The Ra value is the prevalent standard for measuring surface roughness. It is defined as the average height from a mean line of all ordinates of the surface, regardless of sign. With reference to Fig., it can be shown that

$$\text{Ra} = \frac{A_1 + A_2 + \ldots + A_N}{L}$$
$$= \Sigma A/L$$

4.5.5 Methods of measuring surface finish

The methods used for measuring the surface finish is classified into

1. Inspection by comparison
2. Direct Instrument Measurements

4.5.5.1. Inspection by comparison methods:

- In these methods the surface texture is assessed by observation of the surface.
- The surface to be tested is compared with known value of roughness specimen and finished by similar machining process.
- The various methods which are used for comparison are

  1. Touch Inspection.
  2. Visual Inspection.
  3. Microscopic Inspection.
  4. Scratch Inspection.
  5. Micro Interferometer.
  6. Surface photographs.
  7. Reflected Light Intensity.
  8. Wallace surface Dynamometer.

4.5.5.1.1. Touch Inspection

It is used when surface roughness is very high and in this method the fingertip is moved along the surface at a speed of 25mm/second and the irregularities as up to 0.0 125mm can be detected.

4.5.5.1.2. Visual Inspection:

In this method the surface is inspected by naked eye and this measurement is limited to rough surfaces.

4.5.5.1.3. Microscopic Inspection:

In this method finished surface is placed under the microscopic and compared with the surface under inspection. The light beam also used to check the finished surface by projecting the light about 60° to the work.

4.5.5.1.4. Scratch Inspection:

The materials like lead, plastics rubbed on surface is inspected by this method. The impression of this scratches on the surface produced is then visualized.

4.5.5.1.5. Micro-Interferometer:

Optical flat is placed on the surface to be inspected and illuminated by a monochromatic source of light.

4.5.5.1.6. Surface Photographs:

Magnified photographs of the surface are taken with different types of illumination. The defects like irregularities are appear as dark spots and flat portion of the surface appears as bright.

4.5.5.1.7. Reflected light Intensity:

A beam of light is projected on the surface to be inspected and the light intensity variation on the surface is measured by a photocell and this measured value is calibrated

4.5.5.1.8. Wallace surface Dynamometer:

It consists of a pendulum in which the testing shoes are clamped to a bearing surface and a pre-determined spring pressure can be applied and then, the pendulum is lifted to its initial starting position and allowed to swing over the surface to be tested.

4.5.6 DIRECT INSTRUMENT MEASUREMENTS

- Direct methods enable to determine a numerical value of the surface finish of any surface.

- These methods are quantitative analysis methods and the output is used to operate recording or indicating instrument.
- Direct Instruments are operated by electrical principles. These instruments are classified into two types according to the operating principle.
- In this is operated by carrier-modulating principle and the other is operated by voltage-generating principle, and in the both types the output is amplified.
- Some of the direct measurement instruments are
  1. Stylus probe instruments.
  2. Tomlinson surface meter.
  3. Profilometer.
  4. Taylor-Hobson Talysurf

4.5.6.1 Stylus probe instruments.

There are two types of stylus instruments: true datum and surface datum, which are also known as skidless and skid type, respectively. In the skidless instrument, the stylus is drawn across the surface by a mechanical movement that results in a precise path. The path is the datum from which the assessment is made. In the skid-type instrument, the stylus pickup unit is supported by a member that rests on the surface and slides along with it. This additional member is the skid or the shoe.

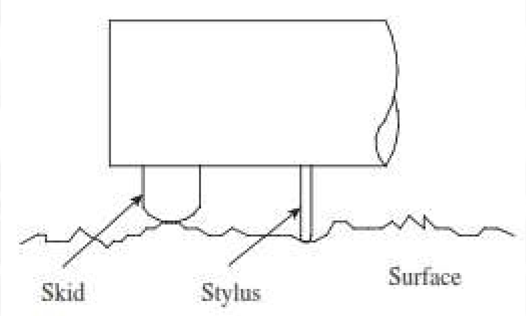


Fig. 4.27 Skid and stylus type

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 224]

Skids are rounded at the bottom and fixed to the pickup unit. They may be located in front of or behind the stylus. Some instruments use a shoe as a supporting slide instead of a skid. Shoes are flat pads with swivel mountings in the head. The datum created by a skid or a shoe is the locus of its centre of curvature as it slides along the surface.

The stylus is typically a diamond having a cone angle of 90° and a spherical tip radius of 1–5 μm or even less. The stylus tip radius should be small enough to follow the details of the surface irregularities, but should also have the strength to resist wear and shocks. Stylus load should also be controlled so that it does not leave additional scratch marks on the component being inspected.

In order to capture the complete picture of surface irregularities, it is necessary to investigate waviness (secondary texture) in addition to roughness (primary texture). Waviness may occur with the same lay as the primary texture. While a pointed stylus is used to measure roughness, a blunt stylus is required to plot the waviness.

Advantage:

Any desired roughness parameter can be recorded.

Disadvantages:

1. Fragile material cannot be measured.
2. High Initial cost.
3. Skilled operators are needed to operate.

4.5.6.2 Tomlinson Surface Meter.

The sensing element is the stylus, which moves up and down depending on the irregularities of the workpiece surface. The stylus is constrained to move only in the vertical direction because of a leaf spring and a coil spring. The tension in the coil spring P causes a similar tension in the leaf spring. These two combined forces hold a cross-roller in position between the stylus and a pair of parallel fixed rollers. A shoe is attached to the body of the instrument to provide the required datum for the measurement of surface roughness.

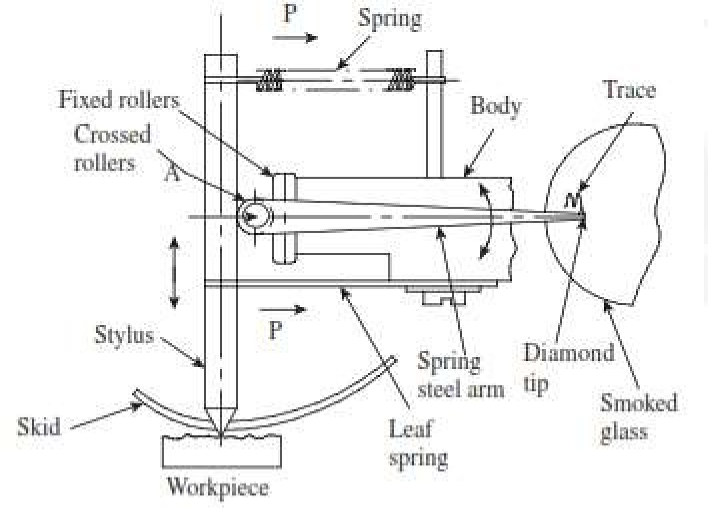


Fig. 4.28 Tomlinson surface meter

A light spring steel arm is P Spring attached to the cross-roller and carries a diamond tip. The translatory motion of the stylus causes rotation of the cross roller about the point A, which in turn is converted to a magnified motion of the diamond point. The diamond tip traces the profile of the workpiece on a smoked glass sheet. The glass sheet is transferred to an optical projector and magnified further. Typically, a magnification of the order of 50–100 is easily achieved in this instrument.

In order to get a trace of the surface irregularities, a relative motion needs to be generated between the stylus and the workpiece surface. Usually, this requirement is met by moving the body of the instrument slowly with a screw driven by an electric motor at a very slow speed. Anti-friction guide-ways are used to provide friction-free movement in a straight path.

4.5.6.3. Taylor–Hobson Talysurf.

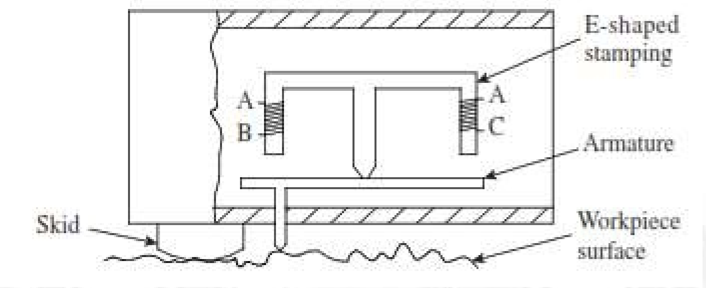


Fig. 4.29 Taylor–Hobson Talysurf

The Taylor–Hobson talysurf works on the same principle as that of the Tomlinson surface meter. However, unlike the surface meter, which is purely a mechanical instrument, the talysurf is an electronic instrument. This factor makes the talysurf a more versatile instrument and can be used in any condition, be it a metrology laboratory or the factory shop floor.

The stylus is attached to an armature, which pivots about the centre of piece of an E-shaped stamping. The outer legs of the E-shaped stamping are wound with electrical coils. A predetermined value of alternating current (excitation current) is supplied to the coils. The coils form part of a bridge circuit. A skid or shoe provides the datum to plot surface roughness. The measuring head can be traversed in a linear path by an electric motor. The motor, which may be of a variable speed type or provided with a gear box, provides the required speed for the movement of the measuring head.

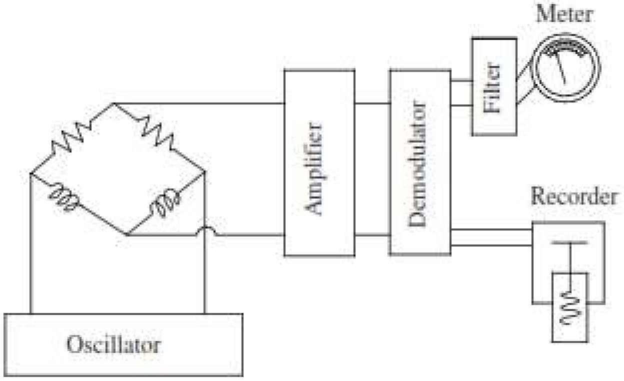


Fig. 4.30 Bridge circuit and electronics

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 225]

As the stylus moves up and down due to surface irregularities, the armature is also displaced. This causes variation in the air gap, leading to an imbalance in the bridge circuit. The resulting bridge circuit output consists of only modulation. This is fed to an amplifier and a pen recorder is used to make a permanent record. The instrument has the capability to calculate and display the roughness value according to a standard formula.

4.5.6.4. Profilometer.

A profilometer is a compact device that can be used for the direct measurement of surface texture. A finely pointed stylus will be in contact with the workpiece surface. An electrical pickup attached to the stylus amplifies the signal and feeds it to either an indicating unit or a recording unit. The stylus may be moved either by hand or by a motorized mechanism.

The profilometer is capable of measuring roughness together with waviness and any other surface flaws. It provides a quick-fix means of conducting an initial investigation before attempting a major investigation of surface quality.

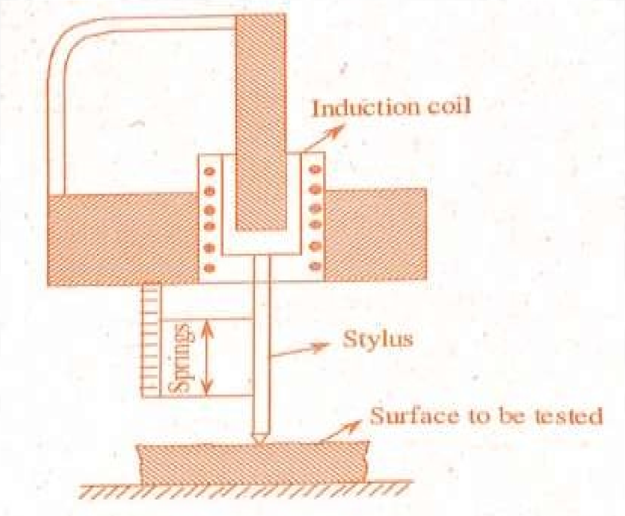


Fig. 4.31 Profilometer

4.5.7 Other methods for measuring surface roughness

4.5.7.1 Profilograph

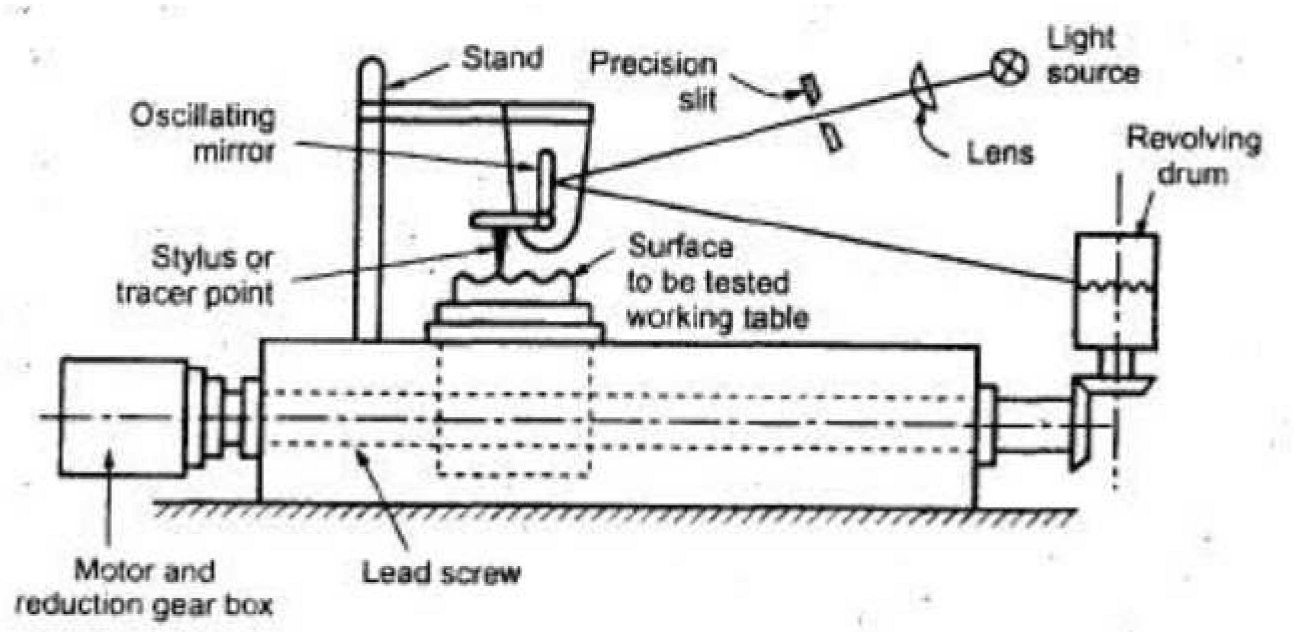


Fig. 4.32 Profilograph

- The surface finish to be checked work piece is placed on the table.
- The table can move either side by lead screw and the stylus is pivoted over the tested surface, so the oscillation in the stylus due to surface irregularities are transmitted to the mirror.
- A light source sends a beam of light through lens and a precision slit to the mirror, and the reflected beam is directed to revolving drum.
- Upon the revolving drum a sensitive film is attached. The revolving drum can be rotated by two bevel gears and the gears are attached to the same lead screw.
- Finally, the profilogram will be obtained from the sensitive film and it is analysed.

4.5.7.2 Double microscope

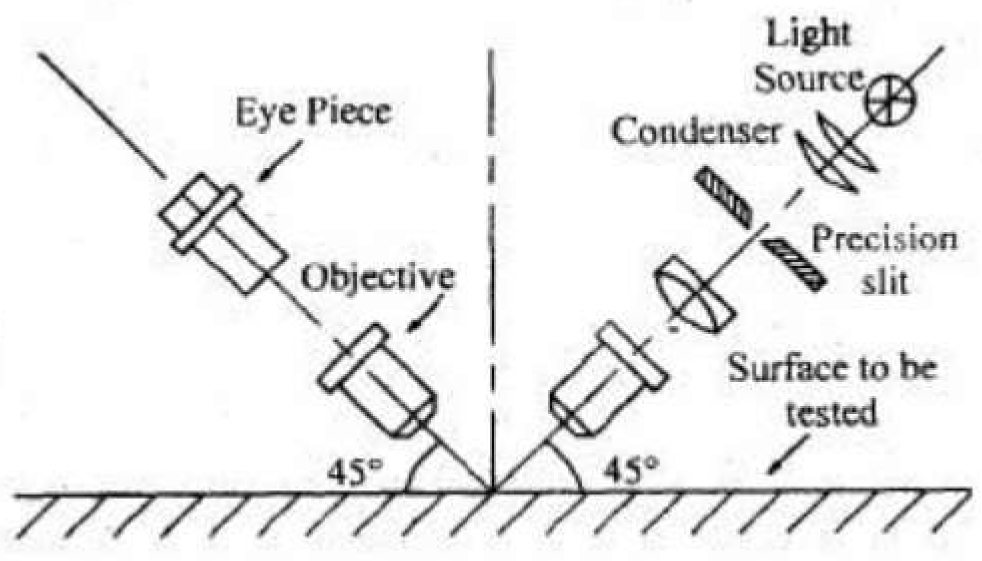


Fig. 4.32 Profilograph

- It is an optical method for measuring the surface roughness, working principle is a thin film of light strikes the surface to be tested by an angle of 45° through the condenser and precision slit and the observing microscope is also inclined at an angle. of 45° to the tested surface.
- The surface is illuminated by a projection tube and it is observed by an eyepiece through the microscope.
- The eyepiece contains an eyepiece micrometer and it is used to measure the irregularities.

4.6 FILTERS

Filtering is a process of excluding wavelengths above or below a particular frequency in surface metrology. The softwares or mathematical models which are used to remove unnecessary data (noise) from required primary profile are called filters.

A morphological filter is generally used to correct the stylus tip effect on raw data. A removal filter is required to clean up data measured with an optical probe. In some cases, a smoothing filter such as a λs or S-filter is required to compare data measured with different instrument methods.

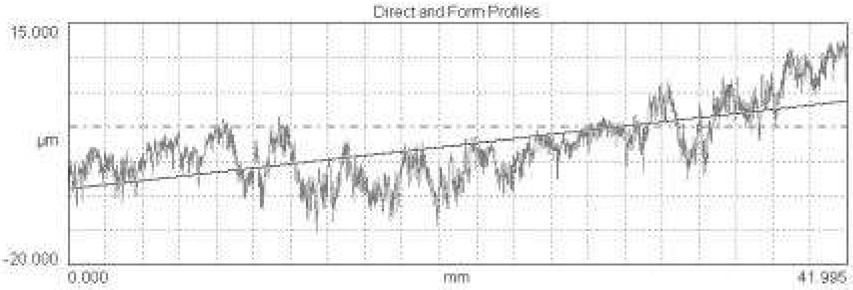
Surface measurement can be understood through the use of 3 fundamental topics:

- Fitting

- Filtering
- Analysis

1. Fitting

The first step in dealing with surface finish or surface "texture" is removing the underlying "shape". In many cases the surface to be measured is tilted relative to the measuring device. In other cases, the surface may be nominally curved. In either case, the underlying geometry must be removed. This involves the "fitting" of a geometric reference such as a line or an arc and then looking at the wiggles (residuals) above and below the reference geometry.



4.33 Surface Roughness Profile with Raw Data

The raw data from the probe is shown in the top (gray) profile. Superimposed on the raw data is a least squares line. In this case the least squares line is used to remove the tilt from the profile. The residuals (above and below the line) make up the blue (primary) profile.

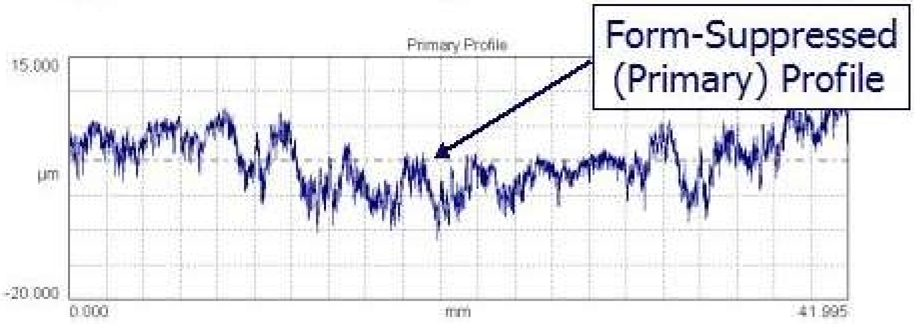


FIG.4.34 Surface Roughness Profile after filtering

2. Filtering

Once the geometry has been removed, we need to separate the waviness and the roughness. This is the most critical aspect of surface measurement and yet it is probably the least understood.

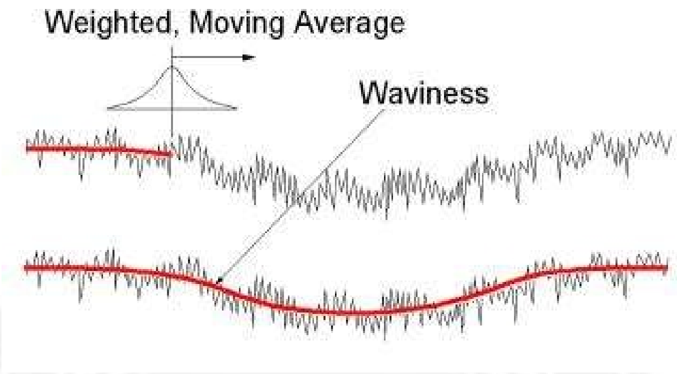


FIG.4.34 Waviness and surface roughness profile in filtering process

Filtering surface profiles involves running a "smoothing" filter through the primary data. The amount of smoothing is based on a "filter cutoff wavelength". The "cutoff wavelength" is the wavelength that separates roughness from waviness. Shorter wavelengths fall into the roughness profile and longer wavelengths appear in the waviness profile.

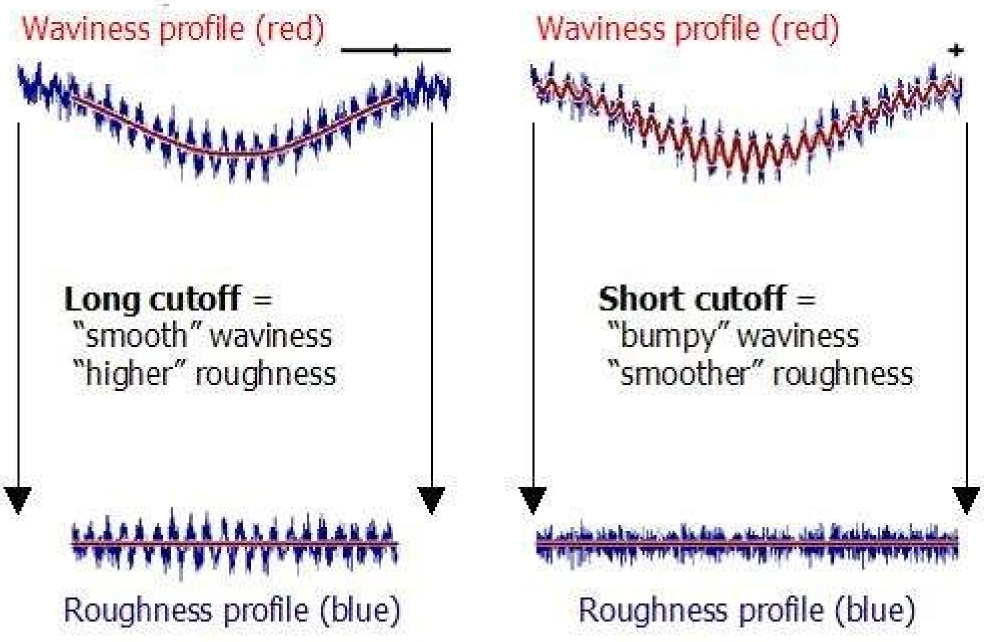


FIG.4.35 Waviness and surface roughness profile in different cutoff

A “Gaussian” filter is recommended in ASME and ISO standards. Gaussian filters are based on passing a Gaussian, weighted average through the primary profile – resulting in the waviness profile. The roughness profile is made up of all of the peaks and valleys (residuals) above and below the waviness profile.

There is a table of “standard” cutoff values (along with selection recommendations) in ASME B46.1-2002 as well as ISO 4288-1996.

3. Analysis

Once we’ve separated things into roughness and waviness profiles, we need to come up with numbers to describe them. After all, pictures are great, but engineers love numbers. The simplest of parameters is the “total” height of a given profile. This is the “peak-to-valley” height of the profile. For the primary profile the total, peak-to-valley height is designated: “Pt”. For the waviness profile it is “Wt” and for the roughness profile it is “Rt”.

4.6.1 Example of Filtering in Surface Finish Measurement

For filtering the signal then measuring on CMM is designed to solve the following tasks,

1. Elimination of gross measurement errors.
2. Minimization of random errors of the touch sensor.
3. Identification and exclusion of imperfections in the surface.
4. Identification of systematic errors in the surface.
5. Excluding the surface roughness from consideration.

The mutual relationship between surface and measurement errors and the filtration methods used is shown in Figure. Here, there is no single filtering method which will solve all necessary tasks. Two or three filters are used to obtain the most effective solution to the required problem.

sometimes, the difficulty involves in separation of errors due to various reasons but a similar manifestation and a mathematical description are required. So, these cases contain errors of the touch sensor and. surface roughness, gross measurement errors and surface imperfections. In the first case of the measurement error, the surface roughness is a real geometric object but the error of the touch sensor is due to the difference in the fixation of the moment of contact in different directions and the oscillations in the system.

In the second case of the measurement error, the gross measurement errors are caused by subjective reasons. At the same time, imperfections are present on the surface. For this, a cluster analysis can be used to separate gross errors and surface imperfections. A gross error is a single ejection from a common set of measurements. The surface imperfections have a certain length and are manifested in several measured points.

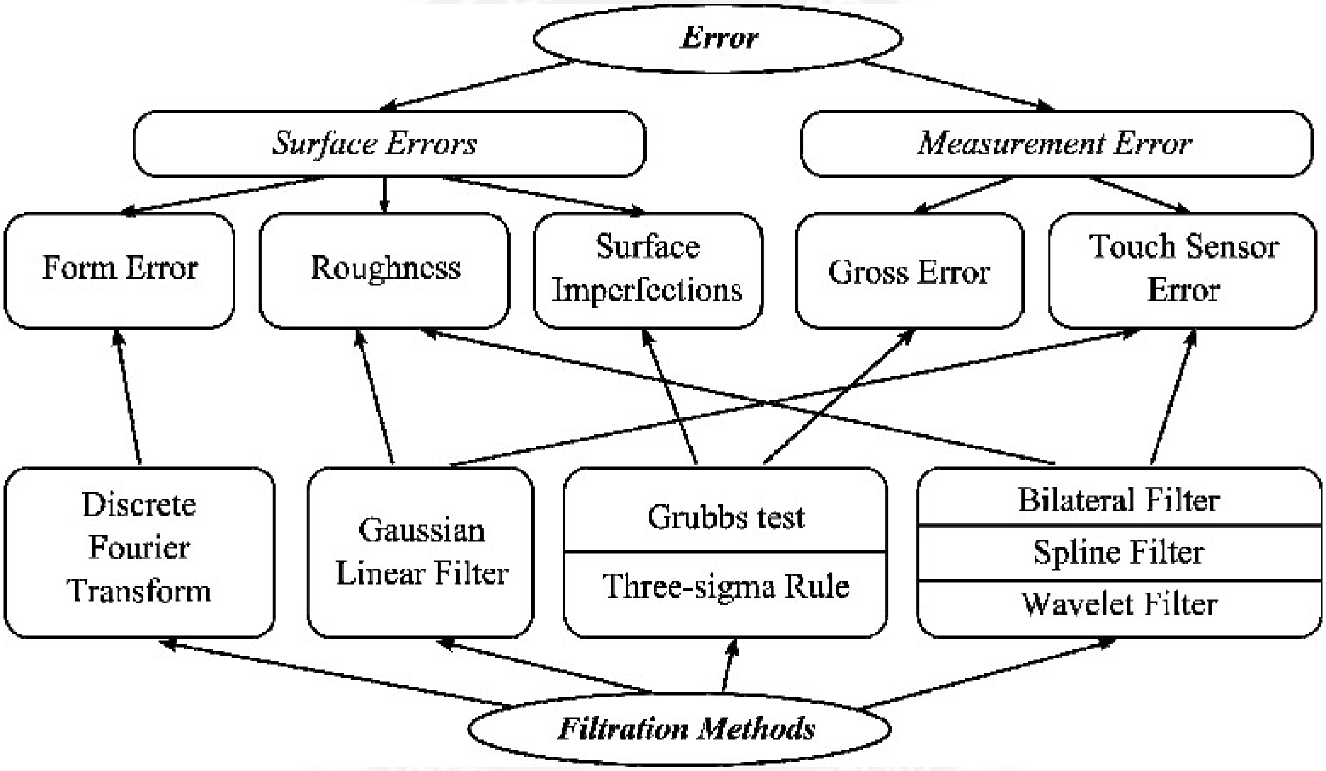


FIG.4.36 Functional relationships of errors and methods of filtration

In this case, the use of linear filtering methods does not allow to obtain an acceptable solution if the signal and noise spectra overlap. In this situation, the optimal solution is a nonlinear filter. Known methods for nonlinear low-pass filtering are wavelet transforms, bilateral filter and smoothing spline. The most hopeful filtering should be considered a bilateral spline which is a further development of the linear Gaussian filter and having two Optimization parameters.

After measuring form error, discrete Fourier Transform is used to filter waviness from raw data. In the case of surface roughness measurement, Gaussian linear filter, bilateral filter, spline filter and wavelet filter are used for filtration.

4.7 INTRODUCTION TO 3D SURFACE METROLOGY

Surface metrology is the measurement of small-scale features on surfaces, and is a branch of metrology. Surface primary form, surface fractality, and surface finish (including surface roughness) are the parameters most commonly associated with the field. It is important to many disciplines and is mostly known for the machining of precision parts and assemblies which contain mating surfaces or which must operate with high internal pressures.

4.7.1 Types of surface measurement

There are two main types of measurements used to measure the surfaces. They are

1. 2D Measurement
2. 3D Measurement

1.2D Surface Measurement

Two-dimensional systems continue to be extremely appreciable for use in many industrial profile analyses. They are generally used for applications where specifications and processes are well defined, applications where the customer or vendor has supplied Standard Operating Procedures (SOP) for measurement and situations where the measurement Sop IS Well understood/documented.

The benefits of a 2D measurement system include:

1. It provides small and portable solutions.
2. 2D is easily accessible with low investment.
3. It is simple to operate and implement.
4. It ensures high flexibility of measuring small to large workpieces.
5. Measurement at difficult areas, positions or bores can be possible.
6. It ensures worldwide traceability.

2.3D Surface Measurement

3D surface measurement (three-dimensional surface measurement) is used by both the industrial sector and scientific community to drive the success of critical research projects, crucial developments, and fundamental productions and process controls.

Much of the early work to develop standard, worldwide 3D surface measurement parameters were completed by a European consortium. Their work resulted in four general categories: amplitude, spatial, hybrid and functional.

The amplitude parameters are based on overall heights and include the root-mean-square of height distribution, skewness (or the degree of asymmetry of a surface height distribution), the degree of peakedness of a surface height distribution (or kurtosis), and an average of the highest and lowest points.

Spatial parameters are based on frequencies of features and include the texture direction of a surface, texture aspect ratio, and the density of summits.

Based on a combination of height and frequency, the hybrid parameters include the mean summit curvature, developed surface area ratios, and the root-mean-square of surface slopes.

4.7.2 Development of 3D surface Measurement

The initial resistance to using the techniques of 3D surface measurement was eventually overcome as R&D engineers took the time to fully understand the advantages of three-dimensional surface analysis and a shift became apparent as the S parameters were employed on more and more drawings and suppliers were being held to those specifications.

It was found that 3D surface parameters helped to improve communication and allowed a process control that traditional R parameters could not do alone.

Three-dimensional area measurement options are a necessity when:

1. The surface to be measured is very fragile or delicate which cannot be touched with a stylus.

2. The surface is too soft, adhesive, discontinuous, etc.
3. Coated and inhomogeneous surfaces are being measured.
4. porous surfaces such as ceramics and cast materials are being measured.
5. The feature or features being measured can only be quantified using 3D parameters such as volume
6. It allows to assess the surfaces without machining structure.

The uses of 3D areal measurements is also more valuable when:

1. Specifications do not exist or are being developed
2. process development, comparison and optimization analysis conducted
3. Researching appearance and properties of engineering surfaces for process control.

Example 1: 3D surface measurement by combined light sectioning microscope and computer vision system

Recently, a new approach was introduced to measure surface roughness in 3D by combining a light sectioning microscope and a computer vision system. It provides the advantages of being non-contact, fast and cheap. A light sectioning microscope is used to view roughness profiles of the specimens to be measured and the vision system is used to capture images for successive profiles. This program has been developed in MATLAB software to analyse the captured images through four main modules such as measurement controller, profile or surface extraction, 2D roughness parameters calculation and 3D roughness parameters: calculation. The system has been calibrated for metric units and verified using standard specimens.

Example 2: 3D optical measurement system

Optical 3D roughness measurement is non-contact and non-reactive measurement It eliminates any damage or influence on sensitive surfaces by the measurement Areal surface roughness measurement data provides an easy and complete view of surface.

Example 3: 3D non-contact surface profilometer

3D non-contact surface profilers use a range of Optical acquisition methodologies to surface topography information from the surface containing confocal and electron microscopy methods generally scan a surface with an incident light source and measure the reflective or refractive light to acquire information about the product's surface topography This metrological method is more selected for contact surface profiling due to invasiveness and improved measurement speeds.

Advantages of 3D Surface Measurement

1. 3D approach produces images closer to a real surface image and the derived parameter possess a greater functional significance.
2. 3D technique permits areal parameters to be derived for the first time in terms texture, strength and direction, material and void volumes, etc.
3. Since the 3D technique obtains data from an area rather than a trace, the have a greater statistical significance and less variation.
4. 3D measurements are visually more effective as a characterisation tool

4.8 PARAMETERS INVOLVED IN 3D SURFACE MEASUREMENT

To avoid complexity in 3D surface measurement parameters, a primary set or suite parameters should be established which are widely recognized. Basically, R parameters define data derived from a 2D parameters are average roughness Ra, root mean square of roughness Rm etc. S parameters illustrate data measured over an area of the surface.

Primary set of 3D surface roughness parameters

S.NO	Notation	Parameter
Amplitude parameters		
1.	S_q	Root-mean square deviation of the surface (μm)
2.	S_z	Ten-point height of the surface (μm)
3.	S_{sk}	Skewness of the surface
4.	S_{ku}	Kurtosis of the surface
Spatial parameters		

1.	S_{ds}	Density of summits of the surface (mm-2)
2.	S_{tr}	Texture aspect ratio of the surface
3.	S_{al}	Fastest decay autocorrelation length (mm)
4.	S_{td}	Texture direction of the surface (deg)
Hybrid parameters		
1.	$S_{\Delta q}$	Root-mean square slope of the surface (µm/ µm)
2.	S_{sc}	Arithmetic mean summit curvature (µm $^{-1}$)
3.	S_{dr}	Developed surface area ratio (%)
Functional parameters characterizing bearing and oil retention properties		
1.	S_{bi}	Surface bearing index
2.	S_{ci}	Core oil retention index
3.	S_{vi}	Valley oil retention index
4.	S_m	Material volume (µm ^{3}/mm ^{2})
5.	S_c	Core Valley volume (µm ^{3}/mm ^{2})
6.	S_v	Deep Valley volume (µm ^{3}/mm ^{2})

The primary parameter set is classified into four groups of parameters as follows

1. Amplitude parameters
2. Spatial parameters
3. Hybrid parameters, and
4. Functional parameters.

1.Amplitude parameters

Amplitude parameters are closer and more based on 2D equivalents which quantity surface heights Sq and Sz and the surface height amplitude distributions S_{sk} and S_{ku}. S_z and s_q are then average roughness and root mean square roughness are calculated for the complete 3D respectively. Mathematically, S_z and S_q are calculated as follows.

Ten-point height of the surface, Sz = $\iint_a \left|Z(x,y)\right|$ dxdy

2.Spatial parameters:

spatial parameters are designed to asses 3D aspects of the surface texture and lay, Also they assess the peak density, texture strength and dominant texture direction. These parameters are mainly used to differentiate highly textured and random surface structures, For example, a surface having a well-defined lay tends to have high values of texture aspect ratio, a short fastest autocorrelation length and a well-defined texture direction. These parameters are highly sensitive to sample spacing during data collection.

3.Hybridparameters:

Hybrid parameters are parameters designed on the basis of considering both amplitude and spatial information. They define hybrid topography properties in terms of numerical values such as the slope of the surface (S&?), the curvature of high spots (sc) and the interfacial area (Sur). The parameters having particular relevance to the contact properties both electrical and thermal, sealing properties, wear and optical reflectance properties of a surface. These parameters are again highly dependent on the data sample spacing.

4. Functional parameters:

Functional parameters are designed to assess the functional topographical features of the surface through analysing the material volumes (Sbi) and void volumes (SCI), Svi is the dimensionless indices or through direct volume calculations. These parameters are used to split the surface into three height zones, peak zone, core zone and valley zones. Next, volume

calculations are done on the basis of three zones. For example, an automotive bearing surface has a high material volume due to good load bearing capability and good lubrication retention (Sm) and a high valley volume (SO but a seal type surface will have a low material volume and a large core volume (sc) where sealing properties require continuous surface ridges.