A COURSE IN ENGINEERING METROLOGY

University of Technology
Department of production engineering & Metallurgy
Industrial engineering branch

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Third year

INTRODUCTION

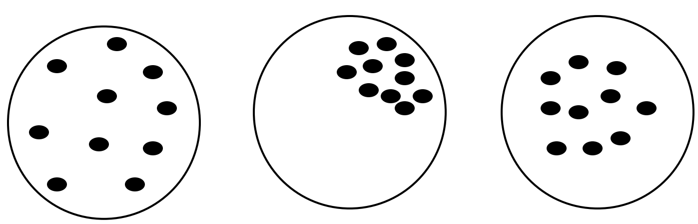
Metrology: The science of measurement. The purpose of this discipline is to establish means of determining physical quantities, such as dimensions, temperature, force, etc.

Or, *the design of comparison process for measurements.*

- ❖ Derived from the Greek word for Measure.
- ❖ It is well-known saying that the knowledge about anything is complete only when it can be expressed in numbers and something is known about it.
- ❖ For every kind of quantity measured, there must be a ***unit*** to measure it and express it in numbers of that unit.
- ❖ There must be a ***universal standard*** and the various units for various parameters of importance must be standardized.
- ❖ Most important parameter in metrology (for production engineers) is the **(Length)** which can be measured in several ways.
- ❖ Other important parameters in **Metrology** are the Time, Mass, Force, Temperature, the flow of an electric current, Angle and so on. or the effects of some of these in combination.
- ❖ The results obtained by measurements provide information upon which decision are made. The purpose of any measurement is to provide a service to enable a decision to be made. The service will not be complete unless the measurement is made to an acceptable degree of accuracy, but it must be realized that no measurement is exact.
- ❖ Thus, **Metrology** is the science of measurement, and measurement is the language of science. It is language we use to communicate about size, quantity, position, condition and time.
- ❖ The metrologist has to understand the underlying principles to be able to design and develop new instruments and also to use the available instruments in the best ways. Metrology is therefore also concerned with the methods, execution and estimation of accuracy of measurements.
- ❖ Thus, it can be said that metrology is mainly concerned with:
    - ➢ Establishing the units of measurements, reproducing these units in the form of standards and ensuring the uniformity of measurements.
    - ➢ Developing methods of measurement.
    - ➢ Analyzing the accuracy of methods of measurement, establishing uncertainty of measurement, researching the causes of measuring errors and eliminating them.
- ❖ Metrological activities start from establishment of measurement standards, appraisal of various physical parameters including dimensions, development of measuring instruments and techniques, and calibration of test and measurement equipments. All this is essential for correct operative measurement for quality and products and services delivered by the industry. Present day industry demands not only one time achievability, but aims for conformity(تطباق) involving such aspects as repeatability, reproducibility, interchangeability, of very many dimensions and characteristics and evidence thereof, for confidence of both producers and customers. This is possible by creation of standards and measurement techniques.
- ❖ Due to mass production, it can be very easily realized that it is not possible to measure the various elements of a component by conventional methods. Thus, other devices, i.e. gauges and comparators are necessary

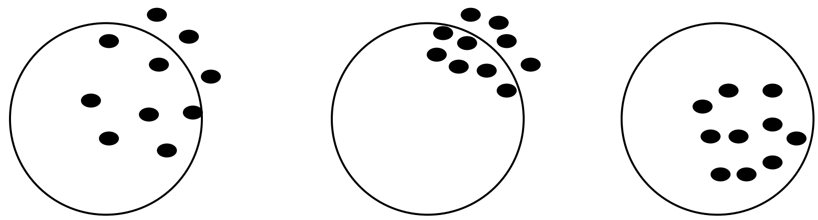
DEFINITIONS

1. **Measurement** - The determination of an unknown dimension. This requires that known standards be used directly or indirectly for comparison.
2. **Basic Dimension** - The target dimension for a part. This typically has an associated tolerance.
3. **Tolerance** - The allowable variation in a basic dimension before a part is considered unacceptable
4. **Dimension** - A size of a feature, either measured, or specified.
5. **Dimensional Metrology** - The use of instruments to determine object sizes shapes, form, etc.
6. **Limits** - These typically define a dimensional range that a measurement can be expected to fall within.
7. **Accuracy** - The expected ability for a system to discriminate between two settings. It is comparison of desired results with undesired results.
8. **Precision** - Implies a high degree of accuracy. It is the measure of the dispersion of the results.
9. **Repeatability** - Imperfections in mechanical systems can mean that during a Mechanical cycle, a process does not stop at the same location, or move through the same spot each time. The variation range is referred to as repeatability.
10. **Standards** - a known set of dimensions, or ideals to compare others against.
    - Standards are the basis for all modern accuracy. As new methods are found to make more accurate standards, the level of accuracy possible in copies of the standard increase, and so on.
    - A well known metric standard is the metric 1m rod.
    - Many standards are available for measuring, and many techniques are available for comparison.
11. **Standard Sizes** - a component, or a dimension that is chosen from a table of standard sizes/forms.
12. **Reliability of measurement-** It is a quantitative characteristic which implies confidence in the measured results depending on whether or not the frequency distribution characteristics of their deviations from the true values of the corresponding quantities are known. It is the probability that the results will be predicted.



	A	B	C
Score:	**10**	**10**	**10**

Which of these targets represents accurate shooting? Precise shooting? Reliable shooting?



A **B** **C**

Score: 7 6 10

A change in one variable, such as wind, alters the results as shown. Dose this show which shooting was the most reliable?

<u>Types of error:</u>

Generally the errors incurred in any measurement can be considered to be of two distinct types, those which should not occur and can be eliminated by careful work and attention to detail, and those which are inherent in the measuring process.

I. Errors Which Can Be Largely Eliminated

1. Calamitous or Catastrophic Errors

These are errors of large magnitude having two fundamental causes:

(a) Misreading an instrument. *A* micrometer is misread as 6•28 mm or 5•78 mm instead of the correct reading of 5•28 mm.

(b) Arithmetic errors. These are usually errors of addition. A simple check is to make the calculation twice using different methods, e.g. add a column of figures twice, first upwards then downwards, to ensure that the two results coincide.

In most cases such errors give a result so different from that expected that it is obvious when an error has occurred, and the measurement is repeated and the error detected. This may not always be so, however, and such errors can only be avoided by care and attention to detail.

2. Alignment Errors

This type of error occurs when the measuring instrument is misaligned relative to the work piece. It usually results in the measured dimension ***M*** being related to the actual dimension ***D*** by one of the trigonometrical ratios. Hence such errors are known as trigonometrical or cosine errors. A simple example is shown in Fig. 1.1, where a dial gauge is inclined at angle θ to the required line of measurement. It can be seen that $D = M \cos \theta$.

Another form of this error is parallax, where the line of sight is not normal to the instrument scale.

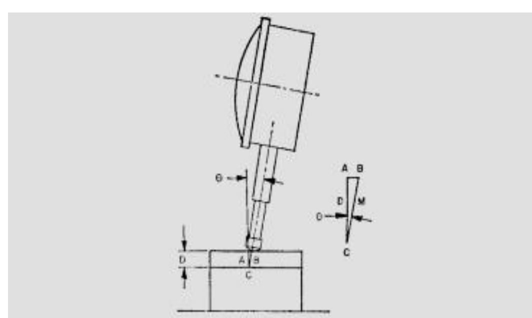


Fig. 1.1. Cosine error due to misalignment of measuring instrument.

3. Errors Due to Ambient Conditions

Most measurements are affected to a greater or lesser extent by the environment in which they are carried out. The most important condition is the temperature, both of the work piece and of its surroundings. The international standard temperature of measurement is **20**°C (68°F) and the ambient temperature should be maintained at this level. However carefully this is controlled, it is to no avail if the temperature of the work piece is allowed to vary. Handling a gauge changes its temperature, so it should be handled as little as possible, and having been handled, allowed stabilizing. Where measurements are being made to a high order of accuracy a time of **20** minutes per **25** mm length of gauge is recommended. During a measurement it is best if all of the components used are left standing on a cast iron surface plate rather than a plastic or wooden bench top. The cast iron, being a good conductor, acts as a heat sink and dissipates temperature differentials more rapidly.

There are two situations to be considered when the effects of temperature are to be discussed:

(a) Direct measurement. Consider a gauge block being measured directly by interferometry. Here the effect of using a non-standard temperature produces a proportional error:

$$Error = l\,\alpha\,(t - t_s)$$

Where l =nominal length

α =coefficient of expansion

$(t - t_s)$ =deviation from standard temperature

(b) Comparative measurement. If we consider two gauges whose expansion coefficients are respectively α_1 and α_2, then the error due to a non-standard temperature will be

$$Error = l\,(\alpha_1 - \alpha_2)(t - t_s)$$

As the expansion coefficients are small numbers, the error will be very small as long as ***both parts are at the same temperature***. Thus in comparative measurements it is important that all components in the measuring system are at the ***same*** temperature rather than necessarily at standard temperature.

Other ambient conditions may affect the result of a measurement. If a gauge block is being measured by interferometry, then relative humidity, atmospheric pressure and carbon dioxide content of the air affect the refractive index of the atmosphere. These conditions should all be recorded during the test and the necessary corrections made.

4. Errors Due to Elastic Deformation

Any elastic body subject to a load will undergo elastic deformation. The magnitude of the deformation will depend upon the magnitude of the load, the area of contact and the mechanical properties of the materials in contact. It is therefore necessary to ensure that the measuring loads are the same in comparative measurement.

In most instruments used in fine measurement, comparators, bench micrometers, etc., the measuring pressure is reasonably constant, and it follows that the greatest difficulty is due to different types of contact when first setting an instrument to a gauge and then taking a reading on the work under test. A striking example of this is in the measurement of the simple effective diameter of a screw thread where the setting master requires two-point contacts and the thread has four-point contacts in the vee form. Tables of corrections are published and may be used if the required accuracy warrants such correction.

If a comparison is to be made to a high order of accuracy between components of different radius and from materials whose elastic properties differ, notably the elastic modulus ***E*** and Poisson's ratio ***v***, then correction can be made for the difference in elastic deformation which will occur when the measuring stylus is brought into contact with the setting gauge and the work piece.

Another form of elastic deformation is that which occurs when a body sags under its own weight. This problem was considered by Sir G. B. Airy, who showed that the positions of the supports can be arranged to give a minimum error. Two conditions are considered, both shown in Fig. 1.2, one where the slope at the ends of the bar is zero and the other where the deflection at the ends is equal to the deflection at the centre. In the case of line standards the bar is made of `**H**' section with the scale engraved on a surface in the plane of the neutral axis. Thus the elastic deformation due to sag has the minimum effect on the length of the scale divisions.

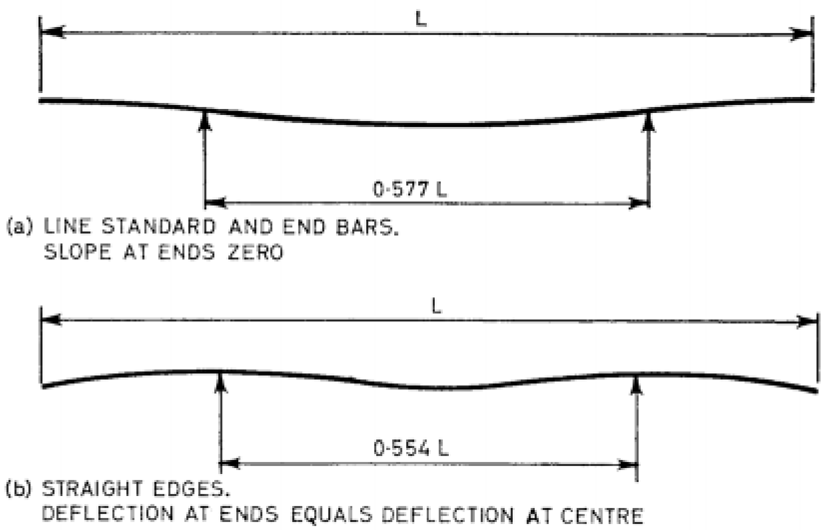


Fig. 1.2. Support positions for different conditions of measurement.

II. Errors Which Cannot Be Eliminated

No measurement can be made to give an exact dimension. Fundamentally this is because eventually the numerical value recorded depends upon the human eye reading a scale. The reading therefore becomes an estimate, the accuracy of which depends on the accuracy of the scale, the ability of the operator to read the scale, and in some cases the sensitivity of touch or feel on the part of the operator.

1. *Scale Errors*

If the scale against which a measurement made is in error, then obviously that measurement will be in error. This can only be overcome by calibrating the instrument scale against known standards of length over its whole length.

In comparative measurements the effects of scale errors are reduced by using as short a length of scale as possible, by choosing a setting master whose size is as close to that of the gauge being checked as is conveniently possible.

2. *Reading Errors*

How accurately can a scale be read? This depends upon the thickness of the rulings, the spacing of the scale divisions and the thickness of the datum or pointer used to give the reading.

As a guide, a reading of a pointer or datum line against a scale division can be taken as having an accuracy of ± 10 % of the scale division. On the other hand the estimate of the position of a pointer between the rulings will be less accurate and should be taken as ± 20 % of the scale division. Thus a reading of - 3 units taken off a scale whose divisions represent 0•001 mm would represent a comparative measurement of -0•003 mm to an accuracy determination of ± 0•0001 mm. If, however, the reading had been -3•4 scale units, then it would represent -0•0034 mm±0•0002 mm.

It must be realized that when a measurement is made with a comparator this type of error occurs twice, first when setting the instrument to a master gauge and again when the reading is taken on the work piece

.

3. *Measuring Errors*

The different types of error discussed above are cumulative, and in some cases a further amount must be added to allow for sensitivity of touch or feel. This will depend upon the type of instrument being used, and in general the effect is eliminated with comparators.

Consider now the problem of measuring the error in a plain plug gauge of nominal diameter 25 mm. The measurement is to be carried out using a comparator having a magnification of 5000 *x* which is set to a gauge block of nominal length 25 mm having a known error of -0•0001 mm to an accuracy of determination ±0•0002 mm. The comparators reading on the gauge block is 0 scale divisions and on the plug gauge -1.2 scale divisions.

In this case the effect of elastic deformation can be ignored as the two parts are of similar material under similar pressure, although the conditions of contact are slightly different. The problem can be set out in a tabular manner as follows.

Error Element	***Amount or Reading***	***Accuracy of Determination***
Gauge block	- 0•0001 rnm	~ 0•0002 mm
Comparator setting	0	±0•0001 mm
Comparator reading	- 0•0012 mm	±0•0002 mm
Totals	-0•0013 mm	±0•0005 mm

Thus the gauge size is found to be 24•9987 mm but the accuracy of determination shows that it can be anywhere between the values of 24•9992 mm and 24•9982 mm.

III. Compound Errors

Many cases occur in which the measurement finally computed is a function of a number of individual measurements *a*, *b*, *c*, etc., all of which have individual accuracies of determination δa, $\boldsymbol{\delta_b}$, $\boldsymbol{\delta_c}$, etc.; then the accuracy of determination of ***M***, which we can denote *d**M***, could be found by substituting in the expression for ***M*** the maximum and minimum values of *a*, *b*, c, etc., and thus finding the maximum and minimum values for ***M***. This would obviously be a laborious process, and the problem is better solved using partial differentiation.

Metrological characteristics of Measuring Instruments:

Measuring instruments are usually specified by their metrological properties, such as range of measurement, scale graduation value, scale spacing, sensitivity and reading accuracy.

1. ***Range of Measurement***. It indicates the size values between which measurements may be made on the given instrument.
2. ***Sca1e range***. It is the difference between the values of the measured quantities corresponding to the terminal scale marks.
3. ***Instrument range.*** It is the capacity or total range of values which an instrument is capable of measuring. For example, a micrometer screw gauge with capacity of 25 to 50 mm has instrument range of 25 to 50 mm but scale range is 25 mm.
4. ***Scale Spacing.*** It is the distance between the axes of two adjacent graduations on the scale. Most instruments have a constant value of scale spacing throughout the scale. Such scales are said to be linear. In case of non-linear scales, the scale spacing value is variable within the limits of the scale.
5. ***Scale Division Value***. It is the measured value of the measured quantity corresponding to one division of the instrument, e.g., for ordinary scale, the scale division value is 1 mm. As a rule, the scale division should not be smaller in value than the permissible indication error of an instrument.
6. ***Sensitivity*** (Implication or gearing ratio). It is the ratio of the scale spacing to the division value. It could also be expressed as the ratio of the product of all the larger lever arms and the product of all the smaller lever arms. It is the property of a measuring instrument to respond to changes in the measured quantity.
7. ***Sensitivity Threshold***. It is defined as the minimum measured value which may cause any movement whatsoever of the indicating hand. It is also called the discrimination or resolving power of an instrument and is the minimum change in the quantity being measured which produces a perceptible movement of the index.
8. ***Reading Accuracy***. It is the accuracy that may be attained in using a measuring instrument.

9. ***Reading Error***. It is defined as the difference between the reading of the instrument and the actual value of the dimension being measured.
10. ***Accuracy of observation***. It is the accuracy attainable in reading the scale of an instrument. It depends on the quality of the scale marks, the width or the pointer/index, the space between the minter and the scale, the illumination of the scale, and the skill of the inspector. The width of scale :ark is usually kept one-tenth of the scale spacing for accurate reading of indications.
11. ***Parallax***. It is apparent change in the position of the index relative to the scale marks, when scale is observed in a direction other than perpendicular to its plane.
12. **Repeatability**. It is the variation of indications in repeated measurements of the same dimension. The variations may be due to clearances, friction and distortions in the instrument's mechanism. Repeatability represents the reproducibility of the readings of an instrument when a series of measurements are carried out under fixed conditions of use.
13. ***Measuring force***. It is the force produced by an instrument and acting upon the measured surface in the direction of measurement. It is usually developed by springs whose deformation and pressure change with the displacement of the instrument's measuring spindle.

Objectives of Metrology

While the basic objective of a measurement is to provide the required accuracy at minimum cost, metrology would have further objective in a modern engineering plant with different shops like Tool Room, Machine Shop, Press Shop, Plastic Shop, Pressure Die Casting Shop, Electroplating and Painting Shop, and Assembly Shop, as also Research, Development and Engineering Department. In such an engineering organization, the further objectives would be as follows

a. Thorough evaluations of newly developed products, to ensure that components designed are within the process and measuring instrument capabilities available in the plant.
b. To determine the process capabilities and ensure that these are better than the relevant component tolerances.
c. To determine the measuring instrument capabilities and ensure that these are adequate for their respective measurements.
d. To minimize the cost of inspection by effective and efficient use of available facilities, and to reduce the cost of rejects and rework through application of Statistical Quality Control Techniques.
e. *Standardization of measuring methods.* This is achieved by laying down inspection methods for any product right at the time when production technology is prepared.
f. *Maintenance of the accuracies of measurement.* This is achieved by periodical calibration of the metrological instruments used in the plant.
g. Arbitration and solution of problems arising on the shop floor regarding methods of measurement.
h. Preparation of designs for all gauges and special inspection fixtures.

Requirements of an Inspection Tool

The requirements of an ideal inspection tool are: It should be

(a) Accurate
(b) require a minimum of operator skill
(c) Inspect a specific type of error
(d) fast to use
(e) Self checking.

The degree of accuracy of calibration depends on the accuracy of the inspecting instruments. Devices which reduce dependence on operator skill contribute to both efficiency and accuracy. The requirement of speed is not for economic reasons but to avoid errors from changes in temperature where inspections become involved. A good inspection tool should be capable of being checked against itself. This feature increases the reliability.

Classification of measurement methods:

In precision measurements various methods of measurement are followed depending upon the accuracy required and the amount of permissible error. Actual measurements may employ one or more combination of the following:

1) ***Direct method of measurement:*** in this method the value is obtained directly by comparing the unknown with the standard. It involves no mathematical calculations to arrive at the results, for example, measurement of length by a graduated scale.
2) ***Indirect method of measurement:*** in this method several parameters (to which the quantity to be measured is linked with) are measured directly and then the value is determined by mathematical relationship. For example, measurement of density by measuring mass and geometrical dimensions.
3) ***Comparison method of measurement:*** this method involves comparison with either a known value of the same quantity or another quantity which is function of the quantity to be measured.
4) ***Substitution method of measurement:*** in this method, the quantity to be measured is measured by direct comparison on an indicating device by replacing the measuring quantity with some other known quantity which produces same effect on the indicating device.
5) ***Differential or comparison method of measurement:*** this method involves measuring the difference between the given quantity and a known master of near about the same value. For example, determination of diameter with master cylinder on a comparator.

2- Gage Blocks

- The ***purpose*** of gauge blocks is to provide linear dimensions known to within a given tolerance.

- **The requirements of gauge blocks are:**
  - The actual size must be known
  - The faces must be parallel
  - The surface must have a smooth finish
  - The surfaces must be flat

- Most gauge blocks are made by normal techniques, but the high accuracy is obtained by a process called lapping.
- **The materials of gauge blocks are selected for:**
  - Hardness

- Temperature stability
- Corrosion resistance
- High quality finish

❖ **Type of gauge blocks**
- Rectangular
- Hoke (square)

❖ **There are four grades of blocks,**
- Reference (AAA)
- High tolerance (± 0.00005mm)
- Calibration (AA) (tolerance +0.00010mm to -0.00005mm)
- Inspection (A) (tolerance +0.00015mm to -0.0005mm)
- Workshop (B) - low tolerance (tolerance +0.00025mm to -0.00015mm)

The metric set has 88 gauge blocks (in mm):

<0.01mm divisions

1.001	1.002	1.003	1.004	1.005	1.006	1.007	1.008	1.009

0.01mm divisions

1.01	1.02	1.03	1.04	1.05	1.06	1.07	1.08	1.09	1.10
1.11	1.12	1.13	1.14	1.15	1.16	1.17	1.18	1.19	1.20
1.21	1.22	1.23	1.24	1.25	1.26	1.27	1.28	1.29	1.30
1.31	1.32	1.33	1.34	1.35	1.36	1.37	1.38	1.39	1.40
1.41	1.42	1.43	1.44	1.45	1.46	1.47	1.48	1.49	

0.5mm divisions

0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	

1cm divisions

10	20	30	40	50	60	70	80	90

two 2mm wear blocks

❖ Most gauge block sets include thin wear blocks that should be included at the ends of a gauge block stack to protect the other gauge blocks.

❖ **How to select gauge blocks for an application?**

From the 88 piece set above, build a stack that is 78.682 mm.

```
 78.682
- 1.002        therefore the gauge blocks are:
 77.680                1.002
 -1.180                1.180
 76.500                  6.500
 -6.500                70.000
 70.000
-70.000
 00.000
```

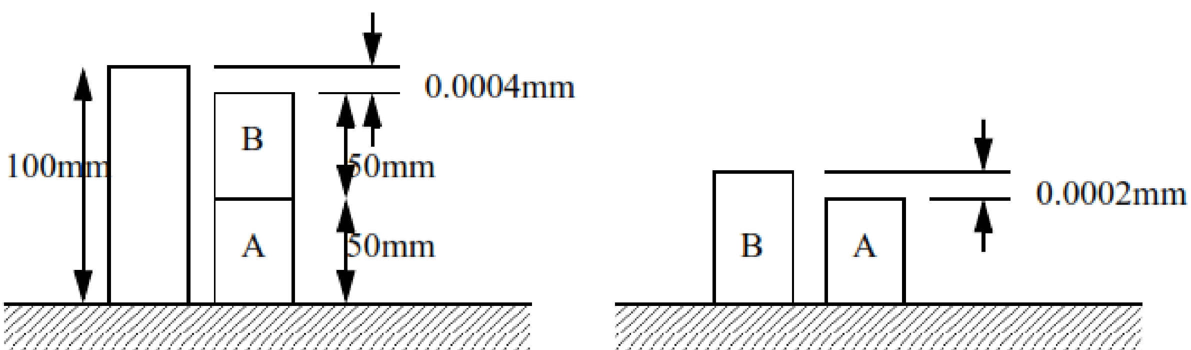
- **To assemble a gauge block stack**:
 1. Remove the gauge blocks required from the protective case
 2. Clean of the oil that they have been coated in using a special cleaner. It is acceptable to handle the blocks; in fact the oil from your hands will help them stick together.
 3. One at a time, hold the blocks so that the faces just overlap, push the blocks together, and slide them until the faces overlap together. This will create a vacuum between the blocks that makes them stick together (this process is known as ***wringing***).
 4. Make required measurements with the gauge blocks, being careful not to damage the faces
 5. Take the blocks apart, and apply the protective coating oil, and return them to their box.
    - When using gauge blocks, minimize the number used. Each block will have tolerance errors, and as the stack of blocks becomes larger, so does the error.
    - Do not leave gauge blocks ***wrung*** together for long periods of time.

- **Manufacturing Gauge Blocks:**

 The basic sequence of operations is:
 1. Machine to basic size
 2. Harden blocks and stress relieve
 3. Grind to size
 4. Lap (8 blocks at a time) to obtain tight tolerance

  - **Johansson's procedure to make the first set**

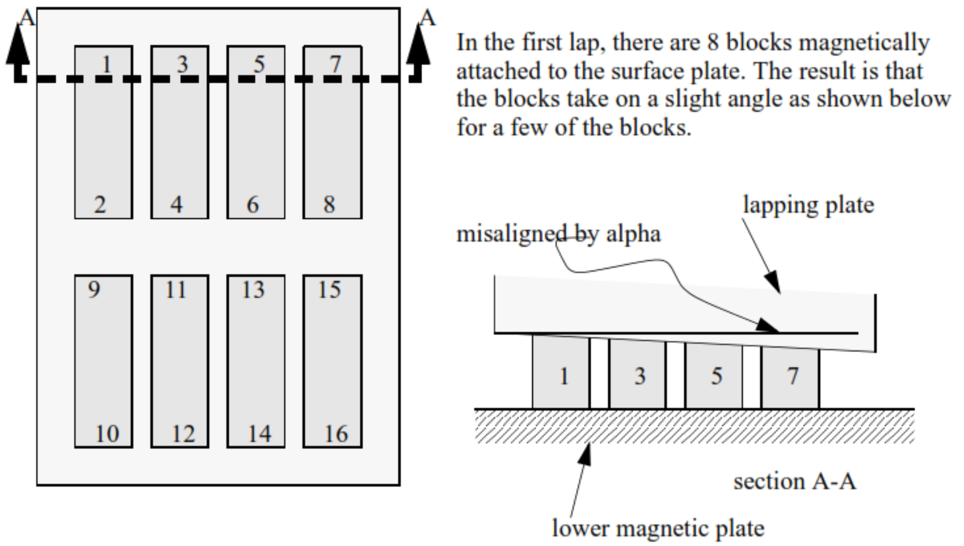
 1. Make a block with a 100mm length
 2. Make two 50mm blocks
 3. Determine the actual size of the 50mm blocks by comparing the difference in height

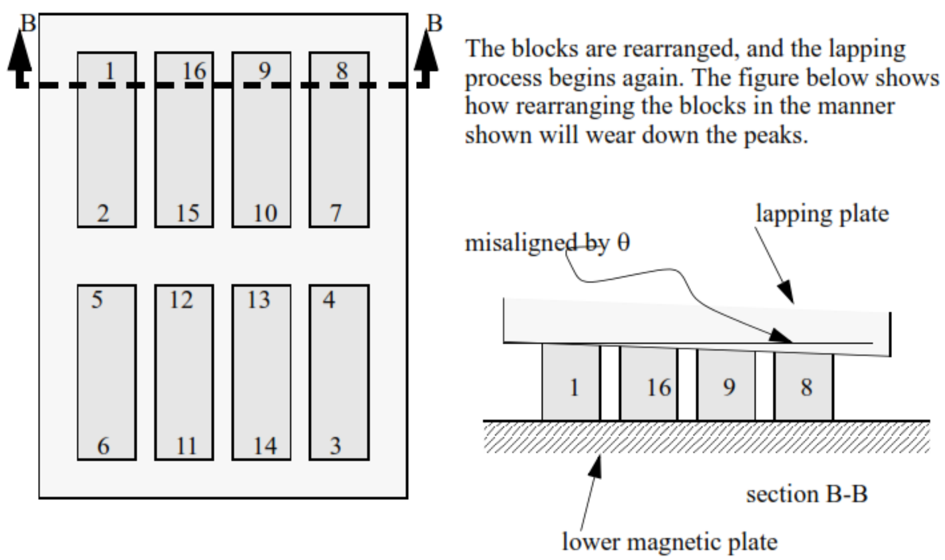


A + B = 100 - 0.0004 = 99.9996mm
A - B = -0.0002mm
2A + B - B = 99.9996 - 0.0002 = 99.9994mm
A = 49.9947mm
B = 49.9949mm

- **Lapping is basically**:
 1. A porous pad is charged with a find grit powder. The excess powder is removed.
 2. The parts to be lapped are secured to a surface plate magnetically (The positions are as shown below).
 3. The lapping plate is placed on the block, and moved about, wearing down the blocks.

4. The lapping plate is removed, and the blocks are repositioned on the surface plate (as shown below) and the process is repeated.
5. The blocks are removed from the surface plate, and now are generally the same height.





- As each stage of lapping is done, the blocks become more even in size, and the lapping plate become more parallel with the lower plate.
- Next, knowing the gauge blocks are all very close in size, the stack of 8 blocks are wrung together into one pile, and compared to the master block using a comparator. The difference in heights, divided by eight, is the error in each block.

❖ Compensating for Temperature Variations:

- As gauge blocks change temperature, they also change size. The metals chosen for gauge blocks do resist this dimensional change, but will generally undergo some.

- The gauge block sets will carry dimensional readings, as well as rated temperatures. It is advised that all readings be taken at these temperatures, but if this is not possible, then some estimate of the dimensional change can be done.
- Basically this is done by using the difference between specified measurement temperature, and actual measurement temperature. This difference is multiplied by the coefficient of linear thermal expansion to give the change in size. This is obviously for small changes in temperature.

- ***Typical coefficients of linear thermal expansion is:***

Steel 9.9 - 13.0 * 10^{-6} in./(in.°C) (typical is 11.5)
Bronze 16.7 * 10^{-6} in./(in.°C)
Aluminum 23.0 * 10^{-6} in./(in.°C)
Chrome carbide 8.4 * * 10^{-6} in./(in.°C)
Tungsten carbide 4 * * 10^{-6} in./(in.°C)

❖ Testing For Known Dimensions With Standards:

- When a dimension is well known, it can be measured by comparison to standards, using high precision, but limited range comparison instruments.
- Most gage blocks are steel which has a non-trivial coefficient of thermal expansion. But, considering that many parts are made of steel, these blocks will expand at approximately the same rate as the parts, and therefore no temperature compensation is required.
- If the gage blocks are made of the same material as the parts temperature compensation is less significant.
- For high accuracy measurements it is necesary to allow temperatures of gages and parts to stabilize.
- The ISO 1 and ANSI Y14.5 standards specify a typical dimensional ambient temperature as 20°C.
- Materials may vary widely from the listed coefficient of thermal expansion. As a result it is best to take them to 20±0.1°C for high precision measurements, and 20±0.01°C for critical measurements.

❖ Odd Topics

- There are also a number of angular gauge blocks for the measurement of angles. The two common sets are,

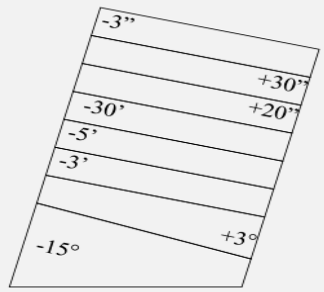
16 pieces set	Degrees	45°, 30°, 15°, 5°, 3°, 1°
	Minutes	30’, 20’, 5’, 3’, 1’
	Second	30”, 20”, 5”, 3”, 1”
13 pieces set	Degrees	1°, 3°, 9°, 27°, 41°, 90°
	Minutes	1’, 3’, 9’, 27’, 0.1’, 0.3’, 0.5’

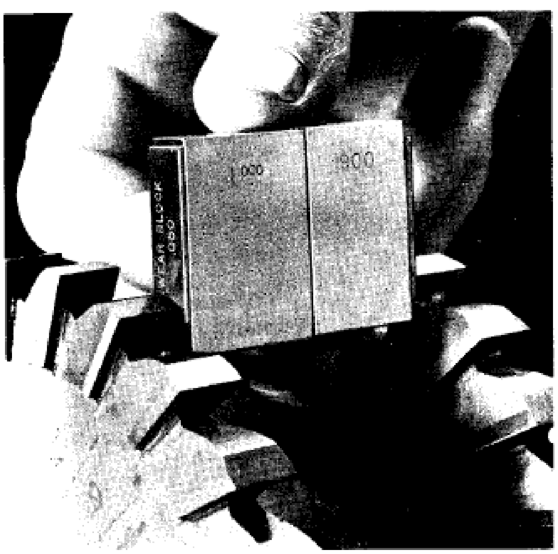
Tool room accuracy ±1 second
Laboratory accuracy ± 0.25 seconds

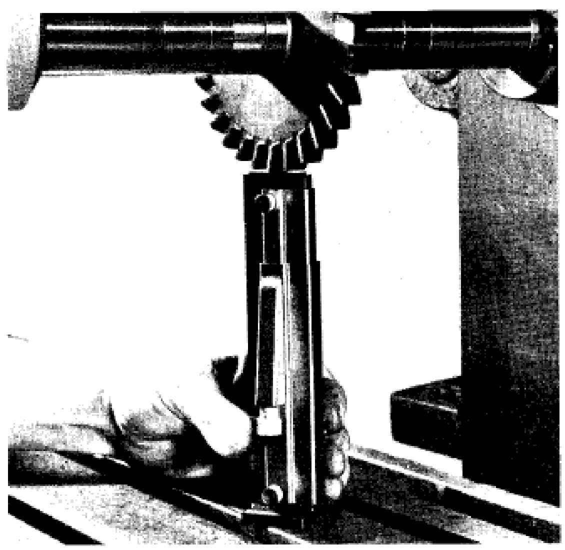
- The selection of angular gauge blocks is similar to the selection of linear gauge blocks, except that subtraction may also be required. (When the blocks are stacked, then angles are simply reversed.

For the angle 12°37’13”, find the angular gauge block stack using the 16 piece set.

12°37’13”	
-3”	
12°37’10”	
+30”	
12°37’40”	
+20”	
12°38’	
-30’	
12°8’	
-5’	
12°3’	
-3’	
12°	
+3°	
15°	
-15°	
0	







Inspectors sometimes get upset when they see precision gage blocks being used for rough and ready setup, such as for these milling machine operations. However they are highly recommended for fast, accurate setups. The one important concern is that gage blocks are never used in this fashion without wear blocks.

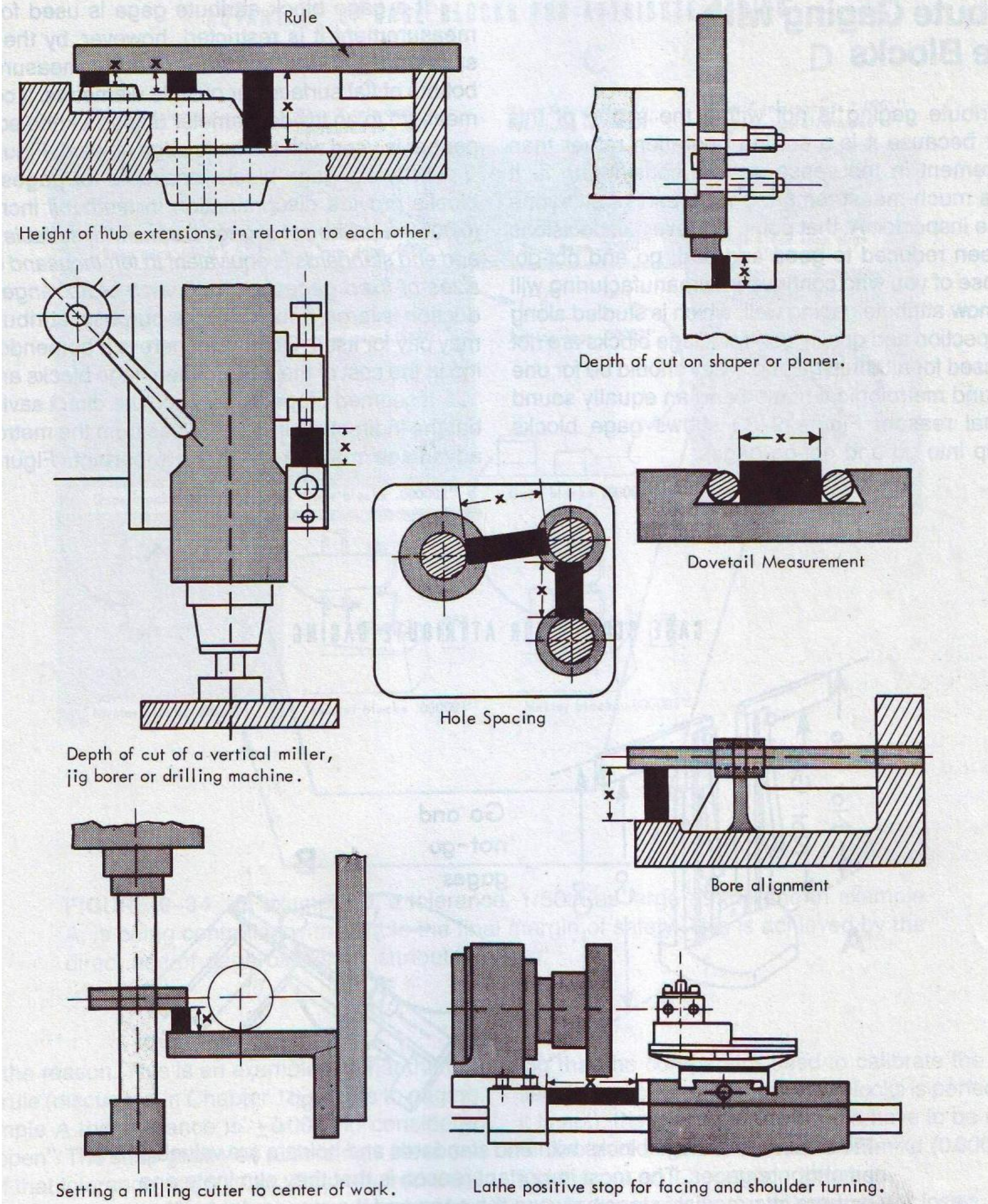


FIGURE 9–32 Direct use of gage blocks to set desired dimensions (x) eliminates errors from transfer of measurement. Gage blocks are also widely used with sine bars and sine plates for angle measurement, as discussed in Chapter 17.

Comparators

Introduction

A comparator works on relative measurements, *i.e.* to say, it gives only dimensional differences in relation to a basic dimension. So a comparator compares the unknown dimensions of a part with some standard or master setting which represents the basic size, and dimensional variations from the master setting are amplified and measured.

Advantages of comparators:

1. Not much skill is required on the part of operator in its use.
2. The calibration of instrument over full range is of no importance as comparison is done with a standard end length.
3. Zero error of instrument also does not lead to any problem.
4. Since range of indication is very small, being the deviation from set value, a high magnification resulting into great accuracy is possible.

The comparators are generally used for linear measurements, and various comparators available differ principally in the method used for amplifying and recording the variations measured. According to the principles used for obtaining suitable degrees of magnification of the indicating device relative to the change in the dimension being measured, the various comparators may be classified as follows:

Classification of comparators:

1. Mechanical comparators
2. Mechanical-optical comparators
3. Electrical and Electronic comparators
4. Pneumatic comparators
5. Fluid displacement comparators
6. Projection comparators
7. Multi-check comparators
8. Automatic gauging machines.

Characteristics of Comparators

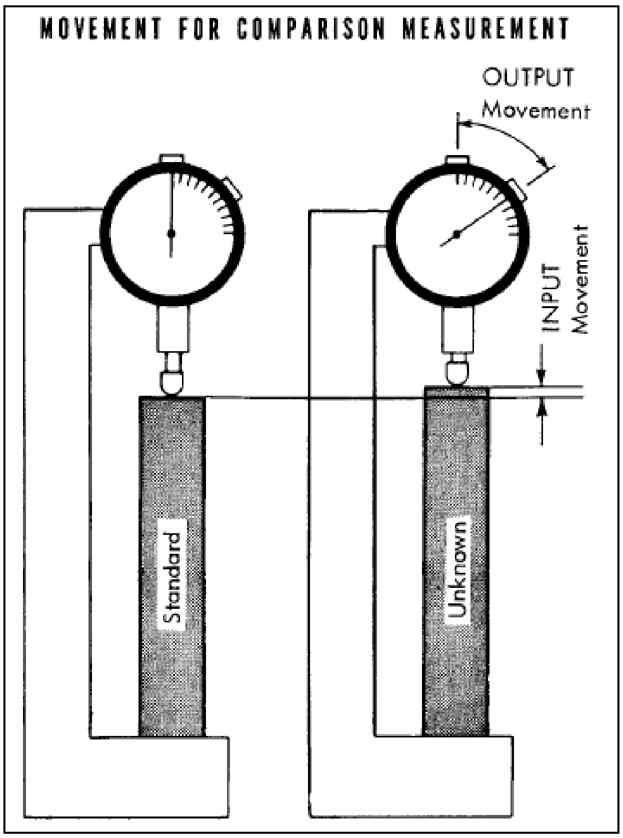
Before we discuss the various types of comparators, let us first look into various fundamental requirements which every comparator must fulfill. These are as follows:

1. The instrument must be of robust design and construction so as to withstand the effect of ordinary usage without impairing its measuring accuracy.
2. The indicating device must be such that readings are obtained in least possible time and for this, magnification system used should be such that the readings are dead beat. The system should be free from backlash, and wear effects and the inertia should be minimum possible.
3. Provision must be made for maximum compensation for temperature effects.
4. The scale must be linear and must have straight line characteristic.
5. Indicator should be constant in it return to zero.
6. Instrument, though very sensitive, must withstand a reasonable *ill usage* (معاملة قاسية) without permanent harm.
7. Instrument must have the maximum versatility, i.e., its design must be such that it can be used for a wide range of operations.
8. Measuring pressure should be low and constant.

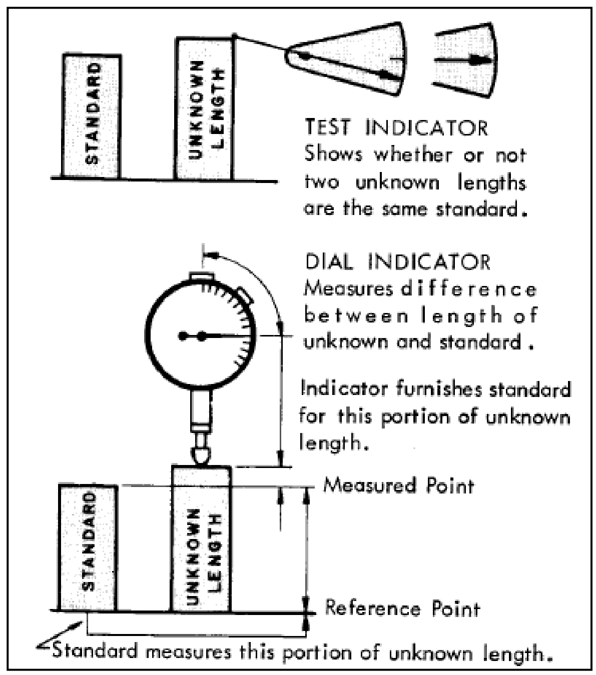
Uses of Comparators

The various ways in which the comparators can be used are as follows:

1. In mass production, where components are to be checked at a very fast rate.
2. As laboratory standards from which working or inspection gauges are set and correlated.
3. For inspecting newly purchased gauges.
4. Attached with some machines, comparators can be used as working gauges to prevent work spoilage (تلف) and to maintain required tolerances at all stages of manufacturing.
5. In selective assembly of parts, where parts are graded in three or more groups depending upon their tolerances.



Comparison measurement requires movement because it is change o f length that is desired.



The dial indicator measures change in length, not the length itself.

1. Mechanical Comparators

In these comparators, magnification is obtained by mechanical linkages and other mechanical devices.

- **Systems of Displacement Amplification used in Mechanical Comparators:**

a- Rack and Pinion: The measuring spindle integral with a rack, engages a pinion which amplifies the movement of plunger through a gear train. Fig (1-a).

b- Cam and gear train: In this case the measuring spindle acts on a cam which transmits the motion to the amplifying gear train. Fig (1-b).

c- Lever with toothed sector: In this case a lever with a toothed sector at its end engages a pinion in the hub of a crown gear sector which further meshes with a final pinion to produce indication. Fig (1-c).

d- Compound Levers: here levers forming a couple with compound action are connected through segments and pinion to produce final pointer movement. Fig (1-d).

e- Twisted Taut (مشدود) Strip: The movement of measuring spindle tilts the knee causing straining which further causes the twisted taut band to rotate proportionally. The motion of strip is displayed by the attached pointer.Fig (1-e).

f- Lever combined with band wound around drum: In this case, the movement of the measuring spindle tilts the hinged block, causing swing of the fork which induces rotation of the drum. Fig(1-f).

g- Reeds combined with optical display. In this case parallelogram reeds are used which transfer measuring spindle movement to a deflecting reed whose extension carries a target utilized in optical path.

i- Tilting mirror projecting light spots.

- **<u>Dial Indicator:</u>**

One of the most commonly used mechanical comparators is essentially of the same type as a dial indicator. It consists of a robust base whose surface is perfectly flat and a pillar carrying a bracket in which is incorporated a spindle and indicator. The linear movement of the spindle is magnified by means of a gear and pinion train into sizable rotation of the pointer on the dial scale. The indicator is set to zero by the use of slip gauges representing the basic size of the part. This is generally used for inspection of small precision-machined parts. This type of comparator can be used with various attachments so that it may be suitable for large number of works. With a V-block attachment it can be used for checking out-of-roundness of a cylindrical component.

- **The Johansson 'Mikrokator'**.
- **Reed Type Mechanical Comparator**.
- **The Sigma comparator**.

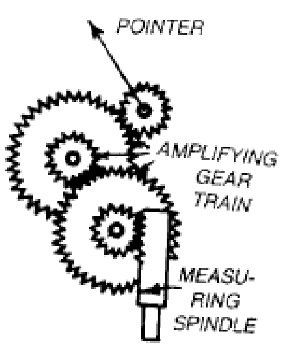


Fig1-a. rack and pinion

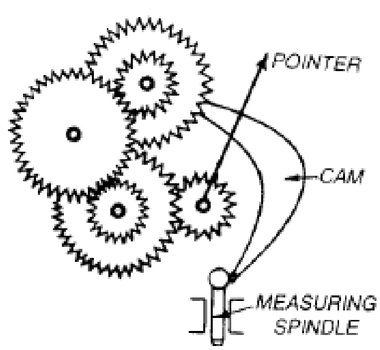


Fig 1-b. cam and gear train

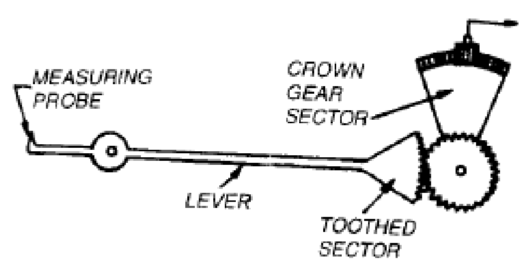


Fig1-c. lever with toothed gear.

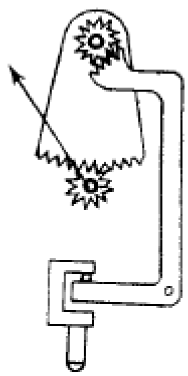


Fig1-d. compound levers.

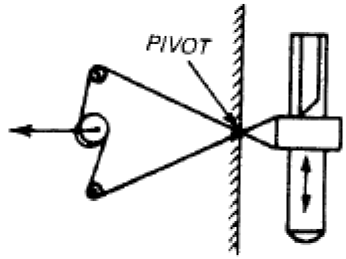


Fig1-f. lever combined with band wound around drum.

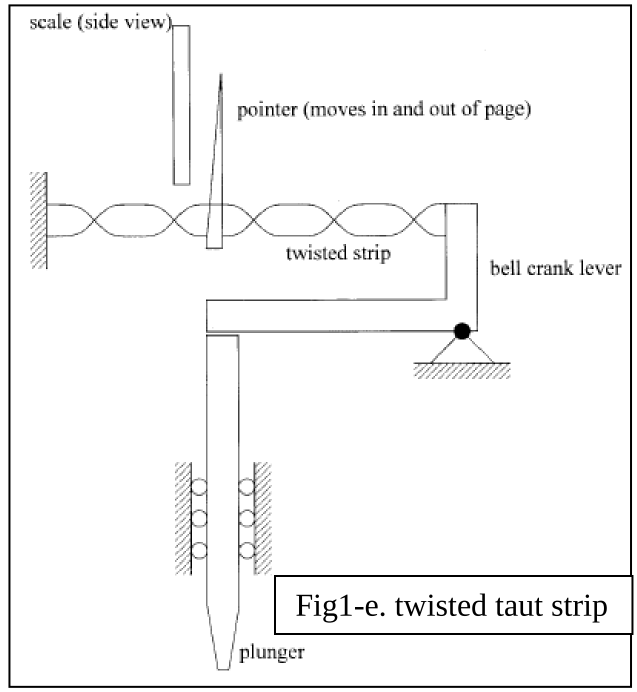


Fig1-e. twisted taut strip

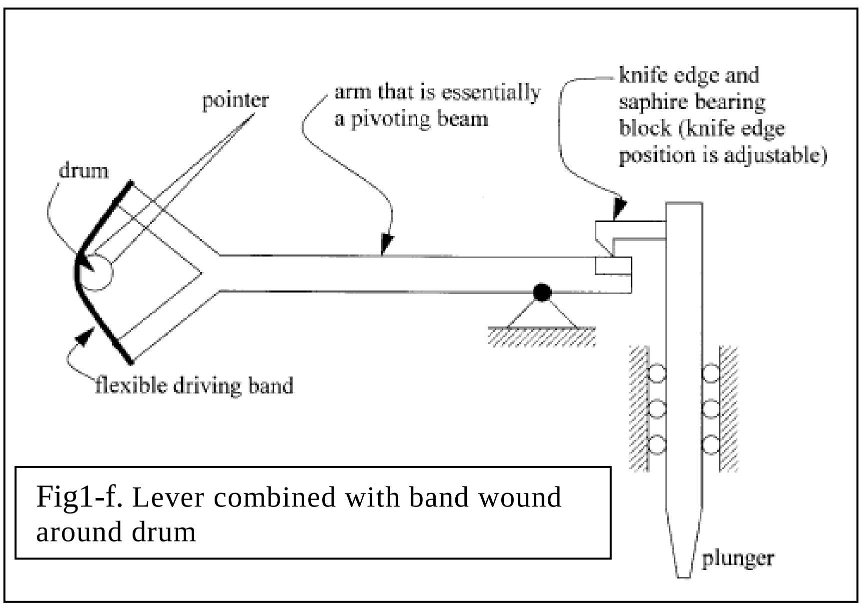


Fig1-f. Lever combined with band wound around drum

Advantages of Mechanical Comparators

i. These are usually cheaper in comparison to other devices of amplifying.
ii. These do not require any external supply such as electricity or air and as such the variations in outside supplies do not affect the accuracy.
iii. Usually the mechanical comparators have linear scale which is easily understood.
iv. These are usually robust and compact and easy to handle.
v. For ordinary workshop conditions, these are suitable and being portable can be issued from a store.

Disadvantages

i. The mechanical comparators have got more moving parts than other types. Due to more moving parts, the friction is more and ultimately the accuracy is less.
ii. Any slackness in moving parts reduces the accuracy considerably.
iii. The mechanism has more inertia and this may cause the instruments to be sensitive vibration.
iv. The range of the instrument is limited as the pointer moves over a fixed scale.
v. Error due to parallax is possible as the moving pointer moves over a fixed scale.

2-Mechanical Optical Comparators

In mechanical optical comparators small displacements of the measuring plunger are amplified first by a mechanical system consisting of pivoted levers. The amplified mechanical movement is further amplified by a simple optical system involving the projection of an image. The usual arrangement employed is such that the mechanical system causes a plane reflector to tilt about an axis and the image of an index is projected on a scale on the inner surface of a ground-glass screen. Optical magnifications provide high degree of measuring precision due to reduction of moving members and better wear resistance qualities. Optical magnification is also free from friction, bending, wear etc.

The whole system could be explained diagrammatically by (fig 2-a,b) which gives very simple arrangement and explains the principle of above comparator.

In this system, Mechanical amplification
= 20 /1 ,

And, Optical amplification

50 /1* x *2

It is multiplied by **2**, because if mirror is tilted by an angle **δθ**, then image will be tilted by **2 x δθ**. Thus overall magnification of this system
= 2* x *(20/1) (50/1 =2000 units)

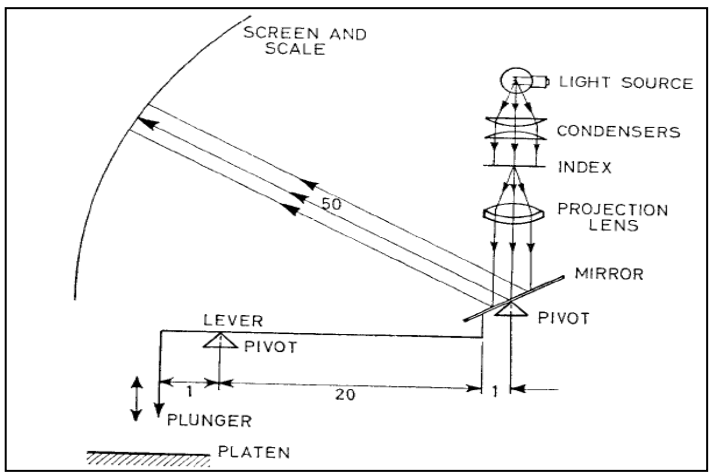


Fig 2-a. principles of Optical Comparator.

Thus it is obvious that optical comparators are capable of giving a high degree of measuring precision owing to high magnification and the reduction of moving members to minimum. Further these possess better wear resistance qualities as the only wearing members are the plunger and its guide and the mirror pivot bearing. Another advantage of the optical comparators is that provision of an illuminated scale enables readings to be taken without regard to the room lighting conditions. The point of importance in optical comparator is that mirror used must be of front reflection type and not normal back reflection type. In normal back reflection type there are two reflected images, one each from front and back. Thus the reflected image is not well defined one, as one bright and other blurred image are observed. If front reflection type of mirror is used, then it requires considerable care in its use to avoid damage to the reflecting surfaces.

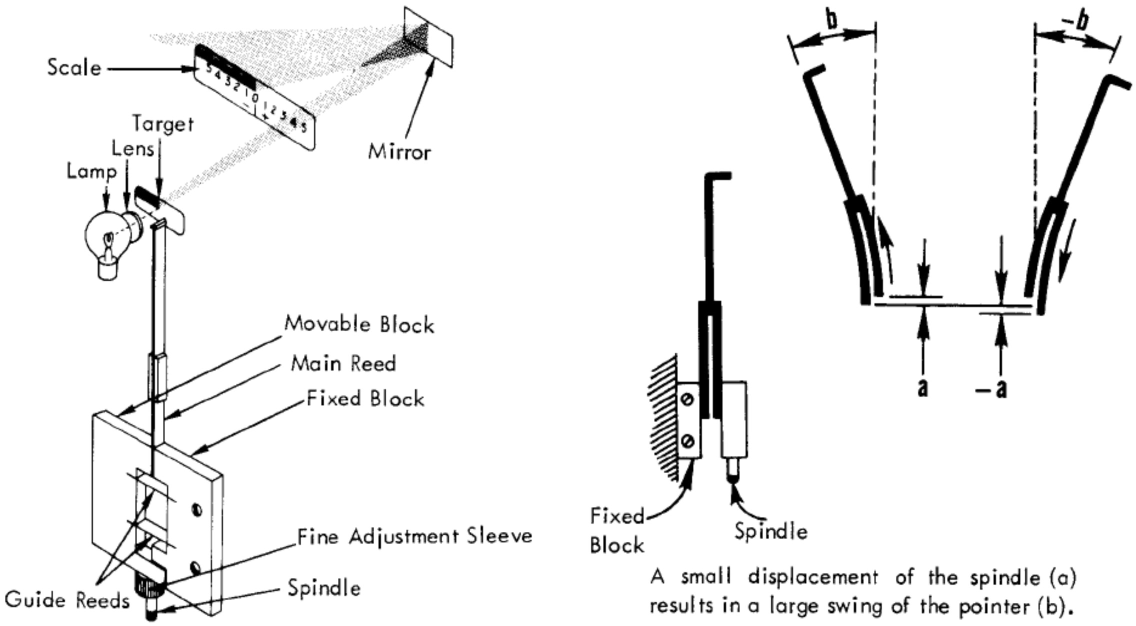


Fig 2-b. an optical lever is used to amplify the reed action. In the actual instrument, the optical path is longer than is shown here and a prism is used instead of a mirror.

Advantages of Optical Comparators:

i. It has small number of moving parts and hence a higher accuracy.
ii. In the optical comparators, the scale can be made to move past a datum line and thus have high range and no parallax errors.
iii. It has very high magnification.
iv. Optical lever is weightless.

Disadvantages:

i. As the instrument has high magnification, heat from the lamp, transformer etc. may cause the setting to drift.
ii. An electrical supply is necessary.
iii. The apparatus is usually large and expensive.
iv. When the scale is projected on a screen, then it is essential to use the instrument in a dark room in order to take the readings easily.
v. The instruments in which the scale is viewed through the eyepiece of a microscope are not convenient for continuous use.

3. Electrical and Electronic Comparators:

These comparators depend for their operation on Wheatstone bridge circuit. In d.c. circuit, a change of balance of the electrical resistance in each arm of the bridge is caused by the displacement of an armature relative to the arm under the action of the measuring plunger. Once out of balance is caused in the bridge, it is measured by a galvanometer graduated to road in units of linear movement of plunger. This circuit is operated by battery. For the bridge to balance, the ratios of the resistances in two arms must be equal.

If alternating current is applied to the bridge, the inductance and capacitance of the arms must also be accounted for along with resistance. In actual measuring instruments, one pair of inductances is formed by a pair of coils in the measuring head of the instrument. The movement of the plunger displaces an armature, thus causing a variation in the inductance of a pair of coils forming one arm of a.c. bridge. The arm carries the armature (Fig. 3-a) and the inductance in the coils is dependent upon the displacement of the armature relative to the coils. There are other refinements in actual instrument such as an electrical method of zero adjusting and a switch to change the magnification. The amount of unbalance caused by movement of measuring plunger is amplified and shown on a linear scale. Magnifications of the order of x 30,000 are possible with this system. Commonly used instruments are Electrichek, Electricator, Electrigage, Electrolimit and Electronic Measuring Equipment.

Electrical Comparators:

Electrical comparators are also known as electromechanical measuring systems as these employ an electro-mechanical device which converts a mechanical displacement into electrical signal.fig3-a.

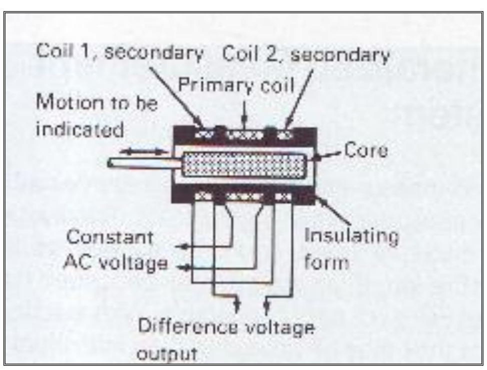


Fig3-a.

This is a LVDT (Linear- Variable-Differential Transformer). Linear movement of the core changes the Impedance. The electrical output changes in proportion to the core movement.

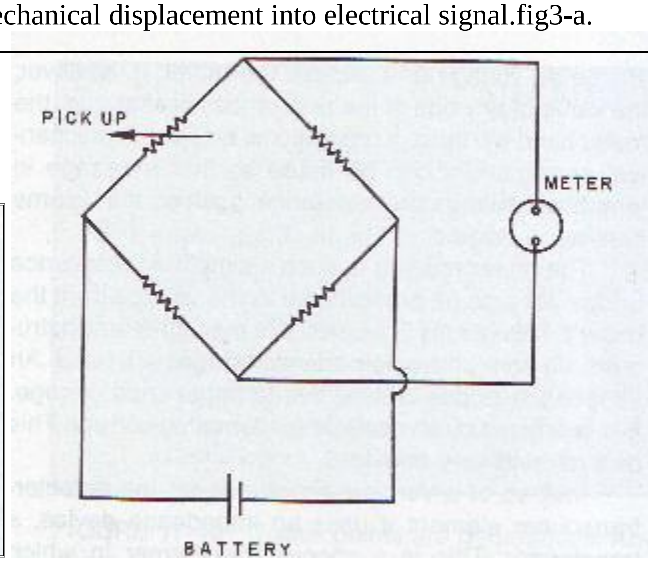


Fig.3-b.

This simplified bridge circuit is similar to those used in electronic comparators.

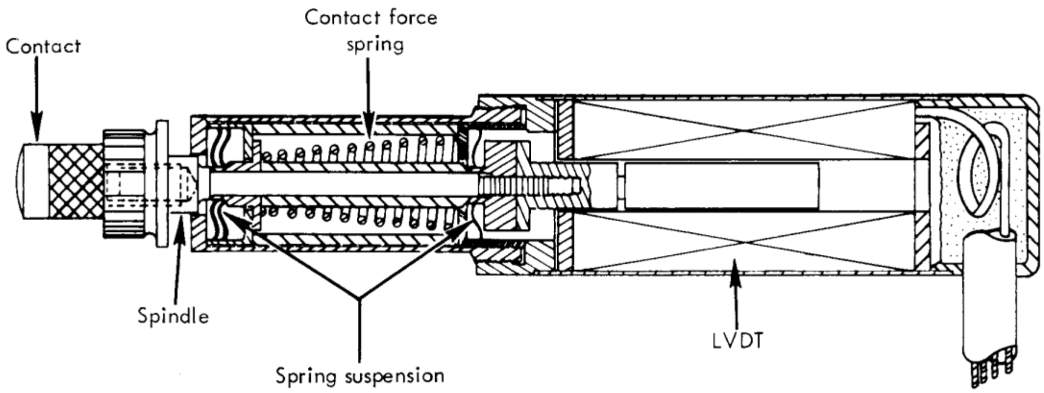


FIGURE 11–24 Frictionless gage heads use flexure springs to support the moving parts. They are used when the highest precision is required. The cylindrical type (bottom) has the same size mounting stem as dial indicators. This makes it interchangeable in indicator setups. However, these may not have the other features needed to utilize fully the capability of the frictionless heads.

Advantages of Electrical Comparators:

i. The electrical comparators have got small number of moving parts.
ii. It is possible to have a very high magnification and the same instrument may have two or more magnifications. Thus the same instrument can be used for various ranges.
iii. The mechanism carrying the pointer is very light and not sensitive to vibrations.
iv. As the instrument is usually operated on A.C. supply, the cyclic vibration substantially reduces errors due to sliding friction.
v. The measuring unit can be made very small and it is not necessary that the indicating instrument be close to the measuring unit, rather it can be remote also.

Disadvantages:

i. It requires an external agency to operate i.e., the A.C. electrical supply. Thus the variations in voltage or frequency of electric supply may affect the accuracy.
ii. Heating of coils in the measuring unit may cause zero drift and alter the calibration.
iii. If only a fixed scale is used with a moving pointer then with high magnifications a very small range is obtained.
iv. This is usually more expensive than mechanical instrument.

4- Pneumatic Comparators

Air gauging has rapidly increased during some past time due to the following important characteristics.

i. Very high amplifications are possible. It can be used to measure diameters, length, squareness, parallelism, and concentricity, taper, centre distance between holes and other geometric conditions.
ii. As no physical contact is made either with the setting gauge or the part being measured, there is no loss of accuracy because of gauge wear. For this reason, air spindle and air snap gauges last very long. Also very soft parts which are easily scratched can be gauged.
iii. Internal dimensions can be readily measured not only with respect to tolerance boundaries but also geometric form. In other words, while measuring a bore it can reveal complete story

of size, taper, straightness, camber and bell mouth etc.

iv. It is independent of operator skill.

v. High pressure air gauging can be done with cleansing of the parts which helps to eliminate errors due to dirt and foreign matter.

vi. Gauging pressures can be kept sufficiently low to prevent part deflection.
(In general, high pressure gauges are suitable for those parts in which tolerances are relatively large and low pressure air gauges are preferable for highly precise work.)

vii. Dimensional variations throughout the length of shaft or cylinder bore can be explored for out of roundness, taperness, concentricity, regularity and similar conditions.

viii. Not only it measures the actual size, but it can also be used to salvage oversized pieces for rework or to sort out for selective assembly, i.e., it is suitable both for variable inspection (measurement of size) and attribute inspection (GO and NO GO) gauging and limits.

ix. The total life cost of the gauging heads in much less.

x. It is accurate, flexible, reliable, universal and speedy device for inspecting parts in mass production.

xi. It is best suited for checking multiple dimensions and conditions on a part simultaneously in least possible time. It can be used for parts from 0.5 mm to 900 mm diameter having tolerance of 0.05 mm or less. It can be easily used for on line measurement of parts as they are being machined and take corrective actions.

Systems of Pneumatic Gauges:

Based on the physical phenomena on which the operation of pneumatic gauges is based, these may be classified as:

i. Flow or velocity type,
ii. Back pressure type.

Flow or velocity type pneumatic gauges operate ***by sensing and indicating the momentary rate of air flow***. Flow could be sensed by a glass tube with tapered bore, mounted over a graduated scale. Inside the bore a float is lifted by the air flow.

i. Free Flow Air Gauges:

(Flow or velocity type): In this case the compressed air after the filtering and pressure reducing unit flows through a tapered glass tube containing a small metal float and then through a plastic tube to the gauge head having two diametrically opposed orifices for air escapement into atmosphere .The position of the tube is dependent upon the amount of air flowing through the gauge head, which in turn is dependent upon the clearance between the bore to be measured and the gauge head.

The flow velocity type pneumatic comparator with zero adjustment and magnification adjustment is shown in **Fig. 4-a**. Magnification can be changed by passing some of the air supply, using a screw at the inlet to the tapered glass tube. The float can be zeroed by a bleed valve installed at the top of the tube. Size is measured by the velocity of air in a tapered glass tube which is measured by the height of the float in tube.

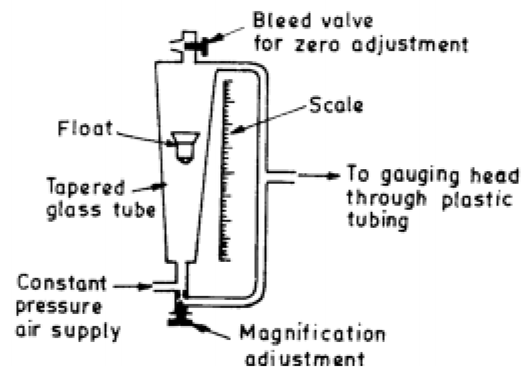


Fig 4-a. zero and magnification adjustment in flow type of pneumatic comparator.

It is possible to read accurately up to microns depending upon scale length, or classify the sizes quickly and accurately. The amplification can be changed by quick change of tube, float and scale. Air gauge amplification and range are based on the tooling and instrument standards of manufacturer. The amplification and instrument are selected by considering the total tolerance spread and choosing the instrument that covers the range. About 50 to 100 mm of column is usually allowed for the actual tolerance spread.

In the gauging head, the air escapement orifices are recessed below its cylindrical surface so that the orifices never contact the part being gauged. Thus the surface wear will not affect the accuracy till it is worn down to orifice level. Also the orientation of gauge or the way operator holds the gauge is of no consequence and same readings will be obtained for given diameter. On the gauge, knobs are also provided for adjusting float position and calibration. Air gauge is set by placing masters for maximum and minimum tolerances on spindle alternatively and adjusting the float position for each master by turning the knurled knobs at the base of the instrument.

Free-flow column type gauges are usually assembled together side by side and thus multiple interrelated readings can be seen at a glance. This is the big ***advantage*** of air gauging that the multiple dimensions and conditions can be inspected with great ease, accuracy and speed.

Pneumatic circuits can be arranged to determine dimensional differences like taper (comprising the diameter of bore at different points along a part), bore centre distance and also to select parts to assemble to predetermined clearances or interference fits.

ii. Back Pressure Gauges: The air pressure variation system is based on the use of a two-orifice arrangement, as shown in **Fig. 4-b**. Air is passed at controlled pressure into the measuring head, and provides the source pressure, P_s. It passes through the control orifice O_1 into the intermediate chamber. Orifice O_1 is of constant size, but the effective size of O_2 may be varied by the distance d. *As* d varies, pressure P_b also changes, and thus provides a measure of dimension d. Thus the indicating device is a pressure gauge or manometer recording the pressure P_b between the orifices.

By suitably matching the diameters of O_1, and O_2 and controlling P_s, the pressure at P_b may be made to vary linearly with the effective size of O_2, over a limited portion of the curve obtained by plotting the relationship of the ratios A_2 / A_1, and P_b / P_s as shown in **Fig. 4-c**, where A_1 and A_2 are the areas of orifices O_1, and O_2 respectively.

For values of P_b / P_s between approximately ***0•6*** and ***0•8,*** the curve is linear within ***1 %,*** and it is these values that are used in the design of such comparators for the relative diameters of orifices.

If we consider the linear portion of the curve, i.e. between the values of ***0•6*** and ***0•8*** for P_b / P_s its law may be written as:

$$\frac{P_b}{P_s} = a - \frac{bA_2}{A_1}$$

The pneumatic magnification is proportional to the input pressure, and inversely proportional to the area, or the square of the diameter, of the control orifice.

It is clear that an essential operating requirement is that pressure P_s is constant. It is thus necessary to have a simple pressure regulator controlling the pressure of the air from the normal supply line, and if necessary reducing it from about ***55 N/cm² to 1 N/cm²***. **Fig. 4-c** shows the circuit diagram of the instrument produced by Solex Air Gauges Ltd., the instrument being arranged for internal measurement.

The air from its normal source of supply, say the factory air line, is filtered, and passes through a flow valve. Its pressure is then reduced and maintained at a constant value by a dip tube into a water chamber, the pressure value being determined by the head of the water displaced, excess air escaping to atmosphere.

The air at reduced pressure then passes through the control orifice, and escapes from the measuring orifice. The ***back pressure*** in the circuit is indicated by the head of water displaced in the monometer tube. The tube is graduated linearly to show changes of pressure resulting from changes in dimension ***d***, **Fig. 4-b**. Amplifications of up to **50 000** are obtainable with this system.

Another back-pressure comparator is produced by **Mercer Air Gauges Ltd**., but this operates at the much higher pressure of ***27•5 N/cm²*** gauge. The constant pressure input is produced from the line pressure by a diaphragm type regulator and passed to the control orifice and thence to the measuring orifice.

Interesting features are:

(a) ***Magnification adjustment***. It has been shown that the magnification can be varied by varying the diameter of the control orifice. This is achieved by means of a taper-needle valve in the control orifice and enables a single scale to be used for all work by adjusting the magnification and zero settings.

(b) ***Zero adjustment***. An air bleed, upstream of the measuring orifice and controlled by a taper-needle valve, provides a zero adjustment.

The pressure measuring device is a Bourdon tube type pressure gauge, the dial being graduated in linear units, i.e. ***0•01 mm, 0•001 mm***, or inch units.

As with all other comparators, initial setting is by means of reference gauges. In this case, it is important that the reference gauges, and the part being measured, are of the same geometric form. For example, slip gauges are applicable as setting gauges for flat work pieces, while circular section work requires the use of cylindrical setting gauges. For work of the type shown in ***Fig. 4-d***, a pair of reference ring gauges is necessary for setting purposes. If this precaution is not taken, the expansion characteristics of the air escaping from the measuring orifice, O_2, are changed and affect the accuracy of pressure readings on the manometer tube.

A possible disadvantage of the back-pressure type of instrument is its relatively slow speed of response under some conditions of use. It is clear that as the volume of air in the system increases, its response to changes of pressure will, due to its compressibility, be reduced. This characteristic is of no great concern when the total length of the circuit is short, but in applications to dimensional control in the operation of machine tools for example, this length may be considerable, and give rise to passivity.

The basic back- pressure system shows changes in the gauging pressure in respect to atmospheric pressure. There is no control over the later. In the balanced system ***Fig.4-e*** the changes in the measuring channel pressure are shown in respect to the reference channel pressure. Both channels are subject to careful control by the restrictors.

By these means some of the difficulties with back- pressure systems are eliminated and some desirable features obtained. Unlike the other systems, this one requires only one master and one adjustment, zero setting.

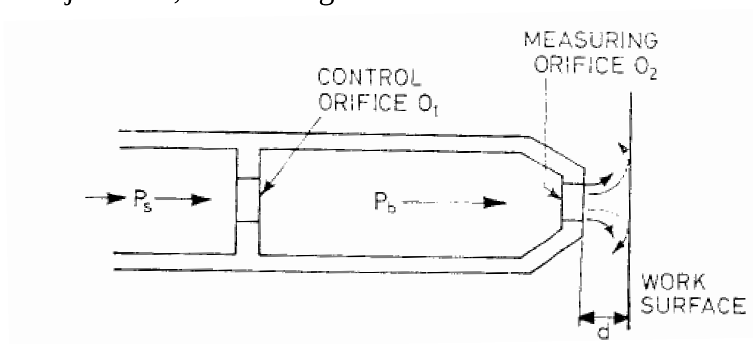


Fig.4-b. Essentials of a back- pressure pneumatic gauging system.

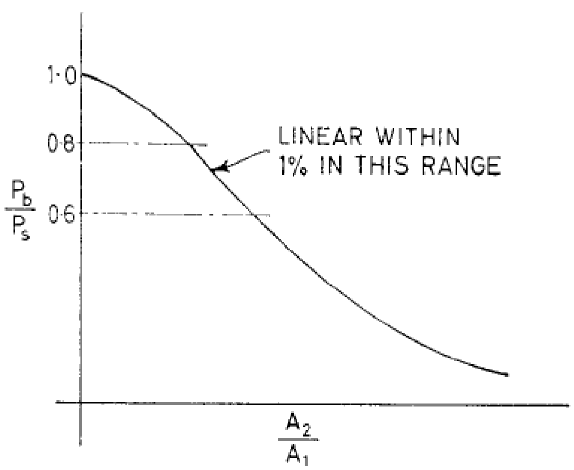


Fig.4-c. Characteristic curve of back- pressure

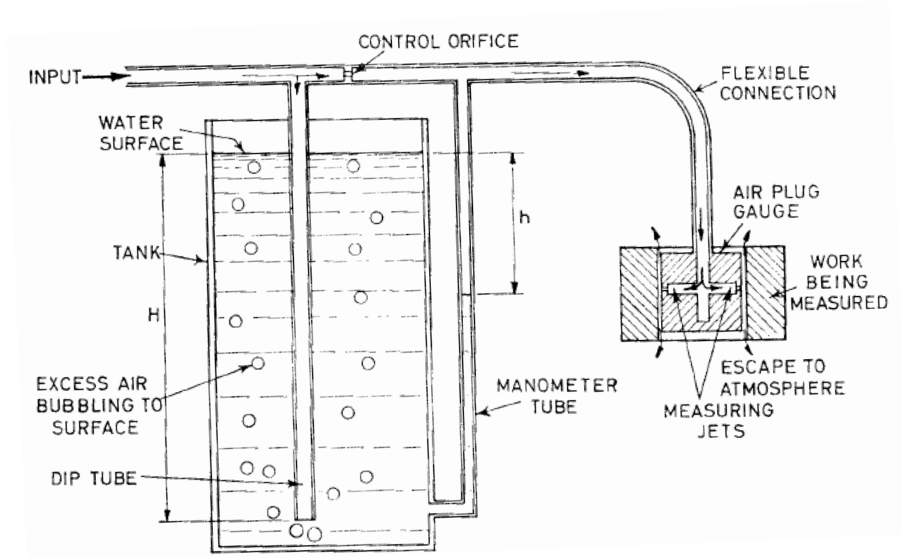


Fig.4-d. Application of back- pressure air gauging system used by Solex Air Gauging Ltd.

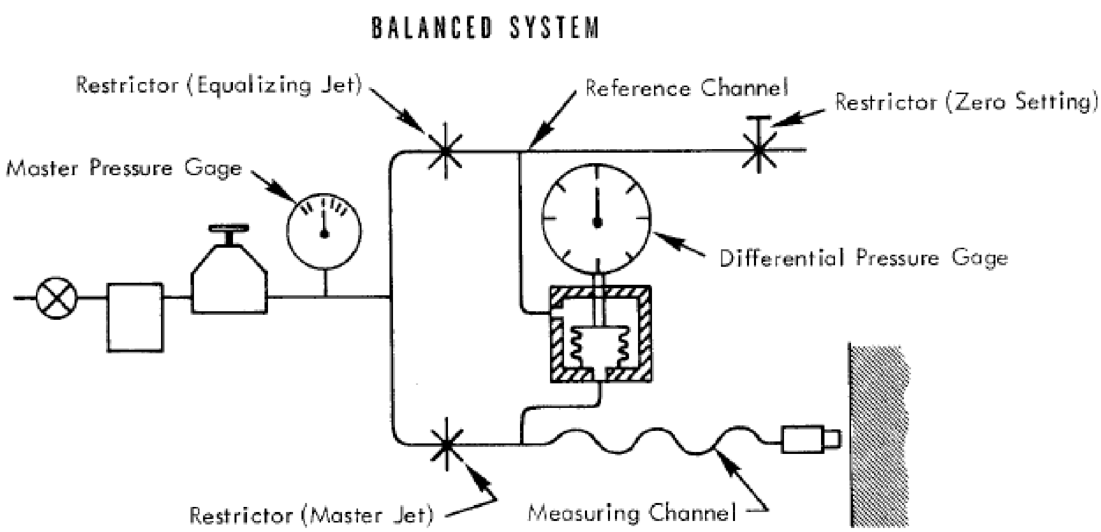


Fig.4-e. The balanced system has fixed amplification. The only adjustment is zero setting.

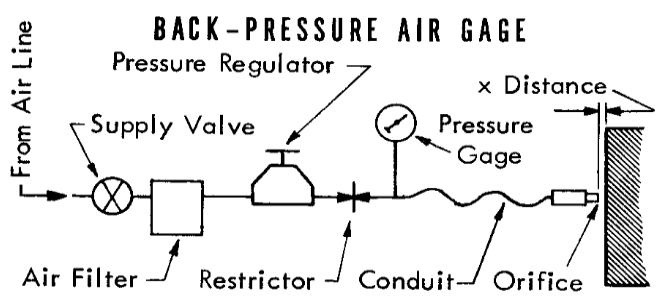


FIGURE 12–3 In the basic back-pressure air gage, a change in x alters the conduit pressure and is read on the pressure gage.

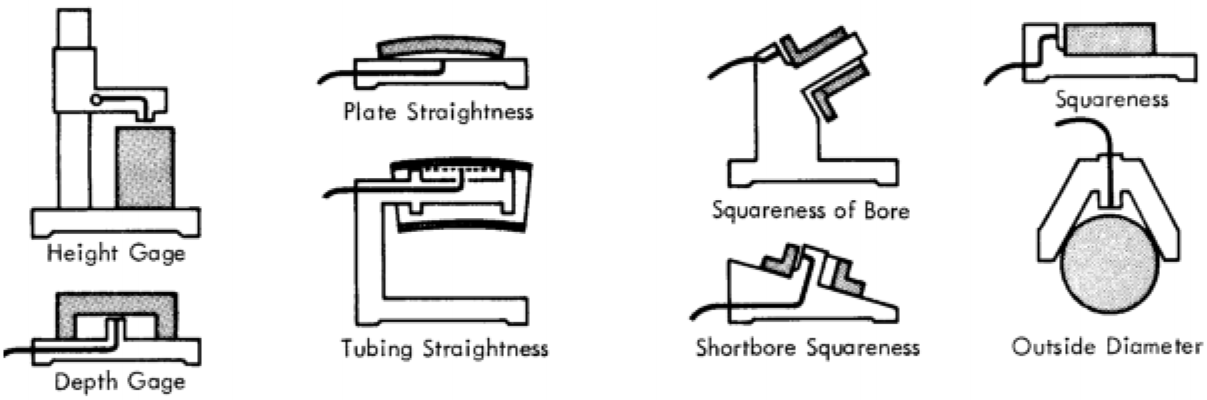


FIGURE 12–13 Single jet nozzles form the basic gaging element as in these examples.

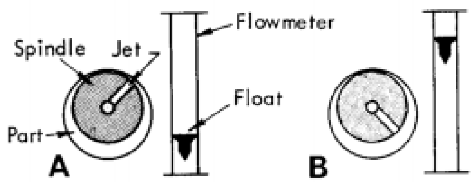


FIGURE 12–14 Rotation of the single jet spindle changes the height of the float.

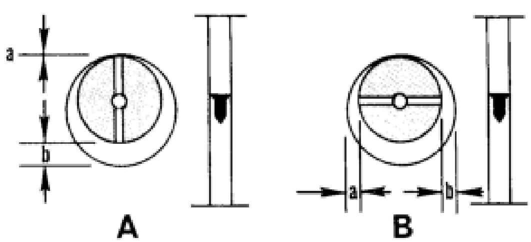


FIGURE 12–15 With opposite jets, rotation of spindle does not change float height because the sum a + b equals x for any position.

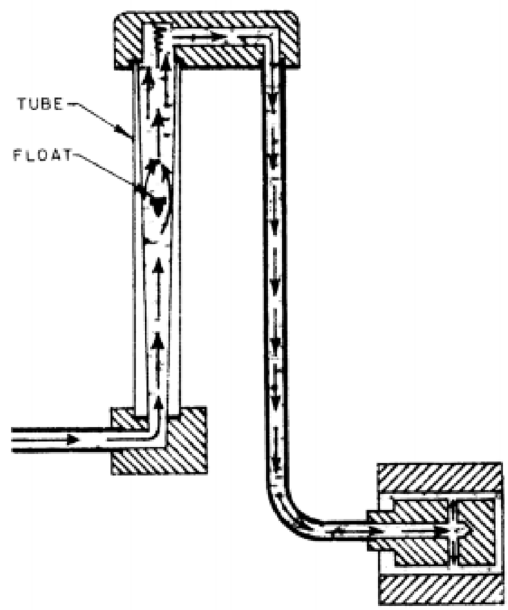


FIGURE 12–16 Cross section of typical spindle for the measurement of inside diameters.

Advantages of Pneumatic Comparators:

i. The gauging member does not come into contact with the part to be measured and hence practically no wear takes place on the gauging member.
ii. It has usually very small number of moving parts and in some cases none. Thus the accuracy is more due to less friction and less inertia.
iii. Measuring pressure is very small and the jet of air helps in cleaning the dust, if any, from the part to be measured.
iv. It is possible to have very high magnification.
v. The indicating instrument can be remote from the measuring unit.
vi. It is very suitable device for measuring diameter of holes where the diameter is small compared with the length.
vii. It is probably the best method for determining the ovality and taperness of the circular bores.

Disadvantages:

i. It requires elaborate auxiliary equipment such as accurate pressure regulator.
ii. The scale is generally not uniform.
iii. When indicating device is the glass tube, then high magnification is necessary in order to avoid the meniscus errors.
iv. The apparatus is not easily portable and is rather elaborate for many industrial applications.
v. Different gauging heads are required for different dimensions.

Light Waves as Standards of Length

1. THE EVOLUTION OF A LENGTH STANDARD

It is fundamental to the science of measurement, and hence the degree of control which it exerts on the development of technologies, that it should be based on an agreed, and if possible internationally agreed, system of standards. For many years the major industrial countries of the world used two systems, imperial and metric.

The disadvantages of such an arrangement are evident when one considers that a very large part of the world's population used metric units, but that important industrial countries, notably the United Kingdom and the U.S.A., used both imperial and metric units, the former being dominant in the industrial field. Virtually the only concession made by these countries was that scientific work was carried out in metric units.

The basis for a solution to this confusion was established in 1960 when the General Conference of Weights and Measures, an international body, recommended that SI units should be brought into use to replace existing metric units. SI is an abbreviation of Systeme International d'Unites (International System of Units) which has grown out of the MKS (meter, kilogram, second) system and the MKSA (meter, kilogram, second, ampere) system. The major industrial countries, including those at present using a metric system, have adopted the recommendation. Thus the United Kingdom is at present in the process of conversion from imperial to SI units. The process will take some years for its completion.

The standard of length, therefore, will be the meter, and for the purposes of this book will be the most important of the SI units considered.

1.1 The Meter Defined

As part of the evolution of a universal standard of length, the International Committee of weights and Measures recommended in 1958 that the meter be defined as

1 650 763·73 x λ

Where **λ** = the wavelength, in a vacuum, of the orange-red radiation of the isotope krypton 86. It is this definition which has been universally adopted by those countries using, or intending to use in the future, SI units.

Clearly, a universal standard must be one which is reproducible with such a degree of accuracy that for all industrial and scientific purposes it may be considered as absolute. By means of ***interferometry***, the error of reproduction of the meter is of the order of ***1 part in 100 million***. Similarly, any subdivision of the meter may be produced, and reference to *B.S. 888: Slip (or Block) Gauges and their Accessories* shows that the practical working standards of length used in industry are of such accuracy that the calibration and reference grades of these must be verified by interferometry, that is, in terms of the wavelength of light.

At the General Conference on Weights and Measures in Paris in October 1983, a new definition of the meter was agreed upon. It was based largely on research by the National Bureau of Standards in the United States. Under the new method the meter is defined as the distance traveled by light in a vacuum during 1/299,792,458 of a second.

It is claimed that this is ten times more accurate than the krypton standard. Even more important, it correlates length with time which is the most accurate of our measurement capabilities.

2- THE NATURE OF LIGHT

Interferometry is that branch of science which is concerned with the manner in which rays of light, produced from a common source, are recombined by a lens system, usually the eye. The difference in path lengths along which the rays travel before being recombined determines their phase relationship, and hence the sensation or otherwise, of light entering the eye.

For an understanding of the phenomena associated with interferometry, it is necessary to consider the nature of light.

Two theories have been advanced to explain the nature of light: the Emission Theory, and the Wave Theory. The former was advanced by Newton, and considered light as consisting of particles emitted by luminous bodies, the impact of the particles on the eye causing the sensation of light.

The wave theory, however, was advanced by Huygens, and considered light as a wave motion propagated in the ether.

It is this theory, and its subsequent development, which satisfactorily explains the phenomena associated with light, including that of interference.

If then light is considered as an electromagnetic wave of sinusoidal form, it may be represented as in Fig. 2. 1.

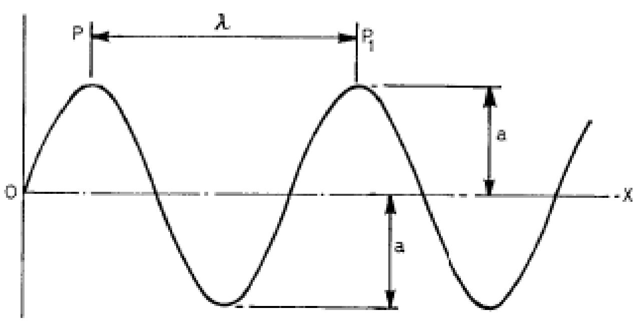


Fig. 2.1. Light represented as a sine wave.

The direction of propagation is along the O-X axis, and the distance travelled by the wave during the time (T) occupied in one vibration, is the wavelength **λ**. That is, at points of equal disturbance such as P P_1, the distance between these points constitutes the wavelength. The maximum disturbance of the wave is the amplitude, a, and its intensity a^2. The velocity, v, of transmission =**λ / T** and frequency =**1 / T.**

For any given monochromatic light source, these characteristics are virtually independent of ambient conditions such as temperature and pressure.

If we now consider, for example, the use of the ***green*** radiation from the spectrum of mercury 198 as a monochromatic light source for the absolute measurement of length, we have a wavelength of ***0•5461 μm*** of such reproducibility and sharpness of definition, that length measurement of an accuracy of ***1 part in 100 million*** may be made.

For many engineering purposes, ***white*** light, formed of the colors and therefore wavelengths of the visible spectrum, constitutes a valuable and convenient light source.

The following chart shows the approximate wavelengths of the colors forming the visible spectrum, and explains why such sources ***cannot be considered as being suitable as the basis***

of absolute length measurement. The individual colors cannot be ***sharply*** defined as being of definite wavelength, but for many practical measuring problems it is appropriate to consider the average wavelength, approximately ***0•5 µm***, of white light formed by the blending of the visible spectrum colors, as being sufficiently accurate to constitute a standard of length.

Colour	*Range of Wavelengths (µin)*	*Range of Wavelengths (µm)*
Violet	**15•7-16•7**	**0•396-0•423**
Blue	**16•7-19•3**	**0•423-0•490**
Green	**19•3-22•6**	**0•490-0•575**
Yello	**22•6--23•6**	**0•575-0•600**
Orang	**23-6-25-4**	**0•600-0•643**
Red	**25•4-27•5**	**0•643--0•698**

That the primary colors have such ***ill-defined*** wavelengths is the principal reason for the intensive efforts made by physicists over many years to produce ***pure monochromatic*** light such as that from mercury 198 or ***krypton 86***, having a precise, reproducible wavelength.

3- MONOCHROMATIC RAYS

A ray of monochromatic light maybe considered as being composed of an infinite number of waves of equal wavelength, the value of which determines the colour of the light.

If we now consider the effects of combining two such rays, we may do so by considering only two waves, one from each ray.

They may combine in such a way that the resultant effect is that the maximum amount of illumination is obtained. This condition is shown in Fig. 2.2 in which two rays, A and B, are in phase at their origin 0, and clearly will remain so for any distance of propagation.

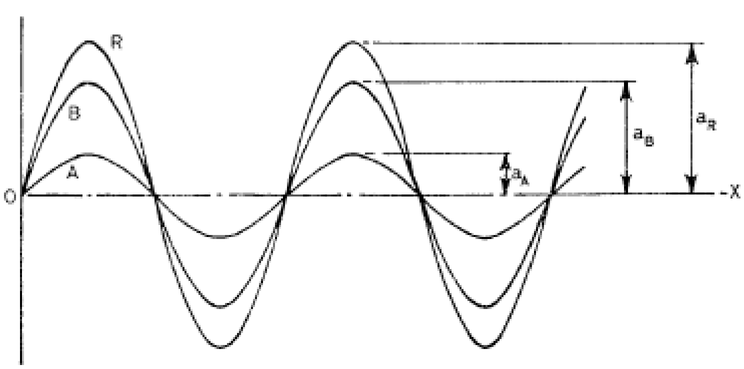


Fig. 2.2. Resultant amplitude a_R of two waves A and B of different amplitudes a_A and a_B, but in phase.

If A and B have the amplitudes shown, then the resultant wave R will have an amplitude $\boldsymbol{a_R = a_A + a_B}$.

In other words, when A and B are of the same wavelength and in phase, they combine to increase the amplitude, and therefore the intensity, of the resultant R to a maximum.

If now we consider the effect of changing the phase relationship of A and B by the amount **δ**, as in Fig. 2.3, it can be shown that when $a_A = a_B$, $a_R = 2a \cos \delta/2$.

That is, the combination of A and B no longer produces maximum illumination.

Further, if we consider the effect of changing the phase relationship of A and B, so that they are displaced 180°, or **λ/2**, then a condition as in Fig. 2.4 occurs, in which R has an amplitude which is the algebraic sum of a_A and a_B and is reduced to a minimum. It is important to note that if a a_A and a_B were equal in value, then a_R would be zero, as cos (180/2)=0. That is, complete interference between two waves of the same wavelength and amplitude produces darkness, and no sensation of light is registered on the retina of the eye.

It is the ability to split light from a single source into two component rays, to combine them, and observe the way in which they recombine, that allows the wavelength of light to be used for linear measurement. It should be noted that it is the linear displacement, **δ**, between two waves which is being measured, and that the maximum interference between them occurs when **δ= λ/2**.

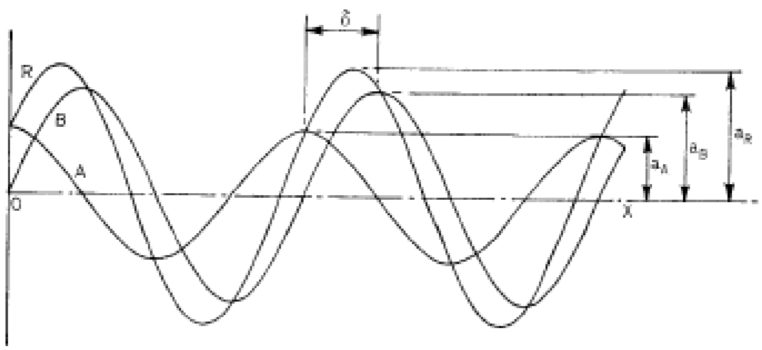


Fig. 2.3. Resultant amplitude a_R of two waves A and B out of phase by an amount δ.

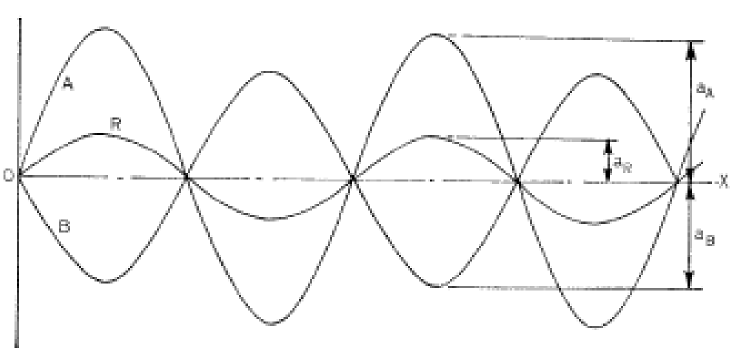


Fig. 2.4. Resultant amplitude a_R of two waves A and B out of phase by half a wavelength (180°).

Interference of two rays of light may be demonstrated in the following way. Referring to Fig. 2.5, **A** and **B** are effectively two point sources of monochromatic light having a common origin. **S** is a screen the plane of which is parallel to the line joining **A** and **B.** **O-O**$_1$ is perpendicular to the screen, and intersects the line **AB** at its mid-point.

The rays from **A** and **B**, since they have a common origin, and are therefore of the same wavelength, will be in phase.

If we now consider the effect at the point $\mathbf{O_1}$, on the screen, of the converging of the two rays from the point sources **A** and **B**, it is clear that since **AO1 =** $\mathbf{BO_1}$ the two rays will

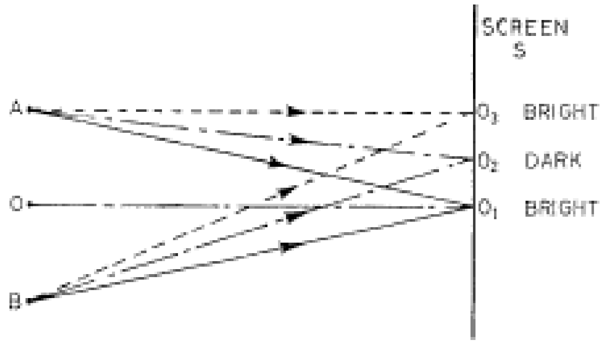


Fig. 2.5. Formation of alternate light and dark areas on a screen, due to waves from sources A and B travelling different path lengths.

arrive at $\mathbf{O_l}$ in phase, and will combine in a manner similar to that shown in **Fig.** ***2.2*** to give the maximum illumination at $\mathbf{O_l}$.

If we now consider a point such as $\mathbf{O_2}$ on the screen, the distance $\mathbf{AO_2}$ is clearly less than the distance $B0_2$, and if $\mathbf{BO_2}$ **-** $\mathbf{AO_2}$ is equal to an odd number of half wavelengths, that is $(2n + 1)\ (\lambda/2)$, where n is an integer, then the waves will be 180° out of phase, complete interference will occur and there will be darkness at this point.

Again, if we consider a point such as $\mathbf{O_3}$, then if $\mathbf{BO_3}$ **-** $\mathbf{AO_3}$ is equal to an even number of half wavelengths, that is $2n\ (\lambda/2)$, then the rays are again in phase, and no interference occurs at $\mathbf{O_3}$, this point receiving maximum illumination.

This process could be repeated at points both above and below **O**, and would result in alternate dark and light areas being formed. The dark areas would occur wherever the path difference of A and B amounted to an odd number of half wavelengths, and the bright where their path difference amounted to an even number of half wavelengths.

It must be emphasized that the phenomena described would occur only if the sources A and B were images of a single source. This can be achieved with a Fresnel biprism by which light passing through a slit is divided into two identical and equally spaced images, the rays from which, emanating from the same source, will be in phase at the images. It is the difference in path lengths of the subsequent rays which causes interference.

Summarizing, it is clear that the following two conditions are necessary for light interference to occur.

(a) Light from a single source must be divided into two component rays.

(b) Before being combined at the eye, the components must travel paths whose lengths differ by an odd number of half wavelengths.

4-INTERFEROMETRY APPLIED TO FLATNESS TESTING

A manufacturing problem frequently encountered in precision engineering is the production of flat surfaces of relatively small area. Such surfaces are normally produced by grinding followed by successive lapping operations until a high degree of flatness combined with a high surface finish is achieved. Virtually the only satisfactory, and certainly the only convenient, method of testing the flatness of such surfaces is by the use of light interference, using an optical flat as a reference plane.

An optical flat is a disc of stress-free glass, or quartz. One or both faces of the disc are ground, lapped and polished to a degree of flatness not normally countered on an engineering surface. For engineering purposes, the optical flat may be considered as a reference of flatness, and used as such for comparing engineering surfaces. Optical flats vary in size from 25 mm diameter to about 300 mm diameter, the thickness being about 50 mm for the largest. In all cases, they are relatively rigid and stress-free discs which, used and stored correctly, will retain their flatness and therefore effectiveness almost indefinitely.

If an optical flat is laid (not 'wrung') on to a nominally flat reflecting surface, it will not form an intimate contact, but will lie at some angle **θ'** as in **Fig. 2.6**, in which θ is greatly exaggerated. A wedge-shaped air cushion may be formed between the surfaces.

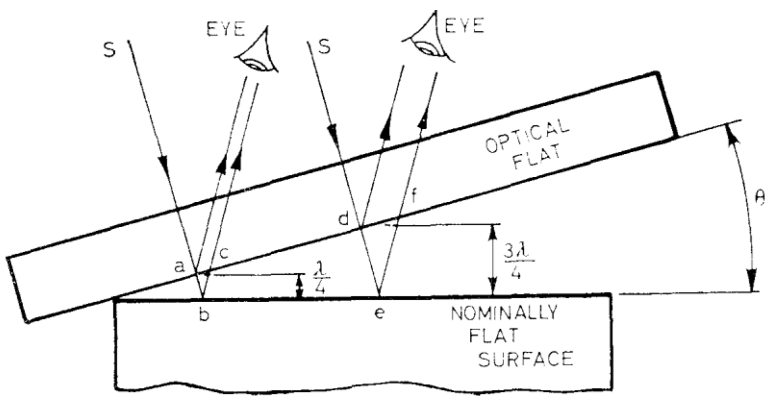


Fig. 2.6. Formation of interference fringes on a flat surface viewed under an optical flat in a parallel beam of monochromatic light.

If this arrangement is now placed in the path of a parallel beam of monochromatic light, we can consider **S** as the source of one wave of the incident beam. Ignoring any refractive effects due to the light passing through media, glass, and air, of differing densities, it is seen that the wave from S is partially reflected at '**a**' and partially transmitted across the air gap, to be reflected at '**b**', a point on the work surface. The two reflected components are collected and recombined by the eye, having travelled paths whose lengths differ by an amount **abc**.

If **abc = λ/2** where **λ** = wavelength of source, then the conditions for complete interference have been satisfied, i.e. the ray from **S** has been split into two components, and recombined; also, the path lengths of the components differ by an odd number (one) of half wavelengths.

If the surface is flat, then at right-angles to the plane of the paper it will be parallel to the optical flat, and these conditions will be satisfied in a straight line across the surface. Thus a straight dark line, or interference fringe, will be seen.

Further along the surface and due to angle **θ**, the ray leaving **S** will similarly split into two components whose path lengths differ by an amount **def.**

If **def=3 λ /2**, the next odd number of half wavelengths, interference will again occur and a similar fringe will be seen.

At an intermediate point, the path difference will be an even number of half wavelengths, the two components will be in phase, and a light band will be seen at this point.

Thus, a surface will be crossed by a pattern of alternate light and dark bands, which will be straight, for the case of a flat surface, as in **Fig. 2.7**. A deviation from straightness would be a measure of the error in flatness of the surface in a plane parallel to the apex of the angle **θ**.

Fig. 2.7. Interference fringes on a flat surface viewed under an optical flat in a parallel beam of monochromatic light.

Referring again to **Fig. 2.6**, it is seen that if **θ** is small (which it must be),

$ab = bc = \lambda/4 \qquad de = ef = 3\lambda/4$

The change in separation between the optical flat and the surface is the difference between **ab** and **de** (or **bc** and **ef**).

$de - ab = 3\lambda/4 - \lambda/4 = \lambda/2$

Thus the change in separation between the surface and the optical flat is equal to one half wavelength between similar points on similar adjacent fringes.

Note that if **θ** is increased the fringes are brought closer together, and if **θ** is reduced, i.e. the surfaces become more nearly parallel, the fringe spacing increases. The possible practical variation in **θ** is very small, since if the surfaces are too closely together ('wrung' together), no air gap exists, and no fringes are observable, and if **θ** is too large the fringes are so closely spaced as to be indistinguishable, and an observable pattern is not maintained.

In practice, it is unlikely that contact between the optical flat and the work surface will occur at one point only as in **Fig. 2.6.** It is probable that contact would be made at a number of points, or along one or a number of lines. **Fig. 2.8** shows the pattern which would be observed if the work surface were spherically convex. Contact is made at the central high point, resulting in a fringe pattern of concentric circles. If now each adjacent fringe represents a change in elevation of the work surface relative to the optical flat of **$\lambda/2$**, then

$2\lambda \times n$=Total change in elevation from point of contact to the outermost fringe.
where λ = wavelength of light used.
and n =number of adjacent fringes observed.

It is clear that the pattern observed when the surface is spherically convex will also be observed when the surface is spherically concave. To distinguish between these two conditions if, when the surface is spherically convex, one edge of the optical flat is lightly pressed, it will rock on a new high spot and the centre of the fringe pattern will move as shown in **Fig. 2.9**, and the outer fringes move closer together.

Also, when the surface is spherically concave, the flat rests on a line passing around the surface, and if the edge of the optical flat is lightly pressed, the edge line does not move as the pressure is varied. Alternatively, light pressure at the centre of the optical flat will cause it to deflect slightly and become more nearly parallel with the concave surface, thus reducing the number of fringes observed.

Commonly, optical flats are used in normal daylight, the spectrum of which has a wavelength of approximately **0•5 µm**. Thus, each fringe interval corresponds to a change in elevation of the surface of **0•25 µm**.

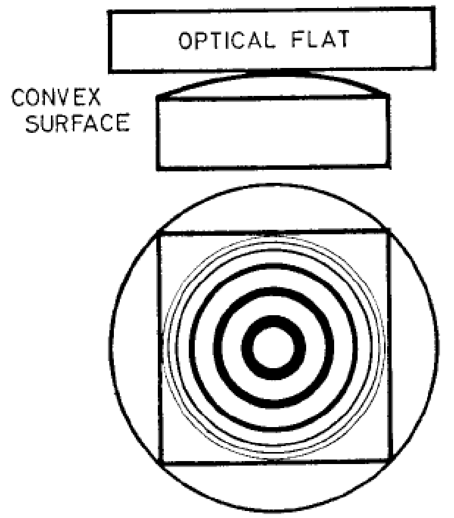


Fig. 2.8. Fringe pattern produced on a convex surface. Note that as the angle between the surface and the optical flat increases the fringes become narrower and more closely spaced.

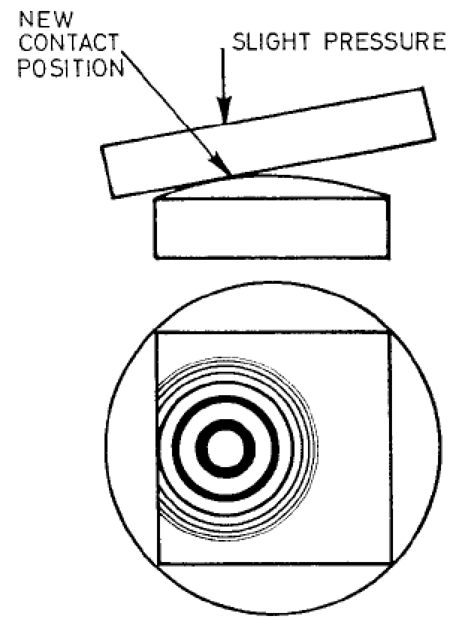


Fig. 2.9. Method of testing to show that a surface is convex.

Suppose an optical flat to be laid on to a surface, and the resulting fringe pattern is that shown in **Fig. 2.10.**

Having first determined the point or line of contact of the optical flat, which is assumed to be at **AA**, it must be remembered that the contour of each fringe lies on points of equal height (in a negative direction) relative to the surface of the optical flat. Thus, the fringe pattern in fact, represents a contour map of the surface under test, the spacing of the fringes representing height intervals relative to the optical flat of **λ /2**.

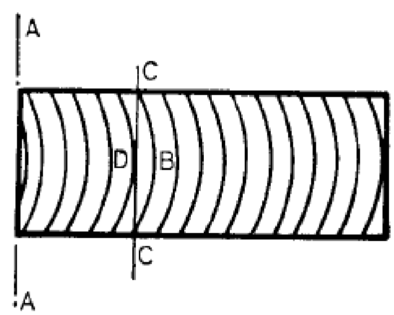


Fig. 2.10. Fringe pattern formed on a surface whose C.L. is half a wavelength higher than its edges.

In **Fig. 2.10**, point **C** is the same distance from the optical flat as point **B**, but **λ /2** farther (or nearer) than point **D**. Therefore the edge at **C** is **λ /2** higher (or lower) than **D**.

If the fringes curve towards the line of contact at **A**, the surface is convex, the opposite case also applying.

Practice in the use of optical flats is essential to a true understanding of the patterns produced, and at this point it may be appropriate to indicate the points to be observed in their use.

(a) Handle optical flats carefully, and the minimum amount.

(b) Ensure that the work surface and the optical flat are perfectly clean, by careful wiping with a cloth of the

'Selvyt' type or with chamois leather.

(c) Never `wring' an optical flat to a work surface. It should be laid on, so that the flat is not distorted by tending to adapt itself to the contour of the work surface, thus producing a false fringe pattern.

(d) Never `wring' two optical flats together. Separation may be difficult and cause damage.

5 INTERFEROMETERS

Although optical flats can be used in either daylight, or, better, in a diffused source of near-monochromatic light, e.g. a light box consisting of a sodium discharge lamp behind a yellow filter, they suffer the following disadvantages for very precise work :

(a) It is difficult to control the `lay' of the optical flat and thus orientate the fringes to the best advantage.

(b) The fringe pattern is not viewed from directly above and the resulting obliquity can cause distortion and errors in viewing.

These problems are overcome by using optical instruments known as interferometers, two of which will be discussed, one for measuring flatness and the other for determining the length of slip and block gauges by direct reference to the wavelength of light.

5.1 The N.P.L. Flatness Interferometer

This instrument, shown in diagrammatic form in **Fig. 2.11**, was designed by the National Physical Laboratory and is manufactured commercially by Coventry Gauge and Tool Co. Ltd., and Hilger and Watts Ltd.

It consists essentially of a mercury-vapour lamp whose radiations are passed through a green filter, thus removing all other colours, and leaving a green monochromatic light whose wavelength is very close to **0•5 µm**. This light is focused on to a pinhole, giving an intense point source of monochromatic light, which is in the focal plane of a collimating lens, and is thus projected as a parallel beam of light. This beam is directed on to the gauge to be tested via an optical flat so that interference fringes are formed across the face of the gauge, the fringes being viewed from directly above by means of a thick glass plate semi-reflector set at **45°** to the optical axis.

It should be noted that the optical flat is mounted on an adjustable tripod, independent of the gauge base plate, so that its angle can be adjusted. Further, the gauge base plate is designed to be rotated so that the fringes can be orientated to the best advantage.

An advantage of this instrument is that it can also be used for testing the parallelism between gauge surfaces. Two methods are used:

(a) For gauges below **25** mm in length.

(b) For gauges greater than **25** mm in length.

When shorter gauges are used interference fringes are formed both on the gauge surface and the base plate. As the gauge is wrung on to the base plate its underside is parallel with its base plate. This means that if the gauge faces are parallel the fringes on the base plate should be equally spaced, and parallel with the fringes on the gauge surface.

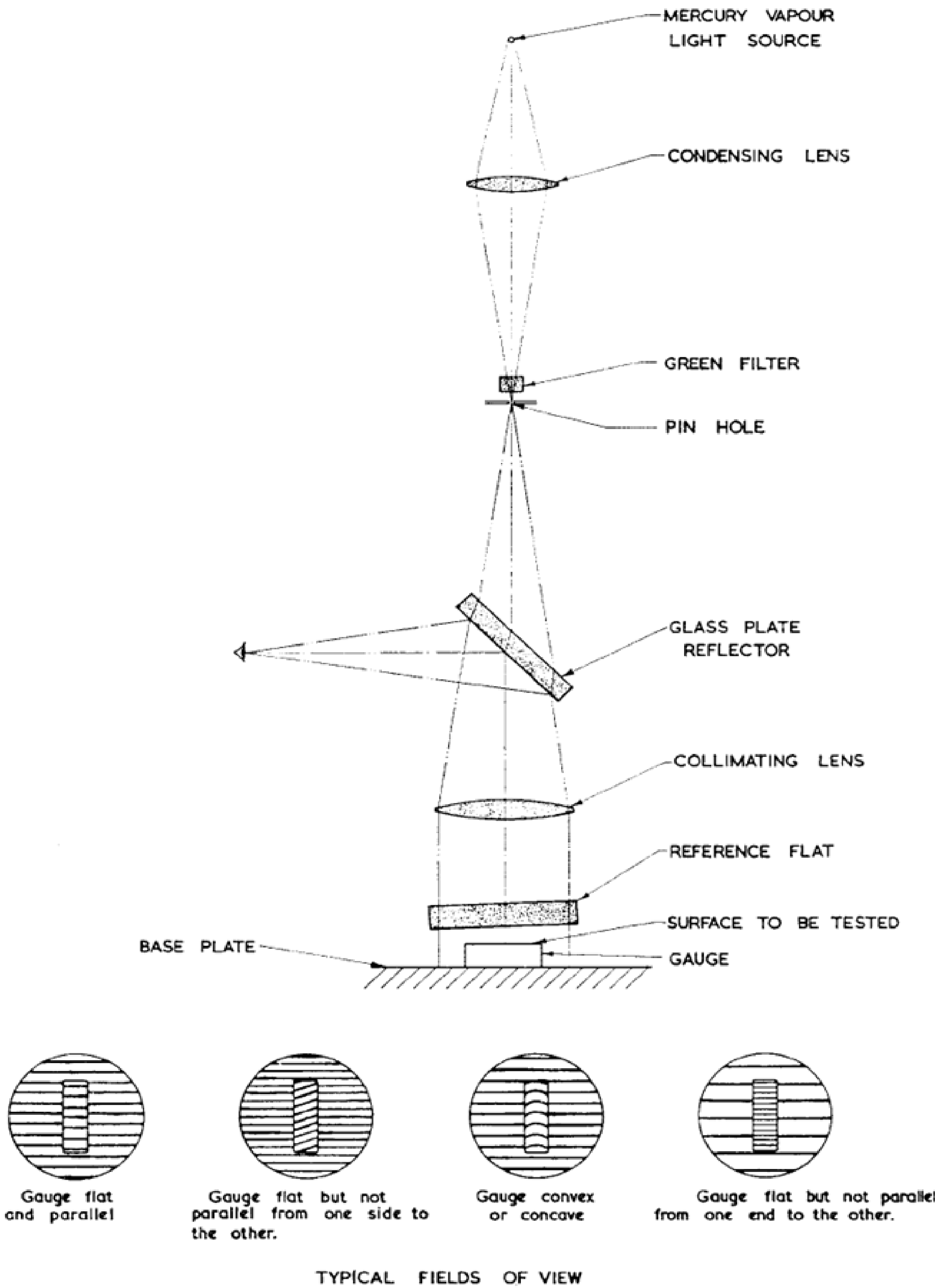


Fig. 2.11. Optical arrangement of interferometer for testing flatness of surfaces.
(*Courtesy of the N.P.L. Crown Copyright*)

If the gauge being tested is more than **25** mm in length the fringe pattern on the base plate is difficult to observe, but the base plate is rotary and its underside is lapped truly parallel with its working surface. Therefore if a non-parallel gauge is viewed the angle it makes with the optical flat will be as in **Fig.** ***2.12*** *(a).* If the table is turned through **180°** the surface is now less parallel with the optical flat, **Fig.** ***2.12*** *(b),* and a greater number of fringes is observed.

Consider a gauge which exhibits **10** fringes along its length in one position and **18** fringes in the second position.

In **Fig.** ***2.12*** *(a)* the distance between the gauge and the optical flat has increased by a distance δ_1 , over the length of the gauge, and in the second position [**Fig.** ***2.12 (b)]***, by a distance δ_2.

It has been shown that the distance between the gauge and the optical flat changes by $\lambda/2$ between adjacent interference fringes.

Therefore, $\delta_1 = 10 \times \lambda/2$ and $\delta_2, = 18 \times \lambda/2$

The change in the angular relationship is $\delta_2 - \delta_1$

$$\delta_2 - \delta_1 = 8 \times \lambda/2$$

But due to the rotation through **180°** there is a doubling effect. Therefore the error in parallelism= $(\delta_2 - \delta_1) / 2 = (8 \times \lambda/2) / 2 = 4\ \lambda/2$

If the wavelength used is **0•5** μm, then $(\delta_2 - \delta_1) / 2 = (4 \times 0.5) / 2 = 1.0\ \mu m$

Thus the gauge has an error in parallelism of **1•0 micro-meters** over its length.

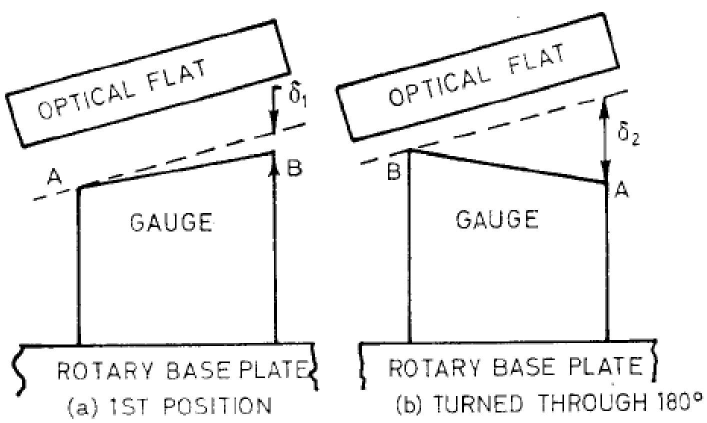


Fig. 2.12. Testing parallelism on gauges over 25 mm in length using flatness interferometer.

5.2 The Pitter-N.P.L. Gauge Interferometer

The mechanical subdivision of end standards of length tends to be laborious, especially when the smaller sizes are considered, and it is therefore liable to error. In view of this, and the requirements of B.S. 4311, it is no longer used for gauges less than **18 in or 50 cm** in length, and has been superseded by interferometric methods of calibration.

A well-known interferometer is the **Pitter-N.P.L.** Direct Measurement Interferometer, which is based on a **N**ational **P**hysical **L**aboratory design. **Fig. 2.13** shows a diagrammatic arrangement of the instrument, and the field of view in the eyepiece.

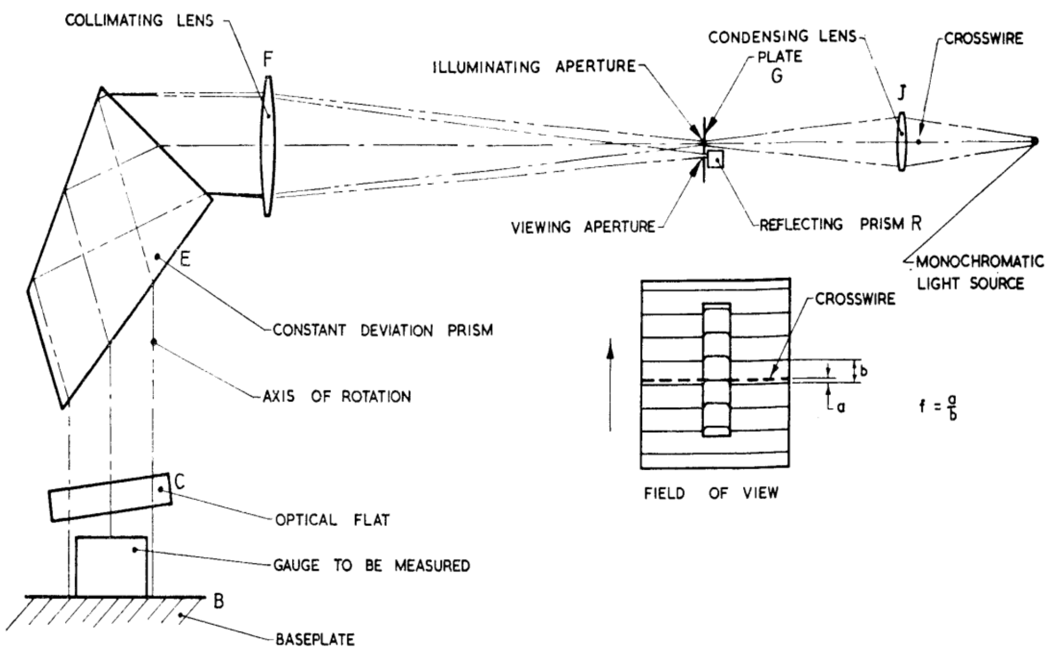


Fig. 2.13. Diagram showing the optical system for the 0–4 in N.P.L. interferometer for measuring slip gauges. (*Courtesy of the N.P.L. Crown Copyright*)

In operation, light from the cadmium lamp is condensed by lens **J** on to the pin-hole plate **G**, thus providing an intense point source, in the focal plane of the collimating lens **F**. The resulting parallel beam passes to the constant-deviation prism **E**, where its colors, and therefore wavelengths, are split up and any one selected as required, by varying the angle of the reflecting faces of the prism relative to the reference plane **B** of the platen. The beam is turned through **90**° and directed to the proof-plane **C**, the lower surface of which is coated with a semi reflecting film of aluminum, which transmits and reflects equal proportions of the incident light. Part of the light is reflected upwards, and part is transmitted through the proof plane to the upper surface of the slip gauge, and to the reference plane of platen **B**. Light reflected from each of these surfaces passes back through the optical system, but its axis is deviated slightly, due to the inclination of the proof-plane, so that it is interrupted by prism **R** to be turned through 90° into the eyepiece and the observer's eye.

The fringe pattern observed may be as shown. One set of fringes is due to the reflecting surface of the platen, and superimposed on this are the fringes due to the upper surface of the slip gauge wrung to the platen. Generally, the sets of fringes will be displaced as shown, the amount of displacement varying for each colour, and therefore wavelength, of light resolved by the constant-deviation prism. The displacement observed, ***a***, is expressed as a fraction of the fringe spacing, ***b***, i.e. $f = a / b$. It is sufficient to estimate this fraction, but to assist in this the cross-wire may be moved across the optical path, its image appearing in the eyepiece. An estimation of f is made for each of the four radiations from the cadmium lamp, red, green, blue, and violet, resolved by suitably rotating the constant-deviation prism.

5.2.1 Method of Measurement

It is important to bear in mind that the physical conditions surrounding measurements of a nature such as this must be standardized and controlled. The standard conditions are as follows:

20°C temperature; **760 mm Hg** barometric pressure; with water vapour at a pressure of **7 mm Hg** and containing **0•03 %** by volume of carbon dioxide. If the conditions of measurement vary from these, correction factors must be applied.

Consider the measurement of a **3 mm** slip gauge, using three wavelengths of the cadmium radiation. The wavelengths used will be as follows:

Red 0.643 850 37 *μm* or, in 1 mm, there are 3106.311 80 half wavelengths.
Green 0.508 584 83 *μm* or, in 1 mm, there are 3932.480 64 half wavelengths.
Violet 0.467 817 43 *μm* or, in 1 mm, there are 4275.172 05 half wavelengths.

Fig. 2.14 (a) shows the arrangement, diagrammatically, of the reference plane or platen, slip gauge, and proof-plane, while **Fig. 2.14 (b)** shows the fringe relationship, $a / b = 0{\bullet}65$ for the red radiation, as viewed through the eyepiece of the instrument. For each of the wavelengths employed, in succession, a different fraction ***a / b*** will be observed.

The height **G** of the gauge will be equal to a whole number of half wavelengths, ***n***, plus the fraction ***a / b*** of the half wavelength of the radiation in which the fringes are observed.

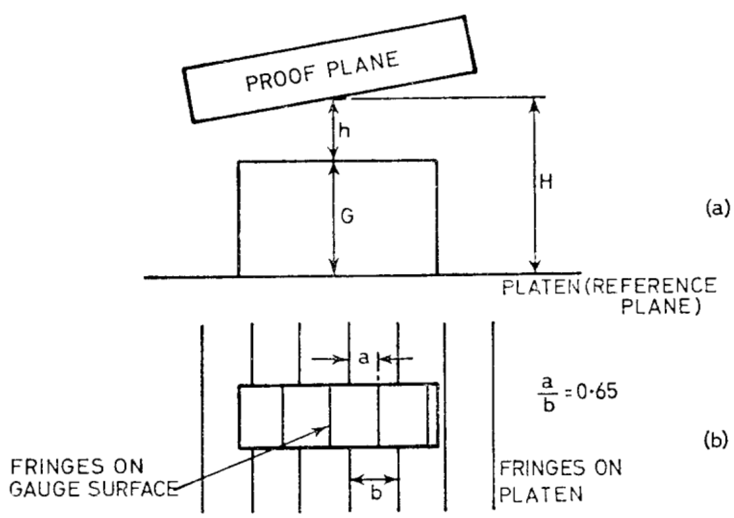


Fig. 2.14. Fringe displacement between gauge and base plate in N.P.L.-type gauge interferometer.

i.e. **$G = H - h = n \cdot \lambda/2 + (a/b) \cdot \lambda/2$**

We thus have observed fractions a_1/b_1, a_2/b_2 a_3/b_3 for each of the radiations, which may be expressed as f_1 ; f_2 ; f_3 respectively.

A series of expressions may now be obtained for the height of the gauge above the platen.

$$G = \lambda_1/2\ (n_1+f_1)\ ;\ G = \lambda_2/2\ (n_2+f_2);\ G = \lambda_3/2\ (n_3+f_3)$$

But the values of f_1 ; f_2, etc., are the observed fractions a/b and not necessarily the values which would be obtained by calculation using the nominal height of the gauge and the values of λ for the three radiations.

We therefore have, for the nominal size:

$G_N = \lambda_1/2\ (N_1+F_1)$

$G_N = \lambda_2/2\ (N_2+F_2)$

$G_N = \lambda_3/2\ (N_3+F_3)$

where G_N =nominal gauge height

N=number of whole half wavelengths in G_N

F=fractional displacement of fringes for any given radiation and due to height G_N in which N and **F** are found by dividing the half wavelength $\lambda/2$ into the nominal height of the gauge G_N

By combining the two sets of equations, we obtain the general expression:

$$G - GN = (\lambda/2)[(n-N)+(f-F))$$

Assume that the observed fractions, f, **are** $f_1 = 0.23$; $f_2 = 0.33$, and $f_3 = 0{\bullet}71$, and that the calculated values of **F** are $F_1 = 0{\bullet}94$; $F_2 = O{\bullet}44$; $F_3 = 0{\bullet}52$ for the three radiations red, green, and violet respectively.

Inserting this information in the above equations we have :

$$G - GN = (0.643/2)\ [(n_1 - N_1) + (0{\bullet}23 - 0{\bullet}94)]\ \mu m$$
$$= (0.508/2)\ [(n_2 - N_2) + (0{\bullet}33 - 0{\bullet}44)]\ \mu m$$
$$= (0.467/2)\ [(n_3 - N_3) + (0{\bullet}71 - 0{\bullet}52)]\ \mu m$$

$$G - GN = (0.643/2)\ [(n_1 - N_1) + (0{\bullet}29)]\ \mu m$$ Note : (1-0.71)= 0.29

$$= (0.508/2)\ [(n_2 - N_2) + (0{\bullet}89)]\ \mu m$$ Note : (1-0.11)= 0.89

$$= (0.467/2)\ [(n_3 - N_3) + (0{\bullet}19)]\ \mu m$$

The values $(n_1 - N_1)$, $(n_2 - N_2)$ and $(n_3 - N_3)$ are unknown but it is known that they are :

(a) whole numbers , and *(b)* relatively small numbers. They can be found by trial and error, and it is found that if:

$$(n_1 - N_1) = 2$$
$$(n_2 - N_2) = 2$$
$$(n_3 - N_3) = 3$$

a closely similar result for all three equations is found. However, this is laborious and a better method is to set the information out in tabular form as follows:

1	2	3	4	5	6	7
Wave-length (λ) μm	*Observed Fractions* (*f*)	*No. of* λ/2 *in* 3·0 mm	*Calculated Fractions* (*F*)	*Col.* 2–*Col.* 4	*Scales Coincide*	*Mean error in Gauge Length*
R=0·643	0·23	9318·9354	0·94	0·29	2·29	0·74 μm
G=0·508	0·33	11 796·441 92	0·44	0·89	2·84	
V=0·467	0·71	12 825·5165	0·52	0·19	3·13	

The values shown in columns **6** and **7** are obtained by the method of scale coincidence. This offers the simplest method of obtaining the whole numbers of half wavelengths and fractions of half wavelengths which are contained in the error in the gauge. A slide rule may therefore be used **(Fig. 2.15)** in which the wave lengths of red, green, and violet are set out to scale, from a common zero. The values obtained in column **5** of the table are found to have a close degree of coincidence at the values shown in column **6**. The lower scale of the slide rule has graduations corresponding to micro-meters and a line passing through the values **2•29, 2•89** and **3•19** on the wavelength scales cuts the linear scale at **0•74 µm**, the error in the height of the gauge.

It is found in practice that the values of (**f**) cannot be read to an accuracy greater than about **0•05** of a fringe spacing. This accounts for the small discrepancies in the fractional parts of the values shown in column **6**, compared with the fractions shown in column **5.** Since the linear error resulting from an observational error of this order will always be much less than **0•02 µm**, it can be tolerated.

It should be noted that the half wavelength units on the negative side of the scales are $\bar{n}$ not **-** ***n***, i.e. the whole numbers are negative but the fractions are still positive. Thus considering the cursor line shown to the left of zero, the displacements are respectively:

Red $\bar{2}$**.48 = (-2+0.48)= -1.52** half wavelengths
Green $\bar{2}$**.09 = (-2+0.09)= -1.91** half wavelengths
Violet $\bar{3}$**•92 = (-3+0.92) = -2.08** half wavelengths

Thus the gauge error is equal to those values multiplied by the respective half wavelengths.

$$\textbf{Error} = \begin{cases} -1.52 \times \frac{0.643}{2} = -0.488\mu m \\ -1.91 \times \frac{0.508}{2} = -0.485\mu m \\ -2.08 \times \frac{0.467}{2} = -0.486\mu m \end{cases}$$

Mean error= - 0 •486 µm

Note that the scale cannot be read to three decimal places. In the authors' opinion it should be used for establishing the position of coincidence and an approximate solution. The actual errors should be calculated, as shown above, for each wavelength, and then the mean value found.

The important fact about this method of measurement is that the gauge length is established without reference to any physical standard, and only in terms of the wavelengths of the various monochromatic radiations employed.

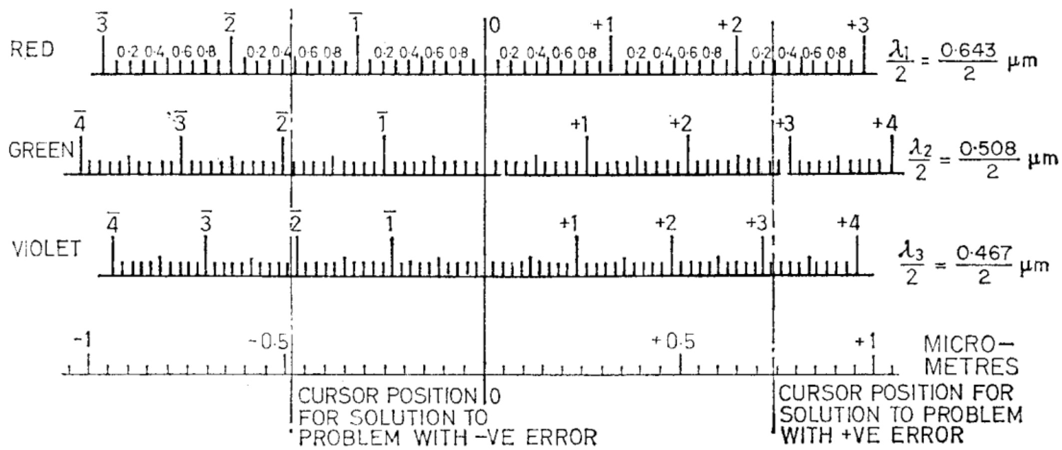


Fig. 2.15. Layout of scales of half wavelength on slide rule for use with N.P.L. gauge interferometer.