i\cdot 2\pi\cdot\phi\cdot(k/a))]\}\cdot OTF_{rf}\,(r) \qquad (1)$$

where

$$FT_{in}(r) = FT_{slt}\,(r)\cdot OTF_{lns}\,(r)\cdot OTF_{ap}\,(r) \qquad (2)$$

and where k is an integer (i.e. $k = 0, \pm 1, \pm 2, \pm 3$ ....) and ϕ is a phase term describing the position of the slit relative to the sampling array.

NOTE More information on the mathematical relationships involved in imaging with sampled systems can be found in [1] (see Bibliography) and in most textbooks dealing with Fourier transform methods.

4.1.2 Special cases

The relationships listed in this clause are given without derivation (a brief explanation of their derivation can be found in annex A).

4.1.2.1 Cut-off spatial frequency of $|FT_{in}(r)|$ is less than or equal to the Nyquist frequency $1/(2\cdot a)$

For this condition and for spatial frequencies less than the Nyquist frequency, the system behaves as a non-sampled system and we have:

$$|FT_{img}(r)| = |FT_{in}(r)|\cdot MTF_{rf}(r) \qquad (3)$$

where

$$|FT_{in}(r)| = |FT_{slt}(r)|\cdot MTF_{lns}(r)\cdot MTF_{ap}(r) \qquad (4)$$

so that

$$\mathrm{MTF}_{sys}(r) = \mathrm{MTF}_{lns}(r)\cdot\mathrm{MTF}_{ap}(r)\cdot\mathrm{MTF}_{rf}(r) = \left|\mathrm{FT}_{img}(r)\right| \;/\; \left|\mathrm{FT}_{slt}(r)\right| \tag{5}$$

4.1.2.2 Cut-off spatial frequency of $\left|\mathrm{FT}_{in}(r)\right|$ is less than or equal to twice the Nyquist frequency (i.e. $1/a$)

For this condition and for spatial frequencies less than twice the Nyquist limit, we get a maximum and minimum value for $\left|\mathrm{FT}_{img}(r)\right|$ as the position of the slit image relative to the sampling apertures of the array is varied. The two values are given by:

$$\left|\mathrm{FT}_{img}(r)\right|_{max} = \left|\left[\left|\mathrm{FT}_{in}(r)\right| + \left|\mathrm{FT}_{in}(r - 1/a)\right|\right]\cdot\mathrm{MTF}_{rf}(r)\right| \tag{6}$$

and

$$\left|\mathrm{FT}_{img}(r)\right|_{min} = \left|\left[\left|\mathrm{FT}_{in}(r)\right| - \left|\mathrm{FT}_{in}(r - 1/a)\right|\right]\cdot\mathrm{MTF}_{rf}(r)\right| \tag{7}$$

from which it can be shown that:

$$\mathrm{MTF}_{sys}(r) = \left|\mathrm{FT}_{in}(r)\right|\cdot\mathrm{MTF}_{rf}(r) \;/\; \left|\mathrm{FT}_{slt}(r)\right| = \left[\left|\mathrm{FT}_{img}(r)\right|_{max} + \left|\mathrm{FT}_{img}(r)\right|_{min}\right]/2\cdot\left|\mathrm{FT}_{slt}(r)\right| \tag{8}$$

for $r < 1/(2\cdot a)$

and

$$\mathrm{MTF}_{sys}(r) = \left[\left|\mathrm{FT}_{img}(r)\right|_{max} - \left|\mathrm{FT}_{img}(r)\right|_{min}\right]/2\cdot\left|\mathrm{FT}_{slt}(r)\right| \tag{9}$$

for $r > 1/(2\cdot a)$

It should be noted that in theory the position of the slit, relative to the sampling array, where one obtains $\left|\mathrm{FT}_{img}(r)\right|_{max}$ and that where one obtains $\left|\mathrm{FT}_{img}(r)\right|_{min}$, can be different for each value of the spatial frequency r. This can however only occur if $\mathrm{LSF}_{in}(u)$ is asymmetrical so that there is a significant (non-linear) variation of the associated phase transfer function (PTF) with spatial frequency. In practice the effect will be small and one can assume that the relevant slit positions are the same for all spatial frequencies.

4.2 Fourier transform of the output from a single sampling aperture for a slit object scanned across the aperture

In this case we define a line spread function $\mathrm{LSF}_{in}(u)$ which is the signal obtained from a single sampling aperture as a function of the position u of a slit in object space (see Figure 2). The modulus of the Fourier transform of $\mathrm{LSF}_{in}(u)$ is given by:

$$\left|\mathrm{FT}_{in}(r)\right| = \left|\mathrm{FT}_{slt}(r)\right|\cdot\mathrm{MTF}_{lns}(r)\cdot\mathrm{MTF}_{ap}(r) \tag{10}$$

and we have

$$\mathrm{MTF}_{ap}(r) = \left|\mathrm{FT}_{in}(r)\right| / \left[\left|\mathrm{FT}_{slt}(r)\right|\cdot\mathrm{MTF}_{lns}(r)\right] \tag{11}$$

Note that MTF_{rf} does not appear in these equations.

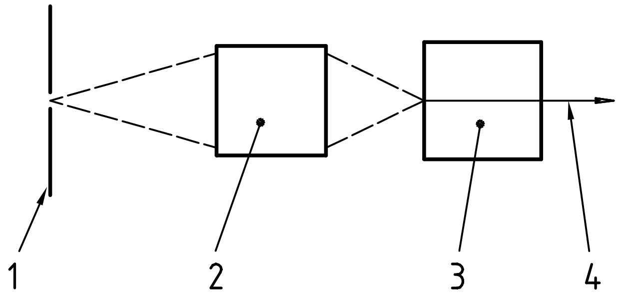
4.3 Fourier transform of the average LSF for different positions of the object slit

If the LSF of the sampled imaging system is measured for many different positions of the object slit relative to the sampling array and the average value of these, $\mathrm{LSF}_{av}(u)$, is taken after adjustment to a common slit position, then the Fourier transform of this average LSF is given by:

$$\left|FT_{av}(r)\right| = \left|FT_{in}(r)\right| \cdot MTF_{rf}(r) \tag{12}$$

and

$$MTF_{sys} = MTF_{lns} \cdot MTF_{ap} \cdot MTF_{rf} = \left|FT_{av}(r)\right| / \left|FT_{slt}(r)\right| \tag{13}$$



Key

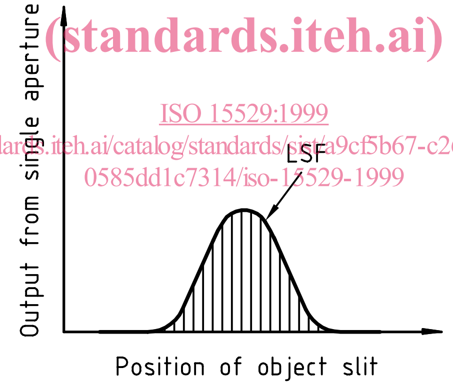
1 Slit object $FT_{slt}(r)$

2 Lens $OTF_{lns}(r)$ / $MTF_{lns}(r)$

3 Sampling apertures $OTF_{ap}(r)$ / $MTF_{ap}(r)$

4 Output from single sampling aperture [see Figure 2 b)]

a) Schematic measurement arrangement



b) Illustration of output

Figure 2 — Output from a single sampling aperture as slit object is scanned

5 Measurement of MTF associated with sampled imaging systems

5.1 General

5.1.1 Range of application

The relationships outlined in clause 4 provide the basis for suitable measurement techniques.

There are, however, many different types of sampled imaging system and each can require the use of a different experimental arrangement for implementing these techniques. The main purpose of this International Standard is to specify these relationships and indicate in general terms how they can be applied to measure the relevant parameters. This International Standard does not describe in detail the measurement techniques for each type of sampled imaging system, but does illustrate the application of a particular method with some specific examples. Most of the measurement techniques and equipment for measuring the MTF of appropriate non-sampled imaging systems may be adapted for testing sampled imaging system by the methods specified in this International Standard.

5.1.2 Additional measurement considerations

This International Standard shall be used in conjunction with the ISO standards listed in clause 2. These define terms used in the present International Standard, and provide guidelines, which are not repeated here, for achieving accurate measurement of MTF.

Many sampled systems include electro-optical devices which may behave in a non-linear fashion under certain operating conditions. It is important to adjust light levels, etc., so that the MTF measurements are made with the system functioning as far as possible in a linear mode.

5.1.3 Specifying the relevant MTF

In general, the most useful of the MTFs specified in this International Standard will be that of the system (i.e. MTF_{sys}) which, as a minimum, will describe the combined effect of the sampling aperture and the reconstruction function, but may also include other components of a system such as lenses and displays. When quoting MTF values for sampled imaging systems, or devices, it will generally be assumed that the values refer to MTF_{sys} unless otherwise specified. When quoting such values, care should be taken to avoid any ambiguities over what constitutes the system.

5.1.4 Test conditions

It is necessary to follow the guidelines set out in ISO 9335 and quote all relevant test conditions associated with a particular measurement of MTF. These will include the spectral response of the measurement system, field positions, focusing criterion, etc.

5.2 Test azimuth

5.2.1 Detector arrays and raster scan devices

For the purposes of this International Standard, the MTF of a sampled system, which includes a detector array, shall refer to a test azimuth. Normally this will be either perpendicular to the row of elements along which the signal is read out, or parallel to them, but may also have other orientations. This also applies to systems which include devices (such as mirror scanners, CRT displays, vidicon tubes, etc.) where an image is generated by a linear raster scan, although in most such cases the system will behave as a sampled system only in the direction perpendicular to the scan lines.

It is important to note that the orientation of the test azimuth can in some cases have significant implications for the detailed manner in which some of the measurement techniques described in 5.3 and 5.4 are implemented. This is particularly so when measurements are being made directly on a video output signal from the system under test. There are two points to note in this case. The first is that the LSF corresponding to a slit object perpendicular to the rows along which the array is read out will appear directly as such in the video signal, but for a slit in the orthogonal direction the LSF shall be constructed from the video signal on sequential video lines. The second point is that the reconstruction function will be different for the two azimuths, and in fact in the latter case it will approximate to a delta function [i.e. $MTF_{rf}(r) = 1$ for all frequencies].

Methods 5.3.3 and 5.3.4 are in general only applicable to test azimuths in the direction of the rows or columns.

5.2.2 Fibre-optic faceplates, channel multipliers and similar devices

For this type of device, where in effect the output from each sampling aperture generates the corresponding image point directly, test method 5.3.3 allows any test azimuth to be used for measuring the MTF, provided the azimuth used is specified unambiguously with the result of a measurement. In practice it will be usual to use azimuths which correspond closely to recognized axes of symmetry in the pattern of sampling apertures.