ANNAMACHARYA INSTITUTE OF TECHNOLOGY AND SCIENCES:: RAJAMPET
(An Autonomous Institution)

DEPARTMENT OF MECHANICAL ENGINEERING

LECTURE NOTES

METROLOGY AND MEASUREMENTS
[23A0353T]

Prepared by
Dr.D.Krishnamohan Raju
Assistant Professor, MED

B. TECH-ME-III-I Sem

		L	T	P	C
23A03503	**METROLOGY MEASUREMENTS**	**3**	**0**	**0**	**3**

	Course objectives: The objectives of the course are to
1	Explain the system of limits, fits &tolerances and design of gauges.
2	Identify the use of flatness and surface gauges
3	Know the measurement of screw thread, Gear profiles.
4	Describe the Measurement of Displacement and Strain.
5	Illustrate the measuring process of Pressure, Force and Torque.

Course Outcomes: On successful completion of the course, the student will be able to,		
CO1	Demonstrate the concept of different types of dimensional tolerances and chose the desire limits and fit component to solve the required fit.	L2, L3,L6
CO2	Explain the basic standards of measurements and also apply the desired flatness and surface gauges to analyze the dimensions.	L2, L3,L4
CO3	Evaluate engineering parts with various precision instruments and choose the required surface roughness instrument to compare the parts.	L4,L5,L6
CO4	List out various measuring techniques for Displacement and Strain. Define the various instruments for measuring the displacement and calibrate the strain.	L2, L1,L5
CO5	Estimate the Instruments accuracy and Perform calibration of Force, Torque and pressure measuring instruments	L6, L5,L1

UNIT I

Concept of measurement

Concept of Measurement: Concept of feedback Control systems -generalized measurement system, units and standards, measuring instruments, sensitivity, readability, range of accuracy, precision, static and dynamic response, repeatability, systematic and random errors, correction, calibration, terminology and limits fits and tolerances, hole basis and shaft basis system, interchangeability.

Limit Gauges And Gauge Design: Plug, Ring, Snap, Gap, Taper gauges. Taylor's principle. Design of Go and No Go gauges.

Linear and Angular Measurement: Linear measuring instruments: Vernier instruments, micrometers, slip gauges, tool makers microscope. Comparators: Mechanical, pneumatic and electrical. **Angular measurements:** Sine bar, bevel protractor and angle dekkor, rollers and spheres used to determine the tapers.

UNIT – II

Flatness and Surface Roughness measurement

Flatness Measurement: Measurement of flatness – straight edges – surface plates, optical flat and autocollimators, interferometers and their applications.

Surface Roughness Measurement: Terminology systems, differences between surface roughness and surface waviness- Numerical assessment of surface finish - CLA, R.M.S Value-Ra , Rz values, Methods of measurement of surface finish-profilograph, talysurf, BIS symbols for indication of surface roughness.

UNIT – III

Screw Thread and Gear Measurement

Screw thread measurements: Elements of threads, errors in screw threads, various methods for measuring external and internal screw threads, screw thread gauges.

Gear Measurement: Gear tooth terminology, measurement of gear elements-run out, lead, pitch backlash, profile, pressure angle, tooth thickness, diameter of gear, constant chord and base tangent method.

Coordinate Measuring Machine (CMM)- Construction and features.

UNIT – IV

Measurement of Displacement and Strain

Measurement of Displacement: Theory and construction of various transducers to measure displacement – Piezo-electric, inductive, capacitance, resistance, ionization and photoelectric transducers, calibration procedures.

Measurements of Strain: Various types of electrical strain gauges, gauge factor, method of usage of resistance strain gauge for bending, compressive and tensile strains, usage for measuring torque, strain gauge rosettes.

UNIT – V

Measurement of Force, Torque and Pressure

Measurement of Force: Direct method - analytical balance, platform balance; elastic members – load cells, cantilever beams and proving rings.

Measurement of Torque: Torsion bar dynamometer, servo controlled dynamometer and absorption dynamometer.

Measurement of Pressure: Standards and calibration, basic methods of pressure measurement, dead weight gauges and manometers, High and low pressure measurement, Elastic transducers.

Textbooks:

1. Beckwith, Marangoni, Linehard, Mechanical Measurements, 6/e, PHI, 2013.
2. R.K. Jain, Engineering Metrology, 20/e, Khanna Publishers, 2013.

Reference Books:

1. Mahajan, Engineering Metrology, 2/e, Dhanpat Rai, 2013.
2. S.Bhaskar, Basic Principles - Measurments and Control Systems, Anuradha Publications, 2014.
3. Anand K Bewoor& Vinay A Kulkarni, Metrology & Measurement, 15/e, McGrawHill, 2015.
4. D.S. Kumar, Mechanical Measurements & Control, Metropolitan Publishers, 5/e, 2015.

Online Learning Resources:

- https://nitsri.ac.in/Department/Mechanical%20Engineering/MEC_405_Book_2,_for_Unit_2 B.pdf
- https://www.digimat.in/nptel/courses/video/112104250/L47.html
- https:/
- www.digimat.in/nptel/courses/video/112106138/L01.ht ml

https://www.digimat.in/nptel/courses/video/112106179/L01

- html https://www.youtube.com/watch?v=tczyyM4Dykc
- https://www.youtube.com/watch?v=_UsAiZ mRC1M
- https://www.youtube.com/watch?v=oCkax I19X8

UNIT-1

Concept of Measurement: Concept of Feedback control systems:

Measurement is the act of observing and quantifying a system's current state, while a feedback control system uses these measurements to automatically adjust the system's input to achieve a desired output by comparing the measurement to a setpoint and minimizing the difference, or error. This process creates a closed loop where the system continuously self-corrects, for example, a cruise control system measures the car's speed and adjusts the throttle to match the set speed, even when going up a hill.

Concept of Measurement

- **Definition:**

Measurement is the process of observing a system's variable and converting it into a signal, such as using a sensor to read a temperature or speed.

- **Role in control:**

Sensors provide the real-world data about the system's current state, which is essential for the control system to understand what is happening.

- **Accuracy and noise:**

The accuracy of the measurement can be affected by noise or other factors, so control systems are designed to handle potential inaccuracies from sensors.

Concept of Feedback Control Systems

- **Core principle:**

A feedback control system uses a measurement of the output to influence the input, creating a continuous "closed loop" to achieve a desired outcome.

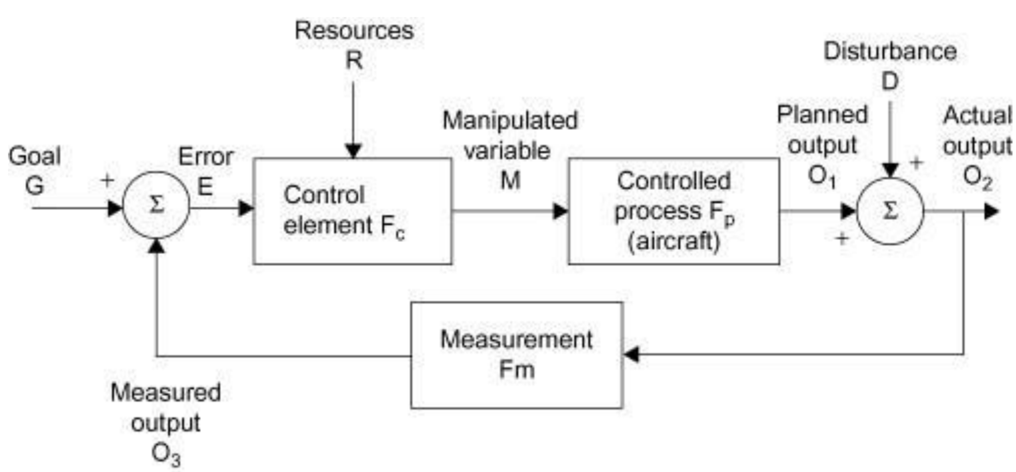
- **Components:**

A typical feedback loop includes:

    - **Plant:** The system or process being controlled (e.g., the engine of a car).
    - **Sensor:** Measures the output of the plant.
    - **Controller:** Compares the measured output to the desired output (setpoint) and calculates the necessary adjustment.

- **Actuator:** The component that adjusts the input to the plant based on the controller's signal (e.g., the throttle).

- **Process:**
  - The controller receives a measurement from the sensor.
  - It compares this measurement to the setpoint, calculating the "error" (the difference).
  - The controller sends a command to the actuator to correct the error.
  - This process repeats, with the system continually adjusting to minimize the error.
- **Benefits:**
  - **Disturbance rejection:** It can compensate for external factors that cause the system to deviate from its goal, such as a hill affecting a car's speed.
  - **Cost-effectiveness:** Sensors can often be built with high accuracy more cheaply than the power components of a system, making feedback control an economically beneficial solution.
- **Example (toasting bread):**
  - **Setpoint:** The desired color of the toast.
  - **Measurement:** The sensor measures the actual color of the bread as it toasts.
  - **Controller:** Compares the current color to the desired color and calculates the error.
  - **Actuator:** The heating element's power is adjusted by the controller. When the error is zero (the color matches the setpoint), the toaster turns off.



Generalized measurement system, Units and Standards:

A generalized measurement system is a block-diagram representation of any measurement device, comprising six functional elements: a primary sensing element, variable conversion element, variable manipulation element, data processing element, data transmission system, and data presentation element. A unit is a standard name for a physical quantity, such as a kilogram, while a standard is the physical embodiment of that unit, like the platinum-iridium cylinder used as the kilogram standard. The International System of Units (SI) is the most widely used system of measurement, built on seven base units.

Generalized measurement system

This model provides a framework for understanding how any measurement system works, regardless of its complexity.

- **Primary Sensing Element:** The first component to interact with the physical quantity being measured.
- **Variable Conversion Element:** Converts the signal from the sensing element into a more usable form.
- **Variable Manipulation Element:** Manipulates and amplifies the signal, often through processes like amplification.
- **Data Processing Element:** Analyzes the signal.
- **Data Transmission System:** Transmits the data between the different elements.
- **Data Presentation Element:** Displays the final result of the measurement to the observer, often in a human-readable format.

Units and Standards

- **Units:**

The names given to a quantity to assign a numerical value. Examples include meter, kilogram, and liter.

- **Standards:**

The physical embodiment of a unit, used as a reference for comparison.

- **Primary Standards:** Ultimate standards of reference, preserved with extreme care and used to calibrate secondary standards.
- **Working Standards:** Standards used in conjunction with instruments for routine measurement and calibration.

- **International System of Units (SI):**

The modern form of the metric system and the most widely used system globally, which has seven base units.

- The SI system is based on a set of fundamental units from which all other units can be derived.
- For example, the standard for length is the meter, and the standard for mass is the kilogram.

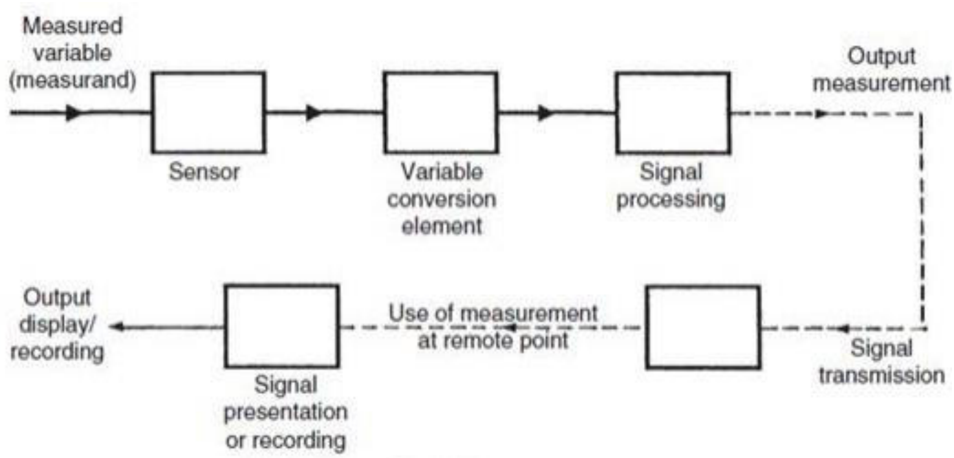


Fig 1.1 Generalised Measurement system

Table 1.2: The Seven Base SI Units

Property	Unit	Abbreviation
Length	meter	m
Mass	kilogram	kg
Time	seconds	s
Amount	mole	mol
Temperature	kelvin	K
electric current	ampere	amp
luminous intensity	candella	cd

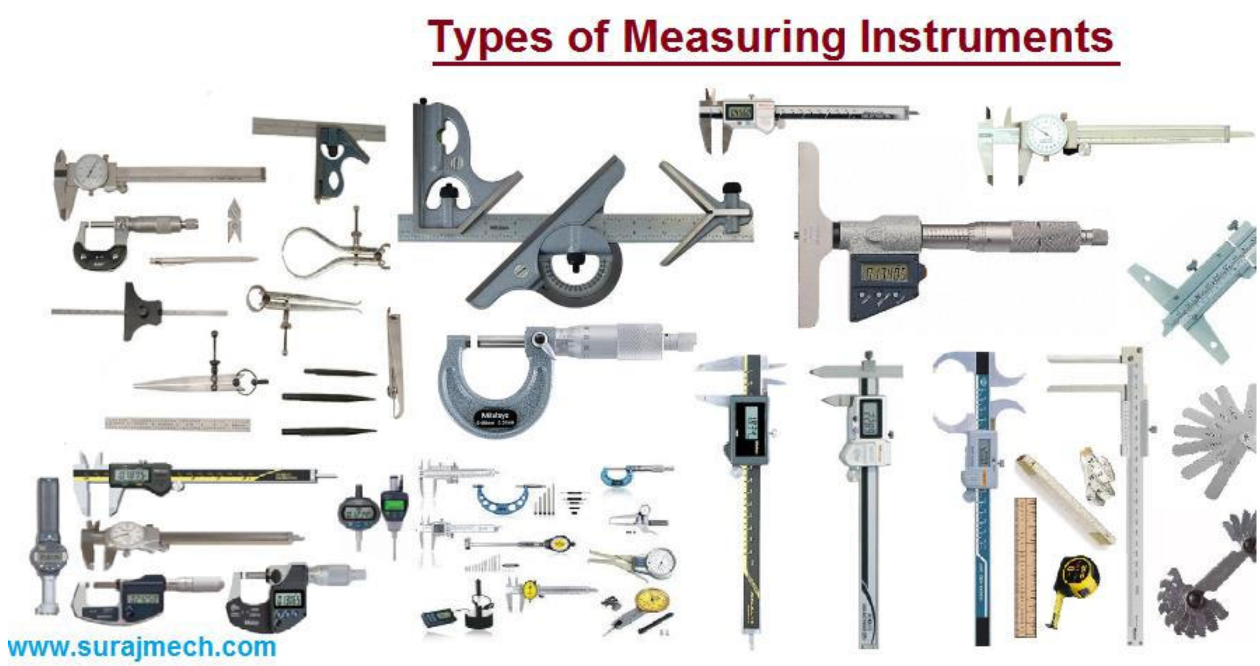
Measuring instruments.:

Measuring instruments are tools used to measure physical quantities like length, mass, volume, and temperature. Examples include rulers for length, balances for mass, graduated cylinders for volume, and thermometers for temperature. Other, more precise instruments include Vernier calipers, micrometers, and stopwatches.

Common measuring instruments

- **For length:**
  - **Ruler/Meter stick:** Measures length for everyday objects.
  - **Measuring tape:** A retractable metal tape for measuring longer distances.
  - **Vernier caliper:** Measures inside, outside, and depth dimensions with high accuracy.
  - **Micrometer:** Measures small distances with a very high degree of precision.
- **For mass:**
  - **Balance/Scale:** Used to determine the mass of an object.
  - **Physical balance:** A type of balance used for scientific measurements.
- **For volume:**

- **Graduated cylinder:** A tall, cylindrical container with markings for measuring liquid volume.
    - **Beaker:** Also used for measuring volume, though often less precise than a graduated cylinder.
- **For time:**
    - **Stopwatch:** Measures a period of time.
- **For temperature:**
    - **Thermometer:** Measures temperature.
- **For other quantities:**
    - **Ammeter:** Measures electric current.
    - **Barometer:** Measures atmospheric pressure.
    - **Dial indicator:** Measures small displacements or variations from a reference point.



Sensitivity, Readability, Range of accuracy, Precision:

Sensitivity is the smallest change an instrument can detect, accuracy is the closeness of a measurement to the true value, precision is the reproducibility of measurements, and readability is how easily a measurement can be read. The range is the minimum and maximum values a device can measure, and the "range of accuracy" is not a standard term but is related to the overall acceptable error, or tolerance.

Sensitivity **Definition:**

The smallest change in the measured quantity that causes a detectable change in the instrument's output.

Ratio: It can be expressed as the ratio of the change in the instrument's output to the change in the input value.

Example: A highly sensitive thermometer can detect a 0.01∘C change, while a less sensitive one may only register a $0.5^{\circ}C$change.

Accuracy

Definition: The degree to which an instrument's reading or measurement is close to the true or accepted value.

Basis: It is measured relative to the true value.

Example: If the true weight of an object is 10.0 kg, a measurement of 10.1 kg is more accurate than a measurement of10.5kg.

Precision

Definition: The degree of closeness between a series of measurements of the same quantity under the same conditions.

Basis: It describes the reproducibility of measurements.

Example: If a scale repeatedly gives readings of 17.4,17.3,17.4, it is precise. If these readings are not close to the true value of 20.0 kg, the scale is precise but not accurate.

Readability

Definition: The ease with which a person can read a measurement from an instrument.

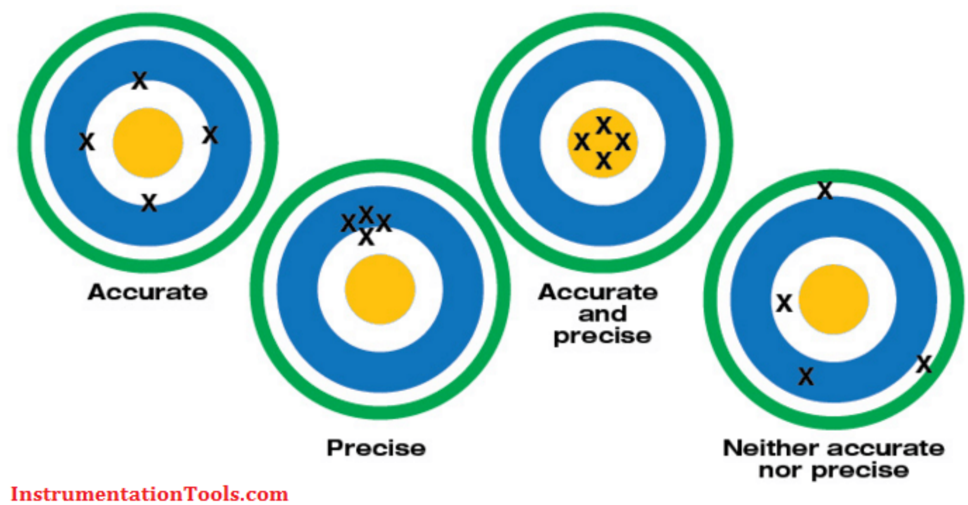
Basis: It is determined by factors such as the clarity of the scale, the size of the markings, and the presence of parallax error.

Example: An instrument with a clear, large digital display has higher readability than one with a small, crowded analog scale.

Range

Definition: The minimum and maximum values of a quantity that an instrument is designed to measure.

Example: A thermometer with a range of $-10^\circ C$ to 110°C can only accurately measure temperatures within this range.



Static response analyzes a system's behavior under constant or slowly changing conditions, focusing on steady-state properties like accuracy and sensitivity. Dynamic response, on the other hand, describes how a system reacts to inputs that change over time, considering factors like speed, lag, and overshoot. Static analysis simplifies calculations by ignoring time-dependent factors like acceleration, while dynamic analysis includes them to provide a more complete picture of the system's transient behavior.

Static response

- **Focus**: The steady-state outcome when the input is constant or changes very slowly.
- **Key characteristics**: Accuracy, precision, sensitivity, linearity, and resolution.
- **Example**: Measuring the final temperature of a cup of coffee after it has cooled to room temperature. The steady-state reading is the final equilibrium temperature.

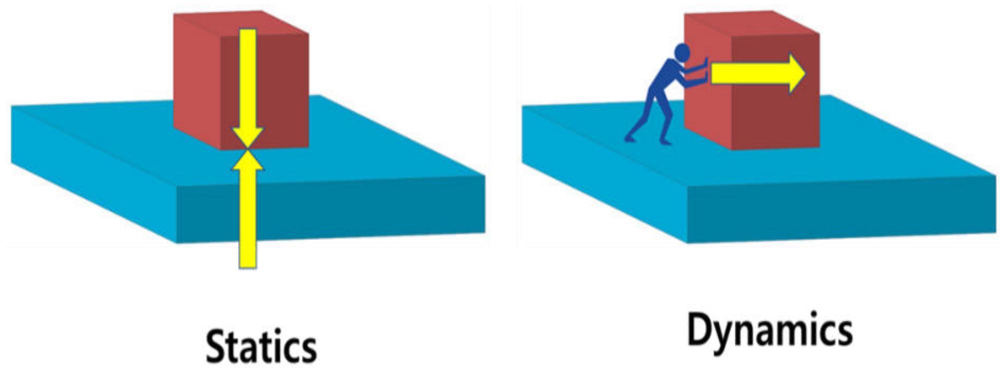
Dynamic response

- **Focus**: The behavior of a system between the time a change occurs and the time it reaches a new steady state.
- **Key characteristics**: Speed of response, lag, overshoot, and fidelity.

- **Example**: Observing how quickly a thermostat detects a change in room temperature and begins to heat or cool the space to reach the new setpoint.

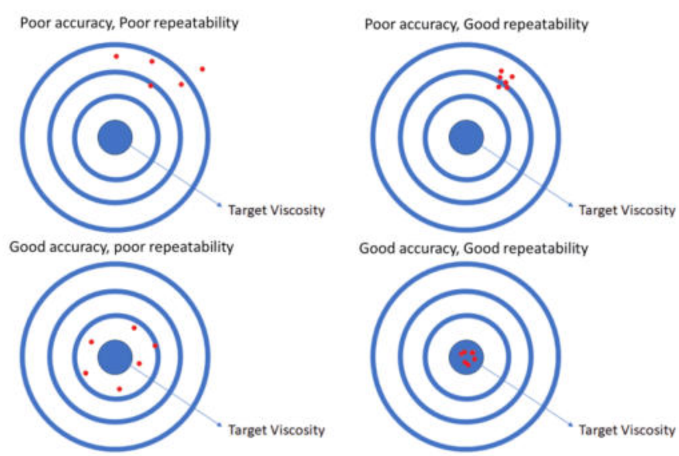
Key differences

Feature	**Static Response**	**Dynamic Response**
Input	Constant or very slow change	Rapid or transient change
Analysis	Ignores time-dependent factors (like acceleration or velocity)	Includes time-dependent factors
Metrics	Accuracy, precision, sensitivity, linearity	Speed of response, lag, overshoot, fidelity
Purpose	To determine the final, stable output of a system	To understand the transient behavior and time-related performance of a system



Repeatability:

Repeatability is the closeness of agreement between the results of successive measurements of the same thing, under the same conditions, over a short period of time. It measures how consistent an experiment or measurement is when repeated, and a high degree of repeatability means that small variations in the output are observed for the same fixed input. This is different from reproducibility, which involves a different team or conditions.

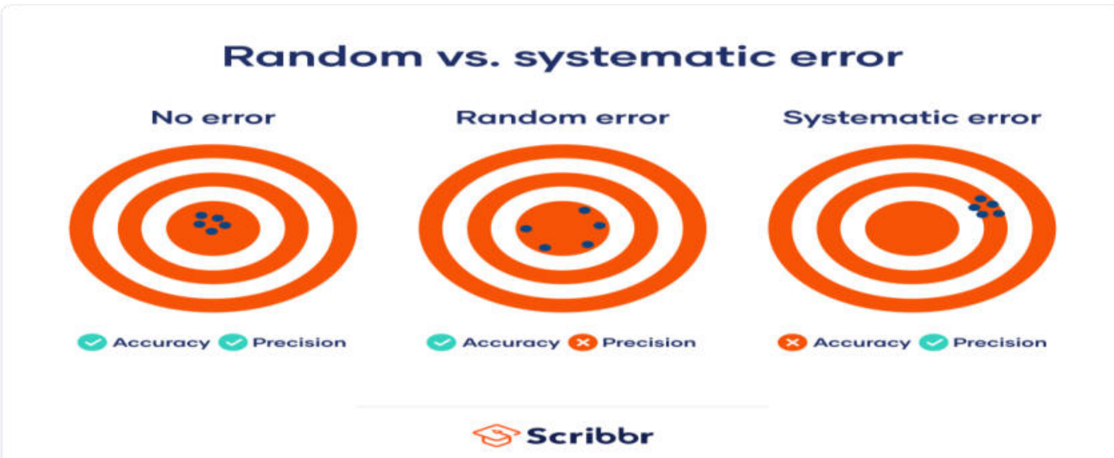


systematic and random errors. Correction:

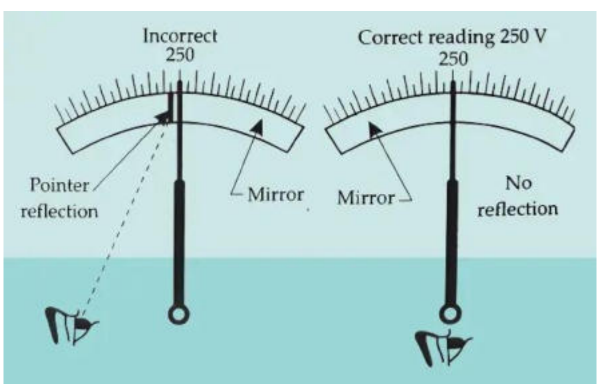
To correct for systematic and random errors, reduce random errors by increasing sample size and replicating measurements, and address systematic errors by identifying and calibrating instruments, controlling variables, and improving experimental design. Systematic errors require a different approach, as they are consistent and repeatable, often stemming from flawed equipment or procedures.

Random errors:

Replication: Repeat measurements multiple times and average the results to reduce the effect of random fluctuations.



Calibration: Regularly calibrate equipment against a standard to ensure accuracy and adjust for consistent deviations.



Calibration:

Calibration is the process of comparing a measuring instrument's readings to a known, accurate standard to check for and correct any inaccuracies. It ensures that instruments provide reliable and precise measurements, which is crucial for safety, quality control, and operational efficiency in fields from medicine to manufacturing. This is often done by adjusting the instrument if its readings drift due to wear, environmental factors, or other issues.

What calibration involves

Comparison: The instrument's output is compared to a reference standard of known accuracy under specific conditions.

Evaluation: The comparison determines if the instrument's readings are within acceptable limits.

Adjustment: If there is a deviation, the instrument is adjusted to correct the error and bring it back to its standard, a process sometimes called "true-up".

Documentation: After successful calibration, a calibration tag is often attached to the device to show it has been checked and certified.

SYSTEMS OF LIMITS AND FITS: Introduction, Definitions:

Limits and fits are fundamental concepts in engineering for ensuring components can be manufactured to a specific standard and will assemble correctly. Limits are the maximum and minimum permissible sizes for a single part's dimension. Fits describe the relationship between two mating parts, such as a hole and a shaft, defining the amount of tightness or looseness upon assembly. Tolerance is the permissible variation allowed between a part's maximum and minimum limits.

Purpose: Limits and fits provide a standardized system to control the variability of manufactured parts, ensuring they can be interchanged and will function as intended.

Function: The system accounts for the fact that perfect, exact dimensions are impossible to achieve in manufacturing. Instead, it uses a system of limits and fits to guarantee compatibility and correct performance.

Application:It is crucial for creating functional and reliable assemblies, from small consumer electronics to large machinery like aircraft engines.

Definitions:

Limits: The two extreme permissible sizes for a dimension.

Maximum Limit of Size: The largest size a part is allowed to be.

Minimum Limit of Size: The smallest size a part is allowed to be.

Tolerance: The total permissible variation in a dimension.

It is the difference between the maximum and minimum limits.

Tolerance allows for some error during manufacturing without the part becoming unusable.

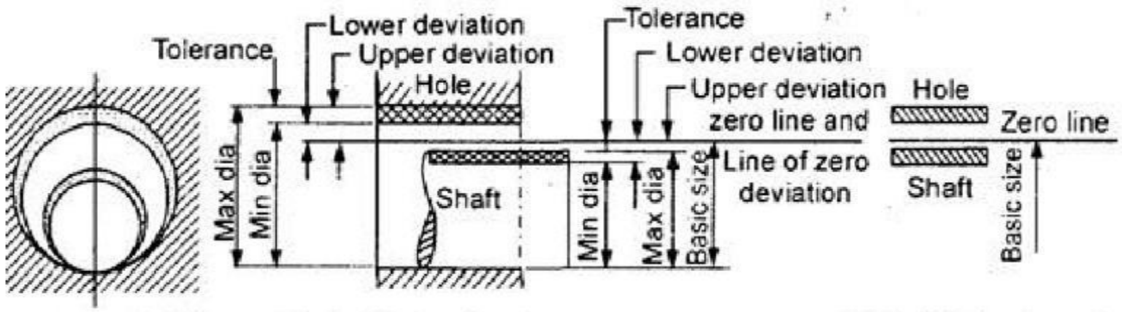
Fit: The relationship between two mating parts, like a hole and a shaft, before they are assembled. It defines the degree of tightness or looseness between the parts.

Clearance Fit: A fit that always leaves space between the parts (e.g., a shaft that can slide freely in a hole).

Interference Fit: A fit where the shaft is larger than the hole, requiring force to assemble and creating a rigid connection (e.g., a wheel pressed onto an axle).

Transition Fit: A fit that can result in either a clearance or an interference, depending on the actual dimensions of the mating parts.

Allowance: An intentional, specific difference in size between the maximum material conditions of two mating parts.

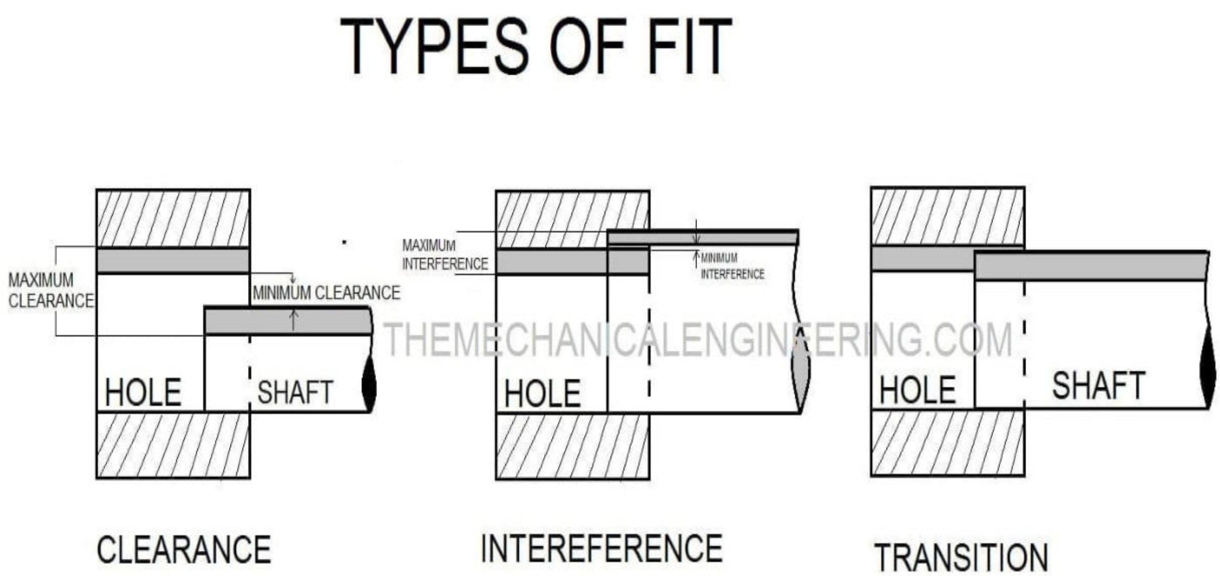


(a) Diagram illustrating basic size deviations and tolerances.

(b) Simlified schematic diagram of clearance fit.

Limits and Fits -Definition

- Basic Size: It is the size with reference to which upper or lower limits of size are defined.
- Shaft and Hole: These terms are used to designate all the external and internal features of any shape and not necessarily cylindrical.
- Hole Designation: By upper case letters from A, B, … Z, Za, Zb, Zc(excluding I, L, O, Q, W and adding Js, Za, Zb, Zc) -28 nos.



Unilateral and bilateral tolerance systems:

Unilateral and bilateral tolerance systems define how a dimension can vary from its basic size. In a unilateral system, the allowed variation is in only one direction (either above or below) the basic size. In a bilateral system, the allowed variation is in both directions, above and below the basic size. The choice between them depends on the part's design, precision requirements, and manufacturing constraints.

Unilateral tolerance system **Definition:** The tolerance is entirely on one side of the basic size.

Example: A hole with a basic size of 20 mm could have a unilateral tolerance of 20.000/19.950mm, meaning the dimension can only be smaller than or equal to the basic size.

Use: Often used for precision parts where variation in a specific direction is critical or easier to control during manufacturing. It can also be used when the total tolerance is only in one direction.

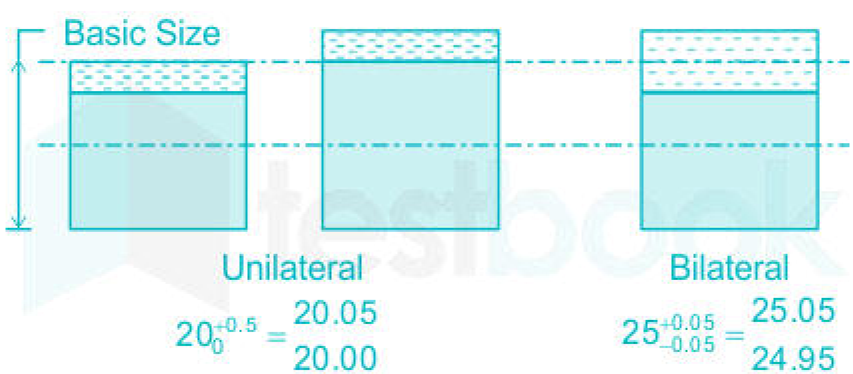
Bilateral tolerance system Definition: The tolerance is divided on both sides of the basic size, allowing variation both above and below it.

Example: A shaft with a basic size of 20 mm could have a bilateral tolerance of 20.000 / 19.980 mm, with an upper limit of+0.020 and a lower limit of −0.020.

Use: Offers a more balanced tolerance zone and is common in interchangeable parts manufacturing.

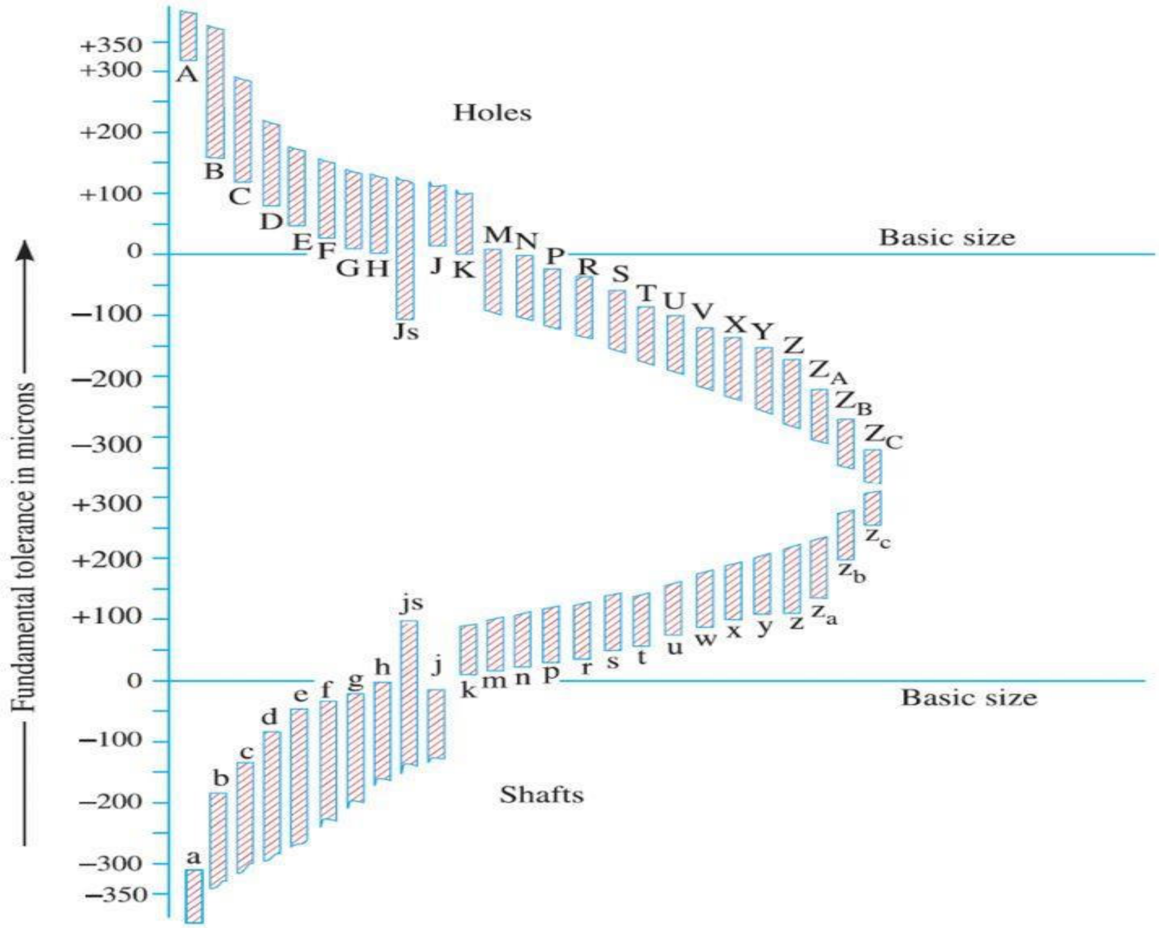
Key differences

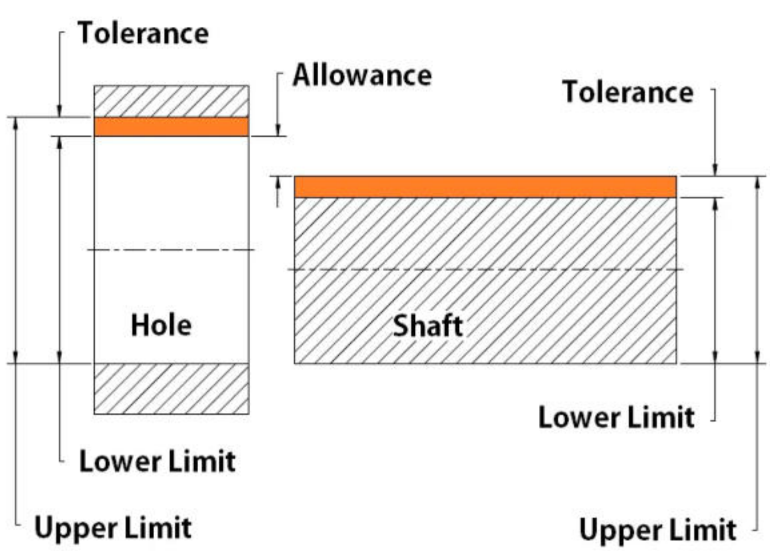
Feature	**Unilateral Tolerance**	**Bilateral Tolerance**
Direction of Variation	Only one direction (above or below)	Both directions (above and below)
Expression	Expressed as one deviation from the basic size	Expressed with two deviations from the basic size
Flexibility	Limits design flexibility, but can simplify manufacturing control	Provides more flexibility, but can be harder to control manufacturing to a tight fit



Tolerance analysis:

Tolerance analysis in limits and fits involves calculating how manufacturing variations affect a product's functionality by analyzing the accumulation of dimensional tolerances in an assembly. Key concepts include specifying the maximum and minimum allowable dimensions for a part (limits), the permissible deviation from a nominal size (tolerance), and the relationship between mating parts like a hole and shaft (fits), which can be a clearance, interference, or transition fit. Tolerance analysis ensures parts will function correctly after assembly, even with variations in manufacturing.





Hole and shaft basis systems:

The two main systems for limits and fits are the hole basis system and the shaft basis system. In the hole basis system, the hole size is kept constant (the basic hole), and the shaft size varies to achieve different fits. Conversely, in the shaft basis system, the shaft size is constant (the basic shaft), and the hole size varies. The hole basis system is more commonly used in manufacturing because it is easier to adjust a shaft's size with turning or grinding than to modify a hole after it has been drilled.

Hole basis system C**oncept:** The size of the hole is held constant, and the shaft's size is varied to achieve the desired fit.

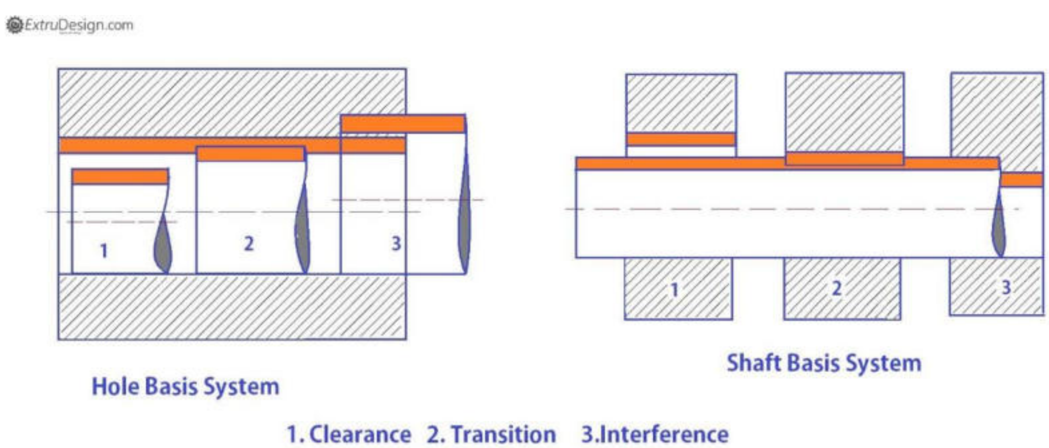
Basic hole: A hole whose lower deviation is zero, meaning its minimum limit is the basic size.

Manufacturing advantage: Easier to achieve precise shaft dimensions through grinding or turning compared to modifying a hole.

Shaft basis system **Concept:** The size of the shaft is held constant, and the hole's size is varied to achieve the desired fit.

Basic shaft: A shaft whose upper deviation is zero, meaning its maximum limit is the basic size.

When to use: Can be preferable when a single shaft needs to fit into multiple different holes, as the hole sizes can be varied accordingly.



Interchangeability and selective assembly:

Interchangeability and selective assembly are two systems for producing and assembling parts that fit together correctly. Interchangeability allows any part from one manufacturing run to be substituted with any part from another, provided they both meet the same specifications and tolerances. Selective assembly is a method where parts are sorted into size groups after manufacturing and then matched to a corresponding group from the mating part to achieve a precise fit.

Interchangeability **Definition:** A system where components are manufactured within specified limits, allowing any part to be randomly selected and assembled with any other mating part from the same group, regardless of the manufacturing source.

Purpose: To enable mass production with reduced assembly time and costs by eliminating the need for trial-and-error fitting.

Types: Universal interchangeability: Parts are made to a single, international standard.

Local interchangeability: Parts are made to local or company-specific standards.

Example: In a factory, hundreds of identical screws are produced. Any one of these screws can be used to assemble a product with any of the corresponding nuts, as they are all within the defined tolerance.

Selective assembly **Definition:** A technique used when a very close fit is required. It involves measuring each manufactured part and sorting it into a specific size group.

Purpose: To achieve precise fits required for some applications while allowing for wider manufacturing tolerances, which reduces costs.

Process: Mating parts are grouped by size. For example, a part from the "A" group of shafts will be paired with a part from the "A" group of holes to achieve the desired fit.

Example: A set of pistons and cylinders is manufactured with wider tolerances. The pistons and cylinders are measured and sorted into size groups (e.g., A, B, C). A "B" size piston is then matched with a "B" size cylinder to achieve a perfect fit that would not be possible with random selection.

Linear measuring instruments-Vernier Instruments, Micrometers, Slip Gauges:

Vernier instruments, micrometers, and slip gauges are all precision linear measuring instruments used to measure length, diameter, and thickness. Vernier calipers use two sliding scales for accurate external and internal measurements, while micrometers use a threaded spindle for highly precise measurements, often down to 0.01mm. Slip gauges are precision blocks with highly accurate, flat, and parallel faces that can be "wrung" together to create a precise reference standard for calibration or measurement.

Vernier instruments Function: Measure external and internal dimensions, as well as depth, with a higher degree of accuracy than a standard ruler.

Mechanism: Utilizes a main scale and a sliding vernier scale. The vernier scale's graduations allow for reading smaller increments, with a common least count of 0.02 mm.

Examples: Vernier calipers, vernier height gauges, and vernier depth gauges.

Micrometers Function: Provide very high-precision measurements of small distances or thicknesses.

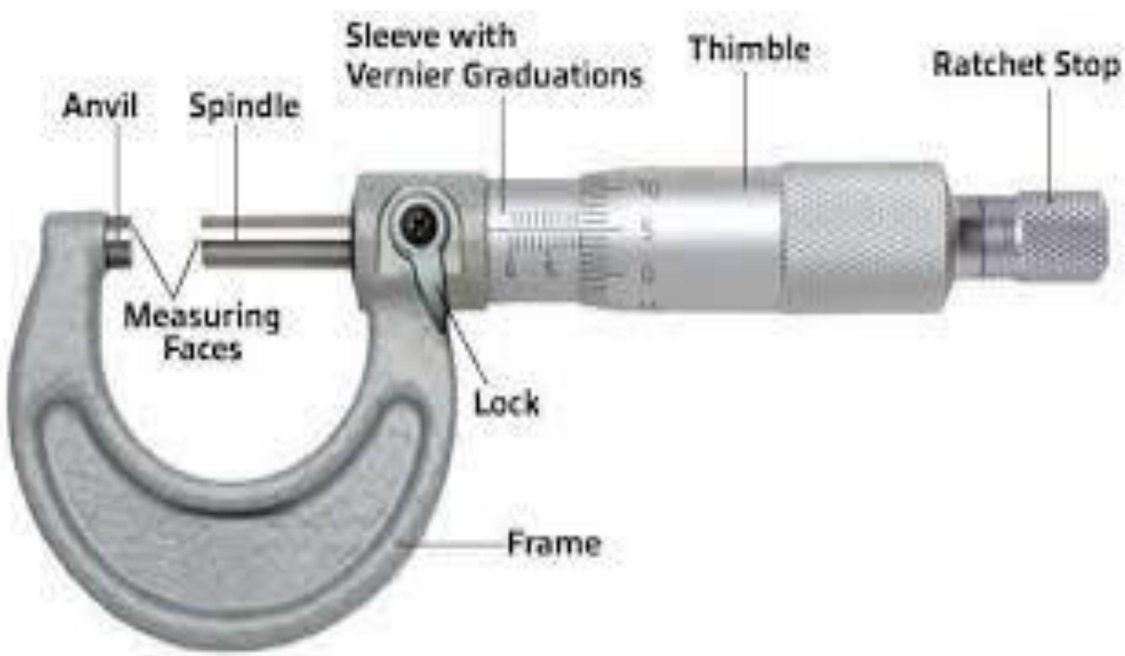
Mechanism: Employ a precisely threaded spindle that moves along a calibrated thimble. Turning the thimble incrementally moves the spindle in and out, allowing for fine-scale measurement, with a common accuracy of 0.01mm.

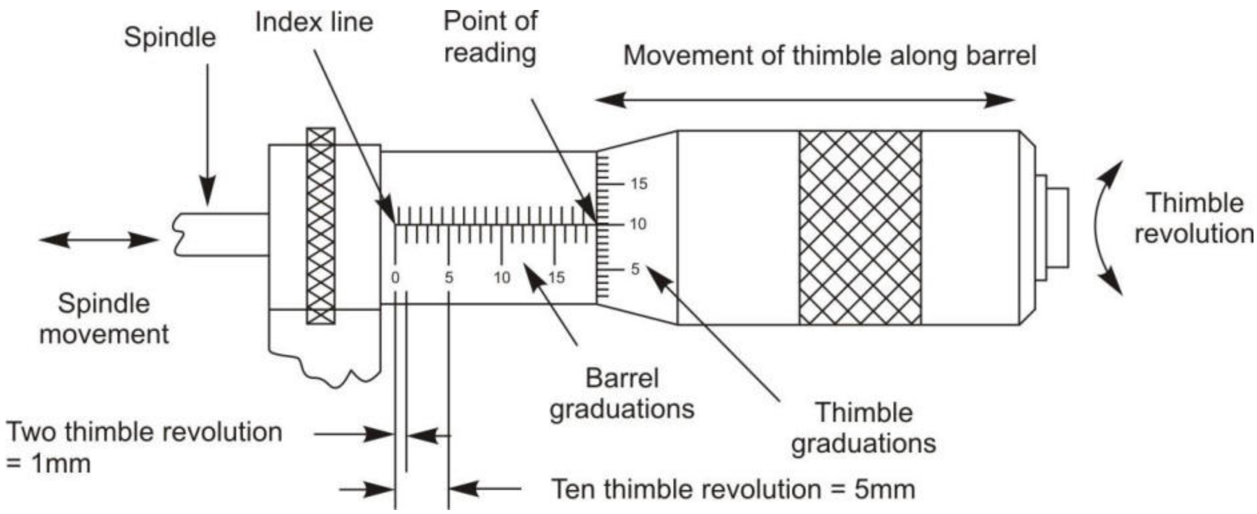
Examples: External micrometers, inside micrometers, and depth micrometers.

Slip gauges **Function:** Act as a standard for comparison or calibration, providing a high-accuracy, known length. They are used to calibrate other measuring instruments like micrometers and vernier calipers.

Mechanism: Made of hardened steel with precision-ground, lapped, and parallel faces. By applying a slight twist, multiple gauges can be "wrung" together due to adhesion, creating a stack with a precise total length for measurement.

Characteristics: They are sold in sets with a variety of sizes, allowing for combinations that create lengths in increments as small as 0.01mm.




Spindle
Index line
Point of reading
Movement of thimble along barrel
15
10
5
0
5
10
15
Thimble revolution
Spindle movement
Barrel graduations
Thimble graduations
Two thimble revolution = 1mm
Ten thimble revolution = 5mm


beam
guiding face
main scale
fine-adjustment device
locking device
probe extension
slider
vernier scale
fixing device
measuring and scribing stylus
measuring face
instrument base
instrument-base reference base

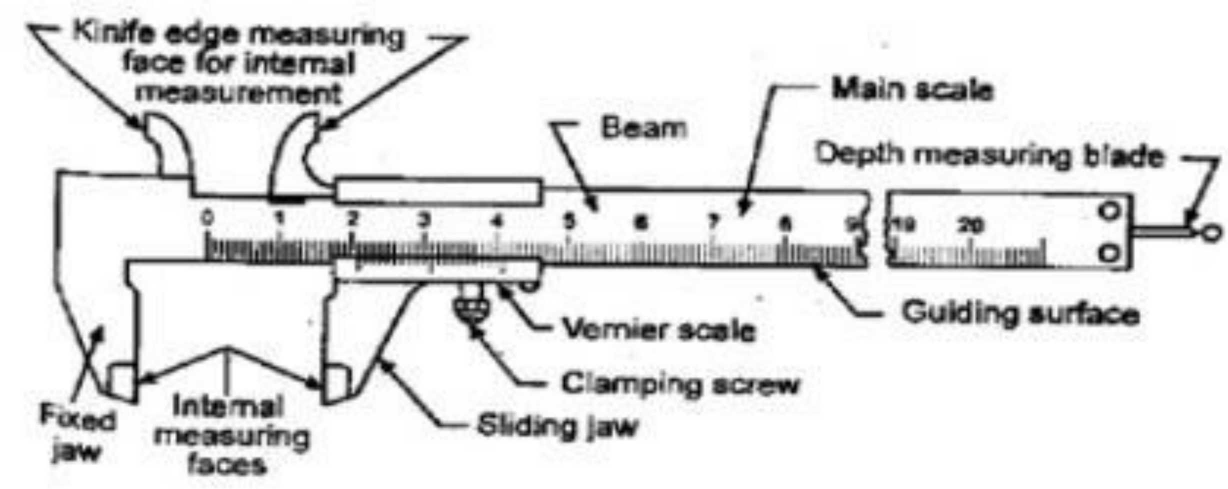
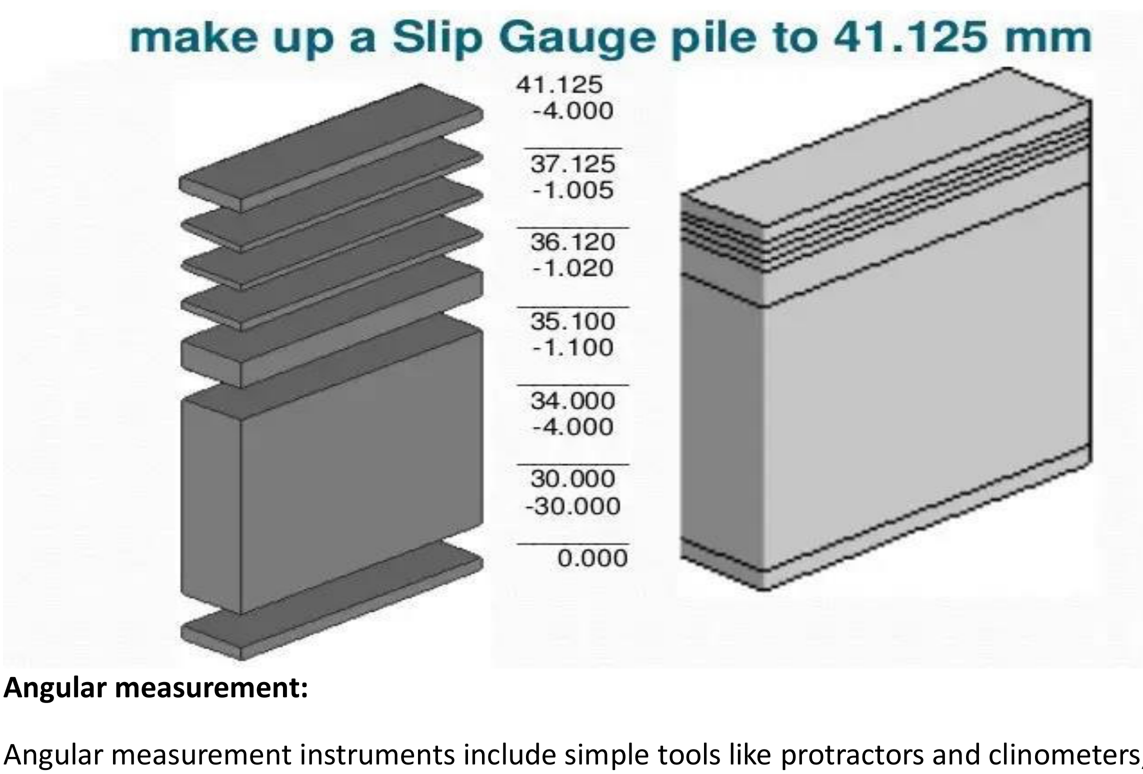


Fig 2.2 Vernier Caliper - Type A



Angular measurement:

Angular measurement instruments include simple tools like protractors and clinometers, as well as precision devices like sine bars, angle gauges, and theodolites. These instruments are used to measure angles on objects or between surfaces for various applications, from drafting to engineering and surveying.

Simple and general-purpose tools

Protractor: A basic instrument, often a semicircular disk, with a scale in degrees used for measuring and constructing angles.

Clinometer: A device specifically for measuring the angle of inclination or tilt of a surface.

Spirit level: Uses a vial of liquid with an air bubble to measure if a surface is horizontal or inclined, and can be used to find angles.

Precision and industrial instruments:

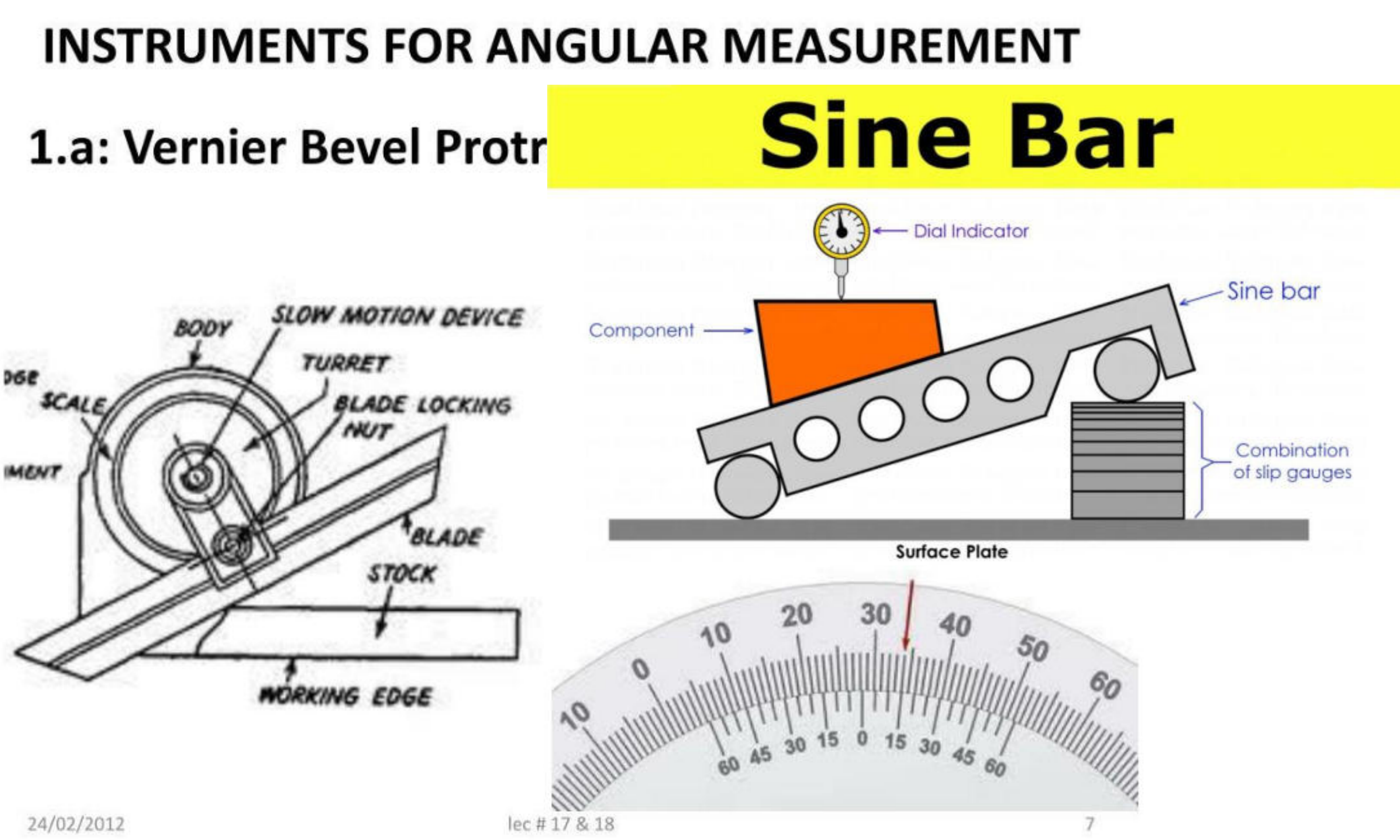
Bevel protractor: A more precise tool used in machining and other industrial settings for measuring and setting angles with a high degree of accuracy.

Sine bar: A high-precision, indirect measuring tool that uses slip gauges and trigonometry to measure angles based on the sine function.

Sine center: A device that works with sine bars to measure angles on tapers.

Angle gauges: Calibrated blocks that can be stacked to create or measure specific angles with great precision.

Auto collimator: An instrument that uses a beam of light to compare angles very precisely.



Toolmaker's microscope:

A toolmaker's microscope works on the principle of projecting a magnified shadow image of an object to take precise measurements using a system of optics and a calibrated stage. A light source illuminates the workpiece, creating a shadow which is then magnified by the microscope's lens system and projected onto a screen or viewed through an eyepiece with crosshairs. Measurements are taken by moving the object on the stage and noting the precise readings on the micrometer screws for the X, Y, and rotational axes.

Working principle breakdown

- **Illumination and shadow projection:**

Light from a built-in source passes through the workpiece. The physical body of the object casts a shadow, creating a clear silhouette against the light.

- **Optical magnification:**

The shadow is then magnified by the objective lens and projected by a system of prisms and lenses.

- **Viewing and comparison:**

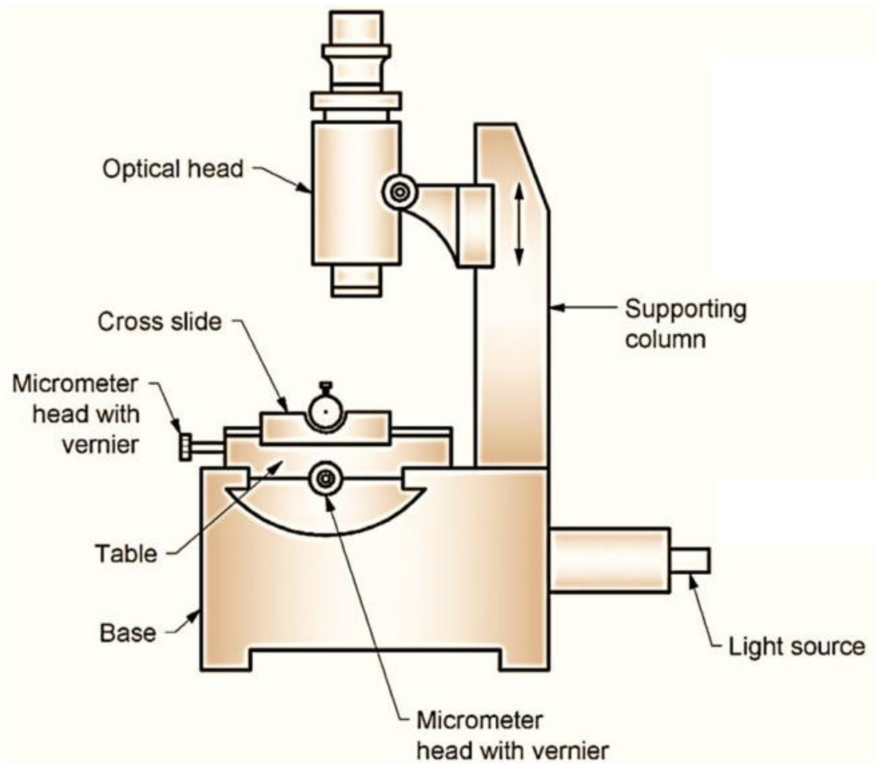
This magnified image can be viewed directly through an eyepiece or projected onto a ground glass screen with a reticle (a pattern of lines or crosshairs) for comparison.

- **Precise measurement:**

The workpiece is placed on a stage that can be moved along the X and Y axes using micrometer screws. By aligning the crosshairs with a feature on the object, recording the micrometer reading, and then moving to another feature and taking another reading, the difference between the two readings gives the measurement. An additional rotating stage allows for angular measurements.

- **Applications:**

The instrument is used for precise measurements of lengths, angles, and profiles, such as checking the pitch and profile of threads.



Mechanical, pneumatic, and electrical comparators are precision instruments for comparing a component's dimensions against a standard, but they operate on different principles. Mechanical comparators use gears and levers to magnify movement, while pneumatic types use variations in air pressure or flow. Electrical comparators convert a physical displacement into an electrical signal for magnification and display.

Mechanical comparator **Principle:** Uses a system of mechanical components like gears, levers, linkages, and springs to magnify small displacements of a measuring plunger.

Working: A plunger moves, and its movement is amplified through the mechanical linkage to move a pointer on a dial or a magnified indicator.

Examples: Dial indicators, Reed type comparators, and Sigma comparators.

Advantages: Simple, inexpensive, and can be portable without external power.

Disadvantages: Lower magnification limits and potential for parallax error.

Pneumatic comparator **Principle:**

Works by using a regulated air supply and measuring the changes in air pressure or flow.

Working: Compressed air is fed through a special nozzle or measuring head. As the distance between the nozzle and the workpiece changes, the airflow and back pressure change, which is then measured.

Advantages: No friction or wear, high magnification is possible, and they are less sensitive to dirt.

Disadvantages: Requires an air supply, compressed air lines, and specialized gauging heads.

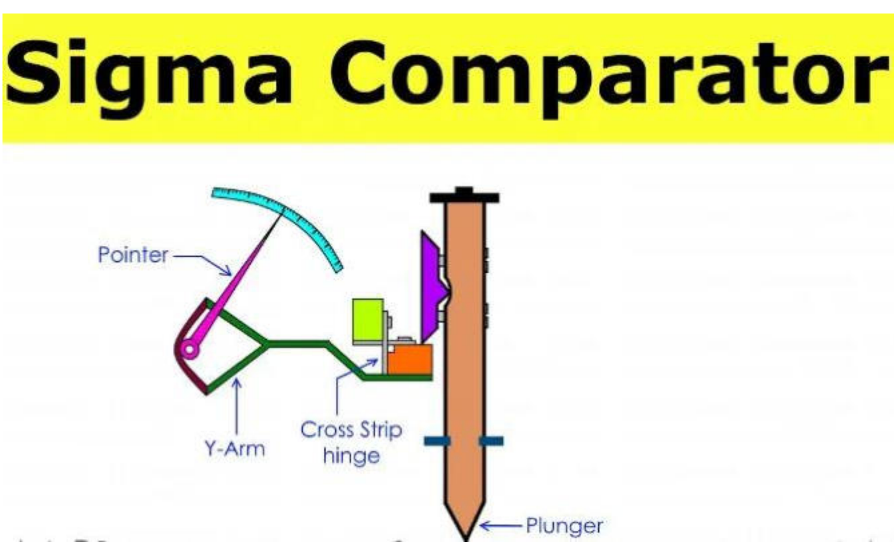
Electrical comparator

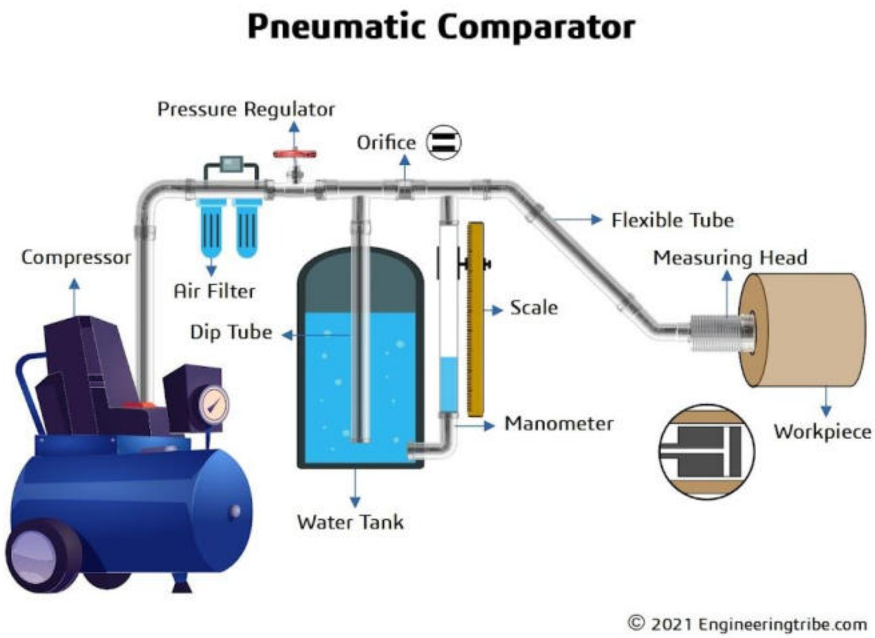
Principle: Converts a mechanical displacement into an electrical signal, which is then amplified.

Working: A measuring probe's movement is detected by a transducer that generates a signal. This signal can be sent to a meter or display, often after being amplified electronically.

Advantages: High magnification (up to 40,000 or more) and allows for remote measurement indication.

Disadvantages: Requires a power source and can be sensitive to environmental factors.




Pneumatic Comparator
Pressure Regulator
Orifice
Flexible Tube
Compressor
Measuring Head
Air Filter
Scale
Dip Tube
Manometer
Workpiece
Water Tank
© 2021 Engineeringtribe.com

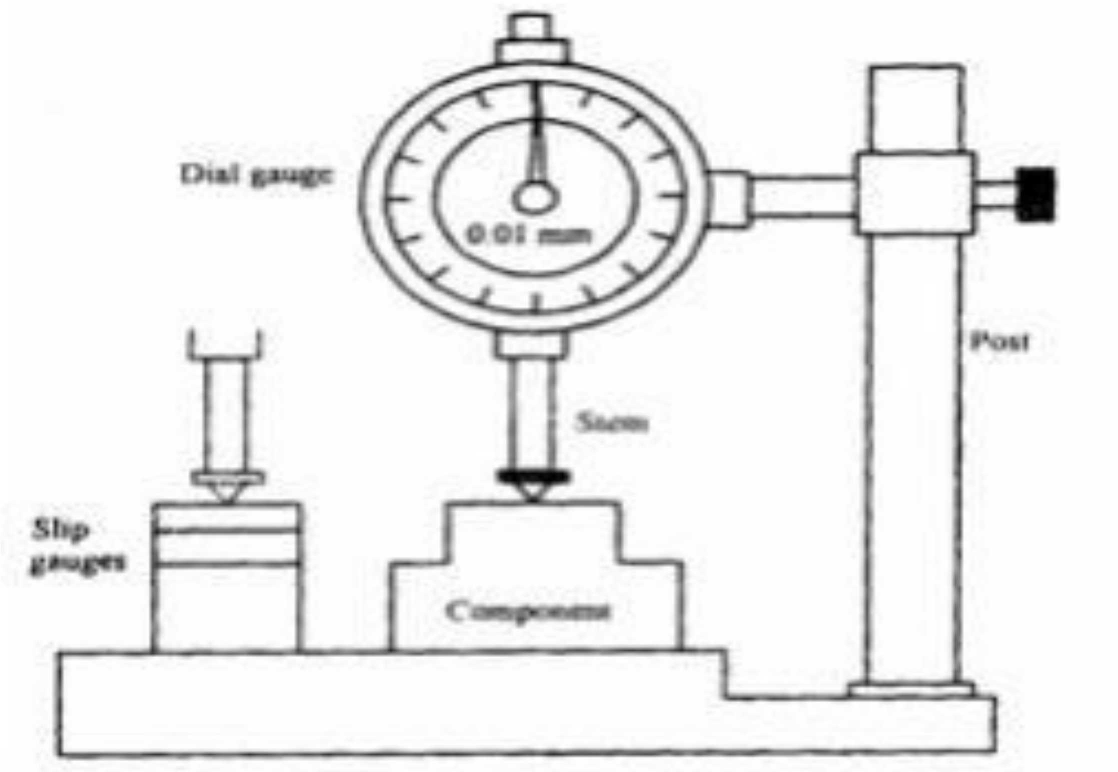


Fig 2.18 Dial Indicator

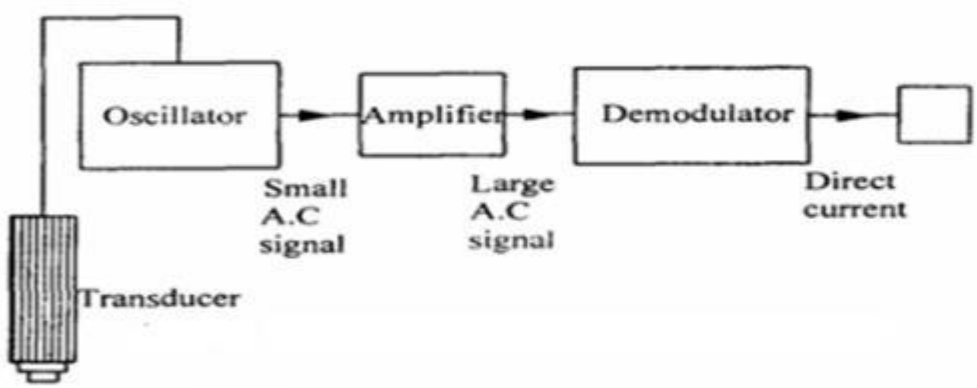


Fig 2.20 ***Principle of operation in electric gauging***

Angle Dekkor:

An Angle Dekkor works by using a light beam from a lamp to create an image of an illuminated scale. This light passes through a collimating lens to a reflective workpiece, and the reflected beam is refocused through the same lens onto an eyepiece. The reflected image of the scale, which is at a right angle to a fixed datum scale, is observed to measure angular deviations of the workpiece surface.

Detailed working principle:

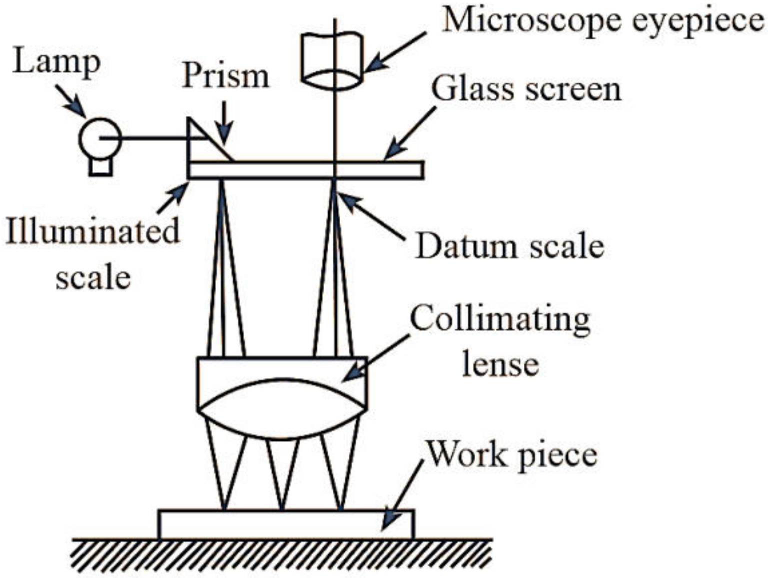
Light Path: Light from a lamp is directed through a prism, then through an illuminated scale on a glass screen.

Collimation: The light passes through a collimating lens, which makes the beam parallel before it hits the workpiece.

Reflection: The workpiece's reflecting surface sends the parallel light beam back to the collimating lens.

Refocusing and Observation: The lens refocuses the reflected beam onto the eyepiece, displaying a rotated image of the illuminated scale.

Measurement: A fixed datum scale is located in the center of the screen, perpendicular to the illuminated scale. The point where the reflected illuminated scale intersects the datum scale indicates the angular deviation of the workpiece from a known angle. The reading is taken by observing the position of the intersection on the scales, which allows for direct reading of angles.



Rollers and spheres used to determine the tapers:

Rollers and spheres are used to determine tapers by placing them in a part and taking precise measurements with tools like a micrometer or slip gauges. The distance between the points of contact and the component's dimensions are then used in a formula to calculate the taper angle. This method is useful for parts with internal features, like dovetails or ring gauges, where direct measurement is difficult.

How to measure taper with rollers/spheres

Place precision rollers or spheres between the internal or external surface of the part and the measuring instrument (like a micrometer). **For external tapers** such as a drill shank, place the rollers on the taper at two different heights. **For internal tapers** such as in a ring gauge, place the spheres/rollers so they contact the tapered faces. **Take a precise measurement** with a micrometer at these contact points. **Alternatively** use slip gauges of known heights. Place slip gauges on the part, then place the rollers/spheres on top of the slip gauges and measure over them. **Use the measurements** from the micrometer, slip gauges, and the known dimensions of the rollers/spheres to calculate the taper angle.

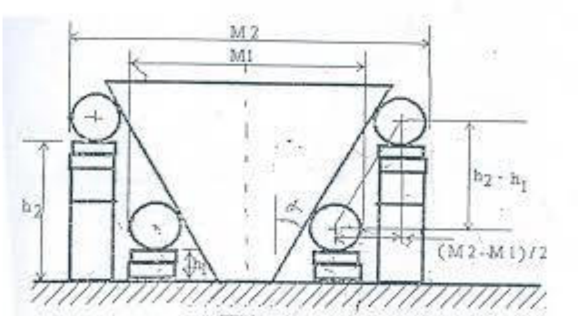


FIG. 2

Limit Gauges and Gauge Design:

Limit gauges are inspection tools used to quickly check if a manufactured part's dimensions are within a specified tolerance range, using a "Go" and "No-Go" system rather than providing a precise measurement. The design, based on Taylor's principle, involves two distinct ends: a "Go" end that must fit, ensuring the part meets its minimum limits (maximum material condition), and a "No-Go" end that must not fit, ensuring the part does not exceed its maximum limits (minimum material condition). Common types include plug gauges for holes, ring gauges for shafts, and snap gauges for external dimensions.

Gauge design principles

Taylor's Principle: This is the foundation for limit gauge design.

"Go" Gauge: Checks the maximum material condition (MMC) and ensures that multiple related dimensions (like diameter, straightness, and roundness) are correct simultaneously. For a hole, the "Go" gauge checks the minimum diameter; for a shaft, it checks the maximum diameter.

"No-Go" Gauge: Checks the minimum material condition (LMC) and only one dimension at a time. For a hole, the "No-Go" gauge checks the maximum diameter; for a shaft, it checks the minimum diameter.

Tolerance: The gauges themselves have a tolerance, typically 1/10th of the workpiece tolerance to ensure they can be calibrated and wear allowances can be factored in.

Wear Allowance: A wear allowance is added to the "Go" gauge to account for wear, especially in high-volume production. Types of limit gauges

Plug Gauges: Used to check the size of internal features, like the diameter of a hole.

Double-ended: A "Go" and a "No-Go" plug on opposite ends of the same bar.

Progressive: Both the "Go" and "No-Go" members are on the same end of the gauge.

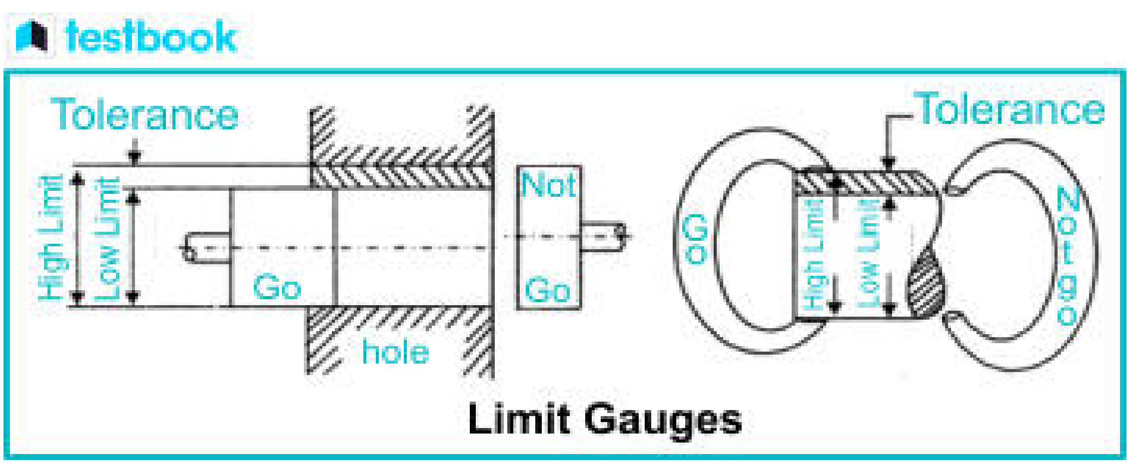
Ring Gauges: Used to check the size of external features, such as the diameter of a shaft.

Snap Gauges: Also used for external dimensions. They typically have adjustable anvils to set them to the desired tolerance limits.

Progressive: Includes both "Go" and "No-Go" anvils on the same gauge.

Adjustable: Allows for setting the gauge to a specific tolerance.

Other types: Taper gauges, thread gauges, and form gauges exist for checking tapers, threads, and specific profiles, respectively.



Limit Gauges

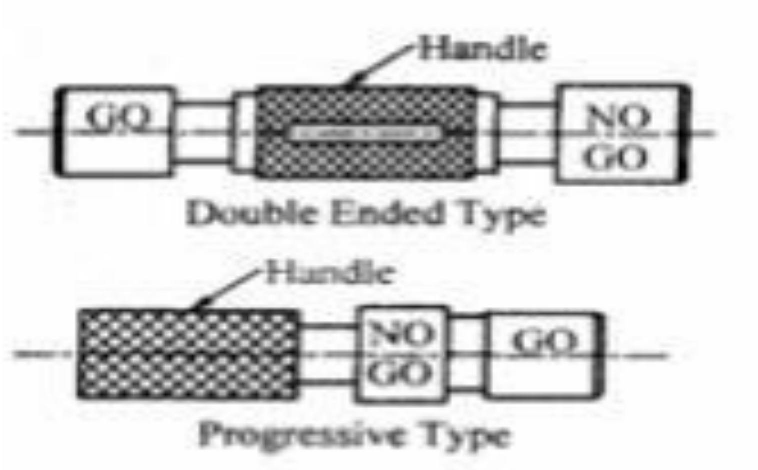
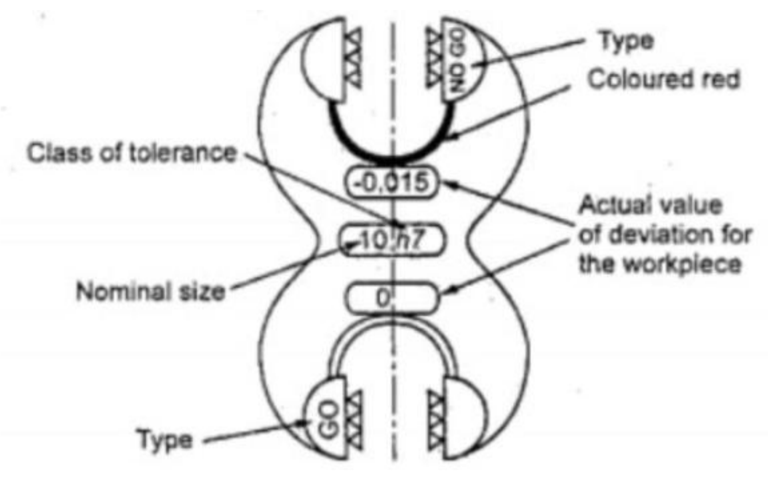


Fig 2.9 Plug Gauge



Combined limit gauge

Taper Gauges:

A taper gauge measurement assesses the angle or gradient of a tapered surface by using a tool with inscribed graduations. These tools, often made of hardened steel, can be flat blades for checking hole sizes or specialized instruments like ring gauges for external taper checks. Measurements are taken by fitting the gauge to the taper and reading the graduations, which indicates the taper's size or angle.

Types of Taper Gauges:

Flat Taper Gauges: These are blade-like tools with inscribed scales for measuring the size of gaps, slots, or holes. They are often made of stainless steel and are convenient for quick checks.

Taper Ring Gauges: These are metal rings with a conical bore designed to check the external diameter of tapered objects, such as shafts or screws.

Internal Taper Gages: For internal features, specialized gauges with contact points are used to measure variations in taper angles within components.

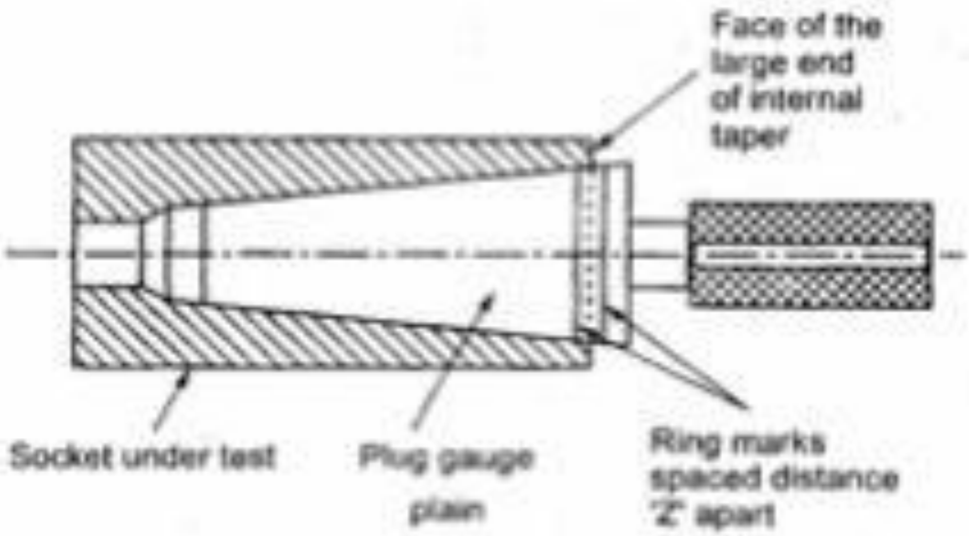


Fig 2.10 Taper Gauge

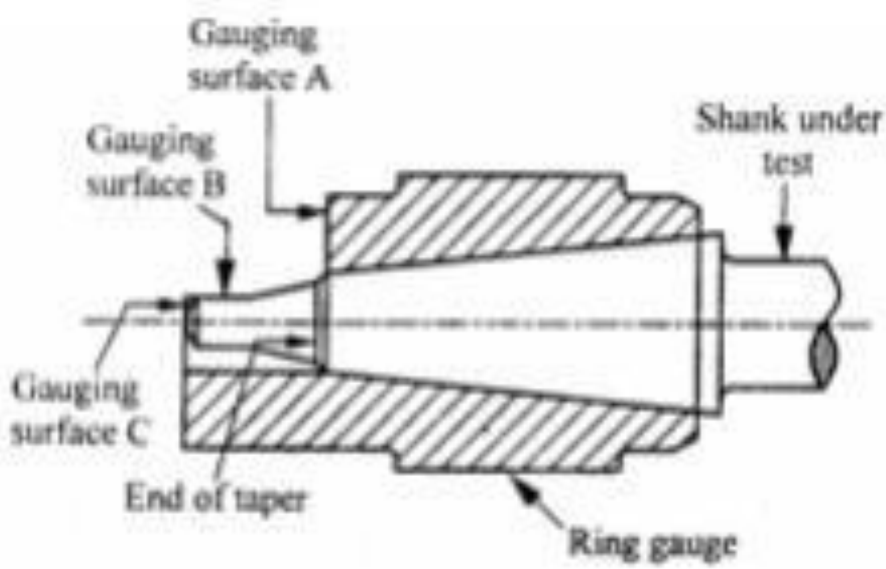


Fig 2.11 Taper ring Gauge plain

Design of Go and no-go gauges:

Go and no-go gauge design involves creating a two-part gauge to verify if a manufactured part is within its specified tolerance limits. The go gauge is designed to fit into the part, checking that it is not undersized (or oversized for a shaft). The no-go gauge is designed to not fit into the part, ensuring it is not oversized (or undersized for a shaft). Key design considerations include the part's tolerance, using the "go" end for maximum material condition (MMC) and the "no-go" end for least material condition (LMC), and accounting for wear on the "go" gauge.

Design principles for a plug gauge (checking a hole) "Go" gauge

Dimension: Equal to the minimum permissible dimension of the hole plus a wear allowance.

Purpose: To enter the hole easily, ensuring it is not smaller than the lower limit.

Calculation: Basic hole size + wear allowance.

Wear Allowance: A small positive allowance is added to the lower limit to account for wear.

"No-go" gauge

Dimension: Equal to the maximum permissible dimension of the hole, minus a wear allowance.

Purpose: To not fit into the hole, ensuring it is not larger than the upper limit.

Calculation: Upper limit of the hole + (negative) wear allowance.

Wear Allowance: A small negative allowance is added to the upper limit, as it's designed to prevent oversized parts from passing.

Design principles for a ring or snap gauge (checking a shaft) "Go" gauge

Dimension: Equal to the maximum permissible dimension of the shaft plus a wear allowance.

Purpose: To fit over the shaft, ensuring it is not larger than the upper limit.

Calculation: Basic shaft size + wear allowance.

Wear Allowance: A small positive allowance is added to the upper limit.

"No-go" gauge

Dimension: Equal to the minimum permissible dimension of the shaft, minus a wear allowance.

Purpose: To not fit over the shaft, ensuring it is not smaller than the lower limit.

Calculation: Lower limit of the shaft + (negative) wear allowance.

Wear Allowance: A small negative allowance is added to the lower limit.

Other design considerations

Gauge Tolerance: The gauge tolerance is typically a percentage of the part's tolerance, often around 10%.

Length: "Go" gauges are often longer (3-4 times the diameter) to check for geometric errors like straightness, while "no-go" gauges are shorter (usually the part's diameter).

Markings: Both gauges should be clearly marked with their designation ("Go" or "No Go") and the part number to avoid confusion.

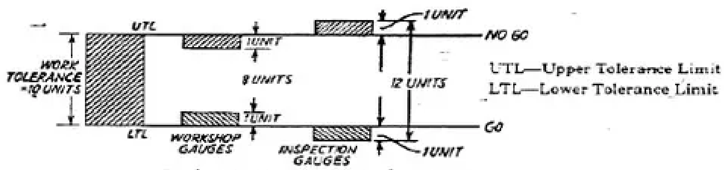
Shape: The shape of the gauge (e.g., plug, ring, snap) is determined by the part it will inspect.

Complexity: "Go" gauges can check multiple dimensions at once, whereas "no-go" gauges are usually designed to check only one dimension.

Gauge maker's tolerance.

1. first system as shown in fig 4.50

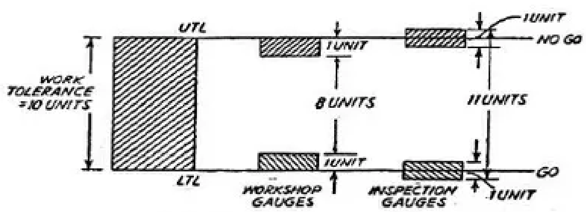
In this method workshop and inspection gauges are made separately and their tolerance zones are different.



Disposition of tolerances on workship and inspection gauges.

2. second system **(revised gauge limits)** as shown in fig 4.51

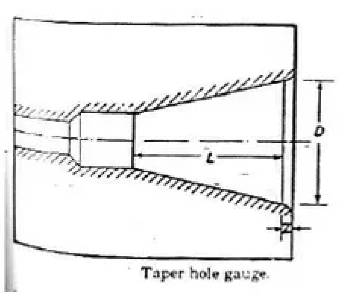
Under this system the disadvantages of inspection gauges are reduced by reducing the tolerance zone of inspection gauge and the workshop gauge tolerance remain the same.



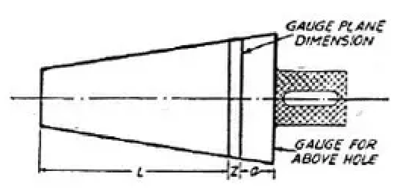
Modified tolerances on inspection gauge.

Gauges for tapers:

a taper is tested by using taper plug and ring gauges. the important thing in testing a tapered job is to check the diameter at bigger end and the change of diameter per unit length.



Taper hole gauge.



Taper plug gauge.

UNIT - 2

Measurement of screw threads- Terminology of screw threads, measurement of major and minor diameter, pitch, flank angle and effective diameter of screw threads, floating carriage micrometer-measurement of gears-tooth thickness-constant chord and base tangent method-Gleason and Parkson gear testing machines- Radius measurement-Surface finish, straightness, flatness and roundness measurements.

TECHNICAL TERMS

- **Pitch**

It is the distance measured parallel to the screw threads axis between the corresponding points on two adjacent threads in the same axial plane. The basic pitch is equal to the lead divided by the number of thread starts.

- **Lead:**

The axial distance advanced by the screw in one revolution is the lead.

- **Addendum**

Radial distance between the major and pitch cylinders for external thread. Radial distance between the minor and pitch cylinder for internal thread.

- **Dedendum**

It is the radial distance between the pitch and minor cylinders for external thread.

Also radial distance between the major and pitch cylinders for internal thread.

- **Pressure angle (a)**

It is the angle making by the line of action with the common tangent to the pitch circles of mating gears.

- **Module(m)**

It is the ratio of pitch circle diameter to the total number of teeth

- **Lead angle**

It is the angle between the tangent to the helix and plane perpendicular to the axis of cylinder.

- **Straightness**

A line is said to be straight over a given length, if the variation of the distance of its from two planes perpendicular to each other and parallel to the general direction of the line remains within the specified tolerance limits

- **Roundness** Roundness is defined as a condition of a surface of revolution. Where all points of the surface intersected by any plane perpendicular to a common axis in case of cylinder and cone.

INTRODUCTION

Threads are of prime importance, they are used as fasteners. It is a helical groove, used to transmit force and motion. In plain shaft, the hole assembly, the object of dimensional control is to ensure a certain consistency of fit. The performance of screw threads during their assembly with nut depends upon a number of parameters such as the condition of the machine tool used for screw cutting, work material and tool.

- Form measurement includes
- Screw thread measurement
- Gear measurement
- Radius measurement
- Surface Finish measurement
- Straightness measurement
- Flatness and roundness measurements

3.1.1 Screw Thread Measurement

Screw threads are used to transmit the power and motion, and also used to fasten two components with the help of nuts, bolts and studs. There is a large variety of screw threads varying in their form, by included angle, head angle, helix angle etc. The screw threads are mainly classified into 1) External thread 2) Internal thread.

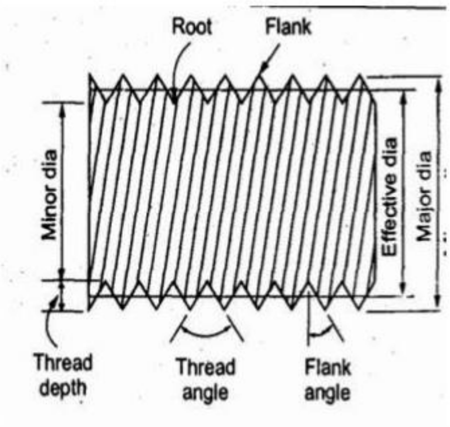


Fig 3.1 External Thread

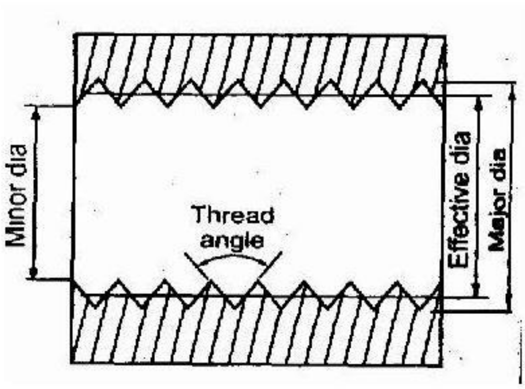
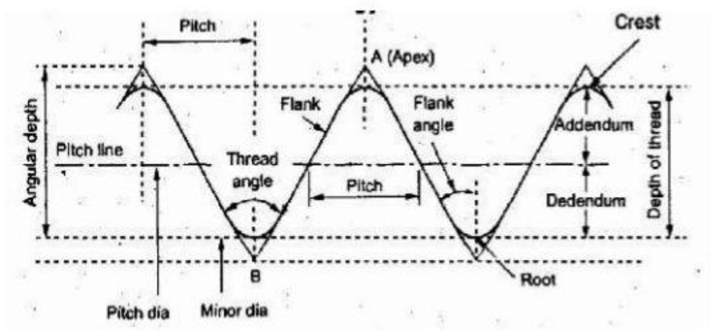


Fig 3.2 Internal Thread

Screw Thread Terminology



- **Pitch**

It is the distance measured parallel to the screw threads axis between the corresponding points on two adjacent threads in the same axial plane. The basic pitch is equal to the lead divided by the number of thread starts.

- **Minor diameter:**

It is the diameter of an imaginary co-axial cylinder which touches the roots of external threads.

- **Major diameter:**

It is the diameter of an imaginary co-axial cylinder which touches the crests of an external thread and the root of an internal thread.

- **Lead:**

The axial distance advanced by the screw in one revolution is the lead.

- **Pitch diameter:**

It is the diameter at which the thread space and width are equal to half of the screw thread

- **Helix angle:**

It is the angle made by the helix of the thread at the pitch line with the axis. The angle is measured in an axial plane.

- **Flank angle:**

It is the angle between the flank and a line normal to the axis passing through the apex of the thread.

- **Height of thread:**

It is the distance measured radially between the major and minor diameters respectively

- **Addendum:**

Radial distance between the major and pitch cylinders for external thread.

Radial distance between the minor and pitch cylinder for internal thread.

- **Dedendum:**

It is the radial distance between the pitch and minor cylinders for external thread. Also radial distance between the major and pitch cylinders for internal thread.

Error in Thread

The errors in screw thread may arise during the manufacturing or storage of threads. The errors either may cause in following six main elements in the thread.

1) Major diameter error

2) Minor diameter error

3) Effective diameter error

4) Pitch error

5) Flank angles error

6) Crest and root error

1) Major diameter error

It may cause reduction in the flank contact and interference with the matching threads.

2) Minor diameter error

It may cause interference, reduction of flank contact.

3) Effective diameter error

If the effective diameter is small the threads will be thin on the external screw and thick on an internal screw.

4) Pitch errors

If error in pitch, the total length of thread engaged will be either too high or too small.

The various pitch errors may classified into

1. Progressive error
2. Periodic error
3. Drunken error
4. Irregular error

1) Progressive error

The pitch of the thread is uniform but is longer or shorter its nominal value and this is called progressive.

Causes of progressive error:

1. Incorrect linear and angular velocity ratio.
2. In correct gear train and lead screw.
3. Saddle fault.
4. Variation in length due to hardening.

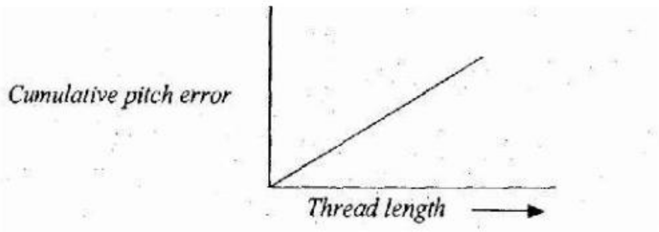


Fig 3.4 Progressive Error

2) Periodic error

These are repeats itself at regular intervals along the thread

Causes of periodic error:

1. Un uniform tool work velocity ratio.
2. Teeth error in gears.
3. Lead screw error.
4. Eccentric mounting of the gears.

3) Drunken error

Drunken errors are repeated once per turn of the thread in a drunken thread. In Drunken thread the pitch measured parallel to the thread axis. If the thread is not cut to the true helix the drunken thread error will form

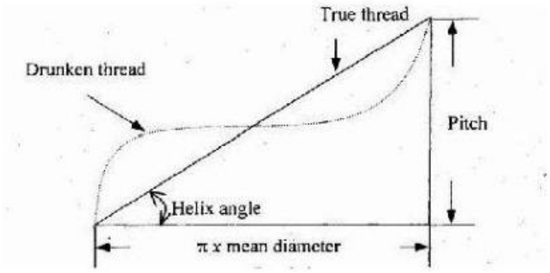


Fig 3.5 Drunken Error

4) Irregular errors

It is vary irregular manner along the length of the thread.

Irregular error causes:

1. Machine fault.
2. Non-uniformity in the material.
3. Cutting action is not correct.
4. Machining disturbances.

Effect of pitch errors

- Increase the effective diameter of the bolt and decreases the diameter of nut.
- The functional diameter of the nut will be less.
- Reduce the clearance.
- Increase the interference between mating threads.

Measurement of various elements of Thread

To find out the accuracy of a screw thread it will be necessary to measure the following:

1. Major diameter.
2. Minor diameter.
3. Effective or Pitch diameter.
4. Pitch
5. Thread angle and form

1. Measurement of major diameter:

The instruments which are used to find the major diameter are by

- Ordinary micrometer
- Bench micrometer.

- **Ordinary micrometer**

The ordinary micrometer is quite suitable for measuring the external major diameter. It is first adjusted for appropriate cylindrical size (S) having the same diameter (approximately).This process is known as 'gauge setting'. After taking this reading 'R the micrometer is set on the major diameter of the thread, and the new reading is 'R2.

- **Bench micrometer**

For getting the greater accuracy the bench micrometer is used for measuring the major diameter. In this process the variation in measuring Pressure, pitch errors are being neglected. The fiducial indicator is used to ensure all the measurements are made at same pressure. The instrument has a micrometer head with a vernier scale to read the accuracy of 0.002mm. Calibrated setting cylinder having the same diameter as the major diameter of the thread to be measured is used as setting standard. After setting the standard, the setting cylinder is held between the anvils and the reading is taken. Then the cylinder is replaced by the threaded work piece and the new reading is taken.

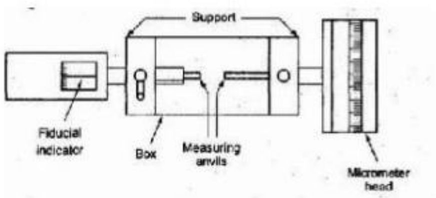


Fig 3.6 Bench Micrometer

∴ The major diameter of screw thread

$$= S \pm (D_2 - D_1)$$

Where, S = Diameter of the setting cylinder.

R_2 = Micrometer Reading on screw thread

R_1 = Micrometer reading on setting cylinder.

- **Measurement of the major diameter of an Internal thread**

The Inter thread major diameter is usually measured by thread comparator fitted with ball-ended styli. First the Instrument is set for a cylindrical reference having the same diameter of major diameter of internal thread and the reading is taken. Then the floating head is retracted to engage the tips of the styli at the root of spring under pressure. For that the new reading is taken,

major diameter of internal thread is $= D \pm (R_2 - R_1)$

D = Cylindrical standard diameter

R_2 = Thread reading

R_1 = Dial Indicator reading on the standard.

2. Measurement of Minor diameter

The minor diameter is measured by a comparative method by using floating carriage diameter measuring machine and small V pieces which make contact with the root of the thread. These V pieces are made in several sizes, having suitable radii at the edges. V pieces are made of hardened steel. The floating carriage diameter-measuring machine is a bench micrometer mounted on a carriage.

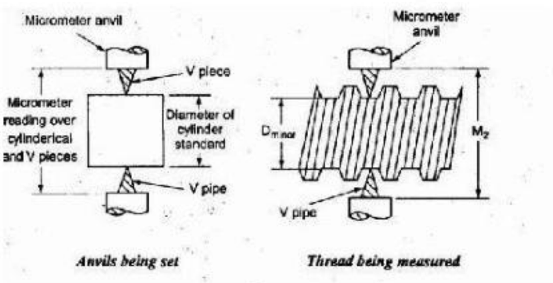


Fig 3.7 Measurement of Minor diameter

- **Measurement process**

The threaded work piece is mounted between the centers of the instrument and the V pieces are placed on each side of the work piece and then the reading is noted. After taking this reading the work piece is then replaced by a standard reference cylindrical setting gauge.

The minor diameter of the thread $= D \pm (R_2 - R_1)$

Where, D = Diameter of cylindrical gauge.

R_2 = Micrometer reading on threaded work piece.

R_1 = Micrometer reading on cylindrical gauge.

- **Measurement of Minor diameter of Internal threads**

The Minor diameter of Internal threads are measured by

1. Using taper parallels
2. Using Rollers.

- **Using taper parallels**

For diameters less than 200mm the use of Taper parallels and micrometer is very common. The taper parallels are pairs of wedges having reduced and parallel outer edges. The diameter across their outer edges can be changed by sliding them over each other.

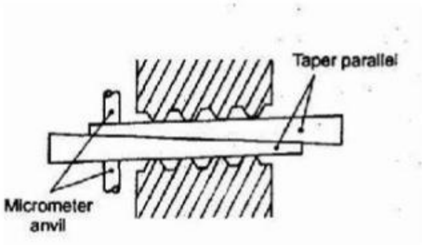


Fig 3.8 Taper parallels

- **Using rollers**

For more than 20mm diameter this method is used. Precision rollers are inserted inside the thread and proper slip gauge is inserted between the rollers. The minor diameter is then the length of slip gauges plus twice the diameter of roller.

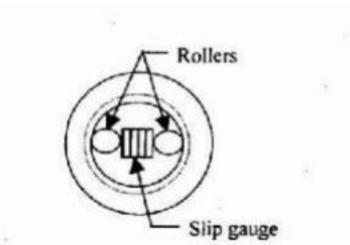


Fig 3.9 Roller gauge

3. Measurement of effective diameter

Effective diameter measurement is carried out by following methods.

1. One wire,
2. Two wires, or
3. Three wires method.
4. Micrometer method.

a) One wire method

The only one wire is used in this method. The wire is placed between two threads at one side and on the other side the anvil of the measuring micrometer contacts the crests. First the micrometer reading dl is noted on a standard gauge whose dimension is approximately same to be obtained by this method.

i.e. 'd_2' then effective diameter $= D \pm (d_1 - d_2)$

When D = Size of setting gauge

Actual measurement over wire on one side and threads on other

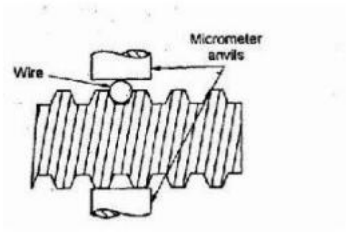


Fig 3.10 One wire method

b) Two wire method

Two-wire method of measuring the effective diameter of a screw thread is given below. In this method wires of suitable size are placed between the standard and the micrometer anvils. First the micrometer reading is taken and let it be R. Then the standard is replaced by the screw thread to be measured and the new reading is taken.

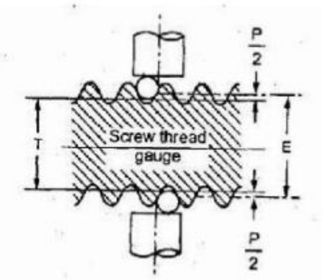
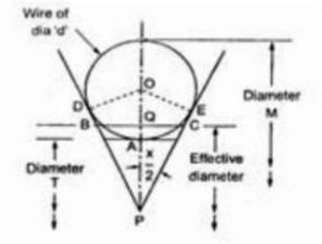


Fig 3.11 Two Wire Method



From the above reading

The effective diameter E is calculated by $E = T + P$

Where, T = Dimension under the wires = $M - 2d$

M = Dimension over the wires

d = diameter of each wire

If P' = Pitch of thread then

$$P = 0.9605\,P' - 1.1657d \Rightarrow \text{Whitworth thread.}$$

$$P = 0.866\,P' - d \Rightarrow \text{For metric thread.}$$

Here, P = The difference between the effective diamet
nd the diameter under the wires.

The diameter under the wires 'T' also can be determined by

$$T = S - (R_1 - R_2)$$

Where, S = The diameter of the standard.

The P value can be derived in terms of P (Pitch), d (Diameter of wire) and x thread angle is as follows

BC lies on the effective diameter.

$$\therefore BC = \frac{1}{2} Pitch = \frac{1}{2} P$$

$$\text{Next } OP = \frac{d\,Cosec(x/2)}{2}$$

And AQ = PQ − AP

Where,

PQ = QC $Cot(x/2)$ = $P/4\ Cot(x/2)$

$$PQ = \frac{P}{4} Cot(x/2)$$

c) Three-Wire method

The three-wire method is the accurate method. In this method three wires of equal and precise diameter are placed in the groves at opposite sides of the screw. In this one wire on one side and two on the other side are used. The wires either may held in hand or hung from a stand. This method ensures the alignment of micrometer anvil faces parallel to the thread axis.

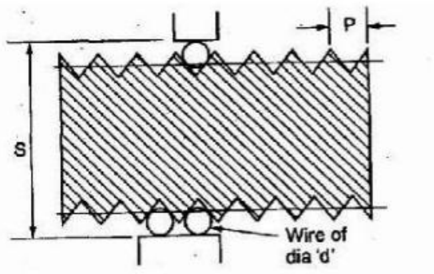


Fig 3.12 Three-Wire Method

4.4 GEAR MEASUREMENT

4.4.1 GEAR TERMINOLOGY

Each gear has a unique form or geometry. The gear form is defined by various elements. An illustration of the gear highlighting the important elements is referred to as ‘gear terminology’. This section explains the types of gears and their terminology.

4.4.1.1 Introduction

- Gears is a mechanical drive which transmits power through toothed wheel.
- In this gear drive, the driving wheel is in direct contact with driven wheel.
- The accuracy of gearing is the very important factor when gears are manufactured.
- The transmission efficiency is almost 99 in gears. So, it is very important to test and measure the gears precisely.
- For proper inspection of gear, it is very important to concentrate on the raw materials, which are used to manufacture the gears, also very important to check the machining the blanks, heat treatment and the finishing of teeth.
- The gear blanks should be tested for dimensional accuracy and tooth thickness for the forms of gears.
- The most commonly used forms of gear teeth are

    1.Involute

    2. Cycloidal

- The involute gears also called as straight tooth or spur gears.
- The cycloidal gears are used in heavy and impact loads.
- The involute rack has straight teeth.
- The involute pressure angle is either 20° or 14.5°.

4.4.2 Types of Gears

The common types of gears used in engineering practices are described in this section. The information provided here is very brief, and the reader is advised to read a good book on ‘theory of machines’ to understand the concepts better.

4.4.2.1 Spur gears These gears are the simplest of all gears. The gear teeth are cut on the periphery and are parallel to the axis of the gear. They are used to transmit power and motion between parallel shafts.

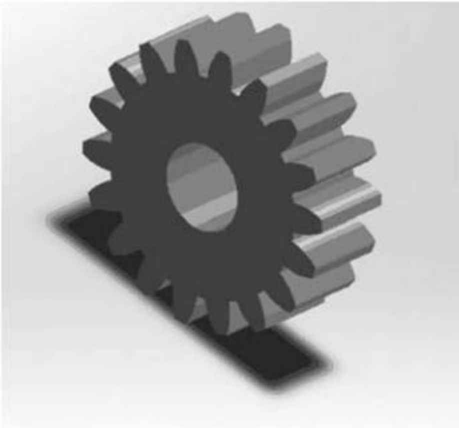


Fig. 4.19 Spur gears

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 189]

4.4.2.2 Helical gears The gear teeth are cut along the periphery, but at an angle to the axis of the gear. Each tooth has a helical or spiral form. These gears can deliver higher torque since there are more number of teeth in a mesh at any given point of time. They can transmit motion between parallel or non-parallel shafts.

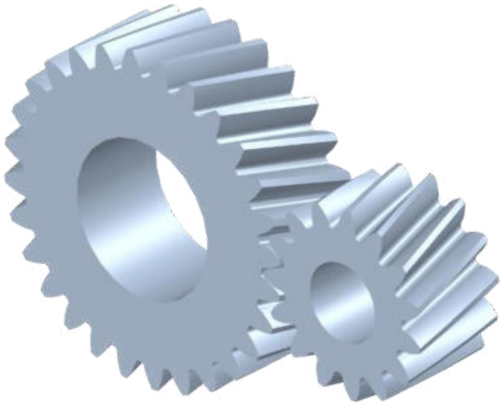


Fig. 4.20 Helical gears

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 189]

4.4.2.3 Herringbone gears These gears have two sets of helical teeth, one right-hand and the other left-hand, machined side by side.

Fig. 4.21 Herringbone gears

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 189]

4.4.2.4 Worm and worm gears A worm is similar to a screw having single or multiple start threads, which form the teeth of the worm. The worm drives the worm gear or worm wheel to enable transmission of motion. The axes of worm and worm gear are at right angles to each other.

Fig. 4.22 Worm and worm gears

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 190]

4.4.2.5 Bevel gears These gears are used to connect shafts at any desired angle to each other. The shafts may lie in the same plane or in different planes.

Fig. 4.23 Bevel gears

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 190]

4.4.2.6 Hypoid gears These gears are similar to bevel gears, but the axes of the two connecting shafts do not intersect. They carry curved teeth, are stronger than the common types of bevel gears, and are quiet-running. These gears are mainly used in automobile rear axle drives.

4.4.3 Gear terminology

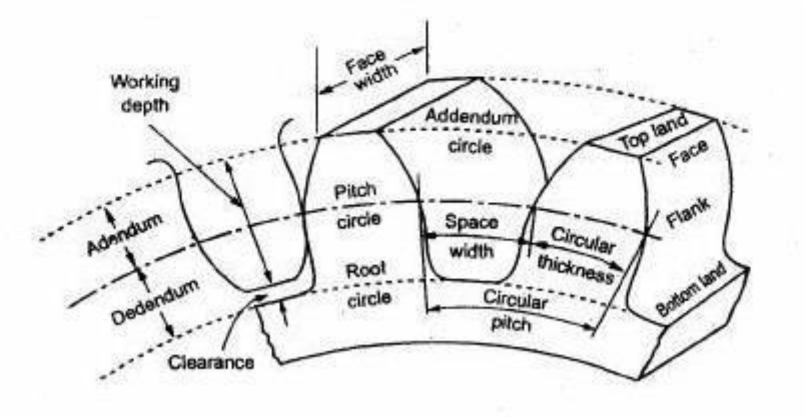


Fig. 4.24 Spur gear terminology

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 190]

1. Tooth profile:

It is the shape of any side of gear tooth in its cross section.

2. Base circle:

- It is the circle of gear from which the involute profile is derived.
- Base circle diameter Pitch circle diameter x Cosine of pressure angle of gear

3. Pitch circle diameter (PCD):

The diameter of a circle which will produce the same motion as the toothed gear wheel.

4. Pitch circle:

It is the imaginary circle of gear that rolls without slipping over the circle of its mating gear.

5. Addendum circle:

The circle coincides with the crests (or) tops of teeth.

6. Dedendum circle (or) Root circle:

This circle coincides with the roots (or) bottom on teeth.

7.Pressure angle (a):

It is the angle making by the line of action with the common tangent to the pitch circles of mating gears.

$$\alpha = 14\ 1/2° \text{ or } 20°.$$

8.Module(m):

`It is the ratio of pitch circle diameter to the total number of teeth.

$$m = \frac{d}{n}$$

Where, d = Pitch circle diameter.

n = Number of teeth.

9. Circular pitch:

It is the distance along the pitch circle between corresponding points of adjacent teeth.

$$P_C = \frac{\pi d}{n} = \pi m$$

10. Addendum:

Radial distance between tip circle and pitch circle. Addendum value = 1 module.

11 Dedendum:

Radial distance between itch circle and root circle, Dedendum value = 1 .25module.

12 Clearance (C):

A mount of distance made by the tip of one gear with the root of mating gear.

Clearance = Difference between Dedendum and addendum values.

13 Blank diameter:

The diameter of the blank from which gear is out. Blank diameter = PCD + 2m

14. Face:

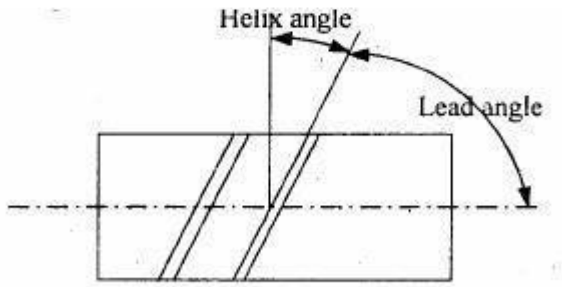
Part of the tooth in the axial plane lying between tip circle and pitch circle.

15. Flank:

Part of the tooth lying between pitch circle and root circle.

16. Top land:

Top surface of a tooth.



The angle between the tangents to helix angle.

18. Lead angle:

The angle between the tangent to the helix and plane perpendicular to the axis of cylinder.

19. Backlash:

- The difference between the tooth thickness and the space into which it meshes.
- If we assume the tooth thickness as t and width ‘t then

$$\text{Back lash} = t_2 - t_1$$

4.4.4 ERRORS IN SPUR GEARS

A basic understanding of the errors in spur gears during manufacturing is important before we consider the possible ways of measuring the different elements of gears. A spur gear is a rotating member that constantly meshes with its mating gear. It should have the perfect geometry to maximize transmission of power and speed without any loss. From a metrological point of view, the major types of errors are as follows:

1. Gear blank runout errors
2. Gear tooth profile errors
3. Gear tooth errors
4. Pitch errors
5. Runout errors
6. Lead errors
7. Assembly errors

4.4.4.1 Gear blank runout errors Gear machining is done on the gear blank, which may be a cast or a forged part. The blank would have undergone preliminary machining on its outside diameter (OD) and the two faces. The blank may have radial runout on its OD surface due to errors in the preliminary machining. In addition, it may have excessive face runout. Unless these two runouts are within prescribed limits, it is not possible to meet the tolerance requirements at later stages of gear manufacture.

4.4.4.2 Gear tooth profile errors These errors are caused by the deviation of the actual tooth profile from the ideal tooth profile. Excessive profile error will result in either friction between the mating teeth or backlash, depending on whether it is on the positive or negative side.

4.4.4.3 Gear tooth errors This type of error can take the form of either tooth thickness error or tooth alignment error. The tooth thickness measured along the pitch circle may have a large amount of error. On the other hand, the locus of a point on the machined gear teeth may not follow an ideal trace or path. This results in a loss in alignment of the gear.

4.4.4.4 Pitch errors Errors in pitch cannot be tolerated, especially when the gear transmission system is expected to provide a high degree of positional accuracy for a machine slide or axis. Pitch error can be either single pitch error or accumulated pitch error. Single pitch error is the error in actual measured pitch value between adjacent teeth. Accumulated pitch error is the difference between theoretical summation over any number of teeth intervals and summation of actual pitch measurement over the same interval.

4.4.4.5 Runout errors This type of error refers to the runout of the pitch circle. Runout causes vibrations and noise, and reduces the life of the gears and bearings. This error creeps in due to inaccuracies in the cutting arbour and tooling system.

4.4.4.6 Lead errors This type of error is caused by the deviation of the actual advance of the gear tooth profile from the ideal value or position. This error results in poor contact between the mating teeth, resulting in loss of power.

4.4.4.7 Assembly errors Errors in assembly may be due to either the centre distance error or the axes alignment error. An error in centre distance between the two engaging gears results in either backlash error or jamming of gears if the distance is too little. In addition, the axes of the two gears must be parallel to each other, failing which misalignment will be a major problem.

4.4.5 MEASUREMENT OF GEAR ELEMENTS

A number of standard gear inspection methods are used in the industry. The choice of the inspection procedure and methods not only depends on the magnitude of tolerance and size of the gears, but also on lot sizes, equipment available, and inspection costs. While a number of analytical methods are recommended for inspection of gears, statistical quality control is normally resorted to when large quantities of gears are manufactured. The following elements of gears are important for analytical inspection:

1. Runout
2. Pitch
3. Profile
4. Lead
5. Backlash
6. Tooth thickness

4.4.5.1 Measurement of Runout

Runout is caused when there is some deviation in the trajectories of the points on a section of a circular surface in relation to the axis of rotation. In case of a gear, runout is the resultant of the radial throw of the axis of a gear due to the out of roundness of the gear profile. Runout tolerance is the total allowable runout. In case of gear teeth, runout is measured by a specified probe such as a cylinder, ball, cone, rack, or gear teeth. The measurement is made perpendicular to the surface of revolution. On bevel and hypoid gears, both axial and radial runouts are included in one measurement.

A common method of runout inspection, called a single-probe check uses an indicator with a single probe whose diameter makes contact with the flanks of adjacent teeth in the area of the pitch circle. On the other hand, in a two-probe check one fixed and one free-moving probe, are positioned on diametrically opposite sides of the gear and make contact with identically located elements of the tooth profile. The range of indications obtained with the two-probe check during a complete revolution of the gear is twice the amount resulting from the single-probe check.

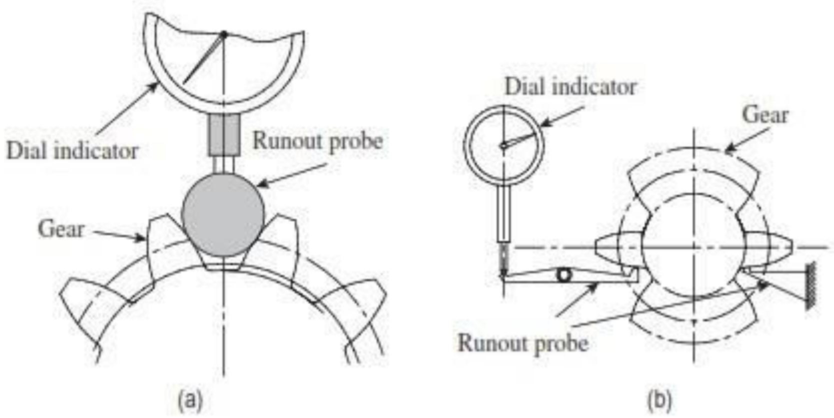


Fig. 4.25 Measurement of radial runout

(a) Single-probe check (b) Two-probe check

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 194]

4.4.5.2 Measurement of Pitch

Pitch is the distance between corresponding points on equally spaced and adjacent teeth. Pitch error is the difference in distance between equally spaced adjacent teeth and the measured distance between any two adjacent teeth. The two types of instruments that are usually employed for checking pitch are discussed in this section.

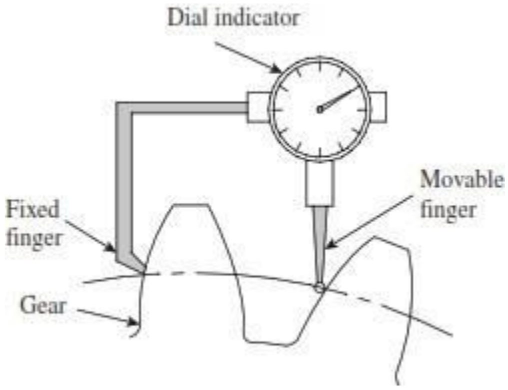


Fig. 4.26 Pitch-measuring instrument

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 194]

Pitch-measuring Instruments

These instruments enable the measurement of chordal pitch between successive pairs of teeth. The instrument comprises a fixed finger and a movable finger, which can be set to two identical points on adjacent teeth along the pitch circle. The pitch variation is displayed on a dial indicator attached to the instrument. In some cases, the pitch variation is recorded on a chart recorder, which can be used for further measurements. A major limitation of this method is that readings are influenced by profile variations as well as runout of the gear.

Pitch-checking Instrument

A pitch-checking instrument is essentially a dividing head that can be used to measure pitch variations. The instrument can be used for checking small as well as large gears due to its portability. It has two probes one fixed, called the anvil, and the other movable, called the measuring feeler. The latter is connected to a dial indicator through levers.

The instrument is located by two adjacent supports resting on the crests of the teeth. A tooth flank is butted against the fixed anvil and locating supports. The measuring feeler senses the corresponding next flank. The instrument is used as a comparator from which we can calculate the adjacent pitch error, actual pitch, and accumulated pitch error.

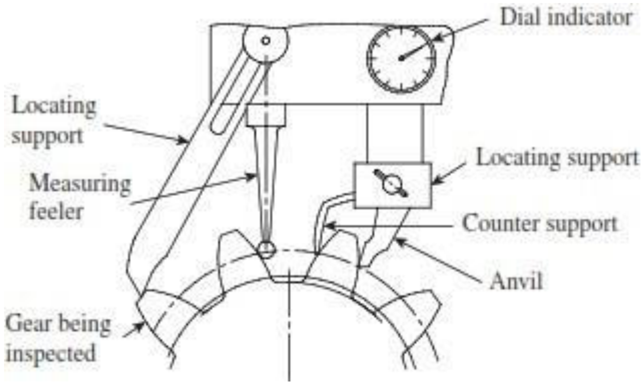


Fig. 4.27 Pitch-checking instrument

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 195]

4.4.5.3 Measurement of Profile

The profile is the portion of the tooth flank between the specified form circle and the outside circle or start of tip chamfer. Profile tolerance is the allowable deviation of the actual tooth form from the theoretical profile in the designated reference plane of rotation. As the most commonly used profile for spur and helical gears is the involute profile, our discussions are limited to the measurement of involute profile and errors in this profile. We will now discuss two of the preferred methods of measuring a tooth profile.

Profile Measurement Using Special Profile-measuring Instruments

The gear to be inspected is mounted on an arbour on the gear-measuring machine. The probe is brought into contact with the tooth profile. To obtain the most accurate readings, it is essential that the feeler (probe) is sharp, positioned accurately, and centered correctly on the origin of the involute at 0° of the roll. The machine is provided with multiple axes movement to enable measurement of the various types of gears. The measuring head comprising the feeler, electronic unit, and chart recorder can be moved up and down by operating a handwheel.

The arbour assembly holding the gear can be moved in two perpendicular directions in the horizontal plane by the movement of a carriage and a cross-slide. Additionally, the base circle disk on which the gear is mounted can be rotated by 360°, thereby providing the necessary rotary motion for the gear being inspected. The feeler is kept in such a way that it is in a spring-loaded contact with the tooth flank of the gear under inspection. As the feeler is mounted exactly above the straight edge, there is no movement of the feeler if the involute is a true involute. If there is an error, it is sensed due to the deflection of the feeler, and is amplified by the electronic unit and recorded by the chart recorder. The movement of the feeler can be amplified 250, 500, or 1000 times, the amplification ratio being selected by a selector switch. When there is no error in the involute profile, the trace on the recording chart will be a straight line. Gleason gear inspection machine, a product of Gleason Metrology Systems Corporation, USA, follows the fundamental design aspect of any testing machine with the capability to handle up to 350 mm dia gears. It also integrates certain object-oriented tools to achieve faster cycle times and a better human–machine interaction.

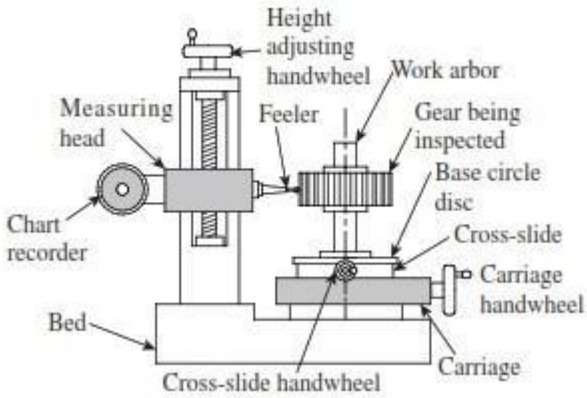


Fig. 4.28 Gear-measuring machine

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 197]

4.4.5.4 Measurement of Lead

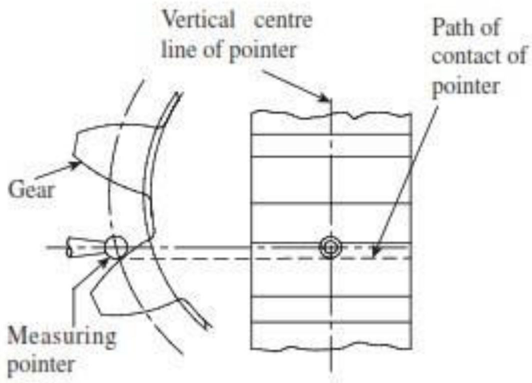


Fig. 4.29 Measurement of lead

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 197]

Lead is the axial advance of a helix for one complete rotation about its axis. In case of spur gears, lead tolerance is defined as the allowable deviation across the face width of a tooth surface. Control of lead is necessary in order to ensure adequate contact across the face width when gear and pinion are in mesh.

A measuring pointer traces the tooth surface at the pitch circle and parallel to the axis of the gear. The measuring pointer is mounted on a slide, which travels parallel to the centre on which the gear is held. The measuring pointer is connected to a dial gauge or any other suitable comparator, which continuously indicates the deviation. The total deviation shown by the dial indicator over the distance measured indicates the amount of displacement of the gear tooth in the face width traversed.

Measurement of lead is more important in helical and worm gears. Interested readers are advised to refer to a gear handbook to learn more about the same.

4.4.5.5 Measurement of Backlash

If the two mating gears are produced such that tooth spaces are equal to tooth thicknesses at the reference diameter, then there will not be any clearance in between the teeth that are getting engaged with each other. This is not a practical proposition because the gears will get jammed even from the slightest mounting error or eccentricity of bore to the pitch circle diameter. Therefore, the tooth profile is kept uniformly thinned. This results in a small play between the mating tooth surfaces, which is called a backlash.

We can define backlash as the amount by which a tooth space exceeds the thickness of an engaging tooth. Backlash should be measured at the tightest point of mesh on the pitch circle, in a direction normal to the tooth surface when the gears are mounted at their specified position. Backlash value can be described as the shortest or normal distance between the trailing flanks when the driving flank and the driven flank are in contact. A dial gauge is usually employed to measure the backlash. Holding the driver gear firmly, the driven gear can be rocked back and forth. This movement is registered by a dial indicator having its pointer positioned along the tangent to the pitch circle of the driven gear.

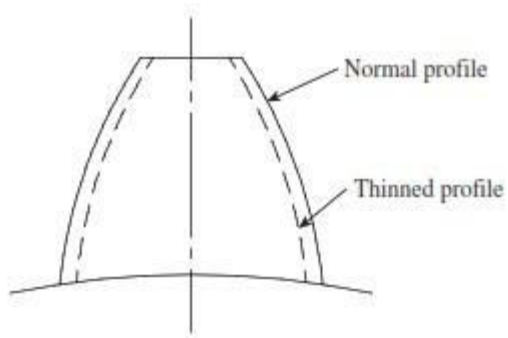


Fig. 4.30 Tooth thinning

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 198]

4.4.5.6 Measurement of Tooth Thickness

Various methods are recommended for the measurement of gear tooth thickness. There is a choice of instruments such as the gear tooth calliper, and span gauging or tooth span micrometer. Constant chord measurement and measurement over rolls or balls are additional options. Two such methods, namely measurement with gear tooth calliper and tooth span micrometer are discussed in detail here.

Measurement with Gear Tooth Callipers

This is one of the most commonly used methods and perhaps the most accurate one. It has two vernier scales, one horizontal and the other vertical. The vertical vernier gives the position of a blade, which can slide up and down. When the surface of the blade is flush with the tips of the measuring anvils, the vertical scale will read zero. The blade position can be set to any required value by referring to the vernier scale.

It is clear that tooth thickness should be measured at the pitch circle (chord thickness C_1C_2 in the figure). Now, the blade position is set to a value equal to the addendum of the gear tooth and locked into position with a locking screw. The calliper is set on the gear in such a manner that the blade surface snugly fits with the top surface of a gear tooth. The two anvils are brought into close contact with the gear, and the chordal thickness is noted down on the horizontal vernier scale.

Let d = Pitch circle diameter

g_c = Chordal thickness of gear tooth along the pitch circle

h_c = Chordal height

z = Number of teeth on the gear

Chordal thickness g_c = Chord C_1C_2

= 2(pitch circle radius) × sin ç

$= 2 \times \frac{d}{2} \times$ sin ç

= d sin ç

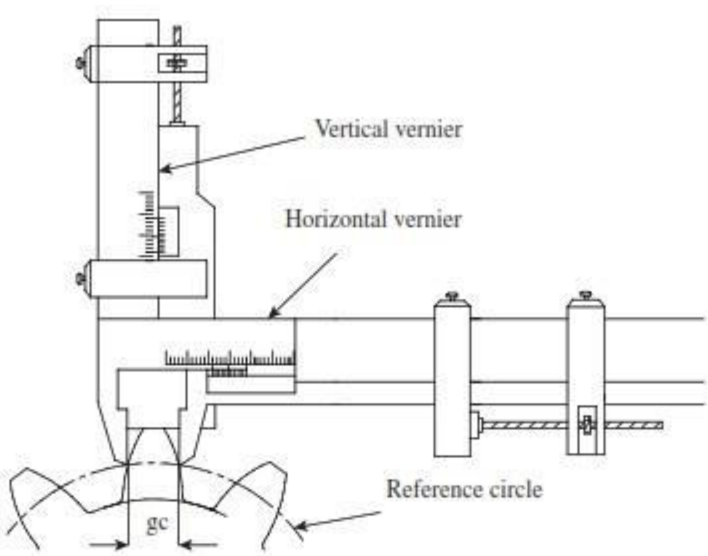


Fig. 4.31 Gear tooth calliper

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 199]

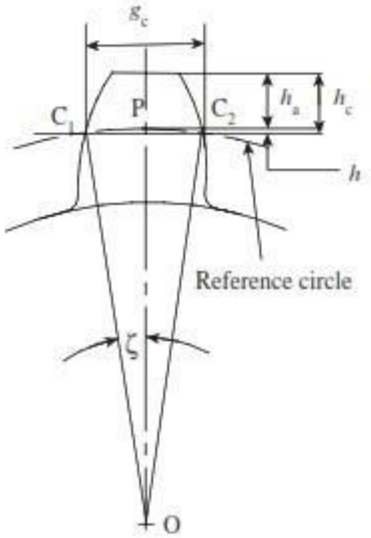


Fig. 4.32 Chordal thickness and chordal height

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 199]

Arc $C_1PC_2 = \frac{d}{2} \times 2ç$ (value of ç in radians)

$= d \times ç = \frac{\pi d}{2z}$

Therefore, $ç = \frac{\pi}{2z}$

$g_c = d\sin(\pi/2z)$ (where $\pi/2z$ is in radians)

$g_c = d\sin(90/2z)$ (argument of sin is in degrees)

Chordal height $h_c = h_a + \Delta h = m + \Delta h$

However, $\Delta h(d - \Delta h) = \frac{gc}{2} \times \frac{gc}{2}$

and $4(\Delta h)^2 - 4\Delta h \times d + g_c^{\,2} = 0$

$\Delta h = [d \pm \sqrt{d^2 - g_c^{\,2}}]/2$

$= [d - \sqrt{d^2 - g_c^{\,2}}]/2$; the other value is neglected because $\Delta h > d$ is not possible.

Neglecting $(\Delta h)^2$, we get $\Delta h \times d = g_c^{\,2}/4$

$\Delta h = g_c^{\,2}/4d$

Thus, $h_c = h_a + g_c^{\,2}/4d = m + g_c^{\,2}/4d$

Therefore, $g_c = d \sin (90°/z)$

and $h_c = m + g_c^{\,2}/4d$

4.4.6 COMPOSITE METHOD OF GEAR INSPECTION

Composite action refers to the variation in centre distance when a gear is rolled in tight mesh with a standard gear. It is standard practice to specify composite tolerance, which reflects gear runout, tooth-to-tooth spacing, and profile variations. Composite tolerance is defined as the allowable centre distance variation of the given gear, in tight mesh with a standard gear, for one complete revolution. The Parkinson gear testing machine is generally used to carry out composite gear inspection.

4.4.6.1 Parkinson Gear Tester

It is a popular gear testing machine used in metrology laboratories and tool rooms. The gear being inspected will be made to mesh with a standard gear, and a dial indicator is used to capture radial errors. The standard gear is mounted on a fixed frame, while the gear being inspected is fixed to a sliding carriage. The two gears are mounted on mandrels, which facilitate accurate mounting of gears in machines, so that a dial indicator will primarily measure irregularities in the gear under inspection. A dial indicator of high resolution is used to measure the composite error, which reflects errors due to runout, tooth-to-tooth spacing, and profile variations.

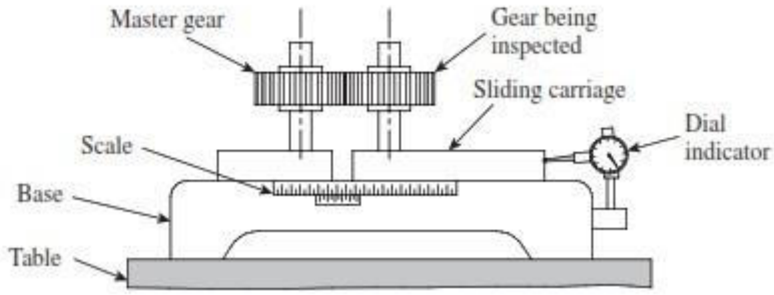


Fig. 4.33 Parkinson gear tester

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 202]

To start with, the two gears are mounted on respective mandrels and the slide comprising the standard gear is fixed at a convenient position. The sliding carriage is moved along the table, the two gears are brought into mesh, and the sliding carriage base is also locked in its position. Positions of the two mandrels are adjusted in such a way that their axial distance is equal to the gear centre distance as per drawings. However, the sliding carriage is free to slide for a small distance on steel rollers under a light spring force. A vernier scale attached to the machine enables measurement of the centre distance up to 25 µm. The dial indicator is set to zero and the gear under inspection is rotated. Radial variations of the gear being inspected are indicated by the dial indicator. This variation is plotted on a chart or graph sheet, which indicates the radial variations in the gear for one complete rotation.

A waxed paper recorder can be fitted to the machine so that a trace of the variations of a needle in contact with the sliding carriage is made simultaneously. The mechanism can be designed to provide a high degree of magnific.

A toolmaker's microscope works by using light to project a magnified shadow of an object onto a screen or through an eyepiece, which is then viewed to measure dimensions like length, angle, and thread profiles with high precision. The instrument's stage can be moved along the X and Y axes, and the light source, objective lens, and stage are precisely controlled to get clear images and accurate readings.

Working Principle

1. **1. Illumination:**

   A light source illuminates the object placed on a glass stage.

2. **2. Projection:**

   An objective lens projects a magnified shadow image of the object onto a viewing screen or through an eyepiece.

3. **3. Magnification:**

   The lens system provides magnification, making it easier to see fine details on the object.

4. **4. Measurement:**

- **Linear Measurement:** The stage moves horizontally (X and Y axes) and is equipped with scales or micrometer screws for measuring distances with precision up to 0.01 mm.
- **Angular Measurement:** A built-in protractor allows for measuring angles, such as the angles of threads on tools.
- **Surface Illumination:** Some models include a surface illumination feature, which helps to view and measure details on the object's surface.

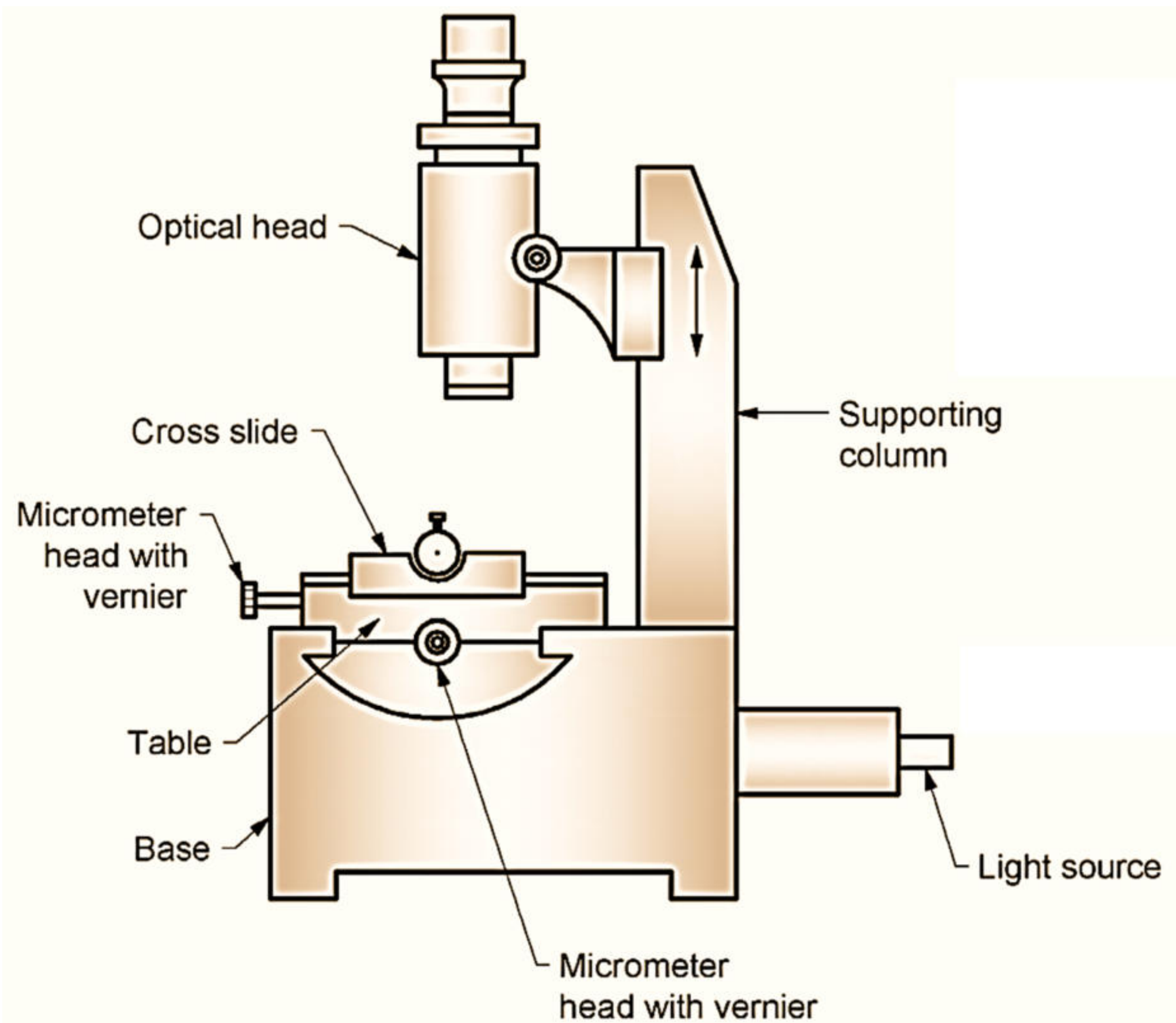
Key Components

- **Light Source:** Provides illumination for the object.
- **Glass Table/Stage:** A movable platform where the object is placed for measurement.
- **Objective Lens:** Magnifies the object's shadow.
- **Eyepiece:** Allows the user to view the magnified shadow.
- **Micrometer Screws:** Used for precise movement of the stage and accurate linear measurements.

- **Protractor:** Measures angular dimensions.

  Applications

- **Thread Inspection:** Measuring the angles and profiles of threads on tools and other components.
- **Geometric Measurements:** Determining the length, width, and other dimensions of small parts.
- **Pattern Comparison:** Comparing a physical object to a drawing or a reference pattern.
- **Inspection of Miniature Components:** Used for inspecting and measuring small mechanical and electronic parts.



A Coordinate Measuring Machine (CMM) measures an object's geometric characteristics using a probe to record X, Y, and Z coordinates. The principle involves the probe, which can be touch-based or non-contact, collecting data points on the object's surface. This data is processed by software to compare the object's actual dimensions against a CAD model or drawings, identifying deviations and ensuring product quality. CMMs are used in various applications, including quality assurance for complex parts, reverse engineering, rapid prototyping, and measuring automotive and mechanical components.

Working Principle

1. **1. Probing:**

   A probe, which can be mechanical (contact) or non-contact (e.g., laser, camera), is moved along the X, Y, and Z axes to make contact with the object.

2. **2. Data Collection:**

   When the probe touches the object, it records a precise X, Y, and Z coordinate for that point.

- **Single-point probing:** The probe touches specific, discrete points on the surface.
- **Scanning probing:** The probe moves continuously along the surface, capturing a dense cloud of points.

3. **3. Data Processing:**

   The collected coordinate data is transmitted to a dedicated computer system running CMM software.

4. **4. Analysis:**

   The software analyzes the captured points to determine the object's geometry and compare it to the design's original CAD model.

5. **5. Reporting:**

   The software provides reports detailing measurements, tolerances, and any deviations from the design, ensuring the part meets quality standards.

Types of CMM Probes

- **Contact Probes:**

  These are the most common, with a physical contact point that deflects upon touching the part.

- **Non-Contact Probes:**

Options like optical (laser or camera-based) probes use light to capture 3D data without physical contact.

Applications

- **Quality Control:**

  Used to inspect complex parts, ensuring they meet dimensional accuracy and geometric tolerances.

- **Reverse Engineering:**

  Capturing the geometry of an existing part to create a 3D model and potentially develop new designs.

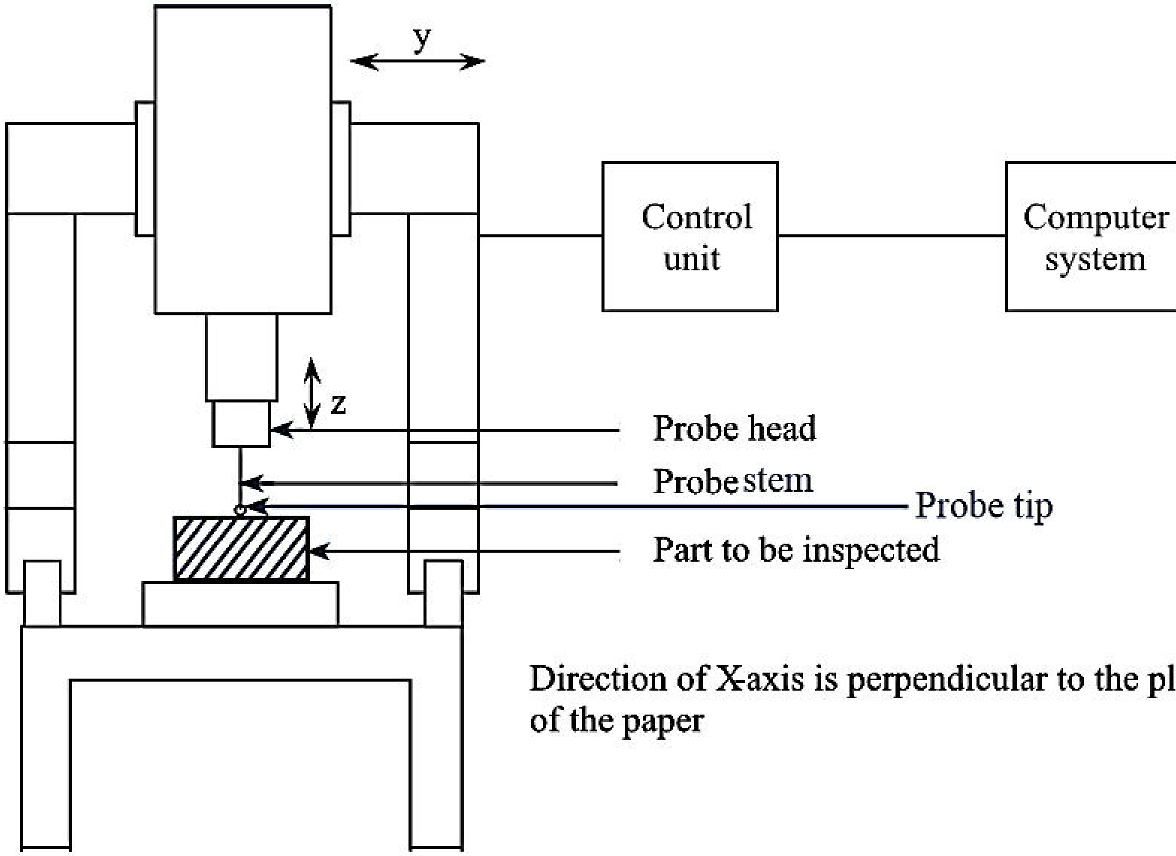
- **Rapid Prototyping:**

  Measuring prototypes to verify their dimensions and fit before mass production.

- **Metrology for Complex Shapes:**

  Ideal for measuring intricate profiles, features, and components that are difficult to measure with traditional tools.

- **Industrial Components:**
  In the automotive and mechanical industries, CMMs measure dies, prototypes, and various mechanical parts for accuracy.



Direction of X-axis is perpendicular to the plane of the paper

UNIT-3

PRINCIPLES OF STRAIGHTNESS:

"A line is said to be straight over a given length, if variation in distance of all points lying on line from two planes perpendicular to each other and parallel to general direction of line, remains within the specified tolerance limits".

The reference planes are so chosen that, their intersection is parallel to the straight line joining two points, which are located on the line to be tested and close to ends of the length under measurement. Tolerance on straightness of a line is defined as, "the maximum deviation in relation to the reference straight line going to the two extremities or ends of line under examination".

Test for Straightness by Using Spirit Level and Auto-collimator

• Tests for straightness can be carried out by using spirit level or autocollimator.

•The above instruments determine the straightness of any surface by measuring the relative angular position of various adjacent sections of surface to be tested.

• For this purpose, initially a straight line is drawn on the surface under test. Then this drawn line is divided into number of equidistant sections.

• If spirit level is used, then length of each section should be equal to length of base of spirit level.

• If auto-collimator is used, then length of each section should be equal to length of base of plane reflector.

• Generally, the bases of spirit level block or reflector are fitted with two legs (or feets), such that,

(i) Feets or legs have line contact with the surface under test, and

(ii) Entire surface of base does not touch the surface under test.

This ensures that, angular deviation obtained is between the two specified points.

(i) Spirit Level:

- The block of spirit level is moved linearly on the surface to be tested, in number of steps. Every step chosen is equal to the pitch distance between centre lines of two feets.

- When block of spirit level is kept on a perfectly flat surface, we observe that, vapour bubble is resting at the middle and topmost position of glass tube indicating zero reading on the scale engraved on glass tube.

- But, when the block of spirit level is moved over surface test, then this vapour bubble moves away from the middle position due to irregularities in straightness of surface. This variation in the spirit level is measured, which gives the angular variation in the direction of block.

- Angular variation can be correlated in terms of the difference of height between two points by knowing the least count of level and length of the base.

- Limitation of spirit level: It can be used to find out variation in straightness of horizontal surface only.

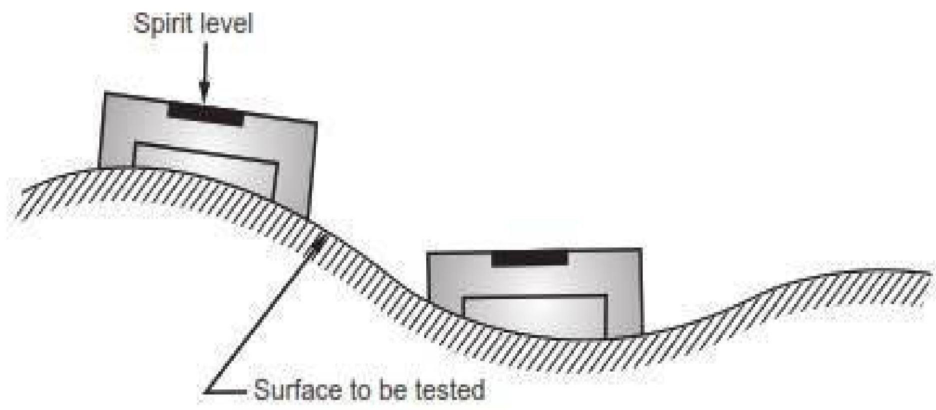


Fig. 4.1 Test for Straightness by Using Spirit Level

[source: Metrology and Quality Control, Vinod Thombre Patil, Pg. No 212]

(ii) Auto-collimator:

- Auto-collimator can be used to measure the straightness of surface in any plane.

• Auto-collimator is placed at a distance of 0.5 to 0.75 metre from the surface to be tested. It is held in desired position on any rigid support, which is independent of the surface to be tested.

• A parallel beam from auto-collimator is projected along the length of surface to be tested.

• A block resting on two legs or feets is placed on the surface under test.

• Block carries a plane vertical reflector mounted on its extreme left side in such a way that, face of reflector is facing auto-collimator.

• Plane reflector and auto-collimator are arranged in such a way that,

(i) image of cross wires of the collimator appears very near to the centre of eyepiece, and

(ii) linear movement of reflector over the entire length of surface under test is completed.

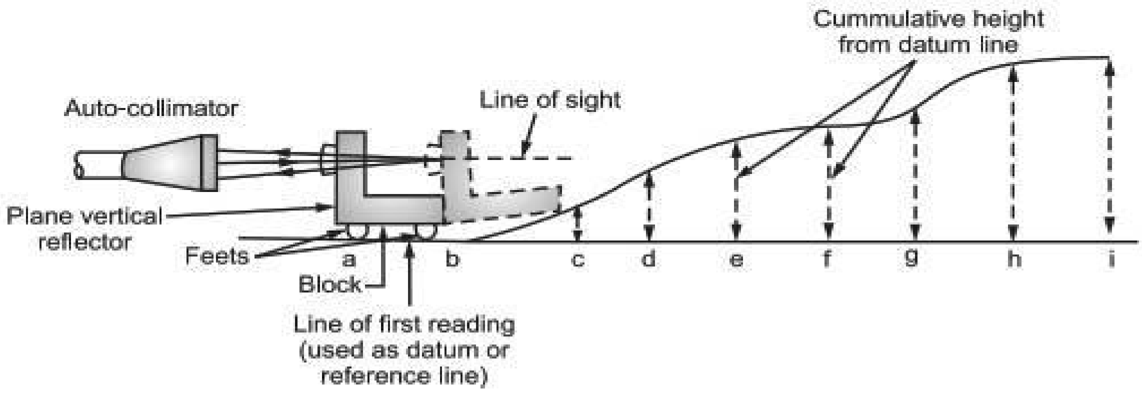


Fig. 4.2 Auto-collimator checking straightness

[source: Metrology and Quality Control, Vinod Thombre Patil, Pg. No 212]

• Now, the reflector is moved towards the other end of surface in steps equal to the centre distance between the two legs or feets. During this movement, the tilting of reflector is noted down in seconds from the eyepiece.

1 second of arc = 0.000006 mm/mm

• Now, the reflector is set at first position a-b (perfectly flat and straight) and first micrometer reading is noted down. This line is labelled as 'a-b' is treated as datum line or reference line. Successive readings at positions b-c, c-d, d-e …… and so on, are taken, till the plane reflector completes its linear movement over the entire length of surface under test.

4.2 Flatness measurement

Machine tool tables, which hold workpieces during machining, should have a high degree of flatness. Many metrological devices like the sine bar invariably need a perfectly flat surface plate.

Flatness error may be defined as the minimum separation of a pair of parallel planes that will just contain all the points on the surface. Figure 10.7 illustrates the measure of flatness error a. It is possible, by using simple geometrical approaches, to fit a best-fit plane for the macro surface topography. Flatness is the deviation of the surface from the best-fit plane.

According to IS: 2063-1962, a surface is deemed to be flat within a range of measurement when the variation of the perpendicular distance of its points from a geometrical plane (this plane should be exterior to the surface to be tested) parallel to the general trajectory of the plane to be tested remains below a given value. The geometrical plane may be represented either by means of a surface plane or by a family of straight lines obtained by the displacement of a straight edge, a spirit level, or a light beam. While there are quite a few methods for measuring flatness,

such as the beam comparator method, interferometry technique, and laser beam measurement, the following paragraphs explain the simplest and most popular method of measuring flatness using a spirit level or a clinometer.

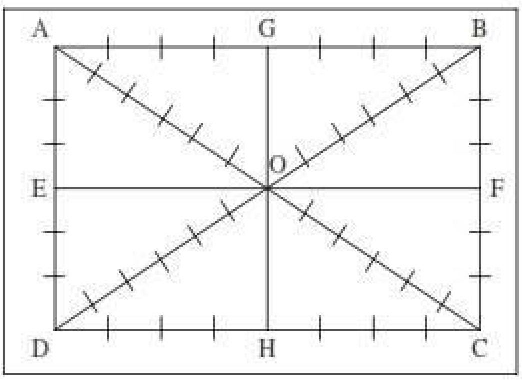


Fig. 4.3 Grid lines for flatness Test

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 255]

4.2.1 Measurement of flatness error

Assuming that a clinometer is used for measuring angular deviations, a grid of straight lines, as shown in Fig. 4.3., is formulated. Care is taken to ensure that the maximum area of the flat table or surface plate being tested is covered by the grid. Lines AB, DC, AD, and BC are drawn parallel to the edges of the flat surface; the two diagonal lines DB and AC intersect at the centre point O. Markings are made on each line at distances corresponding to the base length of the clinometer.

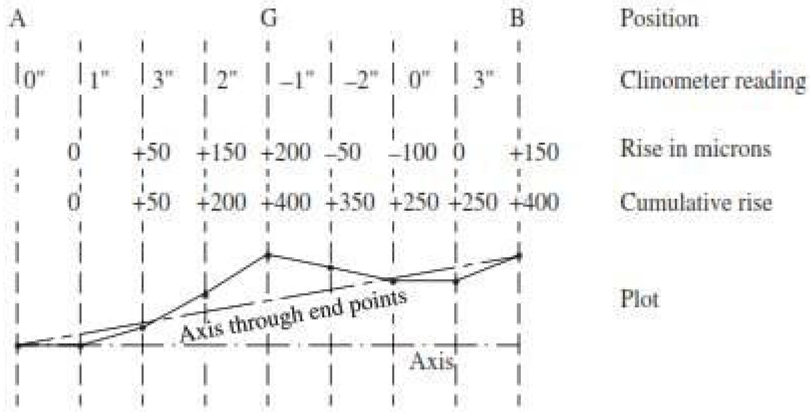


Fig. 4.4 Straightness plot for line AB

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 255]

The following is a step-by-step procedure to measure flatness error:

1. Carry out the straightness test, as per the procedure described in Chapter 5, on all the lines and tabulate the readings up to the cumulative error column. Figure 10.9 gives an example of line AB.

2. We know that a plane is defined as a 2D entity passing through a minimum of three points not lying on the same straight line. Accordingly, a plane passing through the points A, B, and D is assumed to be an arbitrary plane, relative to which the heights of all other points are determined. Therefore, the ends of lines AB, AD, and BD are corrected to zero and the heights of points A, B, and D are forced to zero.

3. The height of the centre 'O' is determined relative to the arbitrary plane ABD. Since O is also the mid-point of line AC, all the points on AC can be fixed relative to the

arbitrary plane ABD. Assume A = 0 and reassign the value of O on AC to the value of O on BD. This will readjust all the values on AC in relation to the arbitrary plane ABD.

4. Next, point C is fixed relative to the plane ABD; points B and D are set to zero. All intermediate points on BC and DC are also adjusted accordingly.

5. The same procedure applies to lines EF and GH. The midpoints of these lines should also coincide with the known midpoint value of O.

6. Now, the heights of all the points, above and below the reference plane ABD, are plotted as shown in Fig. 4.5. Two lines are drawn parallel to and on either side of the datum plane, such that they enclose the outermost points. The distance between these two outer lines is the flatness error.

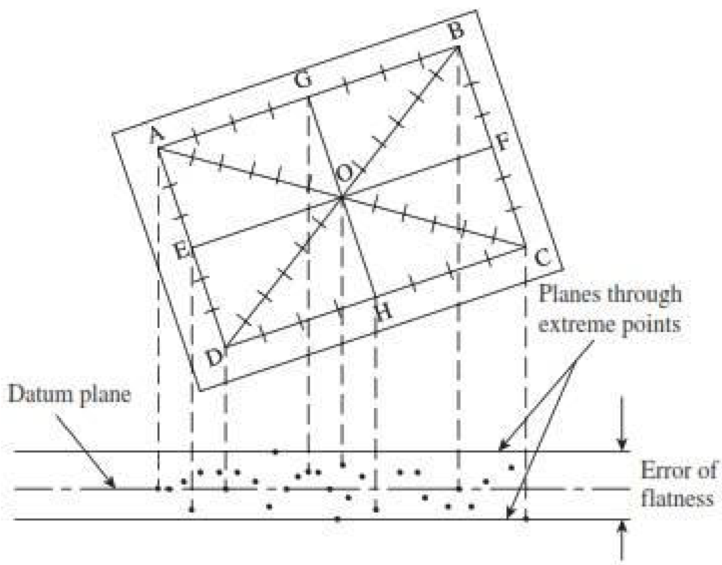


Fig. 4.5 Plot of heights of all points with reference to the datum plane ABD

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 256]

Some authors argue that the reference plane ABD that is chosen in this case may not be the best datum plane. They recommend further correction to determine the minimum separation between a pair of parallels that just contains all the points on the surface. However, for all practical purposes, this method provides a reliable value of flatness error, up to an accuracy of 10 μm.

Optical flat measurement:

Optical flat measurement is a non-contact method for testing surface flatness by using a precisely flat reference surface to create an interference pattern with the surface being tested. When monochromatic light is shone on the optical flat, it creates alternating light and dark bands (interference fringes) that reveal the surface's flatness. The shape, spacing, and number of these fringes indicate whether the surface is flat, concave, or convex, with straight, parallel, and evenly spaced fringes indicating a perfectly flat surface.

How it works

- An optical flat is placed over the surface to be tested, with a thin air gap between them.
- A beam of monochromatic light is directed onto the optical flat.
- Some light reflects off the top surface of the optical flat, while some is transmitted, reflects off the surface below, and then transmits back through the optical flat.
- These two reflected light rays interfere with each other. Where the path difference is an even multiple of a half-wavelength, they are in phase, and a light band is seen. Where the path difference is an odd multiple of a half-wavelength, they are out of phase and destructive interference occurs, resulting in a dark band.
- This process creates a series of light and dark bands (fringes) that act as a visual map of the surface's deviations from perfect flatness.

Reading the results

Perfectly flat: Fringes are straight, parallel, and equally spaced.

Concave surface: Fringes are curved towards the point where the flat rests. The surface is low in the center.

Convex surface: Fringes are curved away from the point where the flat rests. The surface is high in the center.

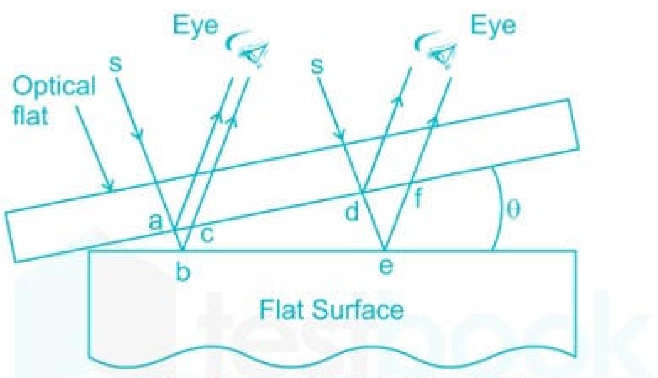
Measuring flatness error: The number of fringes can indicate the flatness error. For example, an error of one fringe corresponds to a deviation of half the wavelength of the light used.

Key parameters

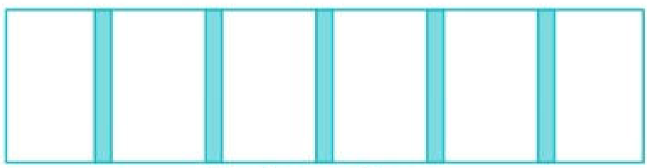
Wavelength: The light used must be monochromatic (single wavelength), such as that from a cadmium lamp.

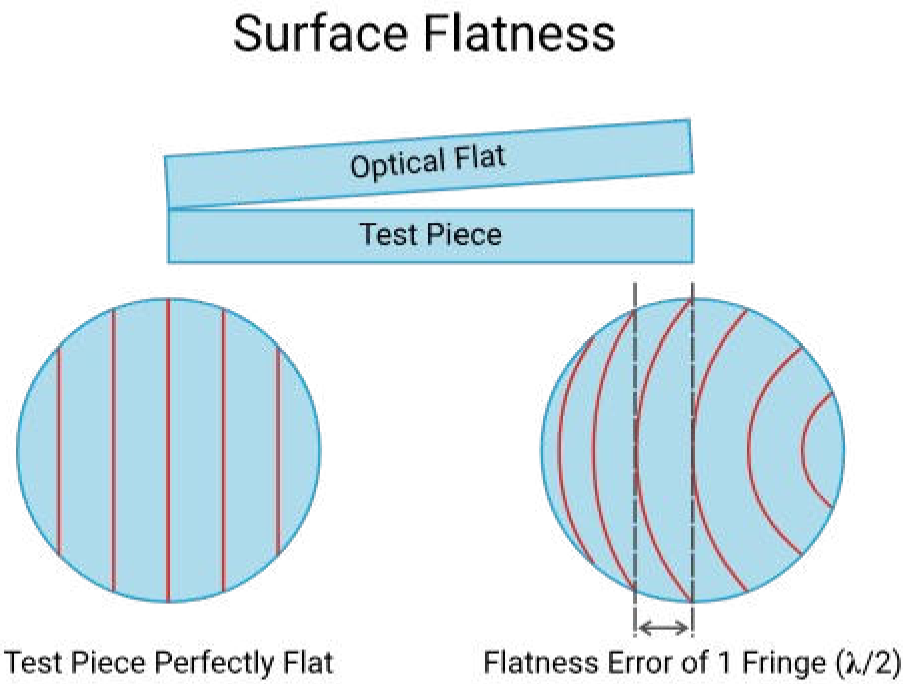
Flatness of the optical flat: The precision of the optical flat is measured in fractions of a reference wavelength, such as $\lambda/4$ or $\lambda/20$.

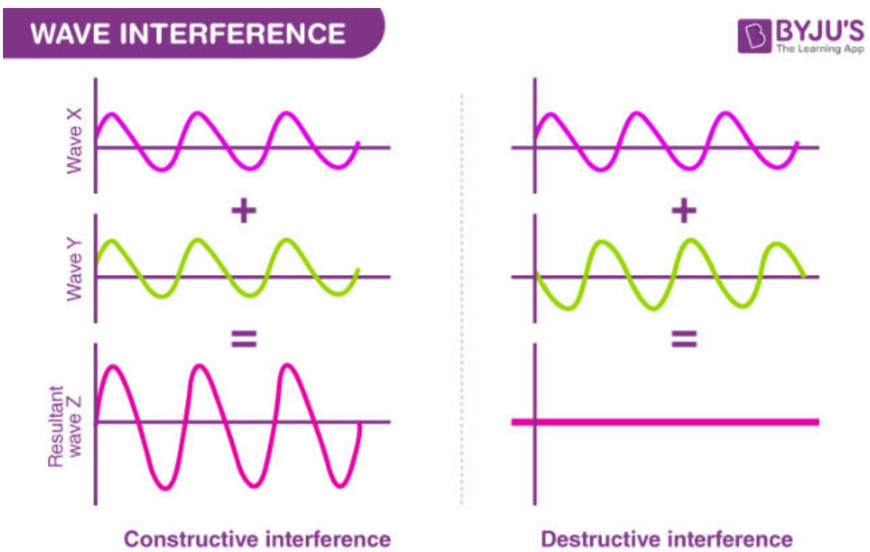
Units: Flatness errors are often measured in fractions of a micron or microinches.

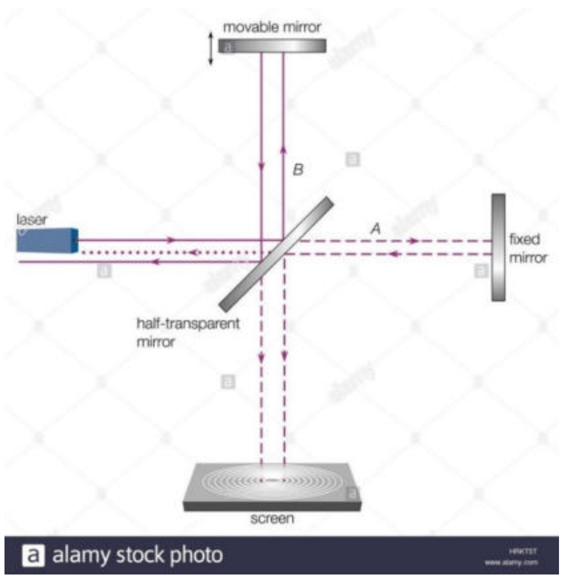


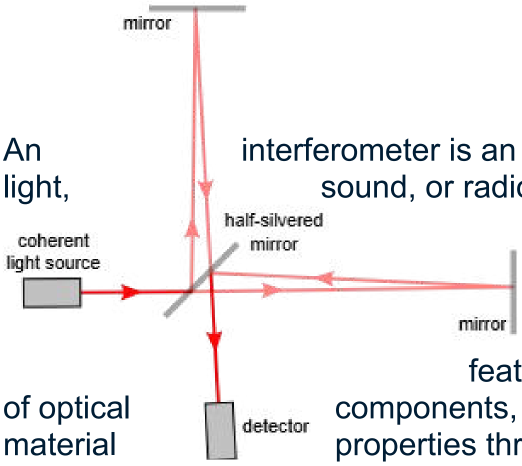
Fringe formation in an optical flat


Interference fringes


Surface Flatness
Optical Flat
Test Piece
Test Piece Perfectly Flat
Flatness Error of 1 Fringe (λ/2)


WAVE INTERFERENCE
BYJU'S
The Learning App
Wave X
Wave Y
Resultant wave Z
+
=
Constructive interference
Destructive interference


movable mirror
B
A
laser
fixed mirror
half-transparent mirror
screen
alamy stock photo



An interferometer is an instrument that uses the interference of waves, such as light, sound, or radio waves, to measure physical properties with extreme precision. By splitting a wave into two or more beams that travel different paths and then recombining them, the resulting interference pattern can reveal minute changes in distance, refractive index, or surface features. Key applications include measuring surface quality of optical components, detecting gravitational waves (like at LIGO), analyzing material properties through spectroscopy, and ensuring precision in manufacturing and engineering fields like microelectronics and large-scale structural alignment.

How an Interferometer Works

1. **Wave Splitting:** A single wave source, like a laser, is split into two or more beams.
2. **Differential Path Length:** These beams travel along different optical paths.
3. **Recombination & Interference:** The beams are then recombined, and their interaction (interference) creates a pattern of constructive (brighter) or destructive (darker) fringes.
4. **Measurement:** The characteristics of this interference pattern—specifically, shifts or changes in the fringes—are used to deduce information about the differences in the optical paths, allowing for highly sensitive measurements.

Key Applications

- **Metrology & Manufacturing:**

  Measuring the surface quality of optical lenses, hard disk drives, and machined parts. It's also used in precision engineering for quality control and calibrating mechanical stage motions.

- **Astronomy & Physics:**

  Detecting gravitational waves, such as with the LIGO observatory, a feat that confirms theoretical predictions and opens new ways to study the universe.

- **Materials Science & Spectroscopy:**

  Analyzing the properties of materials by observing how light interacts with them.

- **Environmental & Atmospheric Monitoring:**

  Measuring temperature and wind patterns in the atmosphere.

- **Biomedical Applications:**

  Identifying viruses and detecting changes in liquids that indicate contaminants or oxygen depletion.

- **Fiber Optics:**

  Ensuring the precision and quality of fiber optic components and connectors.

4.5 SURFACE FINISH MEASUREMENT

4.5.1 Introduction:

- When we are producing components by various methods of manufacturing

process it is not possible to produce perfectly smooth surface and some irregularities are formed.

- These irregularities are causes some serious difficulties in using the components.

So, it is very important to correct the surfaces before use.

- The factors which are affecting surface roughness are

1. Work piece material
2. Vibrations
3. Machining type
4. Tool, and fixtures

The geometrical irregularities can be classified as

1. First order
2.Second order
3 Third order
4.Fourth order

1. First order irregularities:

These are caused by lack of straightness of guide ways on which tool must move.

2. Second order irregularities:

These are caused by vibrations

3. Third order irregularities:

These are caused by machining.

4. Fourth order irregularities:

These are caused by improper handling machines and equipments.

4.5.2 SURFACE METROLOGY CONCEPTS

If one takes a look at the topology of a surface, one can notice that surface irregularities are superimposed on a widely spaced component of surface texture called waviness. Surface irregularities generally have a pattern and are oriented in a particular direction depending on the factors that cause these irregularities in the first place.

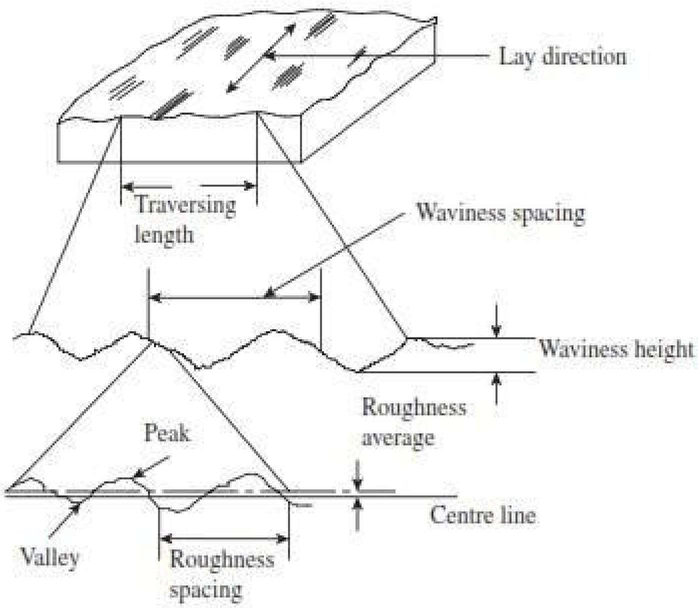


Fig. 4.34 Waviness and roughness

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 218]

Surface irregularities primarily arise due to the following factors:

1. Feed marks of cutting tools

2. Chatter marks on the workpiece due to vibrations caused during the manufacturing operation

3. Irregularities on the surface due to rupture of workpiece material during the metal cutting Operation

4. Surface variations caused by the deformation of workpiece under the action of cutting forces

5. Irregularities in the machine tool itself like lack of straightness of guideways

4.5.3 TERMINOLOGY

Roughness The American Society of Tool and Manufacturing Engineers (ASTME) defines roughness as the finer irregularities in the surface texture, including those irregularities that result from an inherent action of the production process. Roughness spacing is the distance between successive peaks or ridges that constitute the predominant pattern of roughness. Roughness height is the arithmetic average deviation expressed in micrometres and measured perpendicular to the centre line.

Waviness It is the more widely spaced component of surface texture. Roughness may be considered to be superimposed on a wavy surface. Waviness is an error in form due to incorrect geometry of the tool producing the surface. On the other hand, roughness may be caused by problems such as tool chatter or traverse feed marks in a supposedly geometrically perfect machine. The spacing of waviness is the width between successive wave peaks or valleys. Waviness height is the distance from a peak to a valley.

Lay It is the direction of the predominant surface pattern, ordinarily determined by the production process used for manufacturing the component. Symbols are used to represent lays of surface pattern

Flaws These are the irregularities that occur in isolation or infrequently because of specific causes such as scratches, cracks, and blemishes.

Surface texture It is generally understood as the repetitive or random deviations from the nominal surface that form the pattern of the surface. Surface texture encompasses roughness, waviness, lay, and flaws.

Errors of form These are the widely spaced repetitive irregularities occurring over the full length of the work surface. Common types of errors of form include bow, snaking, and lobbing.

4.5.4 ANALYSIS OF SURFACE TRACES

It is required to assign a numerical value to surface roughness in order to measure its degree. This will enable the analyst to assess whether the surface quality meets the functional requirements of a component. Various methodologies are employed to arrive at a representative parameter of surface roughness. Some of these are 10-point height average (Rz), root mean square (RMS) value, and the centre line average height (Ra), which are explained in the following paragraphs.

4.5.4.1 Ten-point Height Average Value

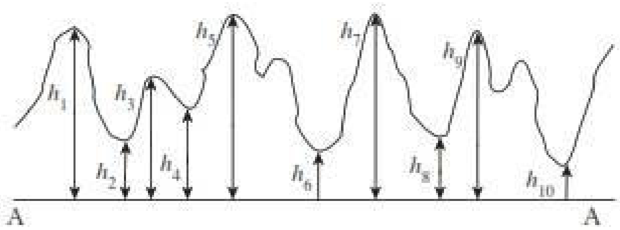


Fig. 4.35 Measurement to calculate the 10-point height average

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 220]

It is also referred to as the peak-to-valley height. In this case, we basically consider the average height encompassing a number of successive peaks and valleys of the asperities. As can be seen in Fig., a line AA parallel to the general lay of the trace is drawn. The heights of five consecutive peaks and valleys from the line AA are noted down.

The average peak-to-valley height Rz is given by the following expression:

$$Rz = \frac{(h_1 + h_3 + h_5 + h_7 + h_9) - (h_2 + h_4 + h_6 + h_8 + h_{10})}{5} \times \frac{1000}{\text{Vertical magnification}} \ \mu\text{m}$$

4.5.4.2 Root Mean Square Value

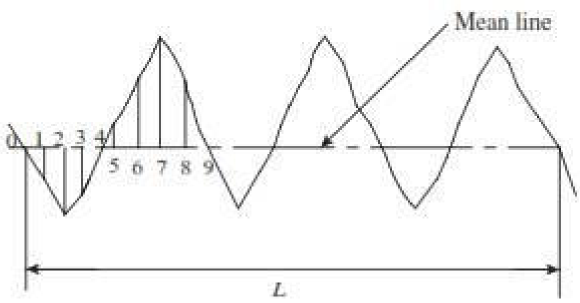


Fig. 4.36 Representation of an RMS value

[source: Engineering Metrology and Measurements, N.V[illegible]. No 220]

Until recently, RMS value was a popular choice for quantifying surface roughness; however, this has been superseded by the centre line average value. The RMS value is defined as the square root of the mean of squares of the ordinates of the surface measured from a mean line.

Figure illustrates the graphical procedure for arriving at an RMS value. With reference to this figure, if h_1, h_2, ..., h_n are equally spaced ordinates at points 1, 2, ..., n, then

$$h_{RMS} = \frac{\sqrt{(h_1^2 + h_2^2 + \ldots + h_n^2)}}{n}$$

4.5.4.3 Centre Line Average Value

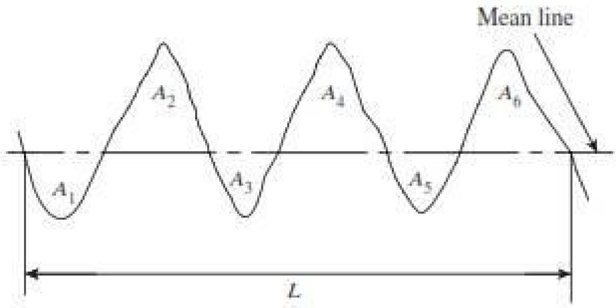


Fig. 4.37 Representation of Ra value

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 221]

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.

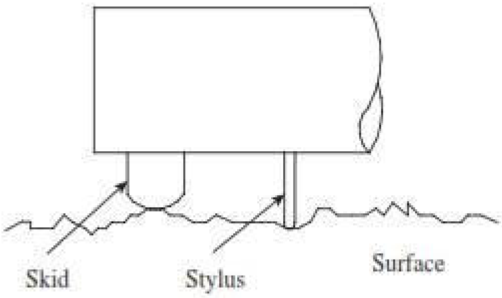


Fig. 4.38 Skid and stylus type

[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
surface roughness. instrument to provide the required datum for the measurement of

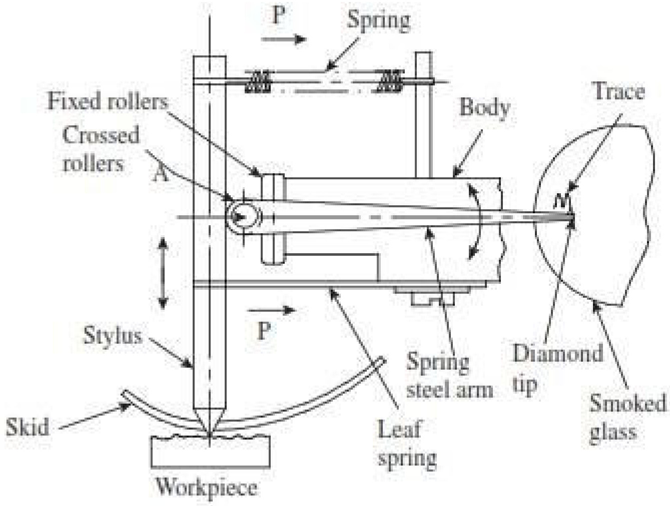


Fig. 4.39 Tomlinson surface meter

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

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.

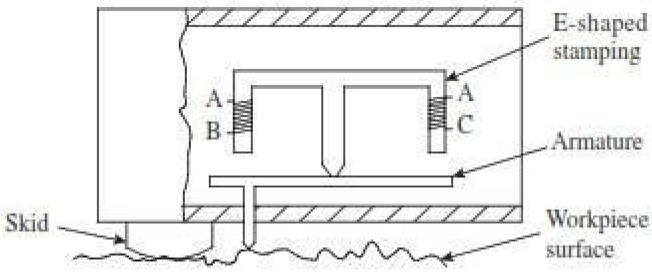


Fig. 4.40 Taylor–Hobson Talysurf

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

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.

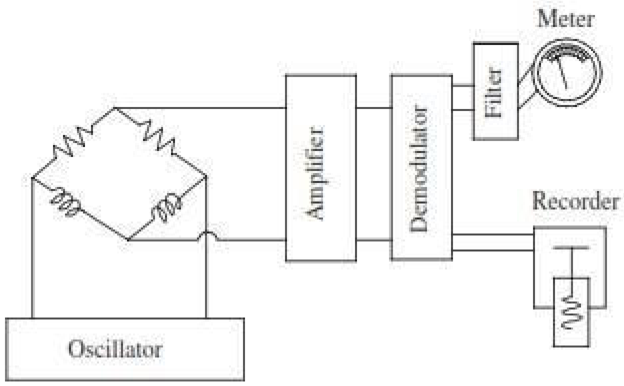


Fig. 4.41 Bridge circuit and electronics

[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.

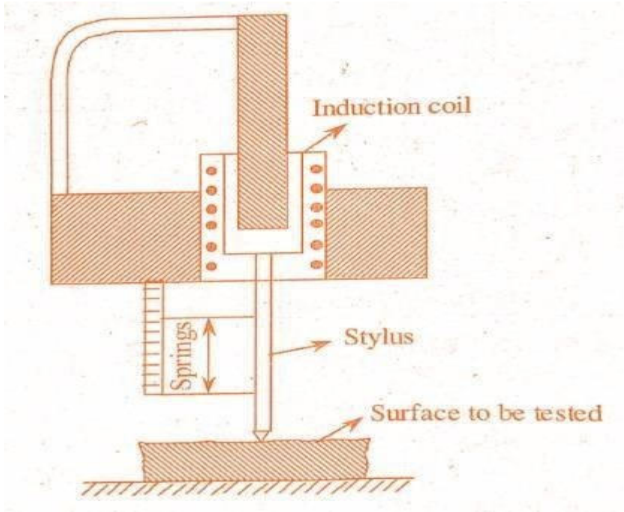


Fig. 4.42 Profilometer

[source: http://www.mechanicaleducation.com/2018/10/what-is-profilometer-and-uses-of-profilometer.html]

4.5.7 Other methods for measuring surface roughness

4.5.7.1 Profilograph

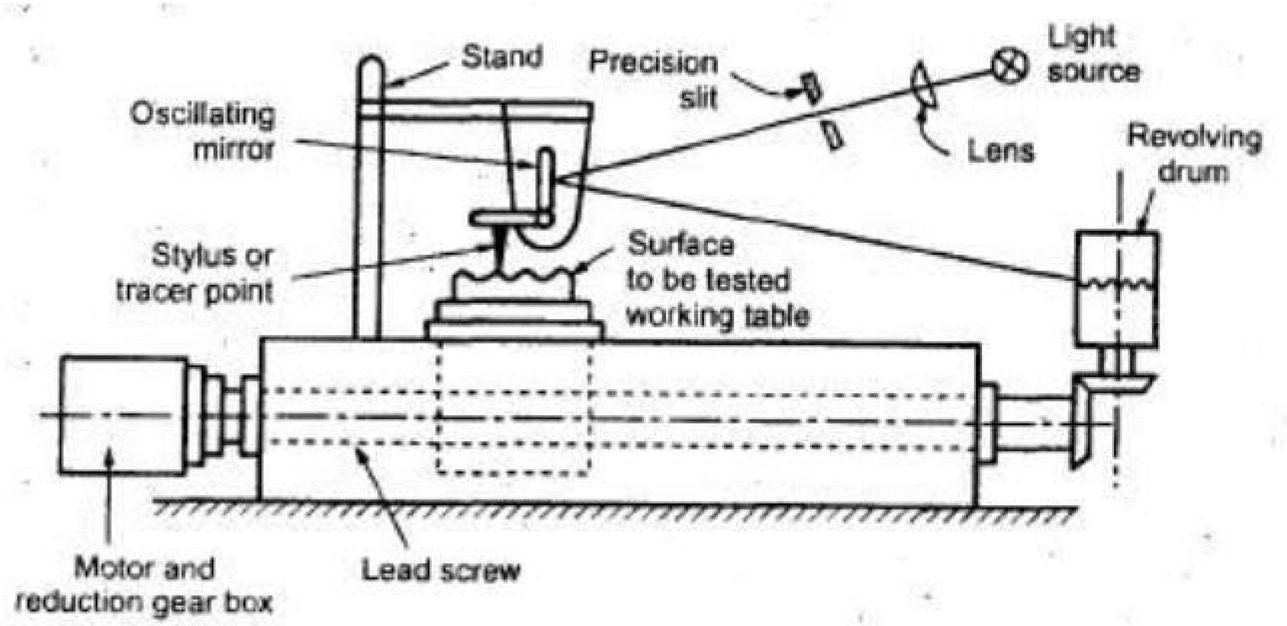


Fig. 4.43 Profilograph

[source: https://www.slideshare.net/navroznavodia/surface-finish-measurement-mechanical-measurement-and-metrology]

- 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

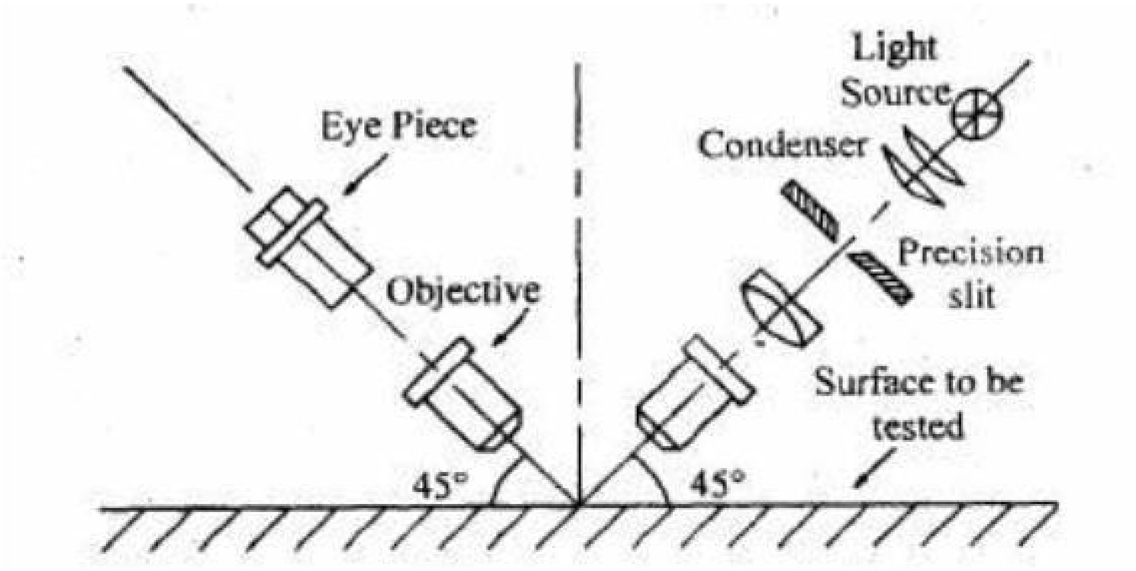
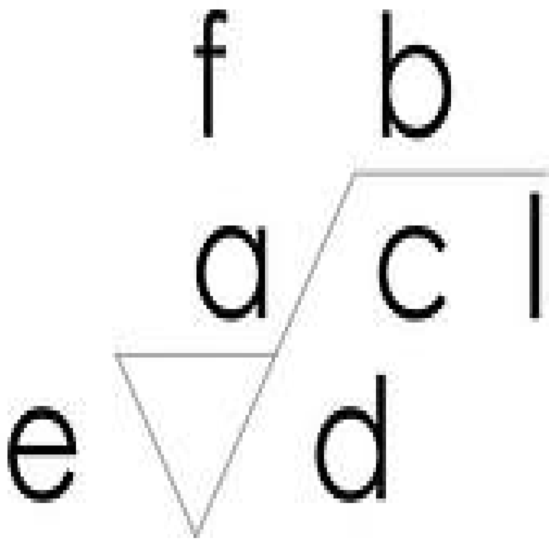


Fig. 4.44 Profilograph

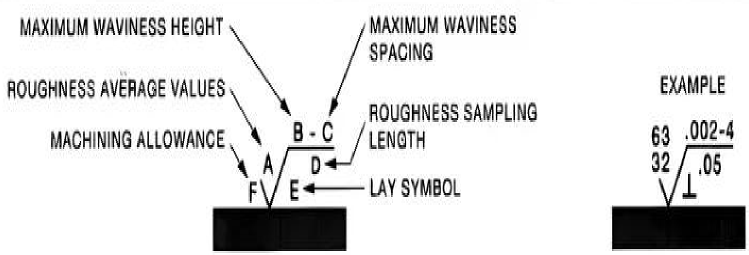
[source: https://www.slideshare.net/navroznavodia/surface-finish-measurement-mechanical-measurement-and-metrology]

- 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.



Graphical Symbol	Description
a	Minimum Roughness
b	Production Method/ Treatment
c	Sampling Length
d	Roughness Spacing
e	Material Removal Allowances
f	Maximum Roughness
l	Other Roughness Values

SURFACE FINISH SYMBOLS



BASIC SURFACE TEXTURE SYMBOL		MAXIMUM WAVINESS SPACING RATING (C). SPECIFY IN INCHES OR MILLIMETERS. HORIZONTAL BAR ADDED TO BASIC SYMBOL.	.002-4
ROUGHNESS AVERAGE VALUES (A). SPECIFY IN MICROINCHES, MICROMETERS, OR ROUGHNESS GRADE NUMBERS.	63 N7	LAY SYMBOL (E)	⊥
MAXIMUM AND MINIMUM ROUGHNESS AVERAGE VALUES (A), SPECIFY IN MICROINCHES, MICROMETERS, OR ROUGHNESS GRADE NUMBERS.	63 32 N7 N6	ROUGHNESS SAMPLING LENGTH OR CUTOFF RATING (D). WHEN NO VALUE IS SHOWN USE .03 INCH (0.8 MILLIMETERS.	.05
MAXIMUM WAVINESS HEIGHT RATING (B) SPECIFY IN INCHES OR MILLIMETERS. HORIZONTAL BAR ADDED TO BASIC SYMBOL.	.002	MACHINING ALLOWANCE (F). SPECIFY IN INCHES OR MILLIMETERS.	.06

NOTE: WAVINESS IS NOT USED IN ISO STANDARDS.

√	Basic symbol for surface under consideration or to a specification explained elsewhere in a note
▽√	Basic symbol for a surface to be machined
○√	Basic symbol for material removal prohibited and left in the state from a previous manufacturing process
√○	Basic symbol with all round circle added to indicate the surface specification applies to all surfaces in that view

UNIT-4

Theory and Construction of Various Transducers to Measure Displacement:

Various displacement transducers use different principles: Potentiometric use a movable wiper on a resistive element, LVDT use electromagnetic induction, Capacitive change capacitance based on plate distance, and Magnetostrictive use the time-of-flight of ultrasonic waves. Their construction involves a sensing element to detect the displacement and a transducing element to convert that into an electrical signal.

Potentiometric Transducers

Theory: Based on the principle of a variable resistor. As a slider (wiper) moves along a resistive element, it changes the resistance, which is proportional to the displacement.

Construction: A resistive track (linear or rotary) with a sliding contact (wiper) that is connected to the object whose displacement is being measured. An input voltage is applied across the ends of the resistive element, and the output voltage varies linearly with the wiper's position.

Linear Variable Differential Transformer (LVDT)

Theory: Uses electromagnetic induction to measure displacement. A movable ferromagnetic core changes the mutual inductance between a primary coil and two secondary coils.

Construction: A primary coil is wound on a former and connected to an AC voltage source. Two secondary coils are placed symmetrically on either side of the primary coil, and a movable ferromagnetic core moves within the coil assembly. The output is the differential voltage between the two secondary coils, which is proportional to the core's displacement from the center position.

Capacitive Transducers

Theory:Works on the principle of variable capacitance. Capacitance changes based on the distance between the plates, the area of the plates, or the dielectric constant of the material between them.

Construction:Typically consists of two parallel plates: one fixed and one movable, with a dielectric material in between. The displacement of the movable plate changes the distance between the plates, altering the capacitance. This change is then converted into an electrical signal.

Piezoelectric Transducer:

A piezoelectric transducer works by converting mechanical stress into electrical energy, and vice versa, through the piezoelectric effect. When a piezoelectric material, like quartz, is subjected to mechanical pressure, it generates a voltage proportional to the applied force. Conversely, when a voltage is applied to the material, it deforms, creating a mechanical stress.

1. Piezoelectric Effect:

The core principle is the piezoelectric effect, where certain materials produce an electrical charge when subjected to mechanical stress (pressure, force, etc.).This effect is reversible, meaning the material also deforms when an electric field is applied.This conversion between mechanical and electrical energy is fundamental to the transducer's operation.

2. Transducer Structure:

A piezoelectric transducer typically consists of a piezoelectric element (like a crystal) sandwiched between two conductive electrodes. The electrodes allow for the application of voltage and the measurement of the generated charge.

3. Sensor Mode (Mechanical to Electrical):

When mechanical stress is applied to the piezoelectric material, it gets distorted at the atomic level, causing a charge separation between the electrodes.This charge difference creates a voltage that can be measured and used to determine the applied force, pressure, or acceleration.

4. Actuator Mode (Electrical to Mechanical):

When a voltage is applied to the electrodes, the piezoelectric material experiences stress due to the inverse piezoelectric effect.This stress causes the material to deform, which can be used to create motion or apply a force.

5. Key Characteristics:

Active Transducer: Piezoelectric transducers don't require an external power source to operate, making them "active" transducers.

Directionality: The polarity of the generated voltage depends on the direction of the applied force (compressive or tensile).

Dynamic Response: Piezoelectric transducers are generally better suited for measuring dynamic (changing) forces rather than static (constant) forces.

6. Applications: Piezoelectric transducers are used in a wide range of applications, including:

Sensors: Measuring pressure, force, acceleration, and strain.

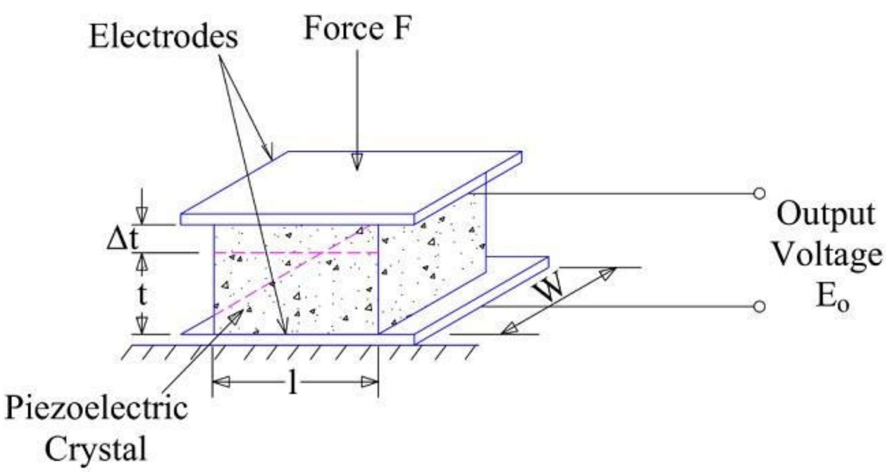
Actuators: Controlling movement and applying force in various devices.

Energy Harvesting: Generating electricity from mechanical vibrations or pressure.

Medical Devices: Ultrasound imaging, and other diagnostic tools.

Consumer Electronics: Speakers, microphones, and other audio devices.

Industrial Applications: Monitoring and control systems.



Inductive transducer:

An inductive transducer converts a non-electrical quantity, like displacement or pressure, into an electrical signal by exploiting changes in inductance or mutual inductance. When the measured quantity causes a change in the reluctance of the magnetic circuit—for example, by altering the air gap or the position of a magnetic core—the inductance of a coil changes. This inductance change is then calibrated to produce a measurable output voltage or current, which can be interpreted as the original non-electrical quantity.

Core Principles

Inductive transducers operate on one of the following electromagnetic principles:

Change in Self-Inductance: As the measured quantity changes, it alters the magnetic path or core position within a single coil, which changes the coil's inductance.

Change in Mutual Inductance: A change in the physical arrangement between two coils (e.g., a primary and a secondary coil) can alter the mutual inductance, resulting in a change in the induced voltage.

Production of Eddy Currents: In some designs, the movement of a conductive object in a varying magnetic field can change the induced eddy currents, which can be used to determine the object's position.

How it Works (Example with Displacement)

1. **Input Quantity:** A non-electrical quantity, such as the linear displacement of an object, is applied to the transducer.
2. **Core Movement:** This displacement moves a magnetic core within a coil, or it changes the air gap in the magnetic circuit of one or more coils.
3. **Inductance Change:** The movement of the core or the change in the air gap alters the magnetic flux path and changes the inductance of the coil(s).
4. **Electrical Output:** This change in inductance is converted into a proportional change in voltage or current output.
5. **Measurement:** The electrical output is then calibrated and interpreted to provide a measurement of the original non-electrical quantity.

physical quantity.

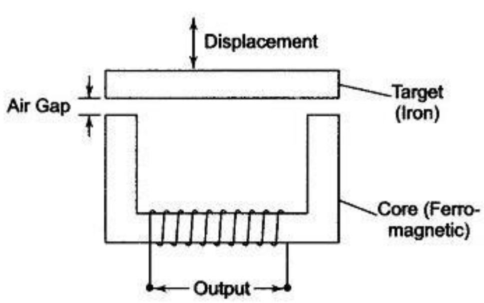


Fig. 13.16(a) ▬ Variable Reluctance Transducer

Capacitive Transducer: A capacitive transducer works on the principle of variable capacitance, where a change in a physical quantity like displacement or pressure alters the capacitance of a system. This change is caused by variations in the overlapping area of the plates, the distance between the plates, or the dielectric constant of the medium separating the plates. The formula $C=\epsilon Ad$ illustrates this relationship, where capacitance (C) is directly proportional to the overlapping area (A) and the permittivity of the dielectric (ϵ), and inversely proportional to the distance (d) between the plates.

Detailed principle:

Two plates and a dielectric: At its core, a capacitive transducer consists of two conductive plates separated by a dielectric medium (like air, gas, or liquid).

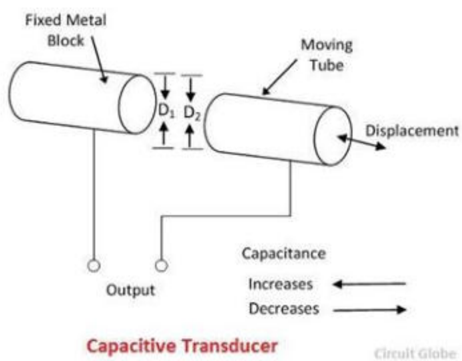
Input physical quantity changes capacitance: When a physical quantity, such as pressure, causes a change in the physical properties of the capacitor, the capacitance changes.

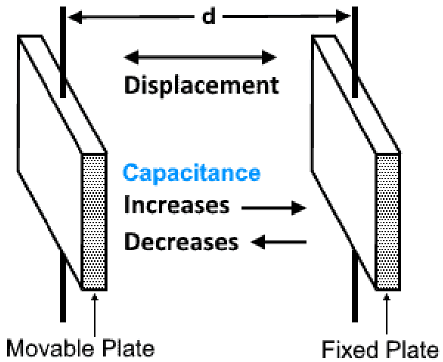
Change in distance: If pressure is applied to a diaphragm that acts as one of the plates, it can move closer to or further from the fixed plate. This change in distance (d) alters the capacitance.

Change in area: A linear displacement can be measured by having one plate slide relative to the other, changing the overlapping area (A) and thus the capacitance.

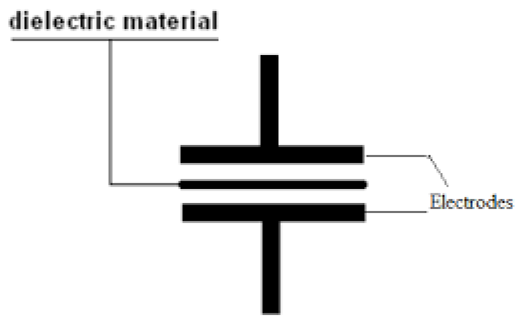
Change in dielectric: The capacitance also changes if the dielectric material between the plates is changed, for instance, by the level of a liquid or gas entering the space between them.

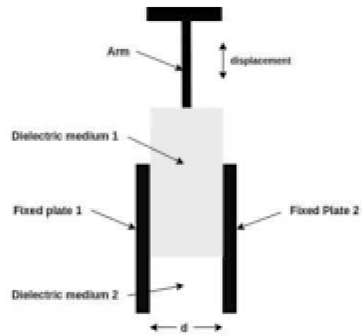
Measuring the change: The resulting change in capacitance is then measured by a suitable circuit, such as an AC bridge or an oscillator. The output of this circuit is a measurable electrical signal that is calibrated to correspond to the original physical input.





Capacitive Transducer using the Change in Distance between the Plates





Resistance:

A resistive transducer works on the principle that a change in a physical quantity (like displacement, force, or temperature) causes a change in the resistance of a material, which is then measured. The resistance of a conductor is determined by its physical properties, specifically its resistivity, length, and cross-sectional area ($R=\rho L/A$). By manipulating one of these properties through a mechanical change, the resistance value can be altered and measured with a simple electrical circuit, often a voltage divider.

Change in length: In a variable resistance transducer like a potentiometer, a slider moves along a resistive wire. As the slider moves, it changes the length of the wire through which the current flows, directly changing the resistance and output voltage.

Change in cross-sectional area: When a force is applied to a strain gauge, it stretches or compresses, changing its cross-sectional area and/or length. This alters its resistance, which can be used to measure force, pressure, or displacement.

Change in resistivity: Some materials have a resistivity that changes significantly with temperature. This is the principle behind a thermistor, which is used to measure temperature by converting the change in temperature into a change in resistance.

Change in light intensity: A photoresistor's resistance changes with the intensity of light. When light strikes the semiconductor material, it creates more charge carriers, which lowers the resistance.

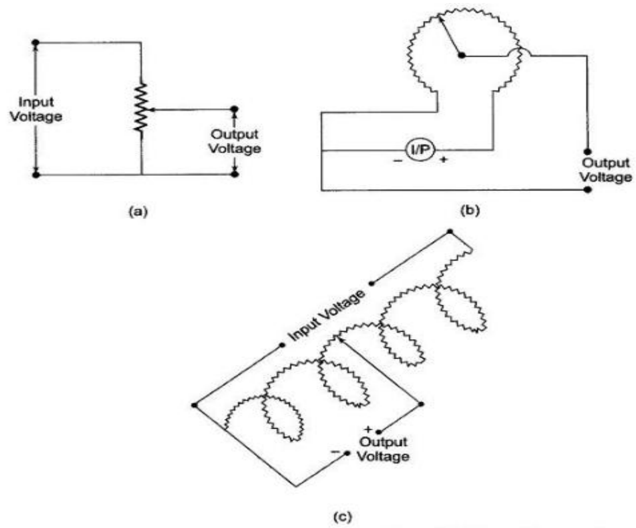


Fig. 13.1 (a) Translatory Type (b) Rotational Type (c) Helipot (Rotational)

Ionization transducer:

An ionization transducer works by using a heated filament to emit electrons that ionize gas molecules within a vacuum chamber; the resulting positive ions are collected, creating a current proportional to the gas pressure or the degree of ionization, which is then converted to a usable electrical signal to measure phenomena like pressure, acceleration, or displacement.

Core Principle: The fundamental principle is that a higher concentration of gas molecules will lead to more ionization events when bombarded by electrons.

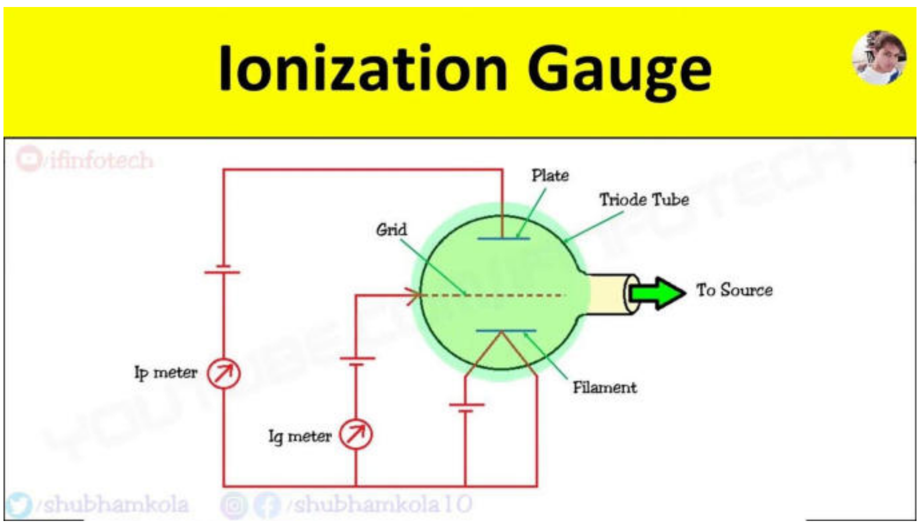
How it Works:

1. **Electron Emission:** A heated cathode (filament) emits a stream of electrons.
2. **Ionization:** These high-energy electrons are accelerated and collide with gas molecules within the chamber. These collisions knock off electrons from the gas molecules, creating positively charged ions and more free electrons.
3. **Ion Collection:** The positively charged ions are then accelerated and collected by a negative electrode (the plate), generating a measurable plate current (Ip).

4. **Signal Conversion:**The magnitude of this ion current (Ip) is directly proportional to the number of gas molecules present and, therefore, to the pressure of the gas.
5. **Measurement:** This current is then converted into a voltage signal, which can be related to the original physical phenomenon being measured.

Applications :

- **Vacuum Gauges:** The most common application is measuring low pressures (vacuum) by detecting the ion current generated in a chamber.
- **Displacement and Acceleration:**Other variations can measure very small displacements or changes in acceleration by detecting changes in the gas's ionization state due to electrode movement.
- **Humidity:** Ionization transducers can also measure humidity by monitoring changes in the gas's properties caused by water vapor.

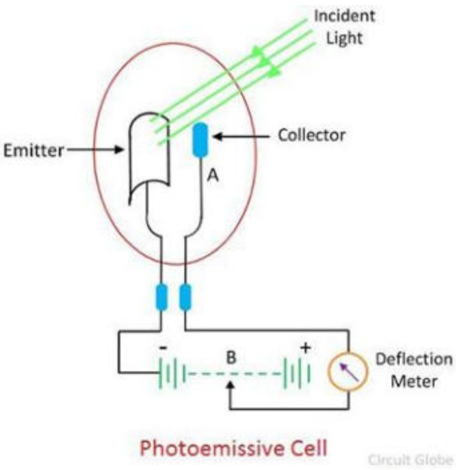


Photoelectric transducers:

Photoelectric transducers convert light energy into electrical energy by using semiconductor materials that eject electrons when struck by photons. This process, based on principles like photoemissive, photoconductive, or photovoltaic effects, results in a change in current, voltage, or resistance proportional to the intensity of the light.

Working principles:

Photo emissive: When radiation (like light) hits a cathode, it causes electrons to be emitted from the surface. These ejected electrons create an electric current.



Photoconductive: When light shines on a photoconductive material, its electrical resistance decreases, and its conductivity increases. This change in resistance can be measured to determine the light intensity.

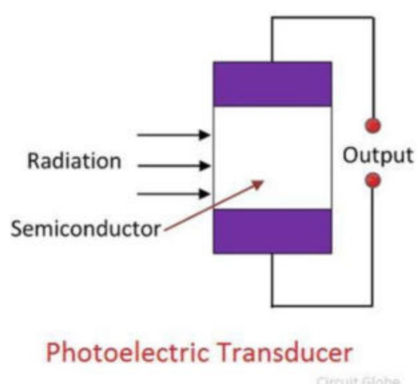
Photovoltaic: Also known as the photoelectric effect, this involves semiconductor materials that generate a voltage when exposed to light. The voltage produced is directly proportional to the intensity of the incident radiation.

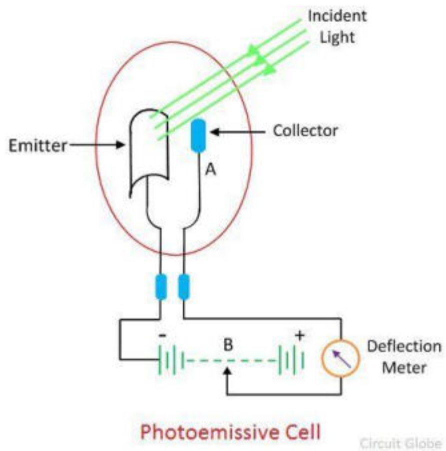
How they work

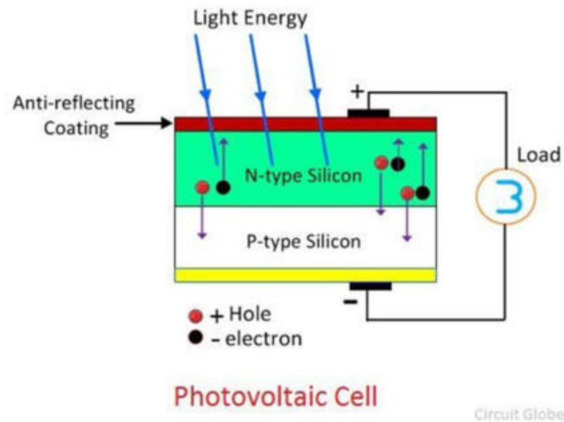
1. **Absorption of light:** A photosensitive semiconductor material absorbs incoming light radiation.
2. **Electron excitation:** The energy from the absorbed photons excites the electrons in the semiconductor material, causing them to move.
3. **Induced electrical signal:** The movement of electrons leads to one of three effects, which are then converted into a measurable electrical output:
   Change in resistance: The material's resistance decreases as more light is absorbed, as in a photoconductive cell.

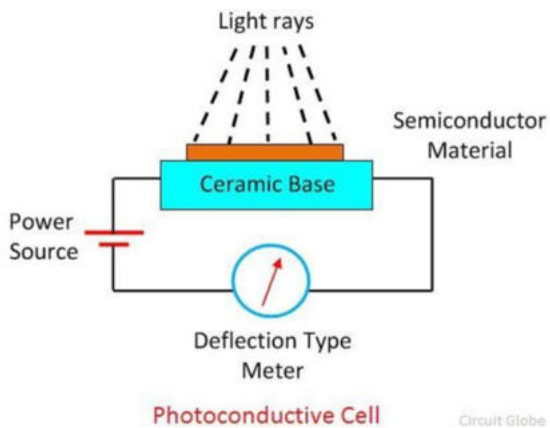
   Change in current: The flow of electrons can be measured as a current, with the magnitude of the current being proportional to the amount of light absorbed, as in a photoemissive cell.

   Change in voltage: A voltage is generated across the semiconductor material, as in a photovoltaic cell.









Calibration Procedures:

Calibration of displacement transducers involves using a calibrated reference, applying known displacements, and measuring the transducer's corresponding output. The procedure typically includes connecting the transducer to a data acquisition system or multimeter, zeroing the output at the center position, and then moving the core in increments across its full range, recording the output at each step. Finally, a calibration factor is calculated, and the accuracy is validated against a reference to ensure it meets required error tolerances.

General steps for calibration

1. **Setup and connection:**

   Mount the transducer and connect it to the appropriate measurement equipment, such as a data acquisition system or a digital multimeter (DMM).

2. **Apply preload:**

   For mechanical setups, apply a preload to bed the transducer in its mounting to ensure a stable and repeatable connection.

3. **Zero the device:**

   Position the core at the central (zero) position and minimize any residual voltage or offset. Record this as your starting point.

4. **Apply known displacement:**

   Move the core in known increments, using a calibrated reference or a precise mechanical stage, across the entire measurement range.

5. **Record readings:**

   At each displacement step, record the corresponding output from the transducer.

6. **Repeat and validate:**

   Move the core in the opposite direction and repeat the steps, or step down to zero, to ensure symmetry and complete the calibration cycle.

7. **Calculate the calibration factor:**

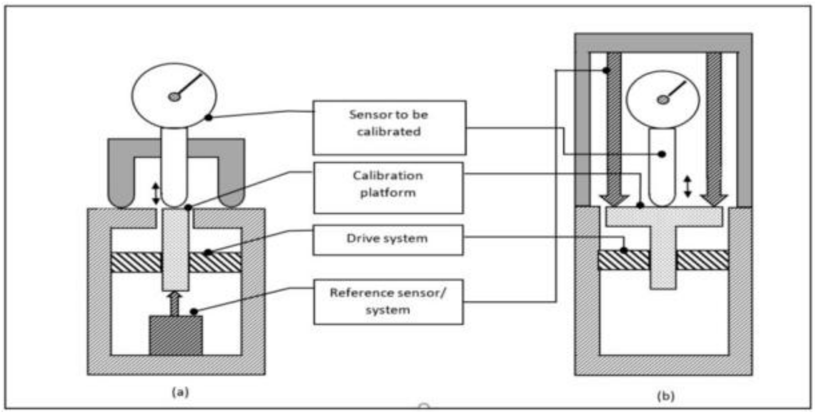
   Determine the relationship between the input displacement and the output signal. This can be done by calculating the slope of the best-fit line through the data points.

8. **Verify accuracy:**

   Compare the data points to the calculated calibration line to check for linearity and non-linearity. A common goal is to achieve an error of less than 1%.

9. **Adjust as necessary:**

   If the error exceeds the acceptable tolerance, readjust the setup and repeat the calibration until the required accuracy is achieved.



The movements of electrons develop the current in the cell, and the current is known as the photoelectric current.

Measurement of Strain: (Electrical Strain Gauges):

Electrical strain gauges can be categorized by their working principle (resistance, capacitance), material (foil, semiconductor, wire), configuration (linear, rosette, shear), and Wheatstone bridge connection (quarter, half, full bridge). Common types include foil strain gauges, which are the most widely used resistance-type, and semiconductor strain gauges, offering higher sensitivity. Strain gauge rosettes are used to measure strain in multiple directions, while bridge configurations like quarter, half, and full bridges are chosen based on the desired accuracy and signal strength.

Here's a breakdown of the different types:

By Working Principle

- **Resistance Strain Gauges:** The most common type, these work by changing their electrical resistance when a strain is applied. They are further divided by their material and construction:
  - **Foil Strain Gauges:** The most widely used type, constructed from thin metal foil in a grid pattern.
  - **Wire Strain Gauges:** An older type consisting of a thin wire grid.
  - **Semiconductor Strain Gauges:** Made from semiconductor materials, these offer much higher sensitivity than metal foil gauges.
- **Capacitance Strain Gauges:** These measure changes in capacitance, which vary with strain.

By Configuration

- **Linear Strain Gauges:** Measure strain in a single direction.
- **Rosette Strain Gauges:** Consist of two or more linear grids arranged at different angles to measure strain in multiple directions simultaneously.
  - **T-Rosette:** Has grids at 90-degree angles.
  - **45° Rosette:** Has grids at 45-degree intervals.
- **Shear Strain Gauges:** Designed to measure shear strain, often V-shaped, with grids oriented for optimal shear measurement.

By Bridge Connection

The configuration of the strain gauges within a Wheatstone bridge determines the output signal and sensitivity.

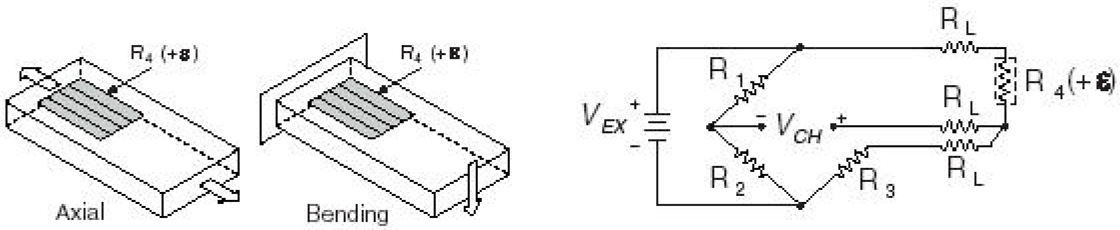
- **Quarter-Bridge:**

  Uses one active strain gauge, resulting in a smaller signal and requiring more sensitive equipment.

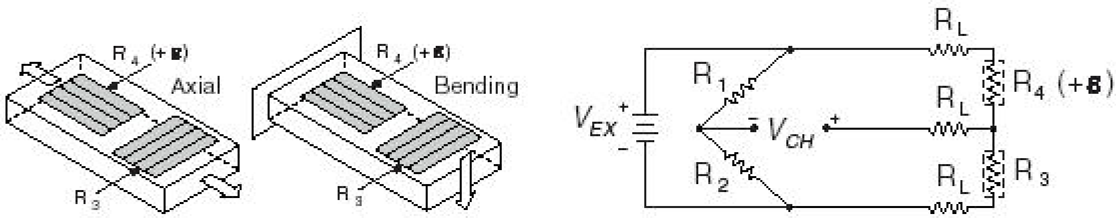
- **Half-Bridge:**

  Uses two active strain gauges, providing more signal output than a quarter-bridge and offering improved linearity and temperature compensation.

- **Full-Bridge:**
  Uses four active strain gauges, providing the highest output and best accuracy, making it ideal for precise measurements.



Quarter Bridge Type I



Quarter Bridge Type II

Gauge Factor (GF):

The gauge factor (GF) is a property of a strain gauge that measures its sensitivity to strain, defined as the ratio of the fractional change in electrical resistance to the fractional change in length (strain). Mathematically, it is expressed as $GF = (\Delta R/R) / (\Delta L/L)$, where ΔR is the change in resistance, R is the original resistance, ΔL is the change in length, and L is the original length (and $\Delta L/L$ is the strain).

Key Aspects of Gauge Factor

- **Sensitivity:**

  A higher gauge factor indicates a greater change in resistance for a given amount of strain, meaning a more sensitive sensor.

- **Components of Resistance Change:**

  The total change in resistance (ΔR) is due to two main factors:

- **Dimensional Effect:** Changes in the length and cross-sectional area of the strain gauge material under stress.
- **Piezoresistive Effect:** Changes in the material's intrinsic resistivity (ρ) due to the applied strain.

Method of Usage of Resistance Strain Gauge For Bending:

To use a strain gauge for bending, attach gauges to opposite sides of the element experiencing bending (one in tension, one in compression) and connect them to a Wheatstone bridge circuit to measure resistance changes caused by the strain. The Wheatstone bridge converts the small, proportional changes in the gauge's resistance into a measurable voltage signal. This voltage is then amplified and recorded by a data acquisition (DAQ) system to determine the bending strain.

Steps to Measure Bending Strain:

1. Surface Preparation:

Clean the surface of the object to be tested.

2. Bonding:

Securely bond the strain gauges to the surface of the object using a specialized adhesive, such as epoxy for long-term use.

3. Placement:

Place a strain gauge on the surface that will be in tension and another on the surface that will be in compression when the element bends. This creates a balanced system that measures bending while canceling out axial strain effects.

4. Wheatstone Bridge Connection:

Connect the active strain gauges into a Wheatstone bridge circuit. This circuit uses the strain gauge's resistance changes to produce a voltage output that is proportional to the strain.

5. Temperature Compensation:

Include a "dummy" strain gauge, also connected to the bridge, in a location where it experiences the same temperature changes as the active gauges but does not undergo strain. This helps to cancel out temperature-induced errors in the measurement.

6. Load Application:

Apply a load to the object to induce bending, causing the object and its bonded strain gauges to deform.

7. Signal Measurement:

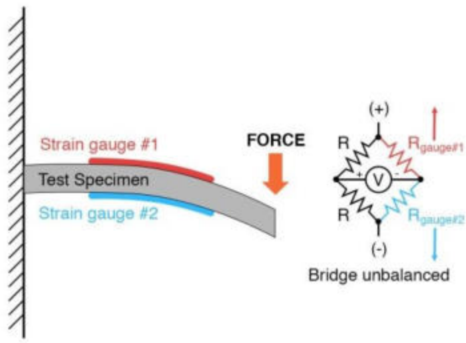
The strain gauge's resistance changes as the object deforms. The Wheatstone bridge converts this resistance change into a voltage signal, which is typically very small (microvolts).

8. Signal Amplification & Processing:

An amplifier increases the small voltage signal, and a data acquisition system (DAQ) digitizes, displays, and records the signal for analysis.

9. Calculation:

The measured voltage is used to calculate the strain, which can then be converted to stress using Hooke's Law if the material's modulus of elasticity is known.



Compressive and Tensile Strains:

Compressive strain occurs when an object decreases in length due to squeezing forces, while tensile strain happens when an object elongates due to pulling forces. Strain, in general, is the ratio of an object's change in dimension to its original dimension. Tensile strain is a positive value representing an increase in length, whereas compressive strain is a negative value indicating a reduction in length.

Compressive Strain

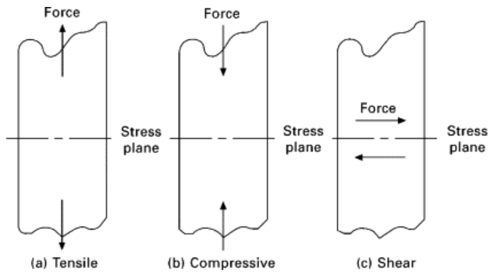
- **Cause:** Occurs when an object is subjected to forces that push or squeeze it, causing it to become more compact.
- **Effect:** Results in a decrease in the object's length or a reduction in its volume.
- **Sign:** Represented by a negative value, as it signifies a decrease in length.
- **Example:** The force applied when a football is kicked, causing it to momentarily shrink, illustrates compressive strain.

Tensile Strain

- **Cause:** Occurs when an object is pulled apart or stretched by forces acting in opposite directions.
- **Effect:** Results in an increase in the object's length.
- **Sign:** Represented by a positive value, indicating an increase in length.
- **Example:** A rubber band being stretched or a wire being pulled until it snaps involves tensile strain.

Key Differences

- **Direction of Force:** Tensile forces pull, while compressive forces push.
- **Effect on Dimension:** Tensile strain causes elongation, and compressive strain causes shortening.
- **Mathematical Sign:** Tensile strain is positive, and compressive strain is negative.



Usage of Strain Gauges For Measuring Torque:

Torque is measured to ensure safety, efficiency, and quality in industries like automotive, aerospace, and manufacturing. Common usages include calibrating torque wrenches for proper tightening of fasteners, testing engine and drivetrain components for performance, monitoring industrial equipment for mechanical failures, and ensuring precision in medical devices. Torque measurements help optimize performance, lower energy consumption, prevent over-tightening, and maintain product reliability.

Applications in various industries

- **Automotive:**

  Measure torque to ensure engine and transmission bolts are properly tightened for safety and performance.
- **Aerospace:**

  Measure torque for critical aircraft components to prevent structural failure due to over-tightening.
- **Manufacturing:**

  Monitor torque in assembly lines to guarantee consistent quality and meet industry standards.
- **Industrial Maintenance:**

  Calibrate torque wrenches and ensure proper assembly of industrial machinery, preventing breakdowns from loose fasteners.
- **Medical Devices:**

Verify torque limits for precision medical instruments and implants, ensuring correct assembly and function.

- **Electromobility:**
  Crucial for improving the efficiency and reliability of electric vehicle drive systems.

  How torque is measured

- **Strain Gauges:**

  Strain gauges are attached to a shaft to detect the slight twist (strain) caused by applied torque.

- **Torque Transducers:**

  These devices use strain gauges or other methods to translate the rotational force into an electrical signal for measurement.

- **Torque Wrenches:**
  A common tool used to apply a specific torque to fasteners like nuts and bolts, preventing over-tightening.

  Key reasons for measuring torque

- **Safety:**

  Prevent catastrophic failures by ensuring parts are tightened to the correct specifications.

- **Efficiency:**

  Optimize the performance of engines, drives, and other systems, leading to lower energy consumption.

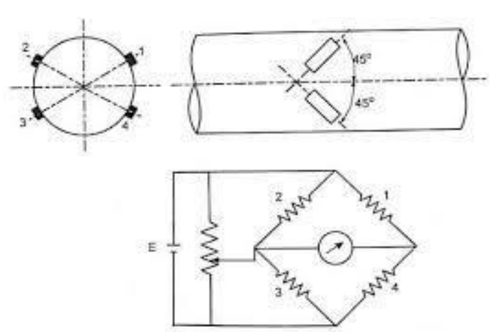
- **Quality Assurance:**

  Maintain consistent product quality in assembly lines and manufacturing processes.

- **Performance Monitoring:**

  Evaluate the performance and efficiency of mechanical systems like pumps, gearboxes, and motors.

- **Preventing Breakdowns:**
  Identify issues with loose fasteners or improper assembly that could lead to mechanical failure.



Strain Gauges arrangement to measure Torque

Strain Gauge Rosettes:

A strain gauge rosette uses multiple strain gauges, typically three, bonded to a surface to measure strain in different directions. When a structure deforms under load, the gauges change their electrical resistance proportionally to the strain experienced, and these resistance changes are measured. Mathematical formulas then use the data from all gauges to calculate the principal strains (maximum and minimum normal strains) and the orientation of the stress or strain field, revealing complex stress patterns that a single gauge couldn't provide.

How a Strain Gauge Rosette Works

1. Bonding: The rosette, a pattern of three individual strain gauges oriented at specific angles (e.g., 0°, 45°, 90°), is bonded to the surface of a component.

2. Deformation: When the component is subjected to a load, it deforms. The strain gauges, being attached to the surface, also deform.

3. Resistance Change: This deformation changes the physical dimensions (length and cross-sectional area) of the strain gauges' electrical conductors. The change in resistance is directly proportional to the amount of strain.

4. Measurement: The strain gauges are connected to a strain indicator, which measures these changes in electrical resistance.

5. Calculation: The electrical resistance readings from each gauge are converted into strain values.

6. Stress/Strain Analysis: Using strain gauge rosette equations, which incorporate the strain values from all three gauges, engineers can determine the principal strains (the maximum and minimum normal strains) and the directions at which they occur, even if the load creates a biaxial stress state.

Why a Rosette is Used

- **Multi axial Stress:** A single strain gauge can only measure strain in one direction (uniaxial).
- **Complex Patterns:** Many real-world applications involve stresses and strains acting in multiple directions simultaneously (biaxial stress state).

- **Comprehensive Data:** A strain rosette provides the necessary data points in different orientations to fully characterize this complex, two-dimensional stress or strain field, providing a complete picture of the material's response to the applied load.

Structure and overview –

A strain gauge rosette is a term for an arrangement of two or more strain gauges that are closely positioned to measure strains along different directions of the component under evaluation. Single strain gauges can effectively measure stress in only one direction, so the use of multiple strain gauges enables more measurements to be taken, allowing a more accurate assessment of surface tension or we can say strain gauge rosettes are used when the direction of the strain in not known or axis of the strain in a component is unknown.

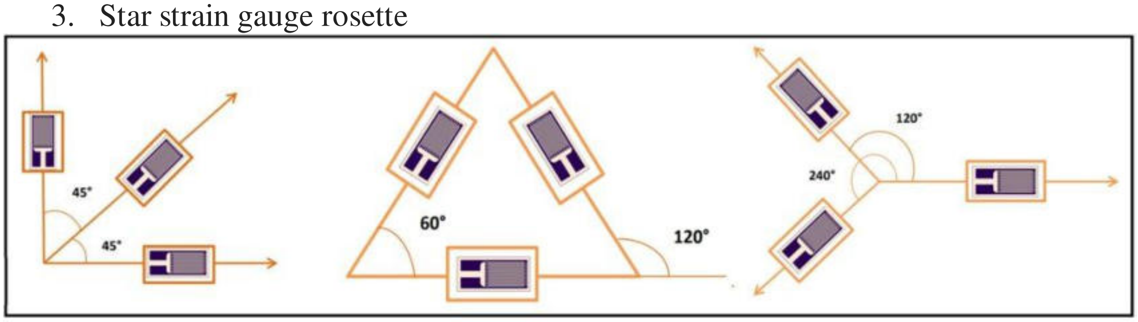
The rosette is designed to be very practical and important work in experimental stress analysis. it can be shown that for the unusual case of the normal biaxial strain states, with unknown principal directions, Three independent tension measurements (in different) direction) are required to determine the dominant strains and emphasizes. and even when the major directions As previously known, two independent strain measurements The major strains and strains are required to be obtained.

Different type of strain gauge rosettes diagram are shown below-

Configuration-

Rosettes are used to determine the absolute deformable position of an object on a surface. The absolute stress state is composed of normal, shear and dominant strains. Depending on the arrangement, strain gauge rosettes are classified in to:-

1. Rectangular strain gauge rosette
2. Delta strain gauge rosette
3. Star strain gauge rosette



Strain Gauge Rosette

Another method of classification can be based on number of strain gauge elements used to design rosette. Such configurations are as follows-

- **Biaxial rosette-**It consists of two gauge element that are mounted perpendicular to each other.

- **Tri-axial rosette-**It is used where three degree measurements are necessary. These gauges are mounted relative to each other at 0°-45°-90° or 0°-60°-120° depending on the measurement requirement.

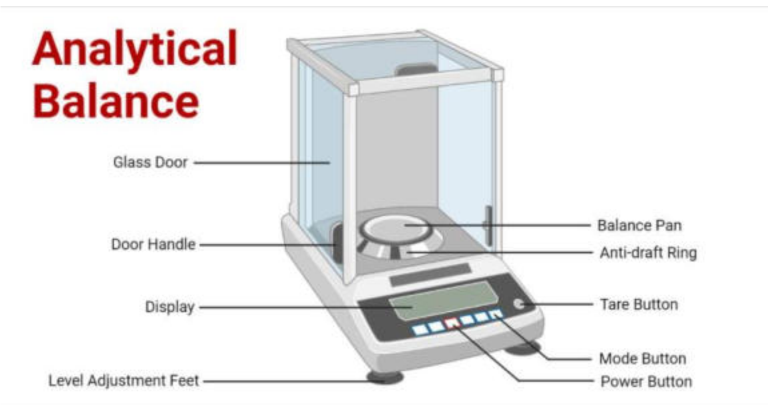
UNIT-5

Measurement of Force: Direct Method – Analytical Balance:

An analytical balance measures force directly by comparing an unknown force (like an unknown push or pull) with the known gravitational force on a standard mass, using the principle of moments. The unknown force is applied to one side of a pivoted beam, and standard masses are added to the other side until the beam is perfectly horizontal, indicating equilibrium and a direct force measurement.

How the measurement is done

- **Set up:** The balance consists of a beam pivoted at its center.
- **Apply unknown force:** An unknown force is applied to one end of the beam.
- **Add standard masses:** Standard masses are placed on the other end of the beam.
- **Achieve balance:** Standard masses are added or removed until the beam becomes perfectly horizontal. This state of equilibrium means the moment created by the unknown force equals the moment created by the standard mass.
- **Direct measurement:** The unknown force is equal to the weight of the standard masses, which is known.
- **Environmental control:** Because analytical balances are sensitive, the weighing pan is typically enclosed in a draft shield to prevent air currents and dust from interfering with the measurement.



PLATFORM BALANCE:

A force plate is used to measure the ground reaction forces and center of pressure (COP) to assess a person's balance and postural control. These platforms can measure a body's weight distribution and movement over time by quantifying the forces and moments of force exerted on the surface. The data collected can be used for static balance assessments (e.g., quiet standing) or dynamic assessments (e.g., walking, jumping).

How it works

- **Measures ground reaction forces**:

According to Newton's third law, the force plate measures the equal and opposite force the ground exerts on a person in contact with it.

- **Measures moments of force**:

More advanced force plates can measure both the force (vertical and horizontal) and the moments (rotational forces) to get a complete picture of the forces and torques acting on the body.

- **Calculates the center of pressure (COP)**:

The platform calculates the COP, which is the point of application for the total ground reaction force vector.

- **Tracks COP movement**:

During a test, the system tracks the movement of the COP over time to provide metrics like velocity, path length, and ellipse area.

Elastic Member- Load Cells:

An elastic member is the core component of a load cell; when a force (load) is applied, this member deforms slightly, and the strain gauges attached to it detect this deformation, which is then converted into an electrical signal to measure the force. The elastic member is a metal bar or beam with a highly repeatable deflection pattern, and the strain gauges are bonded to its surface to measure the stress and strain.

Elastic member and strain gauge in a load cell

- **Elastic member**: This is the transducer's primary part, a precisely machined piece of metal designed to deform predictably under load.

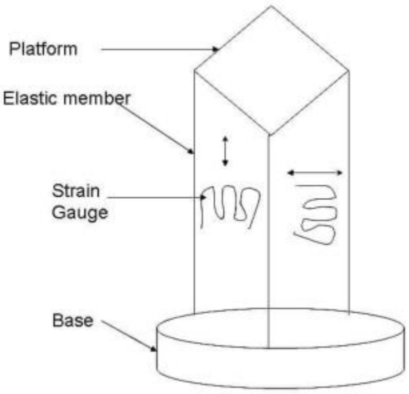
- **Strain gauges**: These are secondary transducers, typically in a Wheatstone bridge configuration, that are bonded to the elastic member.

- **How it works**:

    - When a weight is applied to the load cell, the elastic member deflects.

    - This deflection creates stress at the locations where the strain gauges are bonded.

- The strain gauges either stretch (tension) or compress, which changes their electrical resistance.
- The change in resistance is proportional to the applied force, allowing it to be converted into a precise electrical signal to measure the weight.



Cantilever beams and proving rings.:

Cantilever beams are simple structures fixed at one end, and when a force is applied, they bend, causing strain. Proving ring load cells work by using this principle, where a force deforms a circular ring into an ellipse, which changes the resistance of strain gauges attached to the ring's surface. This change is converted into an electrical signal to measure the load.

Cantilever beam

- A cantilever beam is a rigid structural element, like a beam, that is supported at only one end.
- When a force is applied to the free, unsupported end, the beam bends or deflects.
- This bending creates both tensile (pulling apart) stress on the top surface and compressive (squeezing) stress on the bottom surface.

Proving ring load cell working principle

- **Force application:** A force is applied to the load cell, causing the central, circular ring to deform into an elliptical shape.

- **Strain and resistance:**

Strain gauges are attached to the outer surface of the ring.

As the ring deforms into an ellipse, the outer surface compresses the strain gauges, while the inner surface stretches them.

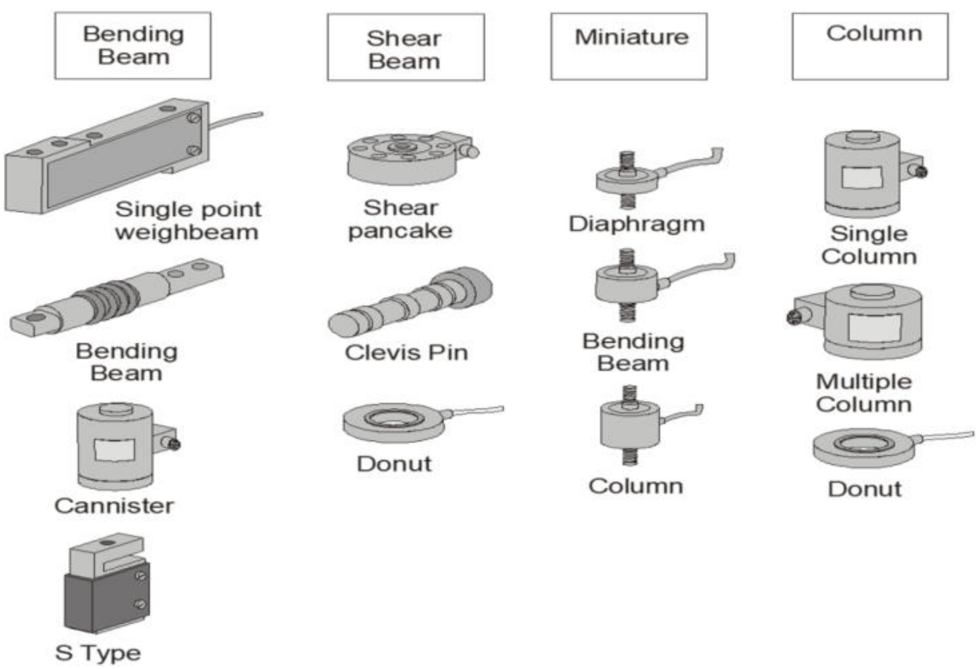
This compression and tension changes the electrical resistance of the strain gauges.

Signal conversion:

The strain gauges are connected in a Wheatstone bridge circuit to measure the change in resistance accurately.

The change in resistance is converted into a usable electrical voltage signal, which is proportional to the applied force.

Measurement: The electrical signal is then amplified and processed to provide a precise reading of the force.



measurement of torque torsion bar dynamometer:

A torsion bar dynamometer works by measuring the angle of twist in a shaft subjected to torque. The working principle is that torque is directly proportional to the angle of twist, which is measured using sensors like strain gauges, optical sensors, or a stroboscope with calibrated scales. The measured angle is then used with the shaft's known material properties and geometry to calculate the applied torque.

Working principle:

Torque and twist: When a torque is applied to a shaft, it causes the shaft to twist along its length. This twist results in an angular displacement between the two ends of the shaft.

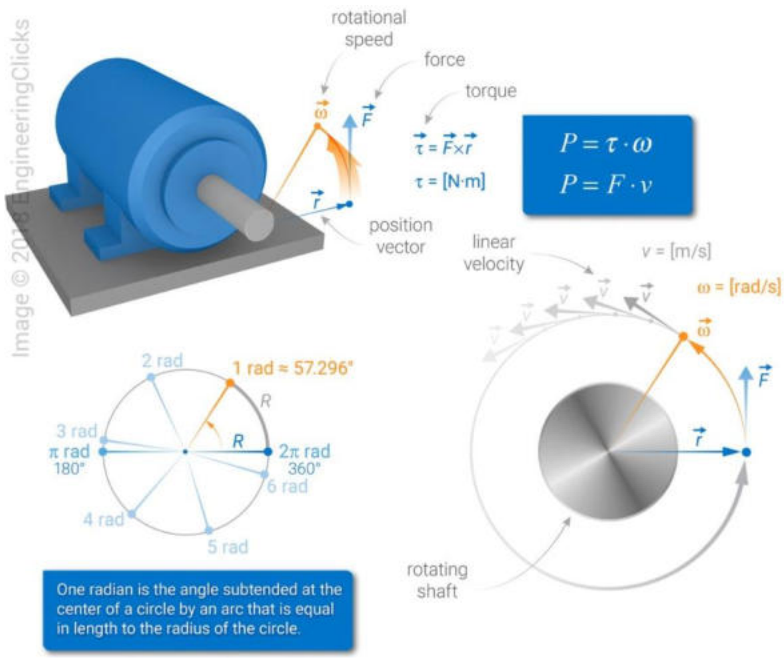
Proportionality: The angle of twist is directly proportional to the applied torque. This relationship is described by the torsion formula, which also incorporates the shaft's material properties (like the modulus of rigidity) and geometry.

Torque measurement: To measure torque, the dynamometer uses sensors to determine this angular displacement.

Sensor types:

- **Strain gauges:** These sensors are attached to the shaft and measure the strain, which is related to the angle of twist.
- **Optical sensors:** Two discs are fixed at a known distance on the shaft. A light source is placed behind one disc, and an eyepiece behind the other. When the shaft twists, the discs are no longer in line, and the light is blocked. The eyepiece is then moved until the light is visible again, and the angular displacement is read from a calibrated scale.
- **Stroboscope:** A stroboscope can be used with the optical method to precisely measure the angle of twist by adjusting the strobe light frequency to create a stationary image of the rotating scale.

- **Calculation:** Once the angle of twist is measured, the torque is calculated using the torsion formula, which relates the torque to the angle of twist, the shaft's polar moment of inertia (J), and the modulus of rigidity (G).



Servo-controlled dynamometer:

A servo-controlled dynamometer uses a closed-loop system to apply a precisely controlled load and measure an engine's torque and rotational speed. The principle involves a servo controller that receives feedback from a position sensor and a load cell (which measures torque) and compares it to a desired set point, sending a control signal to a power absorption unit (like a water brake or electric motor) to adjust the braking load in real-time. This creates a system that can either simulate specific driving conditions or provide a consistent load for testing, with the goal of precisely controlling the engine's performance.

Detailed working principle:

Engine connection: The engine or motor being tested is connected to the dynamometer's roller or shaft.

Load application: A power absorption unit (PAU), such as a water brake, electric motor, or eddy-current brake, is used to apply a load to the engine's shaft.

Torque and speed measurement:

Strain gauges on the dynamometer's frame measure the torque applied to the load cell.

A separate sensor measures the rotational speed (RPM) of the shaft.

Servo control system:

A controller (often using pulse-width modulation (PWM) for a DC servo or a similar method for AC servo) receives the input signals for desired torque and/or speed.

This input is compared to the real-time feedback from the load cell (torque) and the speed sensor.

The servo controller then sends a signal to the PAU to adjust the braking force. For example, it could open a water valve to increase resistance or apply a voltage to an electric motor to increase the load.

Feedback loop: This creates a closed-loop system:

1. The engine provides torque and speed, which are measured.
2. The controller compares these measurements to the target.
3. The controller adjusts the PAU's load to meet the target.
4. This cycle repeats thousands of times per second, allowing for precise control.

An absorption dynamometer measures an engine's power by converting the engine's output into heat using friction, fluid, or electromagnetic means, allowing the absorbed energy to be quantified. Key types include Prony brake dynamometers, rope brake dynamometers, and hydraulic dynamometers, which absorb engine energy and dissipate it as heat through mechanical friction or fluid forces to measure the engine's brake power.

How it Works

1. **Applying Load:** The dynamometer acts as a load on the prime mover (like an engine or motor), creating a resistance against its rotation.

2. **Energy Conversion:** This resistance converts the prime mover's mechanical energy into other forms of energy, primarily heat.

3. **Measurement:** The force and speed at the point of absorption are measured, allowing for the calculation of power.

Types of Absorption Dynamometers

Prony Brake Dynamometer: Uses a band or block to create friction against a rotating flywheel, absorbing power as heat.

Rope Brake Dynamometer: A rope with weights wrapped around the flywheel that creates friction, converting the engine's power into heat.

Hydraulic Dynamometer: Employs an impeller rotating within a casing filled with a fluid, where fluid friction absorbs the power and dissipates the heat through the continuous flow of the fluid.

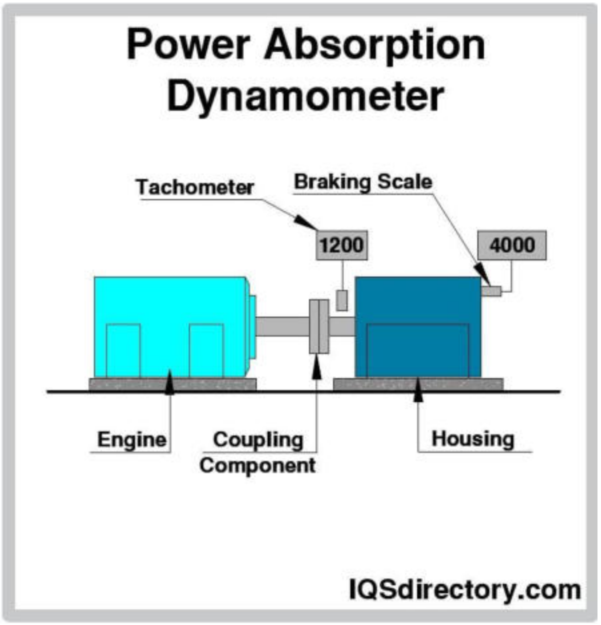
Eddy Current Dynamometer:

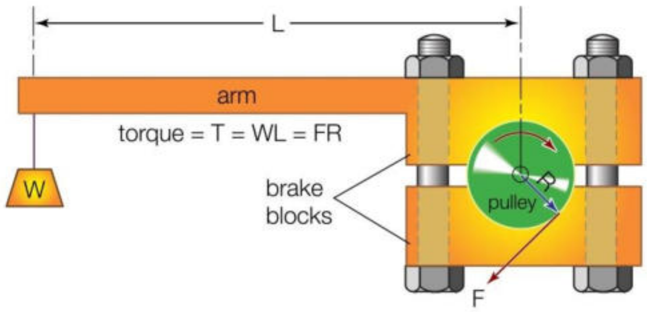
Uses electromagnetic induction to absorb power and convert it into heat, often used in higher power applications.

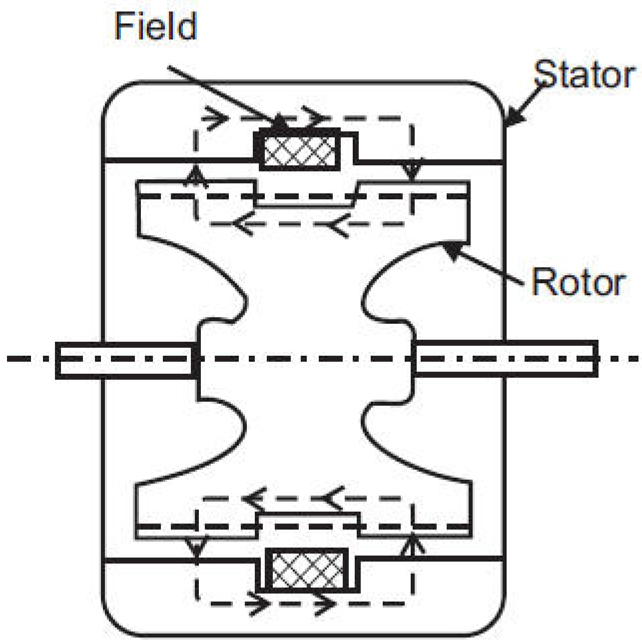
Applications

Absorption dynamometers are used to:

- Determine the brake power of an engine.
- Ensure an engine is capable of powering specific machinery.
- Verify that an engine is operating at its optimal performance.







Measurement of Pressure:

Pressure is measured by determining the force applied over a surface area, typically using devices like manometers and pressure gauges. Common units include the SI unit Pascal (Pa) (N/m^2), pounds per square inch (psi), bar, and atmosphere (atm).

Key concepts

Absolute pressure: The pressure relative to a perfect vacuum.

Gauge pressure: The pressure relative to the local atmospheric pressure. It can be positive (above atmospheric) or negative (below atmospheric, also called vacuum).

Pressure formula: Pressure (P) is calculated as force (F) divided by area (A) P=F/A

Common units of measurement

Pascal (Pa): The SI unit, defined as one Newton per square meter (N/m^2).

Pound per square inch (psi): Commonly used in the U.S. and engineering contexts.

Bar: Used in industry, with 1 bar=100,000 Pa.

Atmosphere (atm): Approximately equal to the average atmospheric pressure at sea level, which is about 101,325 Pa.

Millimeters of mercury (mmHg) / Torr: Often used for blood pressure and vacuum measurements.

Measurement devices and methods

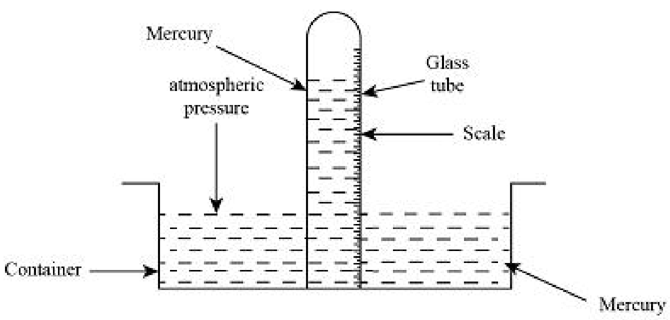
Barometer: Measures atmospheric pressure. A mercury barometer uses the height of a mercury column to measure atmospheric pressure, which is a principle also used in manometers.

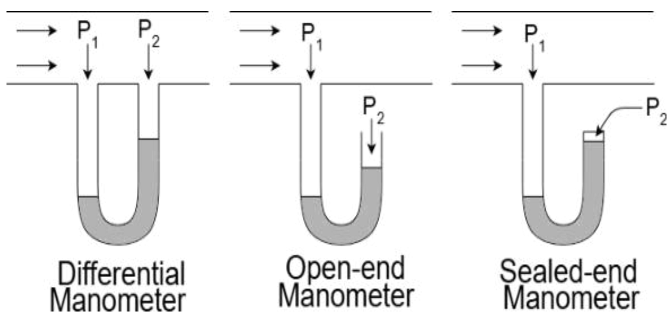
Manometer: A U-shaped tube often containing a liquid like mercury, used to measure pressure differences. The height difference in the liquid indicates the pressure.

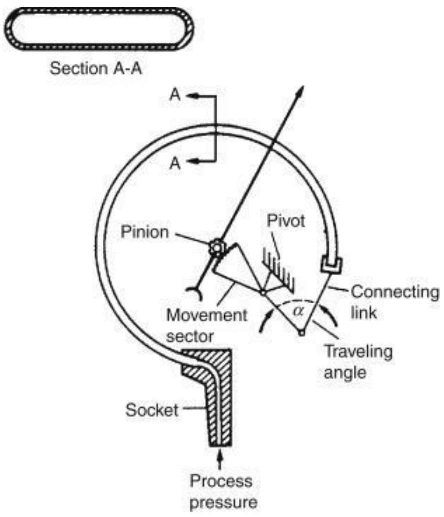
Bourdon tube gauge: A curved tube that straightens as internal pressure increases, moving a pointer on a dial.

Diaphragm gauge: Uses a flexible diaphragm that deflects under pressure. This deflection can be measured electronically, for example, by changes in capacitance or by using a Wheatstone bridge.

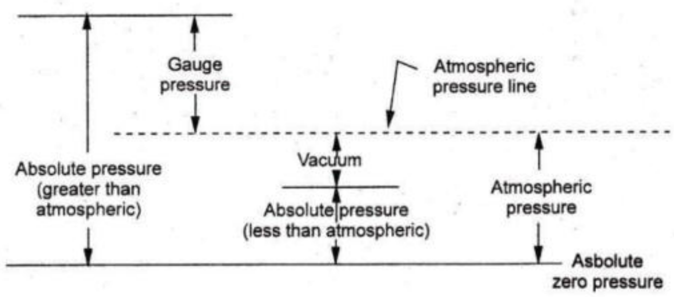
Pitot tube: Measures the pressure of a moving fluid. It can measure static, dynamic, or stagnation pressure depending on the probe's design.







Relation between these pressure terms is illustrated in Fig.



Relation between absolute, gauge and atmospheric pressure

Standards and calibration, basic methods of pressure measurement:

Standards and calibration involve comparing a device under test (DUT) to a more accurate reference standard to verify and adjust its accuracy. Basic pressure measurement methods include using a **deadweight tester**, where a known mass creates a calibrated pressure, or using a **digital pressure calibrator** which compares the DUT's reading to its own highly accurate, pre-calibrated reference.

Standards and calibration:

Calibration process: A common pressure source connects the DUT and a reference standard to compare readings across various pressure points.

Reference standard: This is a highly accurate instrument used as the benchmark for comparison. It should be approximately four times more accurate than the device under test (4:1 accuracy ratio).

Steps: The process includes a visual inspection, an "As Found" test (before adjustment), adjustment if necessary, an "As Left" test to verify accuracy, and documentation of the results.

Traceability: Calibrations are often traced to national metrology institutes like NIST or other governing bodies to ensure quality control and compliance.

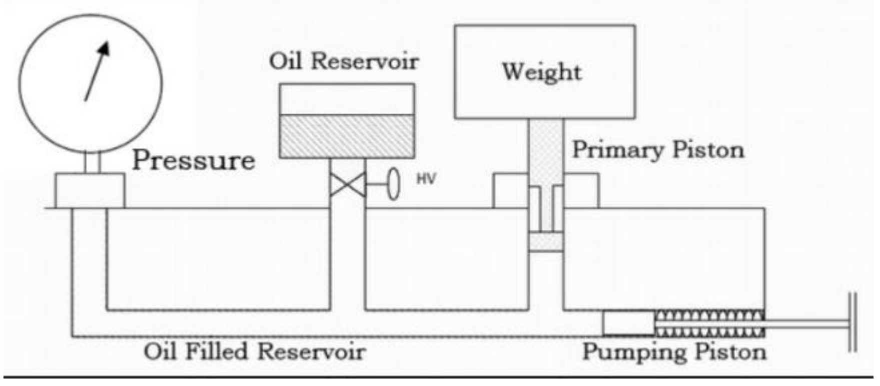
Basic methods of pressure measurement

Deadweight Tester: A primary standard where a known mass is placed on a piston, and the pressure is calculated from the mass and the piston's area.

Digital Pressure Calibrator: A portable and highly accurate device that measures pressure and compares it to the DUT's reading.

Portable calibrators: These devices are used for field calibration and utilize a reference standard that has been previously calibrated (secondary calibration).

Other methods: Calibration can also involve checking the instrument's response to static (steady) and dynamic (changing) pressures, and performing leak tests to ensure there are no leaks or flaws in the connections.



Dead weight gauges and manometers:

Dead weight testers are highly accurate primary standards for pressure calibration, while manometers are simpler devices for measuring fluid pressure by balancing the fluid column against a known reference, such as atmospheric pressure. Dead weight testers use precisely measured weights on a piston to create a known pressure ($P=F/A$), making them ideal for calibrating other instruments, while manometers typically use a U-shaped tube with a liquid to show pressure differences.

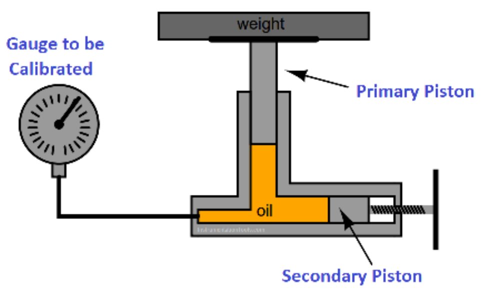
Dead weight gauges (or testers)

- **What they are:** Precision instruments that act as a primary standard for pressure measurement and calibration.

- **How they work:** A known force from a set of weights is applied to a piston of a known cross-sectional area. The resulting pressure is calculated as force divided by area ($P=F/A$).
- **Key features:**
  - Extremely high accuracy (often within 0.05% to 0.1% of reading).
  - Used to calibrate other pressure-measuring devices like gauges, sensors, and transmitters.
  - Offers high accuracy and repeatability.

Manometers

- **What they are:** Simple devices used to measure the pressure of a fluid.
- **How they work:** They work by balancing the pressure of the fluid being measured against a known pressure (often atmospheric) using a column of liquid in a U-shaped tube.
- **Key features:**
  - Used to measure gas or liquid pressure, vacuum, and differential pressure.
  - Accuracy is typically lower than dead weight testers and can be affected by factors like liquid type, temperature, and scale readability.
  - Sufficient for low- to medium-precision applications.



<u>High and low pressure measurement:</u>

High and low pressure are measured using various instruments and conventions, with low-pressure gauges often sensitive to below atmospheric pressure and high-pressure gauges for pressures above 100 atm. For atmospheric pressure, a reading below 29.80 in Hg is considered low, while higher readings are high pressure, and instruments like barometers measure these systems, which relate to different weather patterns. Differential pressure transmitters, in industrial contexts, measure the difference between two pressure points, using "high" and "low" sides to define their input.

For atmospheric and weather systems

- **Barometers:** Used to measure atmospheric pressure.

- **Low pressure:** A reading below 29.80 in Hg (or 1009.144mb) is generally considered low. Low pressure is associated with rising air, clouds, and precipitation.
- **High pressure:** Readings above 29.80 in Hg are considered high pressure, which is associated with descending air, clear skies, and dry weather.
- **Isobars:** Lines on a weather map connecting points of equal atmospheric pressure.

For industrial and scientific applications

- **Low-pressure gauges:**
  - Measure pressures below atmospheric pressure, sometimes down to 100 atm or even lower.
  - Used in vacuum systems.
  - Can use sensitive sensors, like those in a diaphragm gauge, which uses the deflection of a thin membrane to indicate pressure.
- **High-pressure gauges:**
  - Used for pressures above 100 atm.
  - Examples include Bourdon gauges, which use a curved tube that straightens under pressure, or piston gauges for very high pressures.
- **Differential pressure transmitters:**
  - Measure the difference between two points.
  - Have a "high" and a "low" side connection.
  - The output is based on the pressure difference between the two points, not the absolute pressure of either.

Common pressure units

- **Atmospheric pressure:**
  - Inches of mercury (inHg)
  - Millibars (mb)
- **General:**
  - Pounds per square inch (psi)
  - Pascals (Pa)

Elastic transducers:

Elastic transducers convert a physical force like pressure into an electrical signal by using an elastic sensing element to create a mechanical displacement, which is then converted into an electrical output. Common elastic elements include Bourdon tubes, diaphragms, and bellows, which deform or move under pressure, and this movement can be used with secondary components like strain gauges or other sensing mechanisms to generate an electrical signal.

How they work

- **Initial conversion:** An elastic element, such as a diaphragm, bellows, or Bourdon tube, acts as the primary sensing component.
- **Mechanical displacement:** When a force, like pressure, is applied, the elastic element deforms, bends, or moves.
- **Secondary conversion:** This mechanical displacement is then converted into an electrical signal. This can be done through various methods, such as:
  - **Strain gauges:** Attached to the elastic element to measure the physical strain caused by the displacement.
  - **Capacitance or inductance changes:** The movement of the element changes the capacitance or inductance of a circuit, which is then measured.
  - **Direct physical reading:** In some cases, the mechanical movement is linked directly to a physical dial or pointer.

Examples of elastic elements

- **Bourdon tubes:** A curved metal tube that tends to straighten when pressurized, causing its free end to move.
- **Diaphragms:** A thin, flexible metal plate that deflects under pressure.

Bellows: A corrugated metal cylinder that expands or contracts axially with changes in pressure.

Elastic Diaphragm Gauge