THERE IS MEASURE IN ALL THINGS.

HORACE
SATIRES, BOOK I, 35 B.C.

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Metrology

Metrology is presented in the following major topic areas:

- **Introduction**
- **Common Gauges & Instruments**
- **Special Gauges & Applications**
- **Gauge Selection, Handling, & Use**
- **Surface Plate Tools and Techniques**
- **Specialized Inspection Equipment**

Common Gauges & Measuring Instruments is divided into the following subject areas:

- **Variable Gauges**
- **Attribute Gauges**
- **Transfer Gauges**
- **Measurement Scales**

Introduction

Metrology is the science of measurement. The word metrology derives from two Greek words: matron (meaning measure) and logos (meaning logic). With today's sophisticated industrial climate the measurement and control of products and processes are critical. Metrology encompasses the following key elements:

- **The establishment of measurement standards that are both internationally accepted and definable**

- **The use of measuring equipment to correlate the extent that product and process data conforms to specification (expressed in recognizable measurement standard terms)**

- **The regular calibration of measuring equipment, traceable to established international standards**

The terms measuring tool and measuring instrument are used interchangeably in this text. Some commonly used measuring tools are described in summary form only. The reader is advised to seek other sources, Griffith (2003)[13], Farago (1982)[10] and Kennedy (1987)[20], for a more in-depth treatment of specific instruments.

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Variable Gauges

Variable measuring instruments provide a physical measured dimension. Examples of variable instruments are line rules, vernier calipers, micrometers, depth indicators, runout indicators, etc. Variable information provides a measure of the extent that a product is good or bad, relative to specifications. Variable data is often useful for process capability determination and may be monitored via control charts.

Linear Scales

The steel rule and gage blocks are examples of linear scales. A linear scale, for example a ruler, is a scale with equal divisions for equal values.

The Steel Rule

The steel rule is a linear scale which is widely used factory measuring tool for direct length measurement. Steel rules and tapes are available in different degrees of accuracy and are typically graduated on both edges. See Figure 3.1 below.

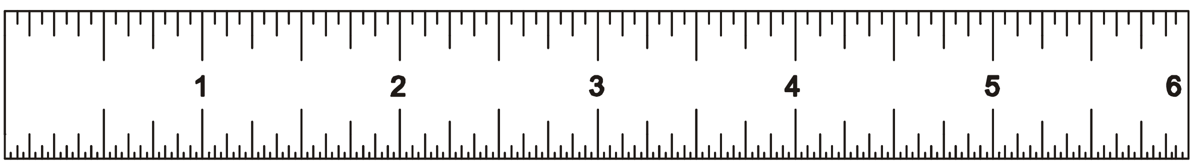


Figure 3.1 A Typical Steel Rule

The fine divisions on a steel rule (thirty-seconds on the one above) establish its discrimination. The steel rule typically has discriminations of 1/32, 1/64, or 1/100 of an inch. Obviously, measurements requiring accuracies of 0.01" or finer should be performed with other tools (such as a digital caliper).

For maximum accuracy, the rule should measure a part with both butted firmly against a rigid flat surface. The end of a rule may be worn, rounded or damaged which produce errors in measurement. If a flat surface is not available the 1" mark may be used as a reference point.

The Steel Rule (Continued)

Figure 3.2 below shows the correct and incorrect methods of measurement.

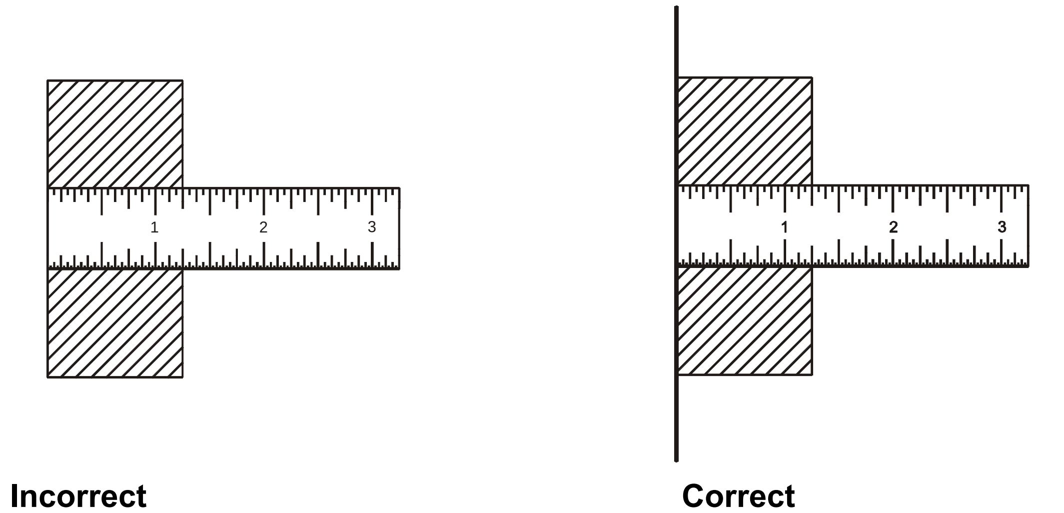


Figure 3.2 Use of a Flat Surface with a Steel Rule

Hook Rules

Steel rules may be purchased with a moveable bar or hook on the zero end which serves in the place of a butt plate. These rulers may be used to measure around rounded, chamfered or beveled part corners. The hook attachment becomes relied upon as a fixed reference. However, by its inherent design, it may loosen or become worn. The hook should be checked often for accuracy.

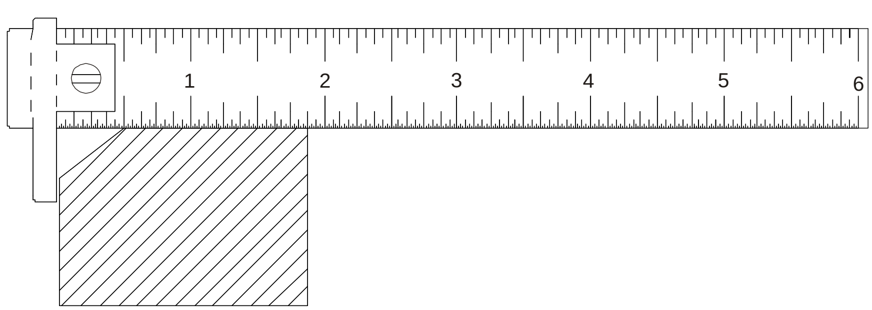


Figure 3.3 Steel Rule with Hook Attachment

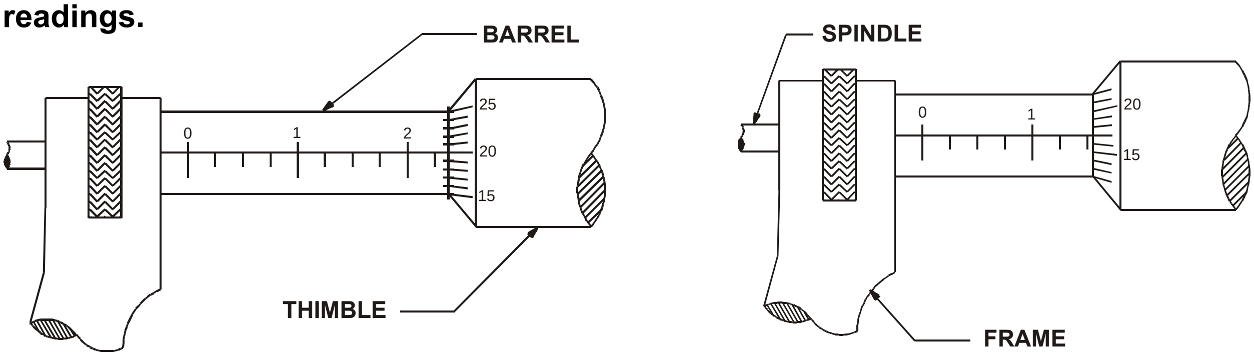
Micrometers

Micrometers, or "mics," are commonly used hand-held measuring devices. Micrometers may be purchased with frame sizes from 0.5 inches to 48 inches. Normally, the spindle gap and design permits a 1" reading span. Thus, a 2" micrometer would allow readings from 1" to 2". Most common "mics" have an accuracy of 0.001". With the addition of a vernier scale, an accuracy of 0.0001" can be obtained. Fairly recent digital micrometers can be read to 50 millionths of an inch.

Micrometers consist of a basic C frame with the part measurement occurring between a fixed anvil and a moveable spindle. Measurement readings on a traditional micrometer are made at the barrel and thimble interface. Micrometers may make inside, outside, depth or thread measurements based upon the customization desired.

The two primary scales for reading a micrometer are the sleeve scale and the thimble scale. Most micrometers have a 1" "throat." All conventional micrometers have 40 markings on the barrel consisting of 0.025" each. The 0.100", 0.200", 0.300", etc. markings are highlighted. The thimble is graduated into 25 markings of 0.001" each. Thus, one full revolution of the thimble represents 0.025".

Shown, in the diagrams below, are simplified examples of typical micrometer readings.



Micrometer set at 0.245"	Micrometer set at 0.167"
0.200"	0.100"
+0.025"	+0.050"
+0.020"	+0.017"
0.245"	+0.167"

Figure 3.4 Two Micrometer Reading Examples

Three-Wire Method of Measuring Pitch Diameter

In order to determine the pitch diameter of screw threads by measuring the corresponding over-wire size, the most practical procedure is the use of three wires, actually small hardened steel cylinders, placed in the thread groove, two on one side and one on the opposite side of the screw. The arrangement of the wires, as indicated in the diagram (below), permits the opposite sensing elements of a length-measuring instrument to be brought into simultaneous contact with all three wires, thus providing a dependable measurement of the over-wire distance.

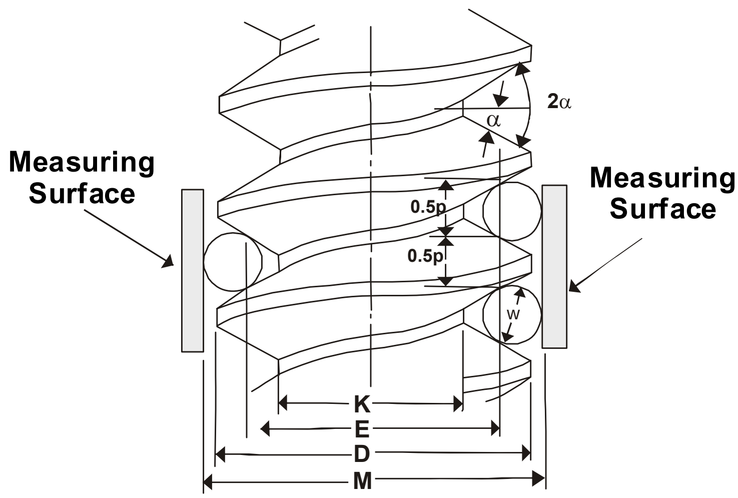


Figure 3.5 An Illustration of Three Wire Measurement

Measuring wires in sets of equal size within a certain diameter range may be used, as long as the wires have a minimum diameter which projects over the crest of the thread, when in measuring position, and a maximum diameter which permits the wires to touch the flanks just below the crest. However, the use of "best-size" wires is recommended. The best wire size may be calculated by:

$$w = 0.5p \sec \alpha$$

Where: w = wire diameter
α = 1/2 the included thread angle
p = thread pitch

For a 60° thread, the above formula reduces to:

$$w = 0.57735\ p$$

$$p = \text{the thread pitch} = \frac{1\ \text{inch}}{\text{no. of threads/inch}}$$

Three-Wire Method (Continued)

The formula to calculate the pitch diameter after measurement is:

$$E = M + (0.86603p) - 3W$$

Where:

E =	pitch diameter	p =	thread pitch
M =	over the wire measurement	W =	wire size used

Example 3.1: Assume that M is 0.360", p is 0.050" and W is 0.030". Calculate the pitch diameter.

$$E = M + (0.86603p) - 3W$$
$$E = 0.360 + (0.86603 \times 0.050) - 3(0.030)$$
$$E = 0.360 + 0.0433 - 0.090$$
$$E = 0.3133 \text{ inch}$$

E is the pitch diameter which must be checked with the tolerance limits on the drawing to determine if the part is acceptable.

Gage Blocks

Near the beginning of the 20th century, Carl Johansson of Sweden, developed steel blocks to an accuracy believed impossible by many others at that time. His objective was to establish a measurement standard that not only would duplicate national standards, but also could be used in any shop. He was able to build gage blocks to an accuracy within a few millionths of an inch. When first introduced, gage blocks or “Jo” blocks as they are popularly known in the shop, were a great novelty. Seldom used for measurements, they were kept locked up and were only brought out to impress visitors.

Today gage blocks are used in almost every shop manufacturing a product requiring mechanical inspection. They are used to set a length dimension for a transfer measurement, and for calibration of a number of other tools.

ANSI/ASME B89.1.9 (2002)[2], *Gage Blocks*, distinguishes three basic gage block forms - rectangular, square and round. The rectangular and square varieties are in much wider usage. Generally, gage blocks are made from high carbon or chromium alloyed steel, however tungsten carbide, chromium carbide, and fused quartz are also used.

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Gage Blocks (Continued)

All gage blocks are manufactured with tight tolerances on flatness, parallelism and surface smoothness. Gage blocks may be purchased in 4 standard grades:

Federal Accuracy Grades		Accuracy In Length *
New Designation	Old Designation	
0.5	AAA	± 0.000001
1	AA	± 0.000002
2	A+	+ 0.000004 - 0.000002
3	A & B	+ 0.000008 - 0.000004

* Applies to gage blocks up to 1". The accuracy tolerance then increases as the gage block size increases.

Master blocks are grade 0.5 or 1
Inspection blocks are grade 1 or 2
Working blocks are grade 3

Table 3.6 Gage Block Grades

Gage blocks should always be handled on the non-polished sides. Blocks should be cleaned prior to stacking with filtered kerosene, benzene or carbon tetrachloride. A soft clean cloth or chamois should be used. A light residual oil film must remain on blocks for wringing purposes.

Block stacks are assembled by a wringing process which attaches the blocks by a combination of molecular attraction and the adhesive effect of a very thin oil film. Air between the block boundaries is squeezed out. The sequential steps for the wringing of rectangular blocks is shown below. Light pressure is used throughout the process.

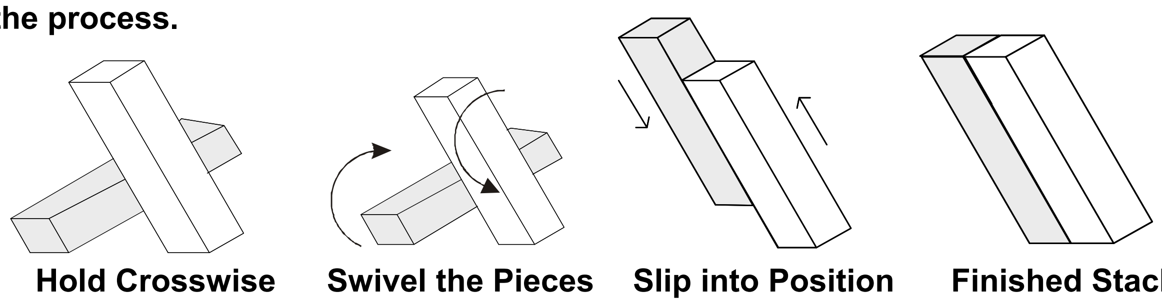

Figure 3.7 Illustration of the Wringing of Gage Blocks

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Gage Blocks (Continued)

Wear Blocks

For the purpose of stack protection, some gage manufactures provide wear blocks. Typically, these blocks are 0.050 inch or 0.100 inch thick. They are wrung onto each end of the gage stack and must be calculated as part of the stack height. Since wear blocks "wear" they should always be used with the same side out.

Gage Block Sets

Individual gage blocks may be purchased up to 20" in size. Naturally, the length tolerance of the gage blocks increases as the size increases. Typical gage block sets vary from 8 to 81 pieces based upon the needed application.

Listed below are the contents of a typical 81 piece set:

Ten-thousands blocks	(9)	0.1001, 0.1002 ... 0.1009
One-thousands blocks	(49)	0.101, 0.102 ... 0.149
Fifty-thousands blocks	(19)	0.050, 0.100 ... 0.950
One inch blocks	(4)	1.000, 2.000, 3.000, 4.000

Also included in the set, are two wear blocks that are either 0.050" or 0.100" in thickness.

Minimum Stacking

A minimum number of blocks in a stack lessens the chance of unevenness at the block surfaces. Stack up 2.5834" using a minimum number of blocks:

2.5834	
- 0.1004	(use 0.1004" block)
2.483	
- 0.133	(use 0.133" block)
2.350	
- 0.350	(use 0.350" block)
2.000	(use 2.000" block)

This example requires a minimum of four blocks and does not consider the use of wear blocks.

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Dial Indicators

Dial indicators are mechanical instruments for measuring distance variations. Most dial indicators amplify a contact point reading by use of an internal gear train mechanism. The standard nomenclature for dial indicator components is shown in the diagram below:

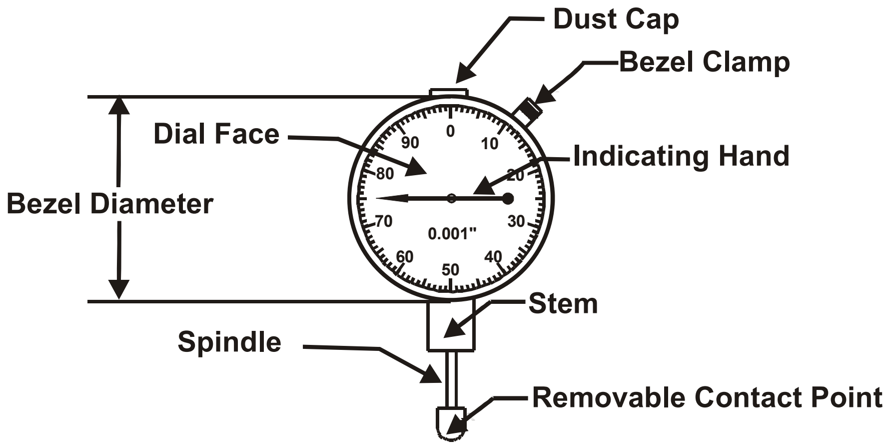

Figure 3.8 Representation of a Continuous Dial with 0.001" Graduations

The vertical or horizontal displacement of a spindle with a removable contact tip is transferred to a dial face. The measurement is identified via use of an indicating hand. See the illustration below:

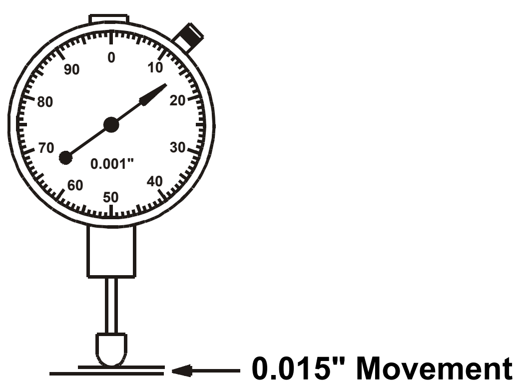

Figure 3.9 Illustration of Dial Indicator Movement

Commonly available indicators have discriminations (smallest graduations) from 0.00002" to 0.001" with a wide assortment of measuring ranges.

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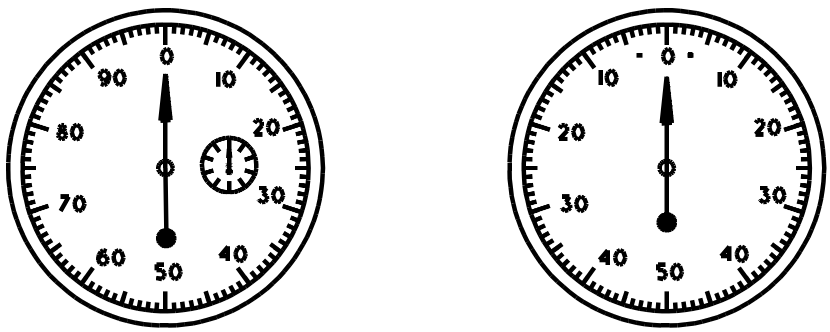
Dial Indicators (Continued)

As indicated earlier, dial indicators are available in a variety of measurement ranges and graduations. Thus, the proper dial must be selected for the length measurement and required discrimination.

Dial indicators also come with balanced or continuous dials. Shown below are examples of both.



Continuous Dial
With Revolution Counter

Balanced Dial

Figure 3.10 Comparison of Continuous and Balanced Dials

Continuous dials feature a continuous number sequence, usually in the clockwise direction. This arrangement is favorable for linear measurements. Balanced dials have a plus (+) and minus (-) direction and are useful in the measurement of bilateral tolerances. Most dials have revolution counters in case the measurement exceeds the total dial face scale.

Most indicators also have an over-travel feature, usually at the 9 o'clock position. When an indicator is moved into position for measurement, it is so located that the hand moves up to the 12 o'clock position.

Contact Tips

Contact points are available in a variety of shapes (standard, tapered, button, flat, wide-face, etc.). The tips are made from a number of wear resistant materials (carbide, chrome plated steel, sapphire or diamond).

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Temperature Probes

There are many measurement devices which can be used to measure temperature. Pyrometers and thermocouples are also discussed later in this Section. Some of the key types are:

- **<u>Pyrometer:</u> A pyrometer is an instrument used for measuring high temperatures. The two main types of pyrometers are a thermocouple with a temperature display and an optical pyrometer, which measures temperature based on the black body color emitted from heated objects, which is a function of temperature.**

- **<u>Thermocouple:</u> Thermocouples consist of two different metal wires, which are joined at one end and connected to a specialized voltmeter at the other. The difference in temperature between the two ends creates a small electromotive force (emf), in the millivolt range. Various metals produce different voltages, which then indicates the temperature.**

- **<u>NTC thermistor:</u> NTC (negative temperature coefficient) thermistor is a temperature sensor that uses the resistance properties of ceramic/metal composites to measure the temperature. They offer many advantages in temperature sensing including miniature size, excellent long-term stability, high accuracy and precision.**

- **<u>RTD sensor:</u> Resistance temperature detectors (RTDs) consist of a fine wire wrapped around a ceramic or glass core. The RTD wire is usually a pure material, for example platinum, nickel, or copper, with an accurate resistance and temperature relationship which is used to determine the temperature.**

- **<u>Thermopile:</u> Thermopile infrared (IR) sensors are designed to measure temperature from a distance by detecting an object's infrared (IR) energy. The higher the temperature, the more IR energy is emitted. The thermopile sensing element is composed of small thermocouples on a silicon chip, and absorbs the energy and produces an output signal. A reference sensor is designed into the package as a reference for compensation.**

(TE Connectivity, 2018)[33]

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Borescopes

Borescopes are optical devices used for visual inspection in inaccessible areas. These devices consist of a rigid or flexible tubes with an eyepiece on one end and an objective lens on the other. They are linked by a relaying optical system.

Borescopes can be used visually or may be fitted with imaging or video devices. Borescopes are commonly used for the visual inspection of gas turbines, diesel engines, and aircraft engines. They assist in the viewing and safety maintenance of many other expensive components.

Thermometers

Thermometers measure temperature or temperature gradients. They can display results in degrees Fahrenheit, degrees Celsius, or degrees Kelvin. A thermometer consists of a temperature sensor (such as mercury in glass display) and some means of converting any change into a numeric value (such as the scale on that display). There are also infrared models that provide digital readouts.

Coordinate Measuring Machines (CMMs)

A coordinate measuring machine (CMM) is used for dimensional measurements in three dimensions. The CMM has three basic directions of movement, the X, Y and Z axes. The Z axis is vertical, the X axis is horizontal left to right, and the Y axis is horizontal front to back. In some cases, the X and Y axes are reversed. Some machines also have a W axis, which is rotational. The base of the CMM is comprised of a surface plate. Workpieces are placed on the surface plate and a stylus is maneuvered to various contact points to send an electronic signal back to the computer that is recording the measurements. CMMs are linked via computers and are known for their volumetric accuracy.

CMMs are touted for their strengths for linear data measurements. There have been discussions concerned with the mathematical formulas used to project geometric characteristics such as flatness and parallelism. The issue is the inability of the mathematical formulas to reproduce the same reading repetitively.

CMMs can be driven by the computer to measure complex workpieces. This lends itself to the automation of the inspection of many complex shapes that would take several hours to lay out by hand.

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