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Flatness

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Synonyms

[Deviation from flatness](#); [Flatness deviation](#);
[Planeness](#)

Definition

The minimum distance separating two parallel planes between which the surface can be contained.

Theory and Application

Scale of Flatness

Although in theory there is no minimum or maximum, in engineering practice we take as minimum size the field of view of a microscope, even an STM type, and as a maximum the size of large telescope mirrors or very large surface plates. This means that sizes where flatness is relevant can range between a few nm² and a few m².

A flatness deviation is a geometrical error, where this error is determined, implicitly or explicitly, for surface wavelengths from a minimum value, while all longer wavelengths that

define the geometrical deviation are not filtered. This implies that the bandwidth can be rather small when flatness is assessed over a coarse grid. For example, for a square grid, this implies that surface wavelengths smaller than twice the pitch are neglected and are assumed to have a negligible influence on the flatness parameter values.

Flatness Reference Planes and Parameters

Flatness deviations are defined in relation to a reference plane that is defined by the assessed surface itself. It is one of the basic geometric tolerances specified in ISO 1011 (2012). The flatness tolerance is indicated by the symbol .

The definitions are given in ISO 12781-1 (2011). Two reference planes are in common use, and two more are mentioned for completeness:

1. Least-squares reference plane (LSPL)

This plane is defined such that the sum of squares of all deviations of the surface from this plane is minimal. The advantage of this reference plane is that its calculation is straightforward and rather independent of the number of measurements, peaks, or outliers. A disadvantage is that it does not follow the definition, which leads to a higher flatness deviation than the minimum-zone plane.

2. Minimum-zone plane(s) (MZPL)

The minimum-zone planes are defined as the planes with a minimum separation between

which all measured surface coordinates are contained. As a single plane, either of these planes can be used or the plane in between these planes. The advantage of this plane is that it gives the minimum deviation value. Also it gives a more stable reference if there are only sharp peaks or only sharp valleys in the surface. A disadvantage is that its calculation is more complicated, its location is sensitive to measurement errors of the maximum and minimum points only, and it tends to be sensitive to the number of points taken.

3. Equal diagonal endpoints

A rectangular plane can be leveled in such a way that the end-points of both diagonals have the same value. Subsequently, the minimum height of the surface can be defined as having zero height. This reference plane is used in the classical Moody (1955) method. Although it gives a unique solution, it is sensitive to errors and is not optimized toward a least-squares or minimum flatness value. For this reason, this method may give FLTt values that are up to 25 % larger than the minimum-zone value. Still there is quite some commercial software for surface plate evaluation that uses this reference plane.

4. Three corners equal

Three corners of a rectangular plane can be defined as having the same height. Subsequently, the minimum height of the surface can be defined as having zero height. This definition is not unique (four possibilities) and is sensitive to several errors. It can be a useful starting point for a calculation, but apart from this, it is generally abandoned as a basis to assess flatness deviations.

Depending on the reference plane (LSPL or MZPL), the following flatness parameters can be calculated:

FLTt	Peak-to-valley flatness deviation. When referenced to MZPL, FLTt is the flatness as it is basically defined. When comparing FLTt values referring to either the LSPL or MZPL, the latter is by definition the lower value. Depending on the surface geometry, in practice the difference between FLTt(LSPL) and FLTt(MZPL) may
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(continued)

	amount between 0 % and 20 % of the FLT value. Using the equal diagonal endpoints or three-corners equal reference plane may lead to up to 25 % higher values compared to using the MZPL reference plane.
FLTp	Peak-to-reference flatness deviation. The reference is the LSPL
FLTv	Valley-to-reference flatness deviation. The reference is the LSPL
FLTq	The root-mean-square flatness deviation. LSPL is the reference. This value is often indicated as the RMS flatness value. If MZPL is taken as the reference, the value will be higher by definition, contrary to the FLTt parameter

For surfaces probed with a rectangular grid, two more parameters, “sphericity” and “torsion,” have been proposed by Meijer and de Bruijn (1981). In optical metrology, where circular-shaped surfaces are commonly measured, it is a common practice to evaluate the results in terms of Zernike polynomials. The first Zernike (1934) polynomial coefficients define the orientation of the least-squares plane and the next represent sphericity and torsion parameters as mentioned. Higher-order terms represent more complicated forms. Evans et al. (1995) have proposed a method to represent these Zernike polynomial coefficients graphically.

As an illustration, the orientation of the same plane for the four mentioned reference plane and the respective FLTt values is given in Fig. 1.

Flatness References

Absolute physical references for flatness do not exist; however, some references exist with small or negligible deviations that can well act as absolute references.

Liquid Surface and Gravity Vector

An undisturbed liquid surface can be considered flat because the gravity vector is parallel over rather large areas. The earth’s curvature causes a flatness deviation of 0.1 μm over a length of 2 m. This deviation decreases quadratic with the maximum length involved. This property is also used if flatness is assessed using (electronic) levels.

Flatness, Fig. 1 Example of a surface relative to different flatness reference planes

Atomically Clean Surface

A crystal surface with its atoms properly ordered can be considered as a flatness reference with the implicit assumption of the absence of internal stress and temperature gradients in the crystal. Such surfaces can act as reference surfaces for SPM instruments.

Straight Propagation of a Collimated Light Beam

Light is considered to propagate in a straight line in space in vacuum. If there is no vacuum, dispersion causes beam bending (see prisms, lenses, etc.). If light propagates through air, small deviations can be caused by temperature and pressure gradients. Note that in the earth's atmosphere, there is always a vertical pressure gradient. This does not cause significant errors at the sizes here concerned.

Absolute, Self-Calibrating Method

Methods exist by which deviations from a perfect form can be determined bias-free, without use of a perfect standard of this form (Evans and Tyler Estler 1996). This holds for flatness and straightness and for flatness where this is composed of a combination of straightness and/or parallelism measurements.

Flatness Assessments Methods

In this section, some flatness assessment methods are summarized. These can be classified as direct flatness assessment, straightness assessments that can be classified as absolute straightness, straightness by gradient measurements, even second derivative measurement, etc. Without pretending to be complete, some methods are discussed below.

Interferometric Surface Measurement

Classical interferometers of the Fizeau or Michelson type give a direct image of surface topography. For large surfaces, Fizeau-type interferometers are in use for optical flats from a few cm² up to close to 1 m diameter. In the microscopic range, Michelson-type interferometric microscope objectives are in use, with variations, e.g., the Mirau- or Linnik-type objectives. The resolution can be at the nm level or even

lower, even for the meter-scale interferometers, however with a bandwidth limitation.

The reference mirror flatness in these interferometers can be calibrated, or its flatness deviation can be eliminated from the measurements, in several ways:

1. A liquid surface

As liquids, mercury and viscous oils have been employed (Debenham and Dew 1980; Powell and Goulet 1998). Vibration sensitivity, edge effects, and general awkward operation have limited applicability of this method.

2. Three-flat absolute calibration method

This only works in the Fizeau configuration. With three optical flats, where two need to be (semi)transparent, absolute flatness can be determined provided that additional measurements can be taken with one flat rotated in one or more steps. Methods are described by Grzanna and Schultz (1990), based on a least-squares approach, and by Evans and Kestner (1996), based on symmetry considerations of Zernike polynomials.

3. Statistical averaging

If a multitude of randomly flat surfaces are measured against a reference surface, the average measured flatness will tend to zero, with the flatness of the reference surface as only remaining systematic effect. This is especially applicable to microscopic flatness measurements. The method was first described by Creath and Wyant (1990) for interferometric roughness measurements. Averaging measurements of uncorrelated areas of a single optical flat result in a flatness figure for the reference surface. Sphericity of the measured optical flat is the only remaining systematic effect that is usually negligible for small subareas.

Gradient Measurements

Gradient measurements can be taken by an autocollimator, a laser interferometer using angular optics, or an (electronic) level. This commonly requires a measurement base with a spacing between 20 and 200 mm. With an autocollimator, also direct measurement of the surface is possible using a pentagon prism.

Straightness Measurements Using a Measurement Base This can be carried out using an autocollimator, laser interferometer, or electronic level. Lines can be measured with the pitch of the measurement base. For combining this into a flatness measurement, a rectangular grid can be used; however, diagonals must be measured also as just straightness measurements of parallel, and perpendicular lines are indifferent to torsion of the surface.

The basic and classical configuration of measured points over the surface is called the “union jack” method, first described by Moody (1955) and later further analyzed by Drescher (2003). This method was generalized by Meijer (1989). Note that the original Moody algorithm equals the diagonal endpoints and does not use the MZPL or LSPL.

Straightness and Parallelism Measurements Using a Measurement Base A measurement base with an electronic level monitoring gradient differences can also determine parallelism of parallel lines. This has the advantage that a square grid can be measured without the need of measuring diagonals, as each line has the same gravity vector as reference. The measurement evaluation may include a least-squares calculation. A comparison of this method to the gradient method was made by Haitjema and Meijer (1993).

Straightness from Direct Gradient Measurements on a Surface An arrangement of an autocollimator and a pentagon prism can be used to measure gradient variations over a surface that must be smooth and optical reflecting. If the beam diameter of the autocollimator can be reduced, the sensitivity can be high and the pitch can be reduced. This is the basis of the arrangement used by Geckeler and Weingärtner (2002) and Geckeler et al. (2002), who claims sub-nm uncertainties.

Direct Coordinate Measurements A general coordinate measurement machine has a flatness measurement as one of its options. Although the ultimate accuracy may not be achieved, it is by far the most versatile measurement system that

allows measurement of smaller and larger parts of a workpiece in any orientation.

Uncertainty and Traceability

Although coarse uncertainty estimates are often approximately correct, explicit uncertainty estimations are geometry dependent and rather tedious. Examples are given by Meijer (1989) and Haitjema (1992) for flatness evaluations using levels and autocollimators, by Drescher (2003) for the union jack configuration, and by Evans and Davies (2013) for optical flat measurements. Further considerations about traceability are given by Evans and Davies (2013).

Cross-References

- [Straightness](#)
- [Traceability](#)
- [Uncertainty](#)

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