

A COMPARATOR ACCESSORY FOR THE
AUTOCOLLIMATOR AND A NEW BORE GAUGE

BY

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DECLARATION

I hereby declare that this thesis has been composed by myself and that it is a record of my own research work. It has not been accepted in any previous application for a higher degree. All quotations are distinguished by quotation marks and the sources of information are specifically acknowledged by means of references.


A. B. DARE

September, 1982.

ABSTRACT

Two new instruments have been designed, constructed and tested.

One is a highly sensitive and accurate comparator accessory for the autocollimator for use in any metrology laboratory or inspection department for internal and external measurements of various types of workpieces. It is capable of measuring workpieces of fairly wide range of sizes, but by varying the length of the styluses in the case of internal measurements.

The second is a fairly sensitive bore gauge for internal diameter measurements in any conventional engineering production shop, based on the principle of locating the bore of the workpiece through three contact points equally spaced at 120° to each other. It can be used to take a minimum bore measurement of 50 mm and by replacing the pin heads with larger ones, the range of measurement could be increased up to twice the minimum dimension.

The tests carried out with the comparator on external measurements show a high degree of accuracy comparable to that obtained from the Universal measuring machine. For internal diameter measurements, both the comparator and the bore gauge gave slight errors which are largely due to functional errors as a result of low production accuracy of some of the parts.

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September, 1982.

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CHAPTER ONE
I N T R O D U C T I O N

1.1. Background And Objective Of The Designs:

The development of technology has increased the demands for design accuracy and this in turn has brought about the necessity for the development of highly sensitive and accurate measuring instruments.

Though the development and manufacture of measuring instruments has not gained wider recognition among engineering industries in Nigeria, these instruments are vital tools on the shop floors and in the inspection departments of these industries.

A lot of work has been done in the field of engineering metrology outside the country which interested engineers in Nigeria can also do like their counterparts elsewhere in the world. But lack of interest on the part of these qualified Nigerian engineers had led to the importation of the various measuring instruments used in the country, even in the engineering schools.

On the production floor, fairly sensitive instruments which can sustain the rough use commonly associated with the engineering production floor are needed, while in the inspection departments, the importance of highly sensitive measuring instruments cannot be overemphasized. Comparators which are used to make

accurate measurements (by comparing with a precision standard) are expensive instruments and if existing instruments can be modified or adapted for such purposes, much saving can be made in investments.

Motivation:

Most of the measuring instruments used in both governmental and private sectors in the country have always been imported.

Considering this short-coming and the problems encountered by the engineering institutions especially metrology research laboratories, the idea to embark on the design of a comparator accessory for an autocollimator and a new bore gauge was conceived and finally transformed into reality.

Objective:

The aim of this work was to produce two new instruments.

The first one is a highly sensitive linear comparator which can be used in taking measurements where accuracy is of high importance. Autocollimators are the most sensitive angle measuring instruments. When two workpieces or standards kept at a distance on a table are bridged with a reflector carrier, a reading can be taken with an autocollimator. If one piece or standard is now changed and another one put in its position, the difference in length of the original one and the replacement can be determined from the change in the angle reading of the autocollimator.

This principle was used in developing a comparator, which is capable of comparing accurately internal and external dimensions of workpieces with known standards.

The second one is a fairly sensitive bore gauge which can be subjected to the rough use associated with the engineering production floor. When measuring a bore, it is important that a true diameter perpendicular to the axis of the bore is measured and this is best done by three-point contacts since only one circle can pass through three points. These three contact points can be achieved by arranging them round a taper block. As the taper block is pressed down and with suitable arrangements, these three contact points can be made to move out equally to locate the bore. With the choice of an appropriate angle of the taper block and the attachment of a linear indicator the increase in diameter of the taper and hence the distance moved out by the three contact points can be determined. Adding this distance to the initial diameter of the instrument will give the diameter of the bore. This has been used in the development of the bore gauge which can measure the internal diameter of workpieces to a reasonable degree of accuracy.

1.2. Outline Of Present Contributions Of The Designs:

The work has brought two new additional measuring instruments into the field of engineering metrology.

One is a highly sensitive and accurate comparator which can be used in any metrology laboratory or

inspection department for accurate internal and external linear measurements.

The second is a fairly sensitive and portable bore gauge which can be used for internal diameter measurements in any conventional engineering production shop.

1.3. Layout Of The Thesis:

This thesis comprises seven chapters of which this introductory chapter is the first. Chapter two deals with the autocollimator, its uses and potentiality as a linear comparator. Here, the discussion centres on the principle, uses, and adaptation of the autocollimator as a linear comparator. Chapter three deals with some of the types of bore measuring instruments and methods and the advantages and disadvantages of each.

Chapter four is on the comparator accessory for the autocollimator, covering the detailed description and the functioning of the instrument while chapter five, which follows the same pattern of description as chapter four, is on the bore gauge.

In chapter six, some of the uses of the new instruments are discussed and the results of measurements obtained using the new instruments are compared with those obtained with standard measuring instruments. Finally in chapter seven, the advantages of the instruments are enumerated and some conclusions as well as recommendations are drawn.

Appendix lists are provided while the main engineering drawings of the instruments are stacked separately at the end of the thesis.

CHAPTER TWO

THE AUTOCOLLIMATOR, ITS USES AND POTENTIALITY

AS A LINEAR COMPARATOR

2.1. Introduction:

Of utmost importance in any engineering design are the underlying principles employed in arriving at the final design stage. This chapter deals exclusively with the autocollimator, its uses and the possibility of its being converted to a linear comparator.

2.2. The History Of The Autocollimator:

The autocollimator is one of the optical instruments used for the precise measurement of small angular variations, having a range of 10 minutes with a sensitivity of 0.2 second. They came into use, first among optical instruments manufacturers for checking parallelism and squareness of optical and mechanical components in instruments. These early ones were not complete instruments in themselves but were made as accessories to other instruments.

Since the 1920s, demands for increasing accuracy in manufacture were met by improved methods of measurement and instruments and the autocollimator was developed as a commercial instrument for use in standards rooms and inspection departments, and sometimes permanently set up on structures used for missile construction and launching.

The use of autocollimators is not restricted to instruments which are sold as such in their own right.

Many optical measuring and other instruments incorporate autocollimating systems. One such instrument is a comparator designed by Zeiss and now made in England by Optical Measuring Tools Limited and Precision Grinding Limited (Hume, 1965).

2.3. Principle Of The Autocollimator:

The functioning of the autocollimator is based on two optical principles. The first is the collimation of a beam of light emerging from a point source at the principal focus of a collimating lens and the second, the deflection of a beam of light caused by the tilting of a plane reflector placed in front of the collimating lens.

In optics, it has been shown that a point source of light from the focal point of a collimating lens will be projected as a parallel beam of light. If the beam strikes a plane reflector normal to the optical axis, it will be reflected along its own path and refocussed at the source A (Fig. 1). If the plane reflector is now tilted through a small angle α , then the reflected parallel beam will turn through 2α and be brought to a focus at B in the focal plane of the lens (Fig. 2), where the distance

$$AB = 2\alpha f$$

(f being the focal length of the collimating lens).

The optical arrangement of the autocollimator is shown in Fig. 3. A pair of target wires in the focal plane of the collimating lens is illuminated from behind and their image projected. This forms an image in the

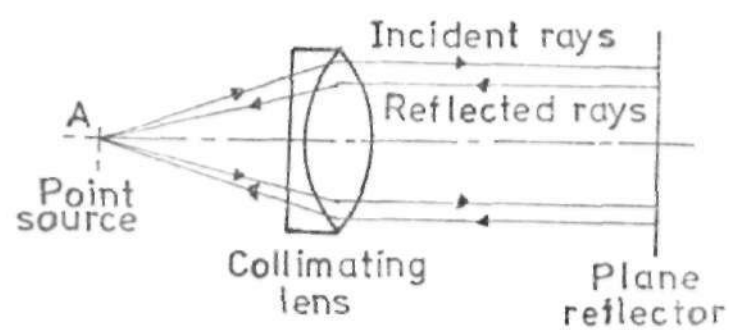


FIG-1- LIGHT PATH WHEN THE REFLECTOR IS KEPT NORMAL TO THE AXIS
OF THE COLLIMATING LENS.

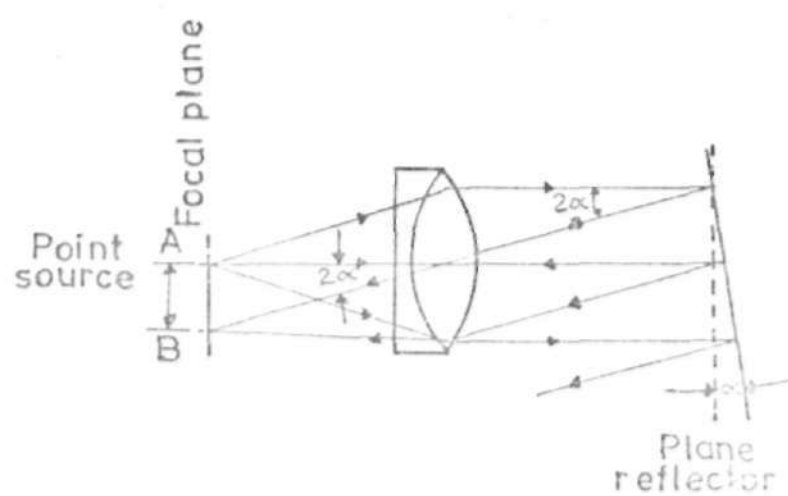


FIG-2 - LIGHT PATH WHEN THE REFLECTOR IS INCLINED TO THE AXIS
OF THE COLLIMATING LENS.

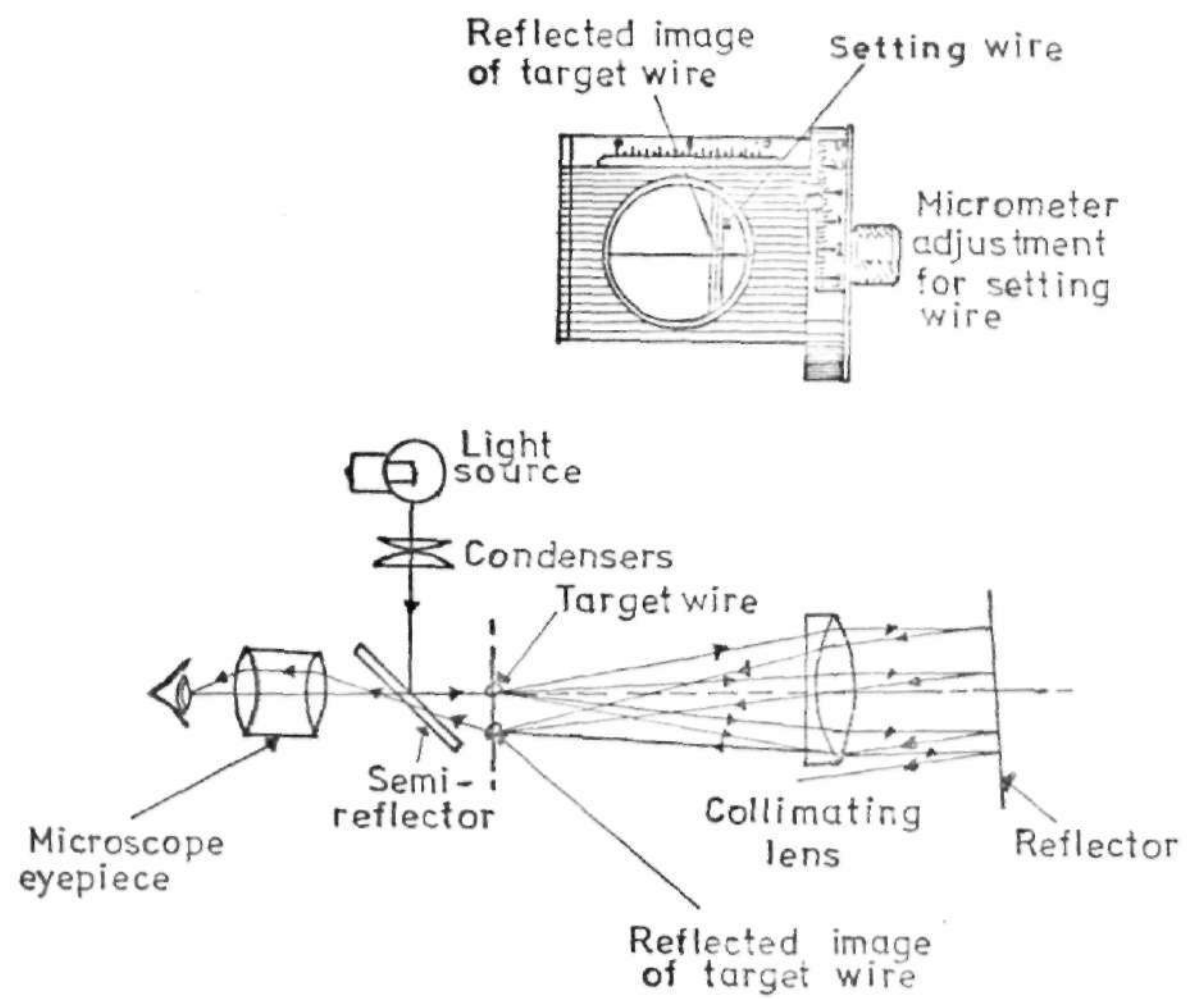


FIG. 3 - OPTICAL ARRANGEMENT OF THE AUTOCOLLIMATOR

focal plane of the lens which is viewed on the eyepiece containing also a pair of adjustable setting wires and a scale. These setting wires are adjusted by a micrometer until they straddle the reflected image. The scale can then be read to the nearest half minute. Since the micrometer drum moving the wire (at half minute per revolution) is first divided into thirty equal parts, and each of these parts is further subdivided into five equal parts, a division of the drum will correspond to an angular variation of the reflector of 0.2 second of arc.

The autocollimator has been used with the Sine formula in the design of the comparator and the set up is similar to that shown in Fig. 4. It is known that

$$\sin \theta = \text{Side opposite to angle } \theta / \text{Hypotenuse}$$

and if θ is very small, then

$$\sin \theta = \theta = \frac{h}{\ell}$$

$$\therefore \theta = \frac{h}{\ell} \text{ or } h = \ell \theta,$$

where h = linear rise and ℓ is the effective length of the reflector carriage (Fig. 4).

Hence if the angular tilt of a reflector is read from an autocollimator and knowing the effective length of the reflector carriage, the above formula can be used to obtain the linear rise or fall when the actual work-piece is compared with a reference standard.

2.4. Uses Of An Autocollimator:

There are various forms in which the autocollimator can be used in conjunction with specific accessories. Its most widely used application is as a sensitive level in which case the reflector carriage will replace the level. Apart from this use, the autocollimator is useful in

- (1) angle measurements
- (2) machine alignment tests
- (3) squareness tests
- (4) straightness tests
- (5) calibration of precision polygons
- and (6) linear comparators.

Of all these, only its use as linear comparators is of significance to this work.

2.5. Linear Comparators:

Linear comparators are usually used for linear measurements by comparing with a standard of known dimension. The comparator magnifies the difference between the workpiece and the standard to a large extent and gives an accurate estimate of the dimension of the workpiece.

There are different principles used in obtaining suitable degrees of magnification of the indicating devices of comparators relative to the changes in the dimensions being measured. Some of these principles are:

- (1) Mechanical
- (2) Mechanical - Optical

- (3) Pneumatic
- (4) Electrical
- and (5) Fluid displacement.

What is common to all these systems is that there is first displacement, then a magnification. It is the magnifying system that differs. Of importance in this work is the Mechanical - Optical system of magnification. Here, small displacements of a measuring stylus are amplified in two stages. First, by a mechanical system of a pivoted lever and secondly by the optical system provided by the autocollimator.

In the design of the comparator, the pivoted lever is in the form of a reflector carrier and the autocollimator measures the angular tilt of the reflector caused by the process of measurement.

2.6. Autocollimator As A Linear Comparator:

As mentioned earlier on, a comparator system that incorporated an autocollimating system was that by Zeiss. Since the introduction of this, many attempts have been made to use autocollimators for linear measurements. Notable among these attempts is the one described by Sharp (1970) for hole diameter measurement which will be discussed later on. To exploit further the potential offered by the autocollimator as a linear comparator, a special unit was designed by the Metrology Department of International Computers Limited (Purvis, 1972). In this unit, a rigid cast iron base plate in form of an inverted

U section supports a reference surface in the form of a granite surface plate and both the support casting and reference surface contain a small co-axial central aperture. The autocollimator is mounted on a base plate by the side of the support casting and the collimated beam of light is deflected through the aperture in the reference surface by a prism mounted in a bracket, which is positioned directly beneath the aperture and in front of the autocollimator. Where the greatest accuracy is required, a lapped platen, also containing a central aperture, may be superimposed over the aperture in the granite surface plate.

Also in the designing of a new precision internal measuring machine by Taylerson and Turner (1953), a main casting supported on an elevated table was used. The machine was able to measure to a very high degree of accuracy, but over an extended range, the measurements would have to be made at lower magnifications with a corresponding proportional drop in accuracy.

Similarly, the autocollimator with a sine bar and a reflector carriage could be used as a linear comparator as shown in Fig. 4. In this case, slip gauges are built up on one side under the sine bar and the reference standard or workpiece is placed under the other side of the sine bar, the slip gauges and the standard or workpiece resting on a flat surface. If L is the effective length of the sine bar and θ is the change in the autocollimator reading as a result of comparing the actual workpiece with a reference standard, then the difference

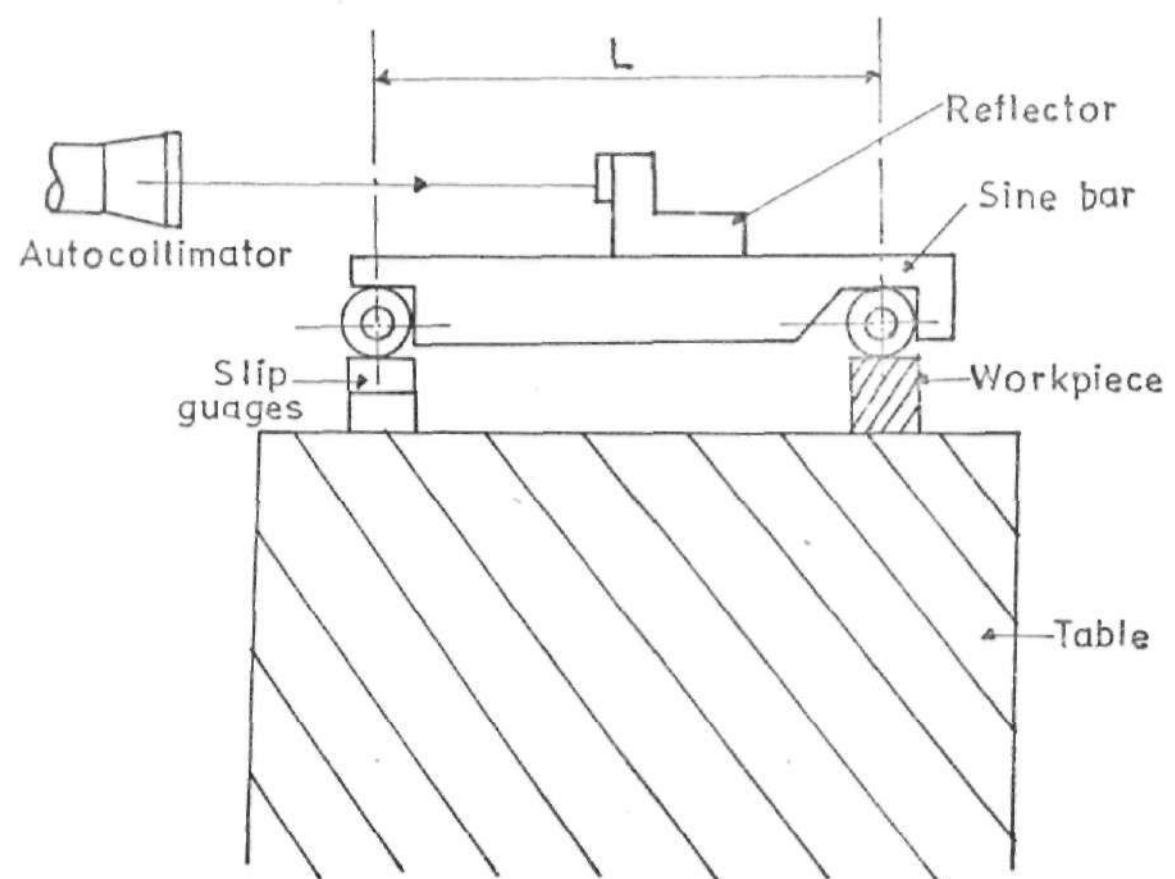


FIG. 4 - AUTOCOLLIMATOR AS A LINEAR COMPARATOR

in length of the workpiece and standard is θ where θ is the angular tilt in radians.

This last principle has been used in the present design of the comparator accessory.

2.7. Concluding Remarks:

It can thus be concluded that the use of an autocollimator as a linear comparator has been due to its high sensitivity and accuracy. Also, most of the adapted uses of the autocollimator has been for one type of measurement, either specifically for internal measurements or for external dimensions alone.

In this work, a device has been designed to use the autocollimator as a comparator capable of making both internal and external measurements.

CHAPTER THREE

BORE MEASUREMENT

3.1. Introduction:

The accuracy of bore measurements depends to a great extent on the accuracy with which the true diametrical axis is located perpendicular to the axis of the bore, especially if the method of measurement involves two-point contacts. Ideally, since only one circle can pass through three points, measurements involving three-point contacts are best. Whilst the accuracy of many types of measurement depends on feel for precision measurement, the measuring pressure should be kept constant.

In this chapter, some of the various instruments and methods of bore measurements are dealt with.

3.2. Internal Diameter Measuring Instruments And Methods:

These instruments and methods range from the simple internal calliper to high precision units, capable of measuring to extremely fine limits.

Common among these instruments and methods are:-

3.2.1. Vernier Calliper:

One jaw of the calliper is kept fixed at one point in the bore and gently pivoting the instrument about this jaw, the other jaw is slowly moved out until maximum diameter can be just felt. The jaw is locked and the reading is taken.

The advantage of this instrument is that it can measure both internal and external diameters and if the end faces of the workpiece are made perpendicular to the axis of its bore, it is certain that the measurement is also made perpendicular to the axis. This is because of the construction of the prongs of the calliper which make contact with both the bore surface and end face during measurement. But its usefulness is limited to the ends of the workpieces as the calliper cannot be used inside the bore. Another drawback of this instrument is that since the measuring scale is off-set from the dimension being measured, any lack of straightness of the jaws causes an error in measurement.

3.2.2. Telescopic Internal Gauge:

This instrument is particularly useful during machining operations. It has a pair of spherical contacts carried on a rod and tube, with a provision for the rod to be able to slide within the tube, an internal spring forcing the two members apart. The spring unit makes the contacts move out and to press on the surface of the hole during measurement. A locking screw is then used to lock it in position, the instrument is taken out and the diameter is measured with a micrometer.

Since only two contact points are made in the bore, it is necessary to insert the gauge into the hole and provide the swinging movements indicated in Fig. 5, to get the correct diameter. This is one of the drawbacks of the instrument, and also it cannot be used for bores smaller than a certain size.

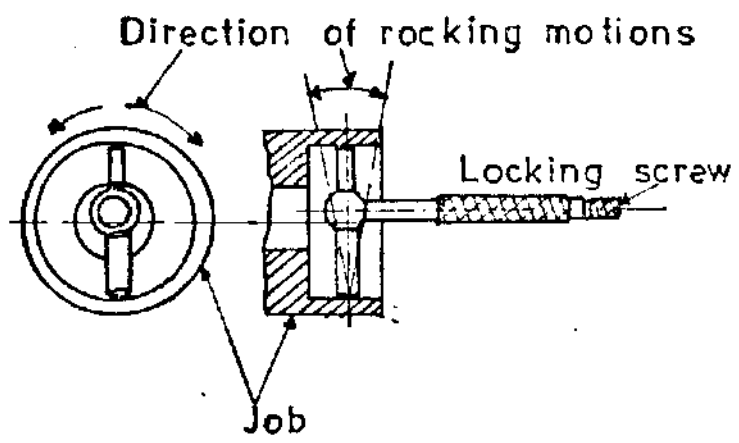


FIG. 5 - TELESCOPIC INTERNAL GAUGE

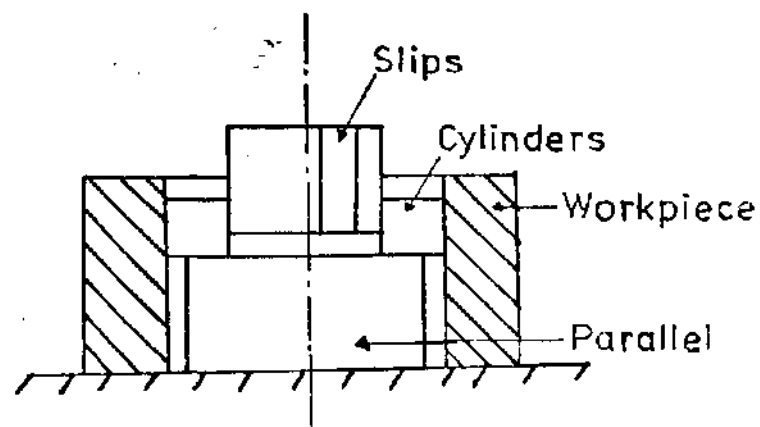


FIG. 6 - CYLINDER SLIP GAUGE METHOD OF BORE MEASUREMENT.

3.2.3. Inside Micrometer:

This instrument can be used for both small (not very small) and large bores with the use of extension rods. It is gently pivoted and rocked about one contact point and adjusted until the correct diameter can be just felt.

The main drawback in this instrument is that to know when the correct size is just felt will more likely depend on a good deal of skill on the part of the operator. Also when taking measurements, apart from the rocking motion, the micrometer knob has to be turned, hence it may not be able to measure deep holes other than at the end of the bores.

3.2.4. Cylinder-Slip Gauge Method:

In this method, two calibrated cylinders are arranged in the bore as shown in Fig. 6. The size between cylinders are taken with slip gauges with gentle rocking movements of the cylinders to make them roll into a diametrical position. The dimension of the bore can then be known.

The accuracy of this method would be high if the slip gauges are inserted between the cylinders with ease, that is, if they are not forced in, and at the same time no gap is left between the slips and the cylinders. The main drawback of the method is the time it may take in selecting the slip gauges that will make up the distance between the cylinders. Moreover, the method is only limited to medium and large bores.

3.2.5. Pin Gauge Method:

In this method, a pin gauge (a bar with

spherical ends, the length of which is slightly less than the diameter to be measured) of known length is placed in the bore with its ends in contact with the bore surface, its axis thus being a chord of the circle. Keeping one end in contact with the bore surface, the other end is brought across to make contact at the other side of a diameter.

By geometry, it can be found out that the diameter D is given by

$$D = \frac{L^2}{\sqrt{L^2 - W^2}}$$

and if the angle of rock is small, then $D = L + \frac{W^2}{8L}$ where L is the length of the pin gauge and W is the swing.

The main advantage of this method is that once W is determined accurately, the diameter could then be fairly accurately determined and large errors in the measurement of W will cause only small errors in the final result. But this method is only useful for large bores and at making measurements at the end of the bores.

3.2.6. Four Precision Balls Method:

In this method, three balls are spaced evenly within the bore and a fourth ball which may not be of the same size as the other three is placed upon them.

From Fig. 7, it is known that $D = 2A + d_1$. Considering triangle JKL, $(KL)^2 = (JL)^2 - (JK)^2$ or

$$A^2 = (JL)^2 - (JK)^2$$

$$\text{but } JL = \frac{d_1 + d_2}{2} \text{ and } JK = \left[H - \left(\frac{d_1 + d_2}{2} \right) \right]$$

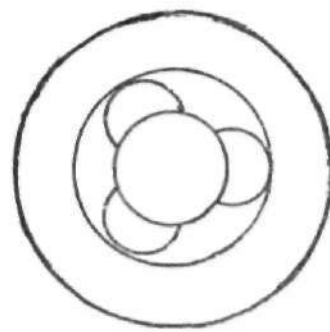
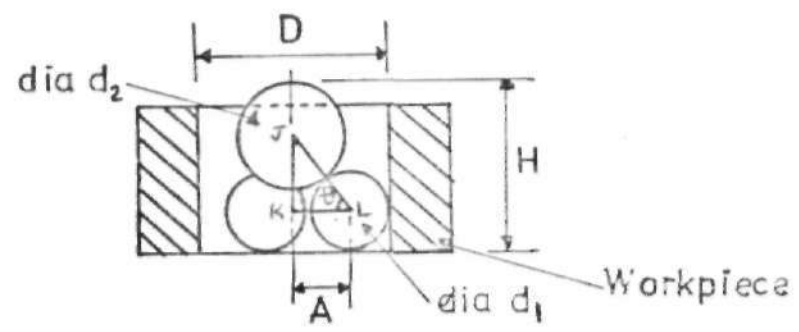


FIG. 7 - MEASUREMENT OF DIAMETER BY FOUR PRECISION
BALLS.

$$\begin{aligned}
\therefore A^2 &= \left(\frac{d_1 + d_2}{2}\right)^2 - \left[H - \left(\frac{d_1 + d_2}{2}\right)\right]^2 \\
&= \left(\frac{d_1 + d_2}{2}\right)^2 - \left[H^2 - \left(\frac{d_1 + d_2}{2}\right)^2 - H(d_1 + d_2)\right] \\
\Rightarrow A^2 &= H(d_1 + d_2) - H^2,
\end{aligned}$$

hence knowing A, D can be calculated.

This method will enable an accurate measurement of large bores to be made and also useful for recessed holes using two balls. The main drawback of the method is the care to be taken in the choice of the sizes of the balls. If the balls are chosen such that the angle θ in Fig. 8 is too small, heavy contact forces between the balls will reduce the accuracy and if too large, small errors in measuring H will result in large errors in the diameter determined.

3.2.7. Taper Pin Internal Gauge:

This method, which is only useful for small bores, is based on the measurement of the axial displacement of the tapered part of the measuring pin in relation to the face plane of the workpiece. With a given taper ratio of the pin, the measured axial displacement determines the diameter of the measured hole.

This is a very useful method for the measurement of holes of nominal size between 0.1 and 1 mm. The instrument has the advantage of reducing rocking motions in the bore, the setback being that it can measure only at the face of the workpiece.

3.2.8. The Lushington Hemispherical Method:

This is also used for measuring small holes. It consists of two spring steel arms having hemispherical

ends. Within these ends, there is a wedge - shaped member attached to a spindle which can be moved endwise by a knurled head. Movement of the wedge towards the head expands the hemisphere and in the opposite direction, contracts them. The gauge is operated by the feel method and after gauging the hole, an external type micrometer is used to check the size of the hole.

With the arms, the instrument can be used to measure small bores at any depth and the wedge also ensures equal movement of the hemispheres, but a direct reading of the bore under measurement cannot be obtained.

3.2.9. Pivoted Stylus And Autocollimator:

A ball-ended stylus, of a small diameter to the hole, is swung along the diameter of the component to make contact with one surface and the other (Fig. 8a). The two mirrors attached to the pivoted stylus are then adjusted so that each of them gives a reflection into the autocollimator. The readings are then compared with similar readings obtained by building up a gap with slip gauges to a dimension almost equal to the diameter of the hole.

The difference in the autocollimator readings of the two mirrors will then be converted into linear rise by using equations 3 a, b and c. Referring to Fig. 8b,

$$\frac{D}{2} - \frac{d}{2} = R \sin (\theta + \beta/2) \text{ -----(3.a)}$$

$$\frac{G}{2} - \frac{d}{2} = R \sin (\theta + \alpha/2) \text{ -----(3.b)}$$

Subtracting (3.b) from (3.a),

$$\frac{D - G}{2} = R \sin (\theta + \beta/2) - R \sin (\theta + \alpha/2)$$

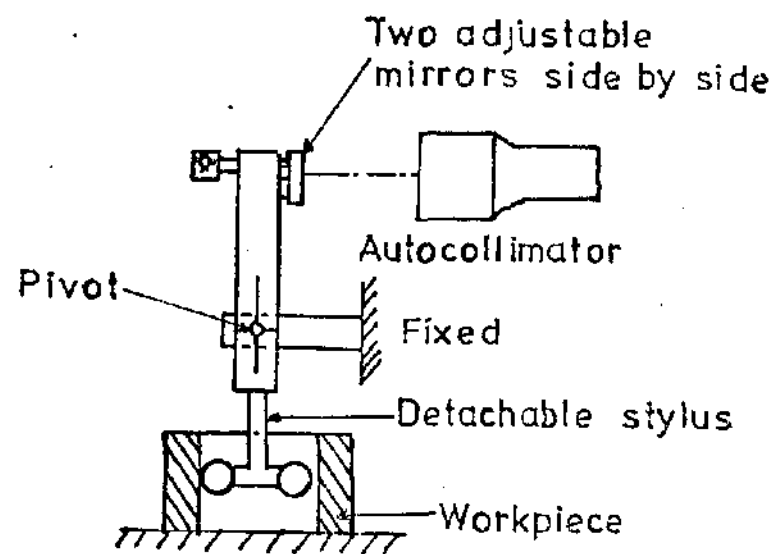


FIG. 8a - SMALL BORE MEASUREMENT BY PIVOTED STYLUS AND AUTOCOLLIMATOR.

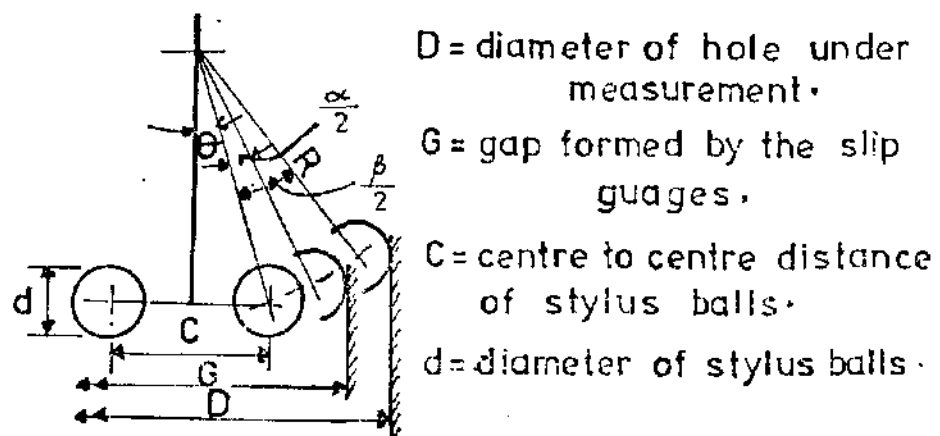


FIG. 8b - GEOMETRY OF SMALL BORE MEASUREMENT.

$$\therefore D - G = 2R(\sin(\theta + \beta/2) - \sin(\theta + \alpha/2)) \text{ ---(3.c)}$$

The value of θ is found from

$$\sin \theta = \frac{c}{2R}$$

and using equation (3.b), α is found. The difference in the angular reading of the autocollimator is equal to $(\beta - \alpha)$, hence β can be found. Finally using equation (3.c), D can be known.

The above equations have assumed that the stylus is centrally disposed in relation to the standard gap and to the hole being measured. This is a necessary condition for accuracy because if not observed, there will be a slight cosine error in the result obtained.

3.2.10. The Societe Genevoise Universal Measuring Machine:

The Universal measuring machine covers a wide range of types of measurements of which bore measurement is a part. In this particular machine, two carriages (longitudinal and transverse carriages) move at right angles on hand-scraped flat and vee shaped guiding surfaces.

The longitudinal carriage carries a microscope and a part of the measuring anvil. Below the microscope, there is a standard scale protected by an optical glass cover plate. The scale is viewed by the right hand microscope. Also an auxilliary scale is attached to the longitudinal carriage to register its approximate position by a pointer attached to the microscope holder.

The transverse carriage carries a universal table on which the workpiece whose internal diameter is to be measured is kept. The universal table can be raised, lowered and tilted with respect to a horizontal plane or a vertical plane. These movements enable the position of the workpiece to be adjusted with respect to the measuring contacts so that the latter will be making a measurement through the centre of the hole as well a perpendicular to its axis.

The universal table is the most important device of the machine that helps to locate the true diametrical position of the workpiece.

3.3. Concluding Remarks:

Apart from measuring internal diameters, some of these instruments and methods are useful for external measurements especially the vernier calliper and the universal measuring machines. In some of these instruments, it may be difficult to locate the true diameter perpendicular to the axis of the bore as their methods of measurement generally involve two point contacts.

Hence in the present design of the bore gauge, the use of three point contacts would help to increase the accuracy with which the true diameter could be located. Also the provision of the extension pin heads will cater for both small and large bores.

CHAPTER FOUR

COMPARATOR ACCESSORY FOR THE AUTOCOLLIMATOR

4.1. Introduction:

The comparator that has been designed and constructed is based on the optical principles of the autocollimator and the sine formula for a right-angled triangle. It can measure both internal and external dimensions of various types of workpieces with a fairly large range of sizes, but by varying the length of the stylus in the case of internal measurements.

4.2. Detailed Description:

By reference to drawing No. 1, it will be seen that the comparator consists essentially of a reflector carrier (7) which carries the measuring stylus (8) (this is to be substituted with another stylus for external measurement of cylindrical workpieces, ref. Dr. No. 3) at its left end and the reflector (4) at the right end. Slightly below the reflector, attached to the carrier, is a cylindrical roller (6) for maintaining a line contact on slip gauges on which the right end of the carrier will be supported while making measurements. While not making measurements, the carrier is supported at two points by the carrier supports (15) which is used in raising or lowering the carrier by means of the raising screw (17) and the support bar (18). The carrier has been provided with three carrier guides (2) to ensure that it moves along the vertical plane passing through the axis of the workpiece or reference standard and a handle (3) for

lifting it when the need arises. Between the head of the raising screw and the support bars, there is a bearing ring (19) with balls (20) to reduce friction.

All these are mounted on a table (14) having legs (11 and 22) at both left and right ends. The workpiece and/or the reference standard to be measured are placed, in turn on the sliding table (10) which can be locked in position by the locking plate (12). Standard screws and nuts have been provided to hold the various units together.

The autocollimator is a separate component which can be placed on a table to face the reflector.

Reflector Carrier (ref. Drg. No. 2)

The carrier is a 10 x 10 mm square bar with a total length of 238.2 mm. It carries the measuring stylus, the reflector and the handle. The carrier is supported at two points by the carrier supports when not taking measurements. When taking measurements, the carrier is supported at two points, one provided by the slip gauges and the other, in the case of internal measurement, by the workpiece or left carrier support and the right carrier support can easily be removed for internal measurements. Adequate consideration has been given to the positioning of these supports so as to minimize the slope and deflection of the reflector carrier when taking measurements, as this may introduce some errors in the measurement. (See Appendix A).

The carrier can be raised or lowered through a range of 120 mm by means of the carrier supports which are in turn raised or lowered by turning the raising screw. When the stylus is contacting the workpiece under measurement and the carrier properly adjusted, the reflector will reflect back the beam of light coming from the autocollimator.

Measuring Stylus:

There are two types of measuring styluses to be used. The first one is the ball-ended stylus (ref. Drg. No. 2), used for taking internal measurements of bores and external measurements of workpieces with flat surfaces. This type of measuring stylus provides only a point contact which may not be suitable for external measurements of cylindrical workpieces as it may be difficult to set the highest true diameter.

The second stylus (ref. Drg. No. 3) which is used for external measurements of cylindrical workpieces is a bit different from the ball-ended one. The contacting end of this stylus is semi-cylindrical, so when placed on a cylindrical workpiece, it can be sure that it is measuring the maximum dimension which is the true diameter.

The positioning of the stylus has been calculated such that a direct reading can be obtained immediately the autocollimator reading is taken. Thus, it has been found out that the centre to centre distance of the stylus and the cylindrical roller should be 206.2 mm, such that the autocollimator reading of one second will correspond to a change in length of 0.001 mm ($1\mu\text{m}$) (See Appendix B).

Carrier Guides (ref. Drg. No. 2)

These are long circular bars of height 166 mm with a threaded end of 18 mm long. There are three guides, placed two on one side and the third on the other side of the reflector carrier. The location of the guides will constrain the raising or lowering of the reflector carrier along the vertical plane passing through the axis of the workpiece. The guides are held in position on the table by nuts.

Table (ref. Drg. No. 2)

The table is a rectangular plate with a surface dimension of 400 x 80 mm and a thickness of 20 mm. It is supported by the left leg (ref. Drg. No. 2) and the right leg (ref. Drg. No. 3).

One half of the table contains the guides, position for the slip gauges, the raising screw and the support bars, while the other half is to accommodate the sliding table. On each side of this latter half, there is a rectangular groove of 3 x 5 mm through which the clamping attachment to the instrument passes. Also in this part, a thick centre line has been marked at the centre of the table for proper alignment of the reference standards and the workpieces.

Sliding Table and Locking Plate (ref. Drg. No. 2)

The workpiece to be measured is placed on the sliding table and in cases where a comparison with a reference standard is to be made, the workpiece and the standard are

placed in turn on the table. The table can be moved inwards or outwards for contacts to be made by the measuring stylus on the workpiece or standard.

After adjusting the position of the sliding table and hence the standard or workpiece, the locking plate (a plate of thickness 2 mm and length 135 mm) is used to hold the sliding table in position by the use of the locking screw (1). The locking plate is permanently fixed to one side of the table by two screws (13).

4.3. Attachments To Instruments:

Separate attachment units have been designed to be used in some cases of measurement. Most of these attachments serve to reduce and in some cases, eliminate functional errors in taking readings. These attachments are:-

- (1) Vee block
- (2) Clamping device
- (3) Taper block and marking bar.

4.3.1. Vee Block (ref. Drg. No. 4)

This has been designed to take the form of a conventional vee block commonly used in the engineering workshop. The base of the vee block is made to tally with the width of the table.

The purpose of the vee block is to act as a seat for cylindrical workpieces. Aligning the centre line of the vee block with the centre line of the table will also align the workpiece centre line with the table centre line.

4.4. Functioning Of Instrument (Assembly):

There are two modes of operation under which the instrument can be used.

- (1) When taking external measurements of:
 - (a) workpieces with flat surfaces that will sit on the sliding table; and
 - (b) cylindrical workpieces that will require the vee block and clamp.
- (2) When taking internal measurements of:
 - (a) hollow workpieces with flat bottom that can sit on the sliding table; and
 - (b) cylindrical workpieces that will require the vee block and clamp.

In 1(a), the reference standard is first placed on the table under the stylus and slip gauges are built up on the right side under the cylindrical roller so that the reflector carrier is almost horizontal and the autocollimator reading is almost in the middle of its range. the autocollimator reading is noted; after which the reference standard is replaced by the workpiece and another reading of the autocollimator is taken. The dimension of the workpiece is then deduced from the knowledge of the height of the standard and the difference in the autocollimator readings.

In 1(b), the workpiece is placed on the vee block and clamped onto the table by means of the clamp attachment. Referring to Fig. 9, the height H_1 is first obtained by means of slip gauges and H_2 can be obtained by followi

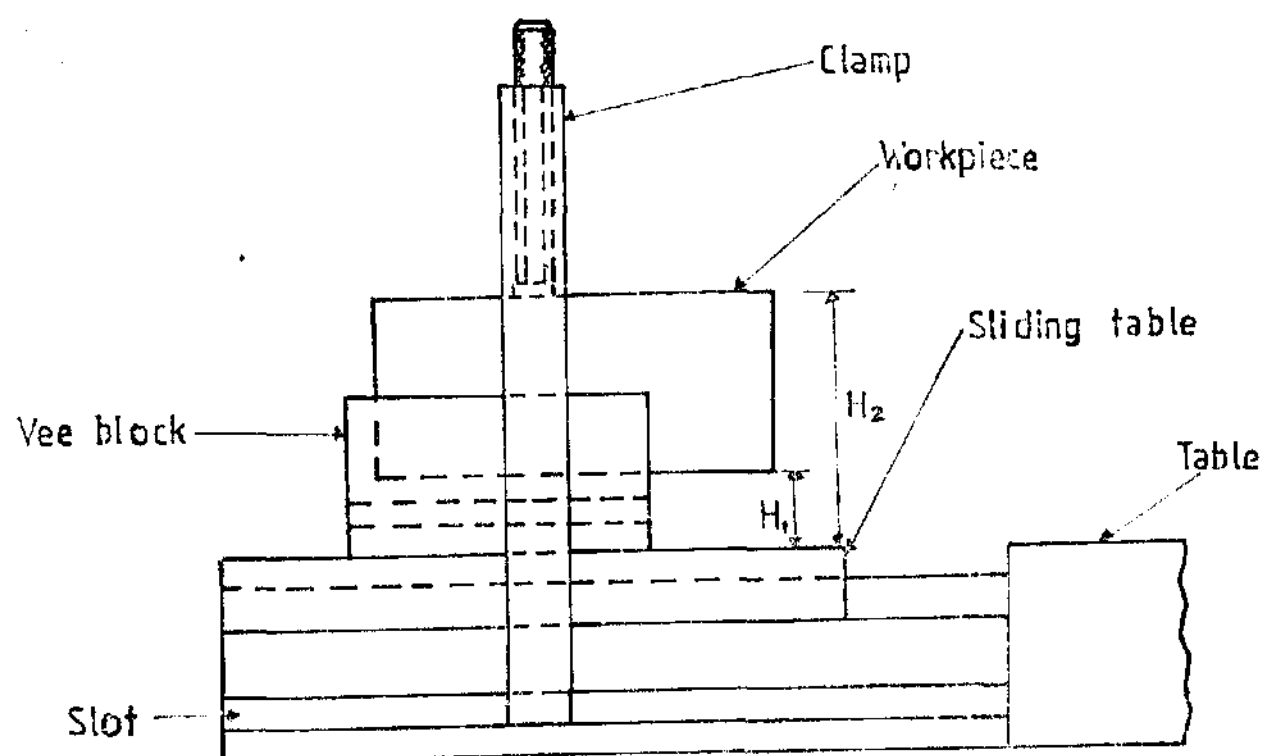


Fig- 9 - MEASUREMENT OF EXTERNAL DIAMETER OF CYLINDRICAL WORKPIECE.



the same procedure employed in 1(a). The difference between H_2 and H_1 will give the external diameter of the cylindrical workpiece.

For taking internal diameter measurements, the procedures for 2(a) and (b) are similar. While in 2(a) the workpiece is clamped directly on the table, in 2(b) the workpiece is placed on the vee block and clamped together to the table. Here, first the stylus is made to contact the lower surface of the workpiece while building up slip gauges on the other side for a reading of the autocollimator to be taken. Next the stylus is made to contact the upper surface of the workpiece. The carrier is now supported by the left side carrier support and slip gauges are built up on the right side for another reading. The internal dimension can be deduced from the two readings, the difference in the heights of the slip gauge piles built up and the height of the stylus.

Generally, the standards or the workpieces are first placed on the sliding table symmetrically and the position of the table adjusted so that the stylus can make contact with the standard or workpiece. In this position, the sliding table is locked by the locking plate and screw. For external measurement, the stylus is made to contact the top of the workpieces and the standards, while for internal measurements, the stylus is made to go into the interior of the workpieces and made to contact opposite points in the hole (diametrically opposite points in case of round holes).

4.5. Concluding Remarks:

The comparator has been designed to be an accessory to the autocollimator and as mentioned earlier on, it has a range of 120 mm. Nonetheless, it could be used for larger measurements with slight modifications.

For example, the height of the carrier guide could be increased and there would also be a corresponding increase in the height of the carrier supports and the raising screw. A limiting factor is the size of the sliding table and therefore the size of the workpiece. The mode of construction can be changed to accommodate bigger workpieces.

CHAPTER FIVE

BORE GAUGE

5.1. Introduction:

The new bore gauge has been designed based on the principle of locating the bore of the workpiece through three contact points equally spaced at 120° to each other. The gauge can be used to take a minimum bore measurement of 50 mm and by replacing the pin heads, the range of measurement could be increased up to twice the minimum dimension.

5.2. Detailed Description:

Referring to drawing No. 5, the bore gauge consists essentially of a cylindrical casing (20), covered on the left side by the left cover plate (7) and on the right side by the right cover plate (1). The casing contains a taper block (6); at the small end of which are three spring loaded pins (3) with interchangeable pin heads (15). The pins are equally spaced at 120° to each other around the casing and can be moved in and out by moving the taper block. There are also two stopper plugs (13) to show when the taper block has reached its highest (left-most) position in the casing.

Passing through the right cover plate is the centralizer (2) to maintain the central positioning of the taper block, and through the left cover plate is the dial gauge carrier (15) which apart from carrying the dial gauge (10) also centralizes the taper block. The plunger of the dial gauge rests permanently on the push

rod (18). The dial gauge carrier is also to be used in pulling out the taper block against the action of a compression spring (16) provided at the top of the taper block. The action of this compression spring is to move the taper block to the right and thus to ensure the pins make contact with the bore surface.

To facilitate the handling of the bore gauge, a handle bracket (9) and a handle (11) have been provided. Standard screws and nuts have been provided as fasteners.
Taper Block (ref. Drg. No. 6)

The taper block is made in the form of a truncated cone whose surface is to be polished and chromium plated. It has attached to it the dial gauge carrier which is also used in pulling out the taper block. As the taper block moves up, the pins move towards the centre of the casing under the action of the compression springs on them. The central position of the taper block is maintained by the centralizer on the right and the dial gauge carrier on the left. The angle of the taper block has been made to be $14^{\circ} 2\frac{1}{2}'$ such that the rate of change of the diameter with respect to the distance moved by the taper block when released will be half of the dial gauge reading (See Appendix C).

There are also the stopper plugs which determine the maximum movement of the taper block towards the left cover plate. They are screwed onto the taper block.
Gauge Carrier and Push Rod (ref. Drg. No. 6)

The gauge carrier is a circular bar of 5 mm diameter with a length of 134 mm. At one end is a threaded portion

of 42 mm. At the right end of the 42 mm threaded portion, there is a 10 x 10 mm square on which the dial gauge rests.

The carrier passes through the left cover plate and the compression spring and screwed onto the taper block. A screw driver groove is provided at the end of the taper block so that a spanner and a wide screw driver can be used in screwing the dial gauge carrier and the taper block together. This is to prevent the taper block becoming loose from the carrier.

As the carrier is pulled out, the dial gauge, which is permanently fixed on it, is also moving out with it and since the dial gauge contact point is resting on the push rod, the push rod can be adjusted by turning, for zero reading of the dial gauge at the left most position of the carrier. Subsequently, when the carrier is released, the push rod pushes in the plunger of the dial gauge for the reading of the distance moved by the carrier and hence the increase in the diameter of the taper block.

Pin and Pin Head (ref. Drg. No. 6)

The pins and their heads have been designed as separate component so that the heads can keep the main bodies of the pins from going into the casing and also to facilitate the insertion of the compression springs. The heads are screwed onto the pins. There are three pin units in all, placed equally at 120° to each other, in the same plane of the bore gauge and all making contact with the taper block. They are also to be chromium-plated.

During measurements, the pins travel outwardly for the heads to make contact with the bore under measurement and they are returned to their original position by the return action of the compression springs when the taper block is pulled to its left most position.

5.3. Functioning Of Instrument (Assembly):

There is a need to set the dial gauge reading to zero before taking the reading. This is accomplished by placing the bore gauge on a table to stand on the right cover plate. The dial gauge carrier is pulled out to its left most position. This is noticeable when the carrier cannot be pulled out any more. When this is done, the bore gauge is inserted into a 50 mm ring gauge and the push rod is turned clockwise or anti-clockwise, as the case may be, such that the dial gauge contact point is touching the push rod and the dial gauge is reading zero, corresponding to the left most position of the taper block.

After setting the instrument, the taper block is pulled out to its left most position by using the dial gauge carrier and released after inserting the bore gauge into the bore of the actual workpiece, with a gentle rocking, and the reading of the dial gauge noted. With the knowledge of the reading taken and the diameter of the 50 mm ring gauge, the true diameter of the bore can be deduced as follows:-

If the dial gauge reading is h mm when the bore gauge is inserted into the bore of the workpiece, then the diameter of the bore under measurement is

$$(50 + \frac{h}{2}) \text{ mm.}$$

Alternatively, the diameter D of the bore is to be determined by using a standard 50 mm ring gauge as follows:-

Without setting the dial gauge to zero, the bore gauge is inserted into a 50 mm ring gauge and the reading of the dial gauge noted. Next the bore gauge is inserted into the actual workpiece and another reading of the dial gauge taken. Supposing the reading is x mm with the ring gauge and with the bore under measurement, the reading is y mm, then the diameter D of the actual workpiece is

$$(50 + \frac{1}{2}(x - y)) \text{ mm.}$$

5.4. Concluding Remarks:

The interchangeable pin heads can be used to increase the range of the instrument. Also it could be possible to produce a small sized instrument on the same principle to measure still smaller holes. The parts to be reduced in size in this case are the cone and the parts inside it.

Similarly, a bigger sized instrument can be constructed for measuring bigger holes.

CHAPTER SIX
USES AND TESTING OF INSTRUMENTS

6.1. Introduction:

The comparator designed can be used in taking both internal and external measurements of various types of workpieces within the measuring range of the instrument. The accuracy of measurement will depend on the accuracy with which the autocollimator reading is taken and the measurement of the reference standard dimension.

On the other hand, the accuracy of the bore gauge, which has been specifically designed to measure internal diameters, will depend on the sensitivity of the dial gauge used with the instrument.

6.2. Uses Of Instruments:

6.2.1. Comparator Accessory for the Autocollimator
(Plate 1)

The comparator was designed and constructed to take internal and external dimensions of various types of workpieces. Most important of these measurements are the linear height of workpieces and the internal diameters of workpieces. In the case of internal diameters, apart from being able to measure bores with concentric holes, it can also be used to measure bores of non-concentric holes, along specified axes. Moreover, it can be used inside deep holes for measurement of diameters at various depths.

In the case of external measurements, the comparator can be used to find the linear heights of workpieces, in comparison with a reference standard and in comparing two workpieces.

It can also be used to test the flatness of a surface by taking autocollimator readings at different points along a single axis on the surface of the workpiece. Comparing the readings so obtained will give an idea of the flatness of the surface. The comparator could as well be used for checking the roundness of cylindrical workpieces by measuring the external diameter at different points on the surface of the workpiece.

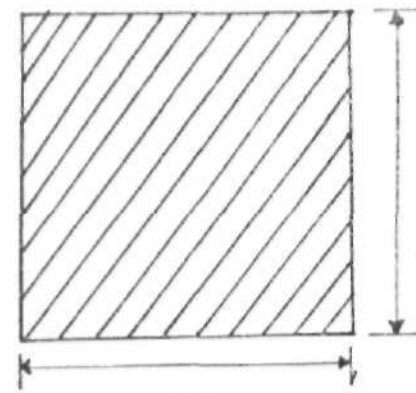
6.2.2. Bore Gauge (Plate 2)

The bore gauge was designed and constructed specifically for taking the internal diameter of workpieces at various depths, the only limiting factor being the base width of the dial gauge which may not be able to go into the bore.

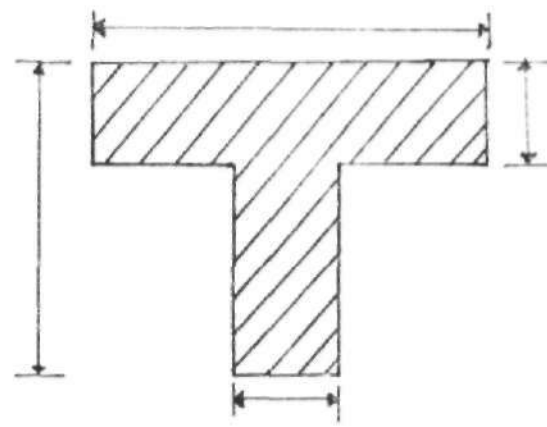
6.3. Various Types Of Workpieces:

The various types of workpieces which the comparator can be used for are shown in Fig. 11 (external measurements) and Fig. 12 (internal measurements).

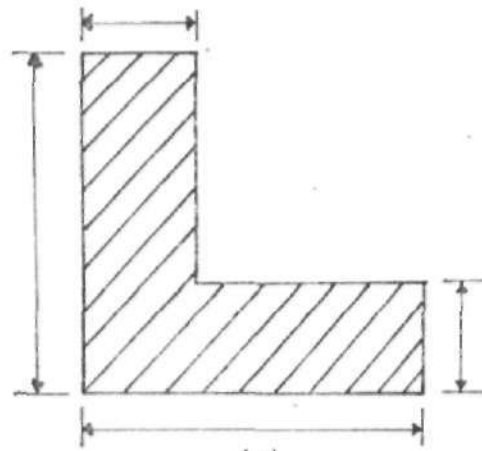
Apart from the various workpieces shown, there can be a combination of the various shapes shown and the same procedures as described in Section 4.4 of Chapter Four can be followed, depending on the type of measurement and the stability of the workpieces on the sliding table.



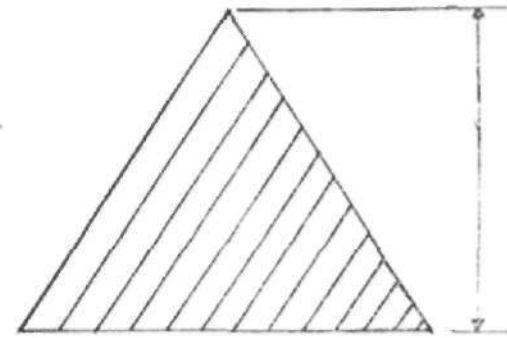
(a)



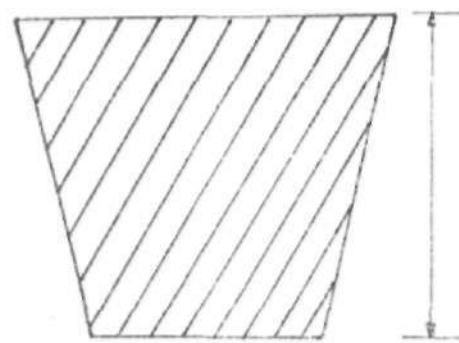
(b)



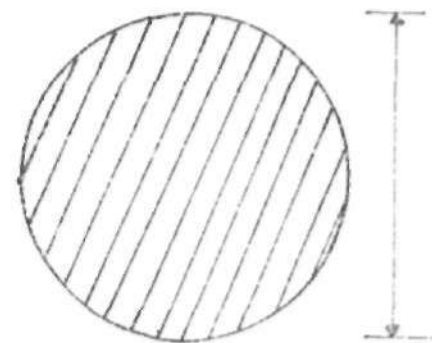
(c)



(d)

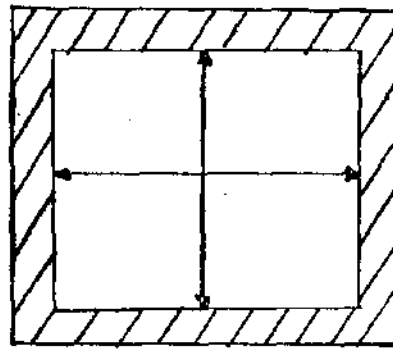


(e)

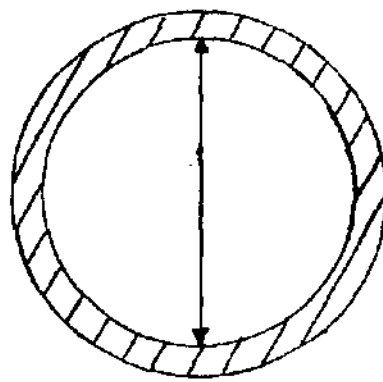


(f)

FIG-10-TYPES OF WORKPIECES FOR EXTERNAL MEASUREMENTS



(a)



(b)

FIG.11 - TYPES OF WORKPIECES FOR INTERNAL MEASUREMENTS .

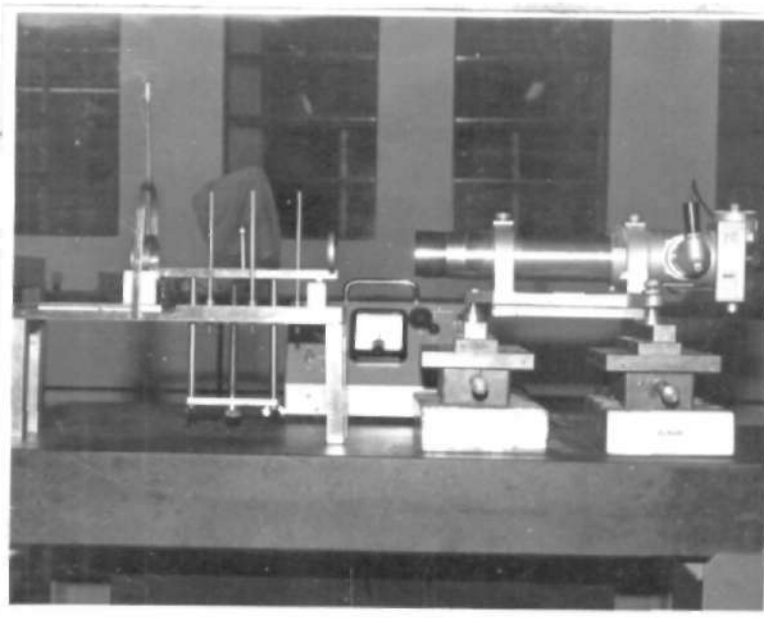


Plate 1 - Comparator Accessory For The Autocollimator

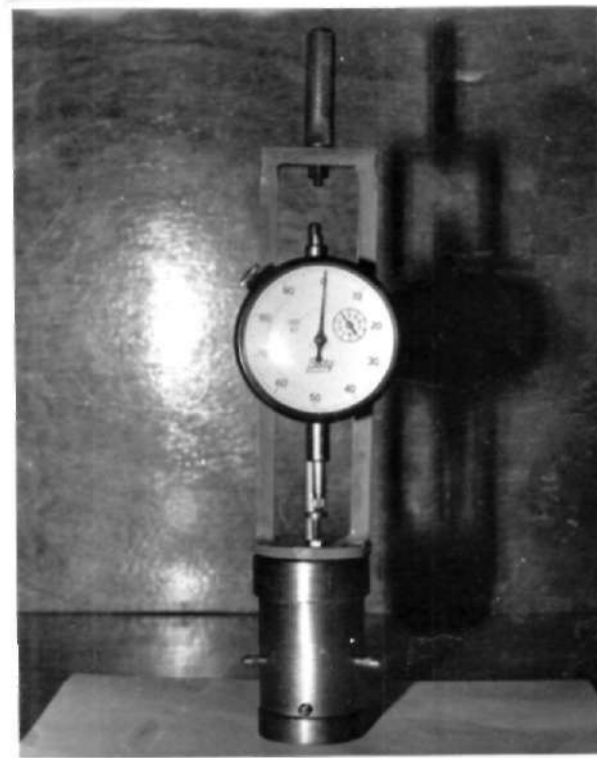


Plate 2 - Bore Gauge

6.4. Taking Measurements And Comparing With Universal Machine:

The strategy adopted in testing the instruments was to use them to take measurements of workpieces and comparing the readings with those obtained from the Universal measuring machine for the same dimensions.

6.4.1. Comparator:

(a) External Measurement:

The external measurement test was carried out using slip gauges as standard and workpiece. While the height of the slip gauges on the right side of the reflector carrier was fixed, the left end was gradually increased to take readings of the autocollimator. The table below shows the results obtained and the errors.

Increment (mm)	Comparator Reading (mm)	Error (mm)
0.001	0.0011	0.0001
0.003	0.0032	0.0002
0.006	0.0059	0.0001
0.010	0.0097	0.0003
0.015	0.0158	0.0008
0.025	0.0251	0.0001
0.050	0.0483	0.0017

For comparison with the Universal measuring machine, one of the increments (0.050 mm) was measured on the machine and it gave 0.054 mm showing an error of 0.004 mm.

(b) Internal Measurement:

This was done by taking the internal diameter of a workpiece along a particular diametrical axis pre-marked before the set-up. The result shows the bore

to be 25.6269 mm and on the Universal machine, it was found to be 25.6385 mm, showing a difference in reading of 0.0116 mm.

(c) Discussion:

In the case of external measurements, the comparator was found comparable to the Universal measuring machine and measurements not affected by the low production accuracy of the comparator.

For internal measurements, the errors are largely due to the low production accuracy of the parts as can be seen from the following defects detected:

- (1) The effective length of the reflector carrier was not accurately made to specification, though the error introduced was not very much significant, about 0.001 mm.
- (2) The shape of the stylus and the cylindrical roller were not properly constructed hence they are not making good contact with the surface of the workpiece and the slip gauges respectively.
- (3) The surface roughness of the table was high hence there are changes in the readings of the autocollimator when the workpiece and slip gauge are placed at different positions on the table. Also dusts might be trapped on the table. We have to consider the fact that the instrument is sensitive to even small variations of size.
- (4) The carrier guides were not made quite perpendicular to the surface of the table hence the

reflector carrier could not be maintained along the centre line of the table.

6.4.2. Bore Gauge:

The bore gauge was tested by comparing two workpieces and verifying on the Universal machine. The diameter of the workpiece was determined to be 52.29 mm and on the Universal machine, found to be 52.2871 mm showing a difference in dimension of 0.0029 mm.

Like the comparator, the sources of error are from the low production accuracy of some important parts like the angle of the taper block which was made to be $14^{\circ} 20.562'$ instead of the calculated value of $14^{\circ} 2.33'$ (Appendix C). Also the pin heads were not properly constructed hence the non-uniformity in their movements. Finally, as it was difficult to get the compression springs with required stiffnesses, those used, which have close stiffness to those required, might have created another source of error as the moving parts are not functioning properly and smoothly as expected.

6.5. Concluding Remarks:

The results of both instruments confirm the workability of the designs. The errors arising from the readings are largely due to the production inaccuracy. If care is taken in the production of these parts, the errors could be minimized or completely eliminated.

7.1. Advantages Of The Instruments:

The advantages of the two new instruments could be enumerated as follows:-

7.1.1. The Comparator:

- (1) The comparator could be used for both internal and external measurements unlike some of the existing comparators which are for a specific purpose (either for internal or external measurements).
- (2) It incorporates a highly sensitive instrument, the autocollimator and hence its high sensitivity. As the accessory is not expensive to produce, it is a big saving on investments for another instrument for the same purpose.
- (3) The comparator is simple in design and can be constructed in any averagely equipped engineering workshop. Hence it is easy to assemble, operate and maintain.
- (4) No rigorous or ambiguous calculations are to be done to obtain the measurements.

7.1.2. The Bore Gauge:

- (1) Its three point contact makes it more accurate than most of the existing bore measuring instruments in which for feeling the correct diameter rocking motions are to be employed.

- (2) It can be inserted into the bore to measure the diameter at various depths as compared to some of the existing bore measuring instruments which can only measure the diameter at the end faces of the workpiece.
- (3) The range of measurement can be increased easily without redesigning the gauge components, by changing the extension pin heads.
- (4) The measuring pin heads could be located easily in the bore perpendicularly to the axis of the bore with a gentle rocking motion.
- (5) The bore gauge is easy to construct, assemble, operate and maintain.

7.2. Errors Envisaged:

All the errors envisaged will be eliminated if care is taken in the production stage of all the parts. Therefore the importance of very high accuracy in the production of the comparator cannot be overemphasized. If high accuracy is maintained, the only source of error envisaged is when taking internal diameters of holes. In this case, when the stylus is made to contact the upper surface of the bore, if the force applied to raise the reflector carrier is too much, the measuring end of the carrier might be deformed through bending while the other end will be lifted up thereby adding to the reading of the autocollimator. Therefore the raising screw should be stopped just when the stylus head is making contact with the upper surface without applying too much force.

The errors envisaged to arise from the use of the bore gauge will very much depend on the accuracy with which the various parts are produced, especially those parts in the cylindrical casing. Of utmost significance is when the length of the pin heads are not the same, then the pins will not move equal distances to locate the bore, hence the diameter may not actually be measured through the centre of the bore.

7.3. Conclusion:

From the uses and testing of the instruments, it can be concluded that, though the two instruments produced have limited ranges of measurements, there is still room for increased ranges.

In the comparator, the dimensions of some of the parts could be increased for a bigger comparator. Such parts include the carrier guides, the supports and the raising screw. All these changes will not in anyway change the mode of construction except if the main table is also to be changed.

On the bore gauge, apart from being able to change the extension pin heads for bigger holes, the cylindrical casing and the parts contained in it could be reduced proportionately for a small bore gauge for the measurement of smaller bores.

In all, the efficiency of both instruments could be increased considerably with proper good finishing and better conformity with the specifications of the various parts in the production stage.

7.4. Recommendations:

Since no engineering design is static due to continued changes in modern technology, the following points are recommended:-

- (1) The two new instruments should be subjected to constant use so as to be able to detect other errors which are not noticeable at present.
- (2) As mentioned in Section 7.2, the force applied to the raising screw should be checked so as not to deform the contacting end of the stylus and lifting the other end of the reflector carrier when the measuring stylus is making contact with the upper surface of the bore. Hence further work should be encouraged to find a means of applying a constant force to the raising screw that will just be enough for the measuring head to just contact the upper surface of the bore without deforming the end of the reflector carrier.
- (3) After series of usage of the bore gauge, there may be a tendency for the taper block to wear due to constant friction as a result of sliding motion between it and the pins in the cylindrical casing. Therefore the taper block should constantly be checked and if found worn, should be replaced immediately.

- (4) As a means of increasing the efficiency of the two instruments, it is necessary that all moving and sliding parts should be properly lubricated as the need arises for reduced friction.

REFERENCES

1. Hume, K. J. (1965): "Metrology with Autocollimator"
London: Higer and Watts Limited.
2. Purvis, R. D. (1972): "Autocollimator Measuring
Units". Metrology and Inspection (April/May
1972 Edition), pp. 7 - 8, 10 - 11.
3. Sharp, K. W. B. (1970): "Practical Engineering
Metrology". London: Sir Isaac Pitman and
Sons Limited.
4. Taylerson, C. O. and Turner, A. (1953): "A New
Precision Internal Measuring Machine",
Engineering Dimensional Metrology - NPL Proc.,
Vol. 1, Paper 4.

APPENDIX A

DEFLECTION AND SLOPE ANALYSIS OF THE REFLECTOR

CARRIER

A.1. General:

The amount of slope and deflection will depend on the position of the supports (span of supports). The carrier has a rectangular cross-section. Its volume

$$\begin{aligned} V &= 238.2 \times 10 \times 10 \text{ mm}^3 \\ &= 23820 \text{ mm}^3 \\ &= 23820 \times 10^{-9} \text{ m}^3. \end{aligned}$$

The material of the reflector carrier is mild steel whose density is 7850 kg/m^3 .

$$\text{Since density} = \frac{\text{Mass}}{\text{Volume}}$$

$$\begin{aligned} \therefore \text{Mass of reflector carrier (M)} &= \text{Density} \times \text{Volume} \\ &= 7850 \times 23820 \times 10^{-9} \\ &= 0.187 \text{ kg}. \end{aligned}$$

$$\begin{aligned} \text{Hence the weight} &= 0.187 \times 9.81 \text{ N} \\ &= 1.834 \text{ N}. \end{aligned}$$

Where the acceleration due to gravity is assumed to be 9.81 m/s^2

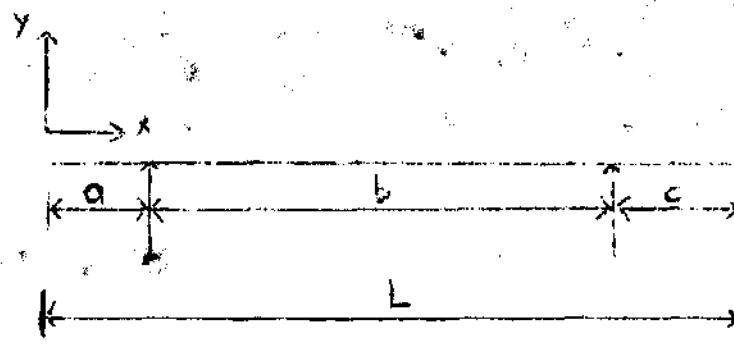
$\therefore$ The weight per unit length (w) of the reflector carrier is

$$\begin{aligned} &= \frac{1.83}{238.2 \times 10^{-3}} \text{ N/m} \\ &= 7.70 \text{ N/m} \end{aligned}$$

$$\text{or } 0.0077 \text{ N/mm}.$$

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The carrier is considered as a beam supported at two points as shown below.



Y = deflection at a distance x from one end as shown in the figure above.

E = Young's modulus of rigidity

$$= 207 \times 10^3 \text{ N/mm}^2$$

I = Second moment of area

$$= AK^2$$

(A = cross-sectional area and K = radius of gyration)

$$= \frac{10^4}{12} \text{ mm}^4 = \underline{\underline{833.33 \text{ mm}^4}}$$

A.2. Deflection Analysis On Reflector Carrier When Supported By The Left Hand Carrier And The Slip Gauges:

It can be shown that the general form of the deflection equation for $0 < x < a$ is

$$EIy = -\frac{wx^4}{24} + \frac{w}{24b} \left[(a+b)^4 - a^4 \right] x - \frac{wLb^2}{12} \left[\frac{L+2c}{b+2c} \right] x + \frac{wLab^2}{12} \left[\frac{L+2c}{b+2c} \right] - \frac{w}{24b} \left[a(a+b)^4 - a^4(a+b) \right]$$

To find the deflection at the point of contact of the measuring stylus,

$a = 65 \text{ mm}$, $b = 151.2 \text{ mm}$, $c = 22 \text{ mm}$ and $x = 10 \text{ mm}$.

Substituting in the general equation,

$$\begin{aligned}
 207 \times 10^3 \times 833.33 \, y &= - \frac{0.0077 \times 10^4}{24} + \frac{0.0077}{24 \times 151.2} \\
 &\left[(65 + 151.2)^4 - (65)^4 \right] 10 - \\
 &- \frac{0.007 \times 238.2 \times (151.2)^2}{12} \left[\frac{238.2 + 44}{151.2 + 44} \right] 10 \\
 &+ \frac{0.0077 \times 238.2 \times 65 \times (151.2)^2}{12} \left[\frac{238.2 + 44}{151.2 + 44} \right] \\
 &- \frac{0.0077}{24 \times 151.2} \left[65(65 + 151.2)^4 - 65^4(65 + 151.2) \right] \\
 &= - 3.2083 + 45981.957 - 50516.354 \\
 &\quad + 328356.29 - 293155.64 \\
 &= 30663.044 \\
 \therefore Y &= \frac{30663.044}{207 \times 10^3 \times 833.33} \text{ mm} \\
 &= 1.778 \times 10^{-4} \text{ mm} \\
 &\text{or } 0.0001778 \text{ mm.}
 \end{aligned}$$

Since the deflection is less than 0.001 mm , it is therefore negligible.

A.3. Slope Analysis At The Right End of The Reflector

Carrier:

The general form of the slope equation for the region $a + b < x < c$ is found to be

$$\begin{aligned}
 EI \frac{dy}{dx} &= \frac{wx^3}{6} + \frac{wL}{4} \left(\frac{1 + 2c}{b + 2c} \right) (x - a)^2 + \frac{wL}{4} \left(\frac{2b - L + 2c}{b + 2c} \right) \\
 &\left[x - (a + b) \right]^2 + \frac{w}{24b} \left[(a + b)^4 - a^4 \right] - \frac{wLb^2}{12} \left(\frac{L + 2c}{b + 2c} \right).
 \end{aligned}$$

At the right end, $x = L$. Therefore the slope equation becomes

$$EI \frac{dy}{dx} = \frac{wL^3}{6} + \frac{wL}{4} \left(\frac{L+2c}{b+2c} \right) (L-a)^2 + \frac{wL}{4} \left(\frac{2b-L+2c}{b+2c} \right) \left[L - (a+b) \right]^2 + \frac{w}{24b} \left[(a+b)^4 - a^4 \right] - \frac{wL}{12} \left(\frac{b^2}{b+2c} \right) \left(\frac{L+2c}{b+2c} \right)$$

(i) When supported by the workpiece and the slip gauges,

$$a = 10 \text{ mm}, b = 206.2 \text{ mm}, c = 22 \text{ mm and } L = 238.2 \text{ mm}$$

then

$$\begin{aligned} EI \frac{dy}{dx} &= - \frac{0.0077 \times (238.2)^3}{6} + \frac{0.0077 \times 238.2}{4} \left(\frac{238.2 + 44}{206.2 + 44} \right) (238.2 - 10)^2 + \frac{0.0077 \times 238.2}{4} \left(\frac{412.4 - 238.2 + 44}{206.2 + 44} \right) \left[238.2 - 216.2 \right]^2 + \frac{0.0077}{24 \times 206.2} \left[(216.2)^4 - 10^4 \right] - \frac{0.0077 \times 238.2 \times (206.2)^2}{12} \left(\frac{238.2 + 44}{206.2 + 44} \right) \\ &= - 17344.621 + 26932.292 + 193.54646 + 3399.4717 \\ &\quad - 7329.9026 \\ &= 5850.7854. \\ \therefore \text{Slope, } \frac{dy}{dx} &= \frac{5850.7854}{207 \times 10^3 \times 833.33} \\ &= 0.00003392. \end{aligned}$$

(ii) When supported by the left hand carrier support and the slip gauges,

$$a = 65 \text{ mm}, b = 151.2 \text{ mm}, c = 22 \text{ mm and } L = 238.2 \text{ mm},$$

then

$$\begin{aligned} EI \frac{dy}{dx} &= - \frac{0.0077 \times (238.2)^3}{6} + \frac{0.0077 \times 238.2}{4} \left(\frac{238.2 + 44}{151.2 + 44} \right) (238.2 - 65)^2 + \frac{0.0077 \times 238.2}{4} \left(\frac{302.4 - 238.2 + 44}{151.2 + 44} \right) \left[238.2 - 216.2 \right]^2 + \frac{0.0077}{24 \times 151.2} \left[(216.2)^4 - (65)^4 \right] - \frac{0.0077 \times 238.2 \times (151.2)^2}{12} \left(\frac{238.2 + 44}{151.2 + 44} \right) \\ &= - 17344.621 + 19885.908 + 123.01702 + 4598.1957 \\ &\quad - 5051.6352 \end{aligned}$$

$$= 2210.8645.$$

$$\therefore \text{Slope, } \frac{dy}{dx} = \frac{2210.8645}{207 \times 10^3 \times 833.33}$$

$$= 0.00001282.$$

The difference in the slope under both cases of measurement is 0.00002110 and is therefore negligible.

APPENDIX B

EFFECTIVE LENGTH OF REFLECTOR CARRIER

The effective length of the reflector carrier is the centre to centre distance of the measuring stylus and the cylindrical roller.

From Fig. 4,

$$\sin \theta = \frac{h}{L}$$

for small θ ,

$$\sin \theta = h/L \approx \theta$$

$$\therefore \theta = \frac{h}{L}$$

where h = linear rise and

L = effective length of the reflector carrier.

In order to obtain a linear rise of $1 \mu\text{m}$ for a reading of the autocollimator of 1 second, that is,

$$\theta = 1 \text{ sec.} = 4.849 \times 10^{-6} \text{ rad.}$$

$$h = 1 \mu\text{m} = 10^{-6} \text{ m.}$$

$$\text{Since } \theta = \frac{h}{L}$$

$$L\theta = h$$

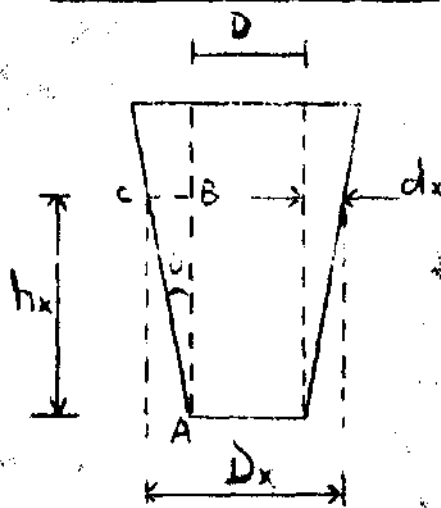
$$\text{or } L = \frac{h}{\theta} \text{ m}$$

$$= \frac{10^{-6}}{4.849 \times 10^{-6}}$$

$$= 0.2062 \text{ m.}$$

$$\therefore L = \underline{\underline{206.2 \text{ mm.}}}$$

APPENDIX C
ANGLE OF TAPER BLOCK



From the figure above,

$$D_x = D + 2dx$$

where D_x = diameter of taper block after moving a distance h_x ,

D = minimum diameter of taper block and

$2dx$ = increase in the diameter of taper block.

From the design of the bore gauge,

h_x = reading of the dial gauge and

dx = distance moved by each pin,

for $\frac{dx}{h_x} = \frac{1}{4}$ or $dx = \frac{h_x}{4}$

from triangle ABC ,

$$\tan \theta = \frac{dx}{h_x} = \frac{1}{4} = 0.25$$

$$\theta = \tan^{-1} 0.25$$

$$= 14.036^\circ$$

$$= 14^\circ 24'.$$

Hence angle of taper is made $14^{\circ} 21'$ for the increase
in the minimum diameter of the bore gauge to be
 $2dx = \frac{hx}{2}$.

Therefore if D_m = minimum bore gauge diameter,
then for a reading of the dial gauge hx , the bore under
measurement is $(D_m + \frac{hx}{2})$ mm.