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K. J. HUME &
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# PRACTICAL METROLOGY

Complete in One Volume


BY

K. J. HUME

B.Sc., M.I.Mech.E., M.I.Prod.E.

*Reader in Engineering Production Technology, Loughborough University of Technology*

Author of *Engineering Metrology*

AND

G. H. SHARP

*Quality Control Manager*

*The Rank Organisation, Rank Taylor Hobson Division*





THE ENGLISH LANGUAGE BOOK SOCIETY

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# CONTENTS

# I

# APPARATUS

The experiments described in this volume have been selected purposely so that they can be performed with relatively simple equipment, of the type not necessarily associated with a standards room or metrology laboratory. The equipment needed should be found in a reasonably well-equipped precision machine shop or toolroom, and in most technical colleges or other training establishments. It should be easily possible to rectify any gaps in the range of equipment already available.

Measuring equipment is, of course, only of value when it is doing useful work, and this, for our purpose, is when it is being used for the measurement of gauges or other tools. Technical colleges when starting instruction in metrology for the first time will probably not have many suitable samples of such work. The actual manufacture of typical plug, ring and gap gauges can provide useful workshop exercises if suitable machine tools are available. Local manufacturers will usually be quite helpful in providing quantities of scrap tools and gauges; these have the advantage that they are probably worn unevenly, thus giving the student good practice in detecting variations in size.

The number of students in a class will obviously determine the number of pieces of any item of equipment which will be required. No hard and fast rules can be laid down, since much depends on the distribution of experiments in a class. Some experiments can be performed directly on the bench; others need an accurate flat surface. Several small surface plates placed on the benches are probably best for individual work, but a larger plate or table can be used to advantage by several groups working round it. Certain experiments, such as the measurement of a taper plug or ring gauge, requiring a flat surface, can be performed quite satisfactorily on a small piece of ground steel if there are not enough plates to go round. A little ingenuity will often get over the lack of exactly correct equipment, but care must be taken to see that accuracy is not impaired.

*Surface Plates*

For most work a hand-scraped Grade A surface plate is suitable. Where all that is needed is a moderately flat support, for example in the measurement of a gap gauge or plain ring gauge, a planed plate is sufficient. For individual work, the plate should not be smaller than 12 in. square, but, as previously mentioned, several people can work round a larger plate.

When not in use, all plates should be greased and kept covered, preferably with a wooden cover; a canvas cover with wooden slats attached is also a good protection and can be conveniently rolled up when removed. Plates should be regularly inspected for burrs, which must be carefully removed. This can be done with an Arkansas or fine India stone; a deep burr may need an expert with a scraper. Inexperienced students should not be permitted to use stones or scrapers on plates (or anything else). A useful tool is a hardened steel block, lapped flat on one face into which have been cut several sharp grooves. If this block weighs about two pounds it can be pushed about the plate and has sufficient momentum for the grooves to shave off small burrs without harming the general surface of the plate.

Scraped plates should not be used for supporting balls in taper measurements, as these are likely to settle in the small pockets between the high spots on the plate. A ground surface, such as a parallel, can usually be used for supporting the balls.

*Micrometers*

Several sizes of micrometer will be required for carrying out the experiments in this chapter, but it should not generally be necessary to use one larger than 3–4 in. range. The plug gauge used in Experiment 1 should preferably be below 1 in. diameter and the taper gauge in Experiment 7 should not exceed 2 in. maximum diameter. Several 0–1 in. micrometers will be needed if the work of a class is not to be delayed unduly.

A vernier scale on a micrometer is a doubtful advantage. It is seldom that exact agreement between the vernier reading and an accurate estimate of the 'thou' division is obtained. In any case, it is better for the student at this stage to practise the estimation of tenths of a division, as described in the next chapter.



*Slip Gauges*

Standard sets of slip gauges in English measure vary from 41 to 81 pieces. The larger set is naturally more adaptable in use, but smaller sets are not to be despised, particularly if equipment has to be carefully chosen to make the most of a limited budget. Workshop grade slip gauges are quite sufficient for all general metrology purposes. Inspection or Calibration grades are only needed for reference purposes and are completely wasted on ordinary gauge work. The Workshop set, or sets, used should, however, be calibrated against accurately known standards and be provided with a table of errors (to the nearest 0·00001 in.).

Ideally, an Inspection or Calibration set should be held and sent to the National Physical Laboratory every two or three years for calibration. If this is not possible, a Workshop set can be sent for calibration to one of the slip-gauge manufacturers or other suitably equipped laboratory.

Slip gauges should, of course, be guarded against accidental damage; the larger and heavier ones are the most vulnerable. Local rectification should be done carefully with an Arkansas stone and it should be made a point of honour in a class for any damage to be immediately reported, without any attempt by students themselves to stone gauges.

An optical flat pushed slowly over the face of a slip gauge will indicate the slightest burr by a sudden change in the interference pattern. A good flat is not necessary for this; a piece of ordinary good *plate* glass will do just as well, since a test on the general flatness of the gauge is not required.

*Rollers and Balls*

Sets of selected rollers can be obtained from the manufacturers; these are guaranteed to be within 0·0001 in. for both diameter and roundness. Balls are not supplied in selected sets and should be carefully checked for roundness and calibrated for diameter. If suitable apparatus is available, rollers should be measured and their diameters recorded (to the nearest 0·00001 in.).

*Dial Indicator and Stand*

The dial indicator should be chosen for its good action, accuracy and clarity of dial. Most reputable manufacturers in this country guarantee their indicators to comply with the B.S. Specification No. 907. A calibration of the dial in thousandths or half-thousandths of an inch is quite sufficient for all purposes required in this volume and for most others as well. A good 'thou' indicator is worth any number of possibly sluggish 'ten-thou' instruments.

The stand chosen must be rigid and have sufficient weight to ensure stability, even when the indicator is at the full extension of its arm. The vertical-pillar type of stand is to be preferred, the clamping arrangements being checked for easy and positive action. Fine adjustments incorporated in the stand should be regarded with suspicion until thoroughly tested. Surface gauge stands should be avoided except for use with small, light-pressure indicators.

*Vernier Height Gauge*

Several good makes of vernier height gauge are available. Perhaps the best (and also the most expensive) is the type with a triangular section column, but the more conventional type is quite satisfactory in the smaller sizes. If a depth attachment is not included with the set, it is not difficult to make one. Alternatively, a slip gauge may be used in Experiment 9.

*Thread Measuring Wires*

For use with a hand micrometer, thread wires are required in sets of three. Such sets are supplied complete with certificate of size and calculated 'P' values for appropriate thread pitches. Substitutes for properly lapped and calibrated wires, such as needles or drills, are not recommended, but, if used, they must be very carefully selected and calibrated.

*Straight-edge and Square*

The straight-edge can be of any convenient size, this being largely governed by the size of the surface plate available for supporting it. In the absence of a proper straight-edge, a good piece of ground steel stock may be used both for the straightness test and the test on the square.

The square is only used as a specimen for test, the most convenient size being 9 or 12 in.



*Miscellaneous Equipment*

It has not been considered necessary to specify in detail other items of general equipment which will be needed for the experiments. Such items include angle plates, vee blocks, clamps, parallels of various sizes, steel packing, Plasticine, string and rubber bands. The last three items may seem a little *infra dig*, but experience shows how greatly they can help in various ways if used intelligently. Plasticine should be carefully cleaned from slip gauges and other steel surfaces after use.

# II

# METHODS

The methods laid down in succeeding pages for each experiment must, of necessity, assume some previous knowledge of procedure or must rely on the instructor to fill in the missing essential basic principles. The instructions are written in a generalised form, since it is obvious that circumstances will vary somewhat in different places. It should, however, be possible to use the instructions as a guide in principle, with intelligent modifications as needed in actual practice.

There are a few essential points which must apply, whatever other variations have to be introduced. While these are referred to in the experiments, it is desirable to deal with them here in rather more detail. Several processes also are common to all or several experiments, and in order to avoid tiresome repetition these are described in the present chapter.

### *Care of Equipment*

Much of the equipment used and the work to be measured consists of steel or iron parts with highly finished ground or lapped surfaces. In most cases, any damage to these surfaces affects the function or accuracy of the part and it is therefore of the first importance to prevent any avoidable damage to these surfaces or other parts of equipment. Careless handling, even where fine surfaces are unaffected, may do serious damage. A micrometer dropped on its frame may show no sign of damage, but it may be quite useless as an accurate measuring tool.

Damage caused by corrosion can be very serious and precautions against this must be constantly taken. All steel measuring surfaces, whether on instruments or gauges, must be protected in some way when not in use. There are various anti-corrosion preparations on the market, some of which contain lanolin in solution. These are quite good and, when properly applied, are suitable for protection of surfaces under the severe conditions of transport by sea through the





tropics. For the protection of laboratory equipment in fairly frequent use, some of the lanolin preparations tend to go rather hard and are a nuisance to clean off. Ordinary petroleum jelly, preferably the white type, is very effective and is easily applied and cleaned off. Although several brands of this may be quite reliable, Vaseline brand has a very low acid content and has proved reliable over many years.

Before discussing the greasing of surfaces it is logical to consider their cleaning. Various spirit solvents may be used, including petrol, benzene, carbon tetrachloride and methyl alcohol. Thawpit and other similar products are essentially carbon tetrachloride and are quite suitable for cleaning. Methyl alcohol or methylated spirit will do, but it does not seem quite so positive in action as the other solvents mentioned. *Clean* rag or 'mutton cloth' is the best medium for applying the solvent, after which the surface should be wiped with another soft cloth or chamois leather. Slip gauges should always be wiped after cleaning, and for this there is nothing quite so good as a soft chamois leather. For millionth comparator work, slip gauges should be cleaned with cotton wool and pure benzene, successive clean pieces of cotton wool being used until all smears have disappeared. This method of cleaning need not be applied for any work described in the present volume.

When an experiment is completed or when putting equipment away, lapped and ground surfaces should be re-cleaned with solvent, wiped and greased. It is quite useless to grease surfaces which are not clean. Finger marks will rust badly into lapped surfaces even under a thick layer of grease; the acid is still there to do its destructive work.

When a box of slip gauges is being used in an experiment, gauges taken out of the box for use must not be replaced without cleaning and greasing. After the first use of a gauge, it should be placed on a clean piece of paper or a chamois leather and need not be wiped or cleaned immediately. If several are being used or tried, it is a good plan to keep them in some order of size so that they can be readily identified when next required. When the experiment is completed, it is obvious that only those gauges that have been taken out of the box will require attention.

Slip gauges and other small pieces are most easily greased with a small piece of chamois leather which is kept in the grease-pot, larger items being greased with a small paint-brush (about $1\frac{1}{2}$ in.

width). It is rather inconvenient to grease surface plates with Vaseline, unless they are to be left for a long period. A light spindle oil or one of the specially prepared anti-corrosion oils can be thinly spread on surface plates and is easily cleaned off.

*Scale Divisions*

It is usual, on most scale-reading instruments such as micrometers and indicators, to estimate fractions of the scale divisions in order to increase accuracy. It must not be assumed, however, that this always leads to greater accuracy; it depends on the instrument. In the case of a good micrometer or thousandth dial gauge, accuracy is gained by making this estimation, even if in the final result it is rounded off again.

Estimation of tenths of a division, on an English micrometer, for instance, is not so difficult as it seems. If the micrometer thimble is set at random and locked, and several observers are asked to estimate the final tenth reading, they will seldom be found to vary by more than one tenth. The novice may feel, for example, that a reading of approximately a quarter of a division is an uncertainty between 0·2 and 0·3. The answer is, of course, that it may be either, but the novice will agree with certainty that it is definitely not 0·1 nor 0·4. Whichever he calls it, 0·2 or 0·3, he will be correct to well within 0·1 of the true value. A little practice on these lines will soon give confidence.

*Fitting of Slip Gauges*

Several experiments involve the fitting of a pile of slip gauges into a gap of unknown size, the size of the pile being varied until the required fit is obtained. A haphazard variation of the slips will result in much loss of time and a systematic approach is much to be preferred.

A rough measurement with a rule will determine the size to the nearest 0·05 in. Assuming the size is required to the ten-thousandth figure, slips should be built up from the larger sizes to a size which is 0·2 in. below the approximate size. On to this pile are then wrung 0·1005 in. and 0·125 in. If this pile is too small, change 0·125 in. for 0·150 in. If this is still too small, the slip in the 0·05 in. series will need changing. If the 0·150 in. is too large, the correct size obviously lies between the 0·125 in. and 0·150 in. slip.

The fatal thing to do now is to start changing by 0·001 in. at a time; one will often go through the whole twenty-five slips before the last one fits. Trial of the slip which lies halfway, say 0·137 in., immediately cuts the uncertain range in half. By halving the remaining range, and so on, the true size is quickly reached. In the above example only some six changes are involved, even in the worst case. When the nearest thousandth slip is reached, the nearest ten-thousandth value is determined in a similar manner by trying the 0·100 in. or 0·101 in. slip in place of 0·1005 in. and again halving the appropriate range.

The correct fit of slips in a gap is not so tight that considerable force has to be used nor so loose that the slips can wobble in the slightest degree. It is usually wise to leave for a few minutes the first pile which appears to fit, so that the slips which have been handled can cool down. Ideally, the assembly should be left for an hour or more, when perhaps another job can be done, but this is not usually possible under class conditions. When temperature has settled, it will often be found necessary to change the slips by a ten-thousandth or two. If the gap is an ordinary plate gauge it will probably have expanded more than the slips and will become tighter on cooling.

*Booking Results*

It is useless making measurements unless they are recorded. The habit of remembering a size which has to be used later is bad practice and in all metrology work each result should be recorded as the measurement is made. The record should, moreover, be made in a note-book and not on the nearest scrap of paper which happens to be about. The pattern of a suitable method of recording results is given for each experiment and, while intelligent deviations from this can be made, beginners are recommended to follow the pattern closely.

Another habit which cuts away the very foundations of accurate measurement is the prejudging of results before the series of observations is complete. If the readings obtained seem wrong it is fatal to try to bias them; the best thing is to carry on or start entirely afresh.

The same principle applies to taking a mean of several results. It is fundamental in all experimental science that *no reading should be rejected unless there is a known and definite reason for doing so.* Rejection of a reading is not permissible simply because one does not like the look of it nor because it spoils an otherwise close agreement. It *may* be closer to the true value than the other readings.

Wherever possible each reading should be repeated, preferably without looking to see what the first reading was. A high degree of self-honesty is necessary, but, with even the best will, it is not easy to acquire.

*Calculations*

In the present volume the calculations that have to be made in most of the experiments are simple arithmetic. In the experiments concerned with measurement of tapers some trigonometrical calculation is necessary and suitable tables will be required. The four-figure tables which are quite suitable for most engineering-class calculations are inadequate for metrology. At least five-figure tables are necessary, and for some purposes six- or seven-figure tables are desirable. Chambers's seven-figure tables will cover anything the student is likely to need, although the volume is rather bulky and contains many tables which are never needed. Castle's five-figure tables are relatively cheap and are handy in size; a handy book of six-figure tables is published by the Ford Motor Company's Technical School.

The slide rule is not to be despised, however. It is very useful for approximate check and calculations and is invaluable for working out proportional differences in the tables. If a calculating machine is available, all students should become conversant with its use, even if there is not much opportunity to acquire a high speed of working. Chambers publish six-figure trigonometrical tables which are particularly suitable for machine calculations.

In the rounding off of final results, the number *5* should be rounded in a direction which will allow for possible unknown wear of standards. For example, it should be considered whether the final figure would be larger or smaller if the slip gauges used had worn below their assumed sizes.

*Assessment of Results*

An experiment is not complete until some assessment of the results obtained has been made. In some cases there will be a British Standard Specification relevant to the work and the results should be compared with the tolerances laid down. In the absence of such a standard, a summary of the results should be made and an



opinion expressed as to the suitability of the work measured, the instructor being consulted if any doubt exists as to the correct standard.

Another important assessment is the probable accuracy or inaccuracy of the actual measurements made. This should also be recorded. It is useless to carry calculations or final results to five places of decimals if the measurements are only accurate to three places.

*EXPERIMENT 1*

## TO MEASURE A DOUBLE-ENDED PLAIN PLUG GAUGE *

*Apparatus*

Plain Plug Gauge, with 'Go' and 'Not Go' ends, preferably under 1 in. diameter and with not less than 0·002 in. difference between 'Go' and 'Not Go' diameters.

0–1 in. Micrometer (or larger to suit gauge), preferably without vernier.

Standard Roller Gauge (or other cylindrical standard) whose size has been accurately calibrated to the nearest 0·0001 in.

*Method*

Clean the protective grease from the gauge, roller and micrometer faces with a clean cloth moistened with petrol, benzene, carbon tetrachloride or other suitable solvent. Wipe with a clean, dry, soft cloth or chamois leather.

Check the feel of the micrometer by operating it over a fair part of its range, watching for any stiffness, roughness, or rubbing of the thimble on the barrel. Report any defect observed.

Take a reading with the micrometer on the standard, using a fairly light feel. If the micrometer is fitted with a ratchet, this may be used if difficulty is found in getting a uniform feel, but such a feel should be cultivated without the ratchet, since most ratchets are too heavy for many purposes.

The micrometer is best held by crooking the little finger round the bow and operating the thimble with the thumb and forefinger. Care must be taken, however, not to heat up the micrometer or gauges by too much handling.

The standard must not be pushed or rotated through the micrometer anvils in order to judge the feel; this must be determined entirely by the force of the finger and thumb on the micrometer thimble.

Estimate tenths of thousandths on the thimble divisions without using the vernier, even if the micrometer is so fitted.

**Read Chapter II before commencing experiment.*





Take readings on the gauge, endeavouring to use exactly the same feel as on the standard. Take four readings at each end, in planes at 90°.

Take a repeat reading on the standard.

*Observations and Results*

Record readings as shown in the following example:

Plug gauge: 'Go' 0·375 in., 'Not Go' 0·380 in. 'Shop'
Standard roller: $\frac{3}{8}$ in., actual size 0·3751 in.

Reading on standard: 0·3752, repeat 0·3752.
Reading on gauge: 'Go' 0·3753–54–52–54.
Size of gauge: . . 0·3752–53–51–53 in.
Reading on gauge: 'Not Go' 0·3798–96–98–97.
Size of gauge: . . 0·3797–95–97–96 in.

*Calculation*

| | |
|---|---|
| Size of Standard | 0·3751 in. |
| Minus reading on Standard | 0·3752 |
| Difference | −0·0001 in. |

*Conclusions*

A new edition of the B.S. Specification for Plain Limit Gauges, B.S. 969:1953 has just been published. In this new edition separate sets of tolerances for Workshop and Inspection gauges have been abolished. It is certain, however, that many gauges will still be found which conform to the old edition of the Specification.

In the earlier specification the tolerances on the gauges were approximately 10 per cent of the tolerances on the work (the difference between nominal 'Go' and 'Not Go' dimensions). The disposition of Shop and Inspection tolerances is shown in the following table:

| | | *Workshop* | *Inspection* |
|---|---|---|---|
| *Plug Gauges* | 'Go' | + | − |
| | 'Not Go' | − | + |

The new Specification provides for a 'General' gauge only, the tolerances for which correspond approximately to those of the old

'Workshop' gauge on the 'Go' end and 'Inspection' on the 'Not Go' end.

The results of the measurement should be assessed to see whether they conform to Shop or Inspection tolerances and also whether the gauge would be satisfactory for the conditions laid down in the new Specification.

## *EXPERIMENT 2*

### TO MEASURE A GAP GAUGE WITH SLIP GAUGES *

*Apparatus*

Suitable Gap Gauge, preferably with 'Go' and 'Not Go' anvils. If no gauge is available, a suitable gap may be made by clamping up blocks and parallels, to a size not less than ½ in.

Set of Slip Gauges (with table of errors).

*Method*

Clean the protective grease from the gauge with a suitable solvent and wipe with a soft cloth or chamois leather.

Find the approximate size of the gap with a rule and build up a first approximation of slip gauges to try in the gap. This pile of slips should contain one slip in the thousandth series and one in the ten-thousandth series. Generally, the pile first tried will be either too large or too small, and it will be necessary to proceed in the manner described in Chapter II (p. 14).

The correct feel of the slips in the gap is rather difficult to define. The most general fault is to try to force in too large a pile of slips. The correct pile will obviously not be loose or have any detectable shake, but should slide quite easily through the gap. If the gap is not parallel it will be necessary to vary the pile of slips to measure the variation in size, and it will be rather more difficult to decide on the exact size at each position in the gap. If, on the other hand, the gap is parallel and its faces are finished by lapping, there is a tendency for the slips to wring to the faces and thus give a false feel, a pile which is really too small giving the feel of one which is too tight. The only remedy in this case is to remove the pile and try it again carefully, after cleaning slips and gauge.

Check the parallelism of the gauge faces by trying the slips at front, centre and back of the gap, altering the pile and recording the sizes carefully at each position, in the manner detailed under the heading *Observations and Results* which follows later.

Throughout this experiment the greatest care must be taken

**Read Chapter II before commencing experiment.*

to avoid undue expansion of the gap gauge and slip gauges with handling. Both should be handled as far as possible with a cloth or chamois leather, and when a correct feel has been obtained at any position the gap gauge with the slips in position should be laid down on a surface plate or other metal surface for several minutes so that temperature differences can be neutralised as far as possible. With a gauge of wide tolerance the care necessary in this respect is not, of course, as great as with a gauge of close tolerance, but it must be remembered that the final accuracy will not be as high.

The handling of a bow-frame gauge at the outer edge of the bow will tend to close the gap and the effect of this is likely to be larger than the expansion of the slip gauges. Consequently the gap will often become larger, relative to the slips, after being left to settle.

Check both 'Go' and 'Not Go' gaps of the gauge where both are provided.

*Observations and Results*

Record results as shown in the following example:

Gap gauge No. 123: 'Go' 0·500 in., 'Not Go' 0·490 in. Shop.

| | *Front* | | *Centre* | | *Back* | |
|---|---|---|---|---|---|---|
| | Slip (in.) | Error (in.) | Slip (in.) | Error (in.) | Slip (in.) | Error (in.) |
| 'GO' | 0·3 | −0·00003 | | | 0·25 | −0·00007 |
| | 0·100 | −0·00006 | | | 0·149 | 0·00000 |
| | 0·1006 | −0·00004 | 0·1002 | −0·00005 | 0·1009 | −0·00003 |
| | 0·5006 | −0·00013 | 0·5002 | −0·00014 | 0·4999 | −0·00010 |
| | =0·50047 in. | | =0·50006 in. | | =0·4998 in. | |
| 'NOT GO' | 0·25 | +0·00007 | | | | |
| | 0·140 | +0·00002 | | | | |
| | 0·1007 | −0·00003 | 0·1008 | −0·00005 | 0·1008 | −0·00005 |
| | 0·4907 | −0·00008 | 0·4908 | −0·00010 | 0·4908 | −0·00010 |
| | =0·49062 in. | | =0·4907 in. | | =0·4907 in. | |

The actual slip gauges used must be recorded as they are taken from the gap and separated. It is *bad practice* to compute the total mentally, as in this way errors can easily occur and cannot afterwards be checked without performing the measurement again.



The error of each slip is recorded at the side and the overall correction made at the end. Again, it is unsound to do this mentally.

*Conclusions*

Although the final sizes work out to five decimal places, due to the slip gauge errors, the true accuracy of measurement is not better than 0·0001 in., and the measured sizes should be rounded off to the nearest 0·00005 in., thus: 'Go' 0·50045 – 0·50005 – 0·4998 in.; 'Not Go' 0·4906 – 07 – 07 in.

These results must then be compared with the appropriate gauge tolerances, as specified in B.S. 969: 1953. In the 1941 edition of this Specification, separate Shop and Inspection gauges are specified and many of these types of gauges are still likely to be available.

In both editions of the Specification the tolerances on the gauges are approximately 10 per cent of the tolerance on the work (the difference between nominal 'Go' and 'Not Go' dimensions). The disposition of the old Shop and Inspection limits is shown in the following table.

| | | *Workshop* | *Inspection* |
|---|---|---|---|
| *Gap Gauges* | 'Go' | − | + |
| | 'Not Go' | + | − |

For very fine tolerances the Shop 'Not Go' tolerance is bilateral, and for coarser tolerances the Shop 'Go' gauge has a wear allowance between the upper limit and the nominal size. A single 'General' gauge is specified in the 1953 Specification, its tolerances corresponding approximately to those of the equivalent Workshop gauge on the 'Go' gap and Inspection on the 'Not Go' gap.

When the correct class of gauge is known, the results must be studied to see whether the gauge is within limits. Any definitely established error which is outside the specified limits renders the gauge unsatisfactory.

In the example given above, the tolerances would be:

'Go' +0 / −0·0010 in. 'Not Go' +0·0010 in. / −0 for a Shop gauge.

It will be seen that the gauge is considerably oversize at the front, probably due to wear, on the 'Go' anvils, but is within limits on the 'Not Go' anvils.

## *EXPERIMENT 3*

## TO MEASURE THE HEIGHT OF A CIRCULAR SPIGOT *

*Apparatus*

A suitable Gauge or fixture, having a cylindrical projection or spigot whose axis is parallel to its base. Failing this, a parallel ground mandrel may be clamped in a vee block. (see Fig. 1)

Set of Slip Gauges (with table of errors).

Surface Plate (grade A).

Micrometer.

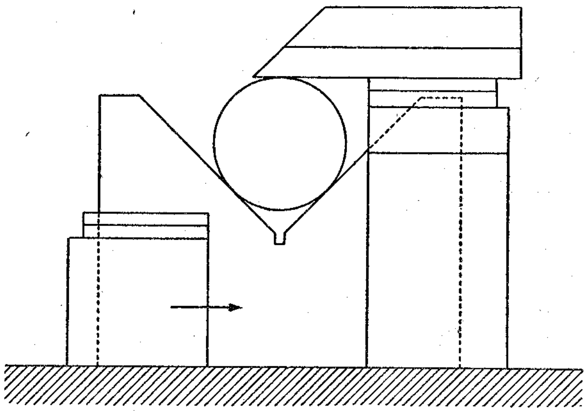


FIG. 1

*Method*

The object of the experiment is to measure the heights of both upper and lower surfaces of the spigot from the surface plate, to measure the diameter, and obtain from these results two independent values for the height of the centre line. It is essential that all these three dimensions should be measured quite independently of one another so that there is no possibility of making the final measurement fit the others.

* *Read Chapter II before commencing experiment.*





The results will enable the student to gauge the accuracy of his use of slip gauges, and agreement between the two final results will give confidence in future work.

Measure, with a rule, the approximate distance from the surface plate to the underside of the spigot and build up a first approximation of slip gauges to fit in the gap. This pile of slips should contain one slip in the thousandth series and one in the ten-thousandth series. Generally, the pile first tried will be either too large or too small, and it will be necessary to proceed in the manner described in Chapter II (p. 14).

It is rather easier to determine the correct pile of slips under a cylindrical surface than in a gap between parallel faces, since an increase in the pile by 0·0001 in., when the correct size has been reached, will result in a definite 'Not Go'.

Measure in a similar manner the height over the top of the spigot. In this case an additional slip must be placed on the top of the pile, protruding over one end, so that it can be passed over the top of the spigot. Another method is to use a small knife-edge straight-edge on top of the pile and pass it over the top of the spigot. The latter method is rather more sensitive than the former.

Measure the diameter of the spigot carefully with the micrometer, estimating to the nearest 0·0001 in. The micrometer should also be checked at a point within its range on a cylindrical standard of known diameter.

If there has been any appreciable handling of the slips, a little time should be allowed for their temperature to settle before taking the final size, when a slight adjustment may be necessary to get the right size.

*Observations and Results*

Record results as shown in the following example:

| | Slip (in.) | Error (in.) |
|---|---|---|
| Under spigot: | 1·0 | −0·00005 |
| | 0·2 | −0·00003 |
| | 0·113 | +0·00001 |
| | 0·1004 | 0·00000 |
| | 1·4134 | −0·00007=1·41333 in. |

| | | |
|---|---|---|
| Over spigot: | 2·0 | −0·00004 |
| | 0·45 | −0·00002 |
| | 0·138 | 0·00000 |
| | 0·1006 | −0·00002 |
| | 2·6886 | −0·00008=2·68852 in. |

Diameter of spigot (by micrometer): 1·2754 in. Radius 0·6377 in.

Centre heights: 1·41333+0·6377=2·05103 in.
2·68852−0·6377=2·05082 in.

Difference: 0·00021 in.

*Conclusions*

Compare the two values for centre height and assess the accuracy of the experiment. Agreement to about 0·0002 in. should be expected if the heights and diameter are not too great. Agreement within 0·0001 in. can be considered very good and indicates careful work and accurate equipment.

## *EXPERIMENT 4*

### TO MEASURE A FLUSH-PIN DEPTH GAUGE*

*Apparatus*

Flush-pin Depth Gauge (see description below).
Set of Slip Gauges (with table of errors).
Dial Indicator on Stand.
Surface Plate.

*Description of Gauge*

A flush-pin gauge normally consists of a steel body through which projects a sliding pin. The gauge is used to check the depth of a hole or recess in a component, and the distance which the pin projects from the face of the body is a measure of this depth. In order to establish limits for the dimension, the upper end of either the pin or the body has a step ground on it and the limits of tolerance are indicated when the steps are, in turn, flush with the reference surface. In the description of this experiment it will be assumed that the steps are ground on the body of the gauge. If a gauge is being used which has the steps on the pin, the slight differences in procedure will be obvious.

*Method*

Two equal piles of slip gauges are selected whose lengths are greater by at least 0·2 in. than the projection of the pin when its upper end is flush with the *lower* step on the body. Stand the body of the gauge with its gauging face resting on the slips which are standing on the surface plate. Care should be taken to see that the correct face is chosen if there are any other projections or spigots on the body, as is sometimes the case.

Place slip gauges under the end of the pin and vary these until the upper end of the pin is accurately flush with the lower step on the body. After the first trial of slips, the pile should be varied in a systematic manner on the same lines as those described for fitting slips to a gap. Accurate estimation of the relative position of the pin

**Read Chapter II before commencing experiment.*

and the step will make this application rather easier. The dial indicator should *not* be used at this stage, however, the position of the top of the pin being judged by feel alone.

Determine in the same way the value of slips required to bring the pin flush with the upper step.

Only when both steps have been checked in this way and the results recorded should the indicator be used to check the accuracy of the settings, since the main object of this experiment is to practise the setting of two surfaces flush without any mechanical aid. Whether an indicator is used at all is left to the discretion of the instructor or supervisor. It should be possible to set within about 0·0003 in. by feel alone.

*Observations and Results*

Record observations as shown in the following example:

| | (in.) | | (in.) |
|---|---|---|---|
| Slips under body: | 2·0 (one side) | Error: | −0·00008 |
| | 1·0 (other side) | | −0·00007 |
| | 0·6 (other side) | | −0·00002 |
| | 0·4 (other side) | | −0·00003 |
| | 2·0 | | −0·00012 in. |
| Mean value: | 1·99990 in. | | |
| Slips under pin: Lower step: | 0·144 | | −0·00002 |
| | 0·1003 | | −0·00006 |
| | 0·2443 | | −0·00008=0·24422 in. |
| Upper step: | 0·115 | | −0·00002 |
| | 0·1001 | | 0·00000 |
| | 0·05 | | −0·00003 |
| | 0·2651 | | −0·00005=0·26505 in. |

Projection of pin: (*a*) lower step flush 1·7557; (*b*) upper step flush 1·7349

It will be noted these last figures are not given to five places of decimals, but the slip-gauge totals have been rounded off to four places. This rounding off should be done at the final figure only; five figures should on no account be given in the final result since even the exact fourth figure will be in some doubt.

## *EXPERIMENT 5*

### TO CALIBRATE A MICROMETER FOR PERIODIC AND PROGRESSIVE PITCH ERRORS*

*Apparatus*

0—1 in. Micrometer.
Set of Slip Gauges.
Micrometer Stand or suitable steel block and Toolmaker's Clamp.
Magnifying Lens.

*Method*

Check the micrometer for smooth running over its whole range and, if necessary, adjust the wear compensating arrangement to eliminate any backlash.

Clean the anvils carefully and examine for burrs. If there are any, remove them with a flat Arkansas stone.

Set the micrometer horizontally in the stand with the anvils uppermost. If no stand is available the micrometer may be lightly clamped by the frame to a convenient block with a toolmaker's clamp. Take care that the thimble is perfectly free of the block. Clamping is necessary to obviate errors due to heat from handling.

It is preferable to avoid using the ratchet, if there is one, and to rely on maintaining a constant 'feel'. If it is desired to use the ratchet (in cases where different people will use the same micrometer), advance the spindle slowly to the anvil and take the reading as soon as the ratchet has slipped (one click). Rapid rotation of the ratchet or friction drive will give false readings.

While the micrometer is cooling to the ambient temperature lay out the following slips (cleaned) on a clean piece of chamois leather or paper: 0·1, 0·105, 0·110, 0·115, 0·120, 0·125, 0·2, 0·3, 0·4, 0·5, 0·6, 0·7, 0·8, 0·9 and 1·0 in.

Having allowed the micrometer to acquire the room temperature, close the anvils and note any difference from the nominal reading (in this case, zero) in units of ±0·0001 in.

Next take a reading on the 0·1 slip and note the error as before. Continue with 0·105, 0·110, etc., up to 0·125, and then 0·2, 0·3, 0·4 and 0·5.

* *Read Chapter II before commencing experiment.*

Wring 0·105 to 0·4 and, after an appropriate interval to allow the slips to cool, take a reading on the combination (0·505) and repeat for combinations of 0·510, 0·515, 0·520 and 0·525.

Continue with single slips, 0·6, 0·7, 0·8, 0·9 and 1·0, and combinations of 0·8 + 0·105, 0·8 + 0·110, etc., up to 0·8 + 0·125.

Allow for slip errors if these exceed 0·00005 in. for any combination.

*Observations and Results*

Tabulate your readings thus:

| Nominal micrometer readings (in.) | 0 | 0·1 | 0·105 | 0·110 | 0·115 | 0·120 | 0·125 | 0·2 | 0·3 |
|---|---|---|---|---|---|---|---|---|---|
| Error 0·0001 in. | −1 | 0 | 0 | +1 | 0 | −1 | 0 | +1 | +1 |

| Nominal micrometer readings (in.) | 0·4 | 0·5 | 0·505 | 0·510 | 0·515 | 0·520 | 0·525 | 0·6 | 0·7 |
|---|---|---|---|---|---|---|---|---|---|
| Error 0·0001 in. | +2 | +2 | +2 | +3 | +2 | +1 | +2 | +2 | +3 |

| Nominal micrometer readings (in.) | 0·8 | 0·9 | 0·905 | 0·910 | 0·915 | 0·920 | 0·925 | 1·0 |
|---|---|---|---|---|---|---|---|---|
| Error 0·0001 in. | +3 | +3 | +3 | +4 | +3 | +2 | +3 | +4 |

The results may be more conveniently examined if they are illustrated graphically (see Fig. 2).

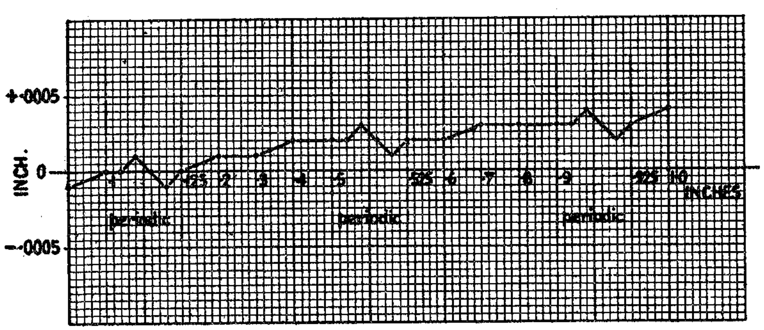



FIG. 2



*Conclusions*

The periodic error is the error existing in one revolution of the micrometer and is usually caused by 'drunkenness' of the thread or eccentricity of the thimble or its graduations. These errors are shown up in the three groups taken between 0·1 and 0·125, 0·5 and 0·525, and 0·9 and 0·925. In this example they amount to ±0·0001 in.

The progressive error is the cumulative error over the total travel of the micrometer and, in this example, is +0·0005 in. (−0·0001 at zero to +0·0004 at 1 in.).

It would appear from a study of the graph that this particular micrometer has a zero error of −0·0001 which is probably caused by slight curvature of the anvils—often found in used micrometers. The error disappears when a 0·1 slip is inserted, which probably bridges a depression in the concave anvil.

The final conclusions regarding this micrometer would therefore be:

| | |
|---|---|
| Periodic error | ±0·0001 in. |
| Progressive error | +0·0004 in. |
| Zero error | −0·0001 in. |

The error of the micrometer at any point on its travel may be derived by adding algebraically the periodic and progressive errors at that point.

If an object were measured by this micrometer and a reading of 0·7950 obtained, then the errors would be:

| | |
|---|---|
| Periodic | −0·0001 in. |
| Progressive | +0·0003 in. |
| Total | +0·0002 in. |

and the actual size of the object would be 0·7948 in.

The tolerances for a micrometer (new) of this size will be found in B.S. 870 and are:

| | |
|---|---|
| Zero reading | ±0·00005 in. |
| Pitch error | 0·0001 in. |

(Combining periodic and progressive errors)

## *EXPERIMENT 6*

### TO MEASURE A PLAIN RING GAUGE*

*Apparatus*

Plain diameter Ring Gauge, preferably 2 to 4 in. diameter.
Set of Slip Gauges (with table of errors).
Pair of Standard Rollers, between ½ in. and 1 in.

*Method*

Place the ring gauge on a surface plate or other suitable metal surface and place the rollers inside the gauge, touching its gauging surface at approximately the ends of a diameter.

Measure the approximate distance between the rollers with a rule and build up a first approximation of slip gauges, trying these between the rollers. This pile of slips should contain one slip in the thousandth series and one in the ten-thousandth series. Generally, the pile first tried will be either too large or too small, and it will be necessary to proceed in the manner described in Chapter II (p. 14).

As the size of slips which will fit between the rollers approaches the true size it will be found more difficult to get them in. As the pile begins to wedge into the radius at the top of the rollers it should be pushed gently to and fro until it passes down between them. In this way the rollers themselves will be rolled until they are exactly across a true diameter when the slips will fall in quite easily, unless they are too large. It is very important not to force them in, for the intensity of pressure between the slips, rollers and ring can be very high. If the slips are oversize they can be removed only with some difficulty and possibly damage.

When the right size has been reached it will slide in easily, and 0·0001 in. addition will make a definite tightening of the feel. Leave the slips in position in the ring with the rollers, all resting on the metal plate, for ten or fifteen minutes if possible, in order to equalise temperature. Adjust the value of the slip gauges after this time if any change in relative size has taken place due to the handling of the slips.

**Read Chapter II before commencing experiment.*





Measure the diameter at two positions at approximately 90°. If there is an appreciable difference between the two sizes, say greater than 0·0002 in., explore the size at other positions in order to find the maximum and minimum diameters. If the ring gauge is more than twice the depth of the rollers, turn it over and measure its diameters at its other end as well, measuring across the same positions as at the first end. If the maximum and minimum diameters occur at different positions at the second end from the first, record these angular positions carefully by marking on the rim of the gauge, in pencil.

*Observations and Results*

Record results as shown in the following example:
Ring gauge: Diameter 2·43 in. (approx.).
Mean diameter of rollers (previously calibrated and recorded): 0·50004.

| *End A* | *Slips* (in.) | *Errors* (in.) | *Rollers* (in.) | *Size* (diameter) (in.) |
|---|---|---|---|---|
| Position 1 | 1·0 | −0·00002 | | |
| | 0·2 | − 1 | | |
| | 0·130 | + 1 | | |
| | 0·1005 | − 3 | | |
| | 1·4305 | −0·00005 | 1·00008 | 2·43053 |
| Position 2 | 0·1001 | −0·00002 | | |
| | 1·4301 | −0·00004 | | 2·43014 |
| *End B* | | | | |
| Position 3 | 0·1004 | −0·00001 | | |
| | 1·4304 | −0·00003 | | 2·43045 |
| Position 4 | 0·1007 | −0·00002 | | |
| | 1·4307 | −0·00004 | | 2·43074 |

Indicate on a sketch the positions measured and note also the measured diameter on the sketch.

*Conclusions*

Unless the work tolerance and limits for which the gauge is intended, either as a 'Go' or 'Not Go' gauge, are known, the suitability of the gauge cannot be accurately assessed. A good quality gauge, between 2 in. and 4 in. diameter, should, however, be uniform in diameter within 0·0002–0·0004 in., even for a wide limit gauge.

If there are excessive variations in diameter, consider whether the general proportions of the gauge are such as to affect its rigidity.

If the limits on the work, for which the gauge is intended, are known, compare the results with the appropriate gauge tolerance in B.S. 969.

## EXPERIMENT 7

### TO MEASURE A TAPER PLUG GAUGE*

*Apparatus*

Taper Plug Gauge, preferably a standard Morse or Brown and Sharpe taper, of moderate size, and with a ground base at the small end.

Several Slip Gauges.

Micrometer or Micrometers of suitable range.

Pair of Standard Rollers, preferably $\frac{1}{4}$ in. diameter, their diameters being previously calibrated.

Surface Plate or other good flat surface.

*Method*

The method of measurement is to stand the gauge with its small end on the surface plate, with a roller on each side supported on equal piles of slip gauges, and to measure the size over the rollers. If $\frac{1}{4}$ in. rollers are used, the micrometer spindle and anvil may generally be rested on the slip gauge, care being taken that the frame does not cause mal-alignment. Several heights of slips are chosen to cover the length of the gauge.

The size of rollers should be chosen so that, if at all possible, the whole variation in diameter can be covered without changing micrometers. From this point of view the advantages of selecting a gauge of slow taper are obvious and it is also much easier to handle a gauge of small diameter than a large one which necessitates the use of a 4 in. or 5 in. micrometer.

Stand the gauge with its small end on the surface table and select two piles of slip gauges which will be sufficient to bring the micrometer clear of the plate when measuring over the rollers placed on the slips. This value can be, say, $\frac{1}{4}$ in. or $\frac{1}{2}$ in. Alternatively, if the gauge is stood near the corner of the plate the rollers may be placed directly on the plate.

Standardise the micrometer carefully on a slip gauge with a roller on each side. Measure the size of the taper gauge over the rollers, tilting

**Read Chapter II before commencing experiment.*

the micrometer slightly up and down over the rollers while taking readings, to ensure that the *maximum* size is obtained. Turn the gauge and measure the size in a plane at 90° to the first position.

Select another value of slips which will bring the rollers about halfway up the gauge and measure in the same planes as before. Select a further value of slips to bring the rollers close to the top of the gauge and repeat the measurements.

It is important to remember that the micrometer is making line contact with the rollers and the rollers are making point contact with the gauge. The pressure used must therefore be extremely light and uniform for all the measurements.

*Observations and Results*

If the taper is slow, as in Morse or Brown and Sharpe gauges, there will be no need to allow for errors on the slip gauges, unless these are large and approaching 0·001 in. on the total build up.

Record results as shown in the following example:

Taper plug gauge No. 3. Morse.
Standard rollers: ¼ in. Mean diameter: 0·250 in.

Nominal Values:

Taper: 0·0502 in. per in., on diameter.
Semi-angle: 1° 26·27′.

Measured Values (in.):
Diameter at small end: 0·7780 in.

| *Slips S* | *Measured size M* | *Difference* | *Nominal difference* | *Error in taper* |
|---|---|---|---|---|
| 0 | 1·2846 | 0 | 0 | 0 |
| 1·5 | 1·3597 | 0·0751 | 0·0753 | −0·0002 |
| 3·0 | 1·4351 | 0·1505 | 0·1506 | −0·0001 |

Diameter at small end:

$$M_{\min} - 0{\cdot}250\left(1 + \cot\frac{90° - 1°26{\cdot}27'}{2}\right)$$

$$1{\cdot}2846 - 0{\cdot}5064 = 0{\cdot}7782 \text{ in.} \quad \text{Error: } +0{\cdot}0002 \text{ in.}$$

Tabulate, in a similar manner, the values for the plane at the 90° position.



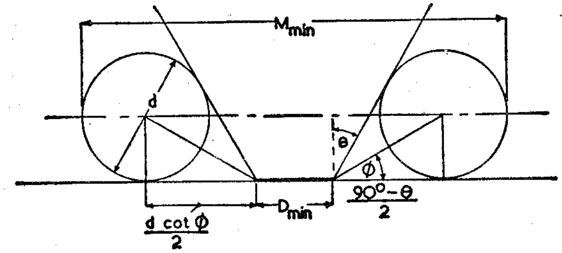



FIG. 3. Calculation of diameter at small end of cone.

*Conclusions*

Observe particularly the errors in taper and note whether the taper is straight. If the errors are uniform or are in a uniform progression, the taper is straight although it may be in error relative to the nominal value. In the example given the overall taper is slow by 0·0001 in. and there is a 'waisting' to the extent of 0·00015 in. at the centre. Such errors scarcely exceed the accuracy of determination obtainable with the apparatus being used.

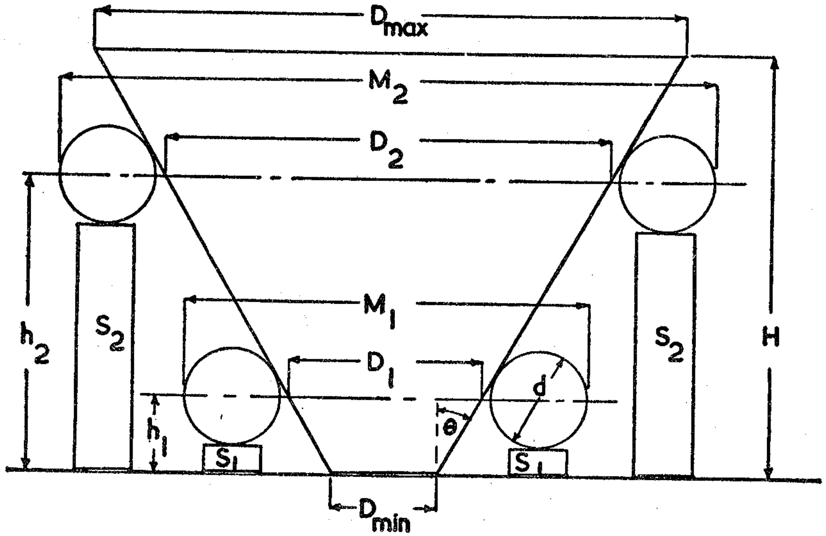
Having calculated the diameter at the small end of the gauge, compare this with the nominal value, if this is known.

Where the gauge is non-standard or the nominal values of taper, etc., are unknown, calculate the angle of taper from the maximum and minimum values of $M$ using the formula:

$$\tan\theta = \frac{M_2 - M_1}{2(S_2 - S_1)}$$

Evaluate nominal values for the intermediate positions and compare the measured values with them. The straightness of the gauge can, of course, be assessed without calculating the angle by examining the uniformity or otherwise of the progression of the measured values. The direct values over the rollers can be used, and the progression of values should obviously be proportional to the heights at which the measurements are taken.

The diameters at the large and small ends may be calculated from the formulae on p. 38.



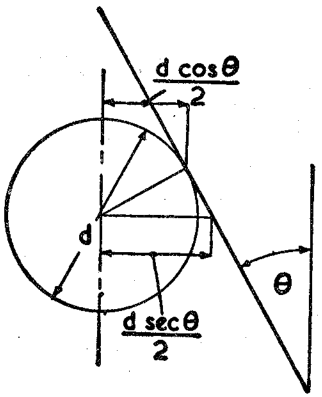




FIG. 4. Taper Plug Gauge measured with rollers, with geometry of roller contact.

$$D_{\min} = M_1 - d\,(1 + \sec\theta) - 2\,(S_1 + \tfrac{d}{2})\tan\theta$$

$$D_{\max} = M_2 - d\,(1 + \sec\theta) + 2\,(H - S_2 - \tfrac{d}{2})\tan\theta$$

## *EXPERIMENT 8*

### TO MEASURE A TAPER RING GAUGE (LARGE DIAMETER)*

*Apparatus*

Taper Ring Gauge of 2 in. to 4 in. diameter, whose depth is less than its diameter.

Pair of Steel Balls, preferably about ¾ in. diameter, their diameters having been previously calibrated.

Set of Slip Gauges (with table of errors).

Lapped or Ground Surface Plate. A scraped plate may introduce errors.

*Method*

Stand the ring gauge, *large* end down, on the surface plate, and place the two balls inside it. With the balls in contact with the taper surface of the gauge build up a first approximation of slip gauges to fit between the balls. This pile of slips should contain one slip in the thousandth series and one in the ten-thousandth series. The first pile tried will generally be too large or too small and it will be necessary to proceed in the manner described in Chapter II (p. 14).

It is very important not to wedge the slips between the balls, as contact is made almost at single points where the intensity of pressure can be very high. It will be necessary to try to move the slips from side to side, rolling the balls against the side of the gauge, to ensure that measurement is being made across a diameter. Any definite clearance between the slips and balls will then be apparent. The correct size of slips will be found to fit snugly without requiring force. Care must also be taken to see that the gauge is not being lifted from the plate. This can easily be detected by noting any tendency for the gauge to rock.

When the correct size has been found, leave the gauge, with slips and balls in position, resting on the plate for ten or fifteen minutes if possible, in order to equalise temperature. Adjust the value of the slip gauges after this time if any alteration of feel has taken place.

Measure the diameter at two positions at approximately 90° apart.

**Read Chapter II before commencing experiment.*

If there is an appreciable variation in diameter, say greater than 0·0002 in., explore the sizes at other positions to find the maximum and minimum diameters.

Next, place the balls on two equal slip gauges or piles of slips of such a size to bring the contact points of the balls near the top of the gauge. Measure the diameter at two positions as before, and if there is much variation, note whether the maximum and minimum diameters are in the same vertical planes as the measurements at the bottom of the gauge.

In some cases it will be found that the gauge is too shallow to allow the balls to be raised a suitable distance on slips, the point of contact when both balls and gauge are resting on the plate being quite high up on the gauge. In such cases the gauge itself may be rested on three equal piles of slips, the balls resting on the plate, thus lowering the point of contact. For the higher position, the gauge may be lowered or the balls may be raised on slips or both methods may be combined. In any case, the relative heights of the ball centres and the base of the gauge are easily determined.

*Observations and Results*

Record results as shown in the following example:

Taper ring gauge—nominal diameter (large end): 4 in.

—nominal taper: 60° included angle.

$\frac{3}{4}$ in. balls—mean measured diameter: 0·75005 in.

| | *Slips S* (in.) | *Slips M* (in.) | *Errors* (in.) | | |
|---|---|---|---|---|---|
| 0° plane | 0 | 1·0 | −0·00003 | | |
| | | 0·75 | −0·00002 | | |
| | | 0·111 | 0·00000 | | |
| | | 0·1008 | −0·00001 | | |
| | | 1·9618 | −0·00006 | =1·96174 in. | |
| 90° plane | 0 | 0·1006 | 0·00000 | | |
| | | 1·9616 | −0·00005 | =1·96155 in. | |
| 0° plane | 0·6 | 1·0 | −0·00003 | | |
| | | 0·05 | 0·00000 | | |
| | | 0·118 | −0·00001 | | |
| | | 0·1006 | −0·00002 | | |
| | | 1·2686 | −0·00006 | =1·26854 in. | Diff. for 0·6 height 0·69320 |
| 90° plane | 0·6 | 0·1004 | 0·00000 | | |
| | | 1·2684 | −0·00004 | 0=1·26836 in. | 0·69319 |



Nominal difference for 0·6 height: 1·2 tan 30° = 0·69282.

Error in taper over 0·6 in.: 0° plane 0·00038 in. fast

90° plane 0·00037 in. fast

Calculate the measured semi-angle of taper from the maximum and minimum values of $M$, using the formula:

$$\tan\ \theta = \frac{M_1 - M_2}{2(h_2 - h_1)}$$

Calculate diameter at large end from the formula:

$$D_{\max} = M_1 + 0{\cdot}75005\ (1 + \cot \frac{90° - 30°0{\cdot}8'}{2})$$

$$= (0° \text{ plane})\ 1{\cdot}96174 + 2{\cdot}04952 = 4{\cdot}0113 \text{ in.}$$

$$= (90° \text{ plane})\ 1{\cdot}96155 + 2{\cdot}04952 = 4{\cdot}0111 \text{ in.}$$

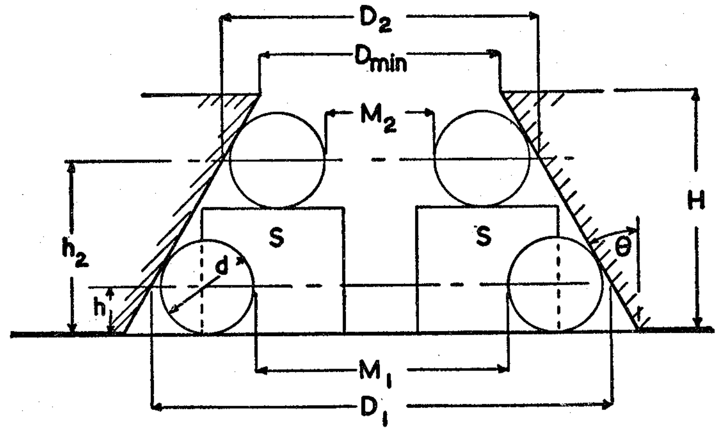



FIG. 5.

*Conclusions*

In the example given above it will be noted that measurements were taken at only two positions of height. These will not, of course, show any error in straightness of the cone and, if the height of the gauge permits, it is advisable to measure at three heights. The straightness can, however, be checked by holding an accurate cylinder, such as a standard roller, against the cone and viewing against a good light. The cylinder must be moved round until its axis lies in a plane with the cone axis before the straightness is judged.

Having calculated the diameter at the large end, compare this with the nominal value, if this is known.

If the diameter at the small end is required, it should be calculated from the smallest measurement, thus:

$$D_{\min} = M_2 + d\,(1 + \sec\theta) - 2\left(H - S - \frac{d}{2}\right)\tan\theta$$

*EXPERIMENT 9*

## TO MEASURE A TAPER RING GAUGE WITH BALLS AND DEPTH GAUGE*

*Apparatus*

Taper Ring Gauge of small angle, preferably not larger than 1 in. diameter and whose length is greater than its diameter.

Two calibrated steel balls, one of which contacts the Ring Gauge towards its small end and the other towards its large end—make certain the centre of the large ball is slightly below the large end of the ring.

Set of Slip Gauges.

Vernier Height Gauge with Depth Attachment.

Scraped Surface Plate.

*Method*

Holding the ring gauge almost horizontal, roll the smaller ball gently inside the gauge until it rests at the small end. If the ball is allowed to drop rapidly, severe wedging between the ball and the gauge will occur, with consequent false readings.

Stand the gauge (with ball inside), small end down, on the surface plate. If the ball protrudes, place the gauge on two equal piles of slips sufficient to keep the bottom of the ball clear of the surface plate.

Lower the depth attachment with the height gauge until it just touches the top of the ball. The slide of the vernier should be lightly clamped to achieve this and lowered 0·001 in. at a time while the depth attachment is passed and repassed over the ball to find its highest point. A slight film of thin oil or paraffin on the surface plate will ease the movement of the height gauge and render the moment of contact more apparent.

The height gauge reading is noted and the procedure repeated about three times in order to give a reliable average value.

Next, remove the smaller ball and insert the larger, as before, and determine its height. Make four measurements and record these.

* *Read Chapter II before commencing experiment.*

Measure the height of the top surface of the gauge (still using the depth attachment) by the same method used over the balls.

Remove the gauge from the slip piles and take a height-gauge reading (again with the depth attachment) on the slips—if slips have been used, otherwise directly on the surface plate.

*Observations and Results*

Record results as shown in the following example:

Taper ring gauge—nominal diameter (large end): 0·925 in.
—nominal taper: 20° included angle.
$\frac{7}{8}$ in. dia. ball, mean measured dia.: ($d_1$) 0·8751 in.; $r_1 = 0{\cdot}43755$ in.
$\frac{5}{8}$ in. dia. ball, mean measured dia.:($d_2$) 0·6249 in.; $r_2 = 0{\cdot}31245$ in.

Slips under gauge: 0·15 in.

Rdg. over top surface of gauge: 8·743 in.
Rdg. over slips (bottom surface of gauge): 7·771 in.
Length of gauge: ($H$) = 8·743 − 7·771 = 0·972 in.
Rdg. over small ball: 8·234. $h_2$ = 8·234 − 7·771 = 0·463 in.
Rdg. over large ball: 9·077. $h_1$ = 9·077 − 7·771 = 1·306 in.

Then:

$$\sin\theta = \frac{r_1 - r_2}{(h_1 - r_1) - (h_2 - r_2)} = \frac{0{\cdot}43755 - 0{\cdot}31245}{(1{\cdot}306 - 0{\cdot}43755) - (0{\cdot}463 - 0{\cdot}31245)}$$
$$= 0{\cdot}174258$$

$\theta$(semi angle of taper) = 10° 2′
(included angle of taper = 20° 4′

$$D_1 = d_1 \sec\theta = 0{\cdot}8751 \sec 10^\circ\, 2' = 0{\cdot}8887$$
$$D_2 = d_2 \sec\theta = 0{\cdot}6249 \sec 10^\circ\, 2' = 0{\cdot}6346$$
$$D_{max} = D_1 + 2\,(H - h_1 + r_1)\tan\theta$$
$$= 0{\cdot}8887 + 2\,(0{\cdot}972 - 1{\cdot}306 + 0{\cdot}43755)\tan 10^\circ\, 2 = 0{\cdot}9253 \text{ in.}$$
$$D_{min} = D_2 - 2\,(h_2 - r_2)\tan\theta$$
$$= 0{\cdot}6346 - 2\,(0{\cdot}463 - 0{\cdot}31245)\tan 10^\circ\, 2' = 0{\cdot}5813 \text{ in.}$$



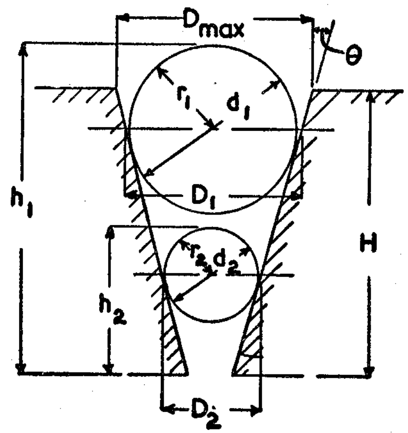



FIG. 6.

*Conclusions*

In the example given above it will be noted that measurements were taken at only two positions of height. These will not, of course, show any error in straightness of the cone, and if the length of the gauge permits, and balls of the required sizes are available, it is advisable to measure at three or more heights.

It may perhaps be thought that the feel of the height gauge and depth attachment is rather insensitive. A short study of the formulae, however, will show that for taper gauges of small angle (for which this method is mostly used) the accurate determination of height is relatively unimportant. On the other hand, knowledge of the precise diameters of the balls and taking care in assembling them are extremely important.

*EXPERIMENT 10*

## TO MEASURE THE MAJOR AND EFFECTIVE DIAMETERS OF A PLUG SCREW GAUGE WITH HAND MICROMETER AND THREAD MEASURING CYLINDERS*

### *Apparatus*

Full form Plug Screw Gauge, preferably larger than $\frac{1}{4}$ in. and less than 1 in. diameter and of about 16 *T.P.I.*

0–1 in. Micrometer.

Set of three Thread Measuring Cylinders suitable for the pitch of thread chosen.

### *Method*

This experiment is one in which considerable manual dexterity is required. It may at first appear almost impossible, but after some practice it will become comparatively easy.

Stand the screw plug on end with the thread to be checked uppermost.

Stick two thread cylinders in adjacent threads with Vaseline, near the point of the gauge. Stick the third cylinder diametrically opposite the other two in the same groove.

Carefully pick up the plug by the handle in the left hand and apply the micrometer over the three wires.

Gently rock the micrometer while closing it so that it beds down well on the wires and at the same time rotate it about the plug to find the greatest reading (i.e. a diameter). Note this reading and repeat at different positions along and around the gauge. Usually three or four readings are sufficient.

As with all accurate measuring, make yourself comfortable for this experiment, since it depends largely on steady hands, good balance and a nice 'feel'. Choose a stool or chair the right height and rest the elbows or forearms on the work bench.

With a larger gauge it is sometimes preferable to leave it standing on the table while applying the micrometer. Use just sufficient

**Read Chapter II before commencing experiment.*





grease to hold the cylinders in position and do not put too much pressure on the micrometer.

The major diameter may be measured in several positions with the micrometer exactly as in Experiment 1.

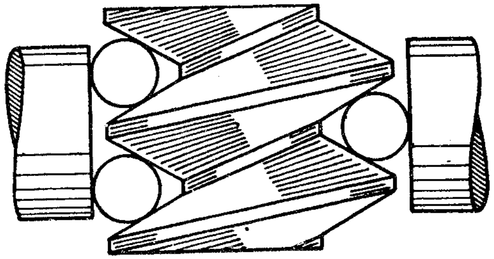


FIG. 7.

### *Observations and Results*

The $P$ value for the thread cylinders should have been calculated from their measured size by some competent authority like the N.P.L. and should appear on a certificate. This constant is primarily for use with a floating-diameter machine and the constant we require is derived thus:

$$C = 2d - P$$

where $C$ is the constant we require for 'over wire' micrometer measurements,

$d$ is the mean diameter of the cylinders as quoted on the certificate,

$P$ is the constant quoted on the certificate.

Should the $P$ value not be known it may be calculated from an extremely accurate measurement of the diameter of the cylinders thus:

$$P = \frac{p}{2} \cot \theta - d\ (\operatorname{cosec} \theta - 1)$$

where $p$ is the pitch of the thread and $\theta$ is the SEMI angle of the thread.

If preferred, the $C$ value may be calculated directly:

$$C = d\ (\operatorname{cosec} \theta + 1) - \frac{p}{2} \cot \theta$$

The effective diameter is calculated simply by subtracting the $C$ value from the measurement over the cylinders:

Effective diameter = diameter over cylinders − $C$.

The major diameter is, of course, obtained from the direct reading of the micrometer without using the cylinders.

Tabulate readings as in this example:

| | |
|---|---|
| Nominal size of thread: | $\frac{1}{2}$ in. × 16 *t.p.i.* Whit. |
| Effective diameter limits: | 0·4600 − 0·4594 in. |
| Major diameter limits: | 0·5000 − 0·4994 in. |
| Mean diameter of cylinders: | 0·03528 in. |
| $P$ value: | 0·01891 in. |
| $C$ value: | 0·05165 in. |

| | *Reading over cylinders* | *Effective diameter* | *Major diameter* |
|---|---|---|---|
| Point | 0·5111 in. | 0·4595 in. | 0·4996 in. |
| Middle | 0·5113 in. | 0·4597 in. | 0·4998 in. |
| Back | 0·5114 in. | 0·4598 in. | 0·4999 in. |

*Conclusions*

This experiment is known as the 'three wire' method of measuring external screw threads. It is not easy to carry out at first, but is a method much used in engineering and with practice an accuracy of ±0·0001 in. may be attained. The usual procedure of standardising the micrometer must be carried out in this and every experiment where micrometers are used.

In a later experiment a diameter machine will be used which eliminates errors due to 'feel'. When the machine is used there are corrections to be applied to the final result due to helix interference and pressure effects on the measuring cylinders. The overall accuracy of the present experiment is not sufficient to justify the inclusion of these corrections.

It is important that the diameter of the cylinders is known precisely. If, as is unfortunately often done, twist drills are used as measuring cylinders, it must be realised that by measuring their somewhat erratic plain diameters with a micrometer the accuracy of the final result will be considerably decreased.



The measured effective diameter of the gauge should be compared with the appropriate tolerance in B.S. 919. As with the Specification for plain limit gauges, this Specification was revised in 1952, the old Workshop and Inspection gauges being replaced by a General gauge, a Reference gauge also being added.

If the gauge is marked *GEN* or *REF* it should correspond to the 1952 Specification; if it is marked *SHOP* or *INSP* it should correspond to the older Specification.

## *EXPERIMENT 11*

# TO CHECK A STRAIGHT-EDGE BY THE WEDGE METHOD*

### *Apparatus*

Straight-edge about 2 ft. long with blade width of not less than ¼ in.

Grade A Surface Plate at least 3 ft. long.

Set of Slip Gauges.

### *Method*

Calculate to the nearest inch the separation of the support points for a minimum deflection (0·554 $l$ in. where $l$ is the length of the straight-edge).

Divide the straight-edge into an equal number of parts which include the points found above. This may be done simply by laying a rule against the straight-edge and marking off the intervals with a hard, sharp pencil on the straight-edge. An inch interval is usually the most suitable.

If the straight-edge is 24 in. there will be 24 lines, leaving ½ in. at each end. Identify these lines 0–23; the support points will then be 5 and 18 (to the nearest inch).

Set the straight-edge up on its side resting on a pile of slips under each support point, and let the piles differ in height by 0·001 in. per inch of separation. In the case we have chosen this would be 0·013 in. In order to avoid unnecessary wringing of slips, choose the values to lie between 0·2 in. and 0·250 in., since there are usually three 0·1 in. slips in a box. In this case place 0·233 in. under the 5 mark and 0·220 in. under the 18.

If the surface plate and the straight-edge are perfectly straight, the gap between them will vary by 0·001 in. between each line, from 0·238 in. at line 0 to 0·215 in. at line 23.

Successive piles are therefore tucked into the gap at each line. If the correct pile of slips does not contact at its proper line, increase or decrease it until it does. Remember that a 0·0001 in. change in the size of the slips will change the contact point along the straight-

**Read Chapter II before commencing experiment.*





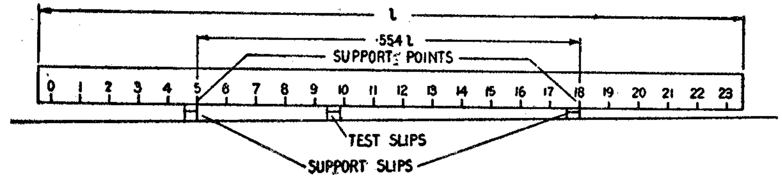



FIG. 8.

edge by 0·1 in., so the method is extremely sensitive. Should two piles of slips, different by 0·0001 in. straddle the proper contact point, then the actual size lies between them.

Scrupulous cleanliness is essential in this experiment. Care must be taken not to let the slips wring to the surface plate, but quite firm pressure may be exerted in sliding the measuring pile into the wedge. If too much pressure is used, this will immediately be noticeable because one or both of the supporting piles will become loose.

### *Observations and Results*

Record results as shown in the following example:

Straight-edge No.: 12K. Length: 24 in.

Support points: 0·554 $l$ = 13·296 in. Distance chosen: 13 in.

Measuring point interval: 1 in.

Supporting slips: 0·220 in. and 0·233 in.

| *Position* | *Nominal slips* (in.) | *Actual slips* (in.) | *Error in metal of straight-edge* (in.) |
|---|---|---|---|
| 0 | 0·238 | 0·2385 | −0·0005 |
| 1 | 0·237 | 0·2374 | −0·0004 |
| | etc. | etc. | |
| 5 | 0·233 | Support point | 0 |
| | etc. | etc. | |

The results are best shown finally as a graph (Fig. 9):

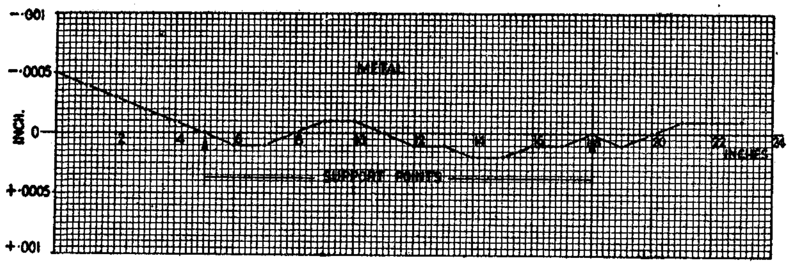



FIG. 9.

*Conclusions*

This method may be made as sensitive as required by changing the angle of the wedge and the number of measuring positions.

Instead of altering the size of slips to obtain contact at the correct point, the distance along the straight-edge by which the correct slips fail to contact it may be translated into terms of plus or minus metal, since the rate of taper of the wedge is known.

The method assumes no error in the surface plate. A later experiment will show how a similar method will determine the errors of both straight-edge and surface plate.

Compare the errors found with the tolerances laid down in B.S 863.

## *EXPERIMENT 12*

### TO CHECK AN ENGINEER'S SQUARE*

*Apparatus*

Engineer's Square (preferably 9 in. or 12 in.).

Selected Parallel (about 12 in. long and parallel to 0·0002 in.).

Means of holding the Parallel vertically (steel cube and finger clamps).

Set of Slips.

Grade A Surface Plate at least twice as long as the stock of the square.

*Method*

Set up one side of the parallel in the vertical position by sighting it against the square under test. Clamp the parallel in this position, taking care to leave the parallel sides free from obstruction. The parallel should be in the centre of the surface plate. It is immaterial which side of the parallel is chosen first, but for the purpose of this experiment it will be assumed that it is the side on the right of the student.

Holding the stock firmly down on the surface plate, slide the blade up to the right-hand side of the parallel until it just traps a clean 0·1005 in. slip held between the parallel and the lower end of the blade (but clear of the surface plate).

While still trapping the lower 0·1005 in. slip, try a 0·1004 in. slip between the parallel and the top of the blade. If this is loose, try the 0·1006 in. and continue until a slip of the correct size is found. Record the values of the top and bottom slips.

A slip at the top which is too large will cause the lower slip to fall. A slip which is too small but larger than the lower slip will slide down the blade and stick at some intermediate position. If the 0·1004 in. slip is too small and the 0·1006 in. too large, it would indicate that the correct slip for the top is the 0·1005 in. Unless the student is fortunate in having another box of slips available and hence another 0·1005 in., he must change the lower slip to a 0·1 in. *protector* and try 0·1 in. in the top.

*Note:—*Read Chapter II before commencing experiment.*

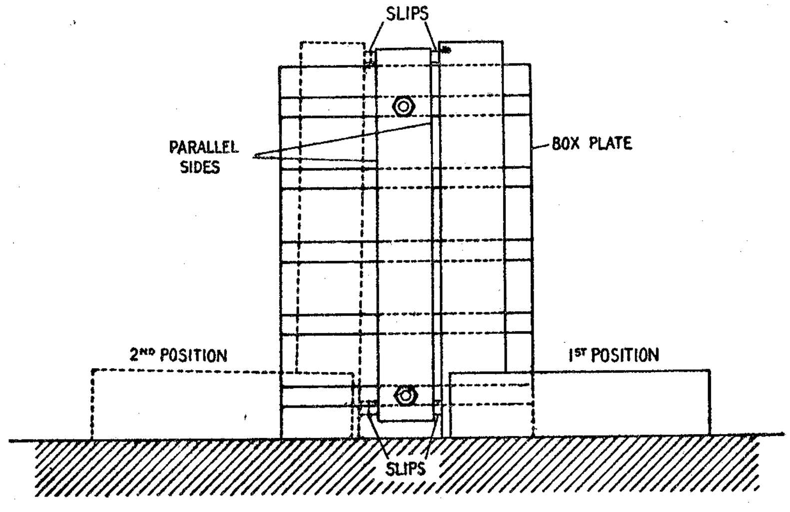



FIG. 10.

Should it not be possible to find a slip in the ten-thousandth range then, of course, the lower slip must be changed to give a greater range. A suitable combination is: 0·108 + 0·112, giving 0·220 in. The top slips can then be a combination of the ten-thousandth slip and 0·120 in. or 0·119 in., or 0·121 in., etc. Since the parallel was set to the square, however, the single slips should suffice and are easier to handle.

Care must be taken not to press the square too hard against the lower slip and parallel. This may cause the square to tilt or allow the blade to bend if too large a slip is forced at the top.

Remove the square and slips and, without moving the cube and parallel, apply the square to the left-hand side of the parallel, this time using the 0·220 in. combination at the bottom.

Proceed as before and note the values of the top and bottom slips.



*Observations and Results*

| Engineer's square | Size 12 in. | No. 6K |
|---|---|---|
| *Right-hand side of parallel* | Bottom slips | 0·1005 in. |
| | Top slips | 0·1008 in. |
| | Blade is out of square by (in terms of + or − metal at the top) | −0·0003 in. |
| *Left-hand side of parallel* | Bottom slips | 0·2200 (0·108+0·112 in.) |
| | Top slips | 0·2181 (0·118+0·1001 in.) |
| | Blade is out of square by (in terms of + or − metal at the top) | +0·0019 in. |

$$\text{Real squareness error} = \frac{\text{algebraic sum of errors}}{2} = \frac{-0{\cdot}0003+0{\cdot}0019 \text{ in.}}{2}$$

$$= +0{\cdot}0008 \text{ in.}$$

Direction of error: excess material at top of blade.

*Conclusions*

This is an extremely sensitive method, because the total error measured is double the actual error. The principle involved is known as a *reversal process* and is greatly used in accurate measurement.

Very simple apparatus is all that is required—the only stipulations being that the parallel *is* parallel and the surface plate *is* flat. A later experiment will show that even inaccuracy of the parallel can be allowed for.

If the separation of the slips has not been sufficient to cover the entire length of the blade, the error may be extended by simple proportion.

If the squareness of the inner faces of the blade and stock are required, it may be derived by checking the stock and the blade for parallelism and applying these values to the squareness errors found in the experiment.

Slip errors must, of course, be incorporated in the calculations.

Compare the errors found with the tolerances laid down in B.S. 939.

*British Standard Specifications referred to in experiments 1–12.*

Expts. 1, 2 and 6. B.S. 969 (1941 & 1953 editions). Plain Limit Gauges, Limits and Tolerances.

Expt. 5. B.S. 870 External Micrometers.

Expt. 10. B.S. 919 (1940 & 1952 editions). Screw Gauge Limits and Tolerances.

Expt. 11. B.S. 863 Steel Straightedges of Rectangular Section.

Expt. 12. B.S. 939 Engineers' Squares.

## *EXPERIMENT 13*

### TO MEASURE A PLUG GAUGE ON A COMPARATOR

*Apparatus*

Plain Plug Gauge, with 'Go' and 'Not Go' ends, preferably under 2 in. diameter and with not more than 0·002 in. difference between 'Go' and 'Not Go' diameters.

Suitable Comparator. This may be mechanical, pneumatic, optical or electrical, and must be of such magnification that variations in size of 0·00001 in. can be detected and estimated accurately. The smallest graduation on the scale will normally be 0·00005 in.

Set of Slip Gauges (with table of errors).

*Method*

Select slip gauges which correspond to the size of the gauge to be measured. If the difference in size between 'Go' and 'Not Go' ends falls easily within the range of the comparator scale only one pile of slips will be needed to set the comparator. The value should be approximately midway between the two sizes. If, however, the comparator is one of relatively high magnification it will be desirable to wring together two piles of slips corresponding to the nominal values of the 'Go' and 'Not Go' ends of the gauge.

The slip gauges, the comparator table and the tip of its measuring plunger should be cleaned of grease and wiped with a chamois leather or other soft cloth. Having raised the comparator head sufficiently, the appropriate size of slip gauges should be wrung to the table under the measuring plunger. The comparator head is then carefully lowered until the measuring plunger makes contact with the slips and a reading is obtained on the scale at about the mid-point or zero position. The comparator head is then clamped to its column.

It is not possible to give detailed instructions on the adjustment of the comparator, since this varies with different types, but many of these instruments will be found to have a coarse screw-thread adjustment on the column for raising and lowering the head. If the comparator used is not so fitted, the greatest care must be taken to ensure that the head does not drop suddenly, with almost certain damage to the instrument. Various forms of fine adjustment will be met; these may operate on the table or the comparator head itself, or both. In the Sigma comparator, which is widely used for this class of work, a fine adjustment and clamp operate on the work table, while a final close setting may be obtained by rotating a small knob on the instrument which gives a slight movement to the dial. Having set the comparator as closely as possible to zero, gently operate the plunger-lifting trigger and observe whether the previous scale reading is repeated.

It may be that some slight alteration to the fine adjustment will be necessary before a suitable reading is obtained. Record the reading on the slip gauges in terms of scale divisions in the manner indicated under the heading 'Observations and Results'. Remove the slips and pass the 'Go' end of the plug gauge under the measuring plunger, taking care that the length of the gauging surface rests firmly on the measuring table. Note the maximum reading on the comparator scale; this will correspond to a true diameter measurement on the gauge. Take three readings along the gauging surface in one plane and three more readings along a plane at 90°.

If the gauge provided is one of small diameter, say ¼ in. or less, it may be found that the handle portion is larger in diameter than the gauging end, and this will prevent the gauge surface making proper contact with the measuring table. In such cases it will be necessary to wring a slip gauge of suitable thickness on to the comparator table and use this as a base for measurement. Such a gauge must obviously also be in position when the setting is made on the standard slips. After the readings on the 'Go' end of the gauge have been taken, the standard slips must be replaced and the standard reading repeated and recorded.

If the repeat is satisfactory, i.e. within 0·00002in. of the initial reading, the same procedure should be adopted for measurement of the 'Not Go' end. As the length of the 'Not Go' gauge surface is usually shorter, it may only be possible to take two readings along the length. Another repeat reading on the standard must then be taken.



*Observations and Results*

Record results as shown in the following example:

Plug gauge 'Go' 0·500 in. 'Not Go' 0·501 in.

| | 'Go' | *Error* | 'Not Go' | *Slip Error* |
|---|---|---|---|---|
| Standard slips: | 0·5 | —0·00002 | 0·4 | —0·00001 |
| | | | 0·101 | —0·00003 |
| | 0·49998 in. | | 0·501 | —0·00004 |
| | | | | —0·50096 in. |

Unit of reading 0·0001 in.

| 'Go' | *Readings Std.* | *(Div.) Gauge* | *Difference from Std. (Div.)* | *Size of Gauge* (in.) |
|---|---|---|---|---|
| 0° plane | 0·0 | +0·1 | +0·1 | 0·49999 |
| | | +0·2 | +0·2 | 0·50000 |
| | | +0·1 | +0·1 | 0·49999 |
| 90° plane | | +0·3 | +0·3 | 0·50001 |
| | | +0·2 | +0·2 | 0·50000 |
| | 0·1 | +0·2 | +0·2 | 0·50000 |
| 'Not Go' | | | | |
| 0° plane | 0·0 | +0·7 | +0·6 | 0·50102 |
| | | +0·6 | +0·5 | 0·50101 |
| 90° plane | | +0·8 | +0·7 | 0·50103 |
| | 0·2 | +0·8 | +0·7 | 0·50103 |

The mean of the first standard reading and its repeat is taken for calculating differences. The mean is calculated to the nearest 0·1 division.

*Conclusions*

The results of the measurements should be compared with the appropriate specification for plain limit gauges B.S. 969. The 1941 edition specifies tolerances for both workshop and inspection gauges, and the values of these were approximately 10% of the work tolerances (the differences between nominal 'Go' and 'Not Go' dimensions). The disposition of shop and inspection tolerances is shown in the following table:

| | | *Workshop* | *Inspection* |
|---|---|---|---|
| *Plug* | 'Go' | + | — |
| *Gauges* | 'Not Go' | — | + |

The 1953 edition of the specification provides for a 'General' gauge only, the tolerances for which correspond approximately to those of the old workshop gauge on the 'Go' end and inspection on the 'Not Go' end. The results of the measurements should be assessed to see whether they conform to Shop or Inspection tolerances and also whether the gauge would be satisfactory for the conditions laid down in the new specification.



*EXPERIMENT 14*

## TO MEASURE THE ANGLE OF A TAPER PLUG GAUGE WITH A SINE BAR

There are several ways in which this experiment can be performed, depending on the apparatus available. The most straightforward method is to mount the gauge on centres, but in this case it is necessary for there to be a precision surface directly under the centres on which to place the sine bar. If such equipment is not available, it will sometimes be possible to set up centres on two vee blocks accurately aligned on a surface plate.

Another method is to support the gauge itself on the surface of the sine bar; this is only practicable with a fairly small gauge and is rather more difficult to set up. The principles of both methods will be described although it should be realised that other variations of setting up can be used.

### *METHOD I*

*Apparatus*

Taper Plug Gauge; this should be of fairly small included angle, not exceeding about 90°.

Suitable Centres, as described above.

Set of Slip Gauges (with table of errors).

Sine Bar.

Light Box or Stand Lamp with a suitable diffusing screen.

Dial Indicator on Stand.

*Method*

Set up the taper plug gauge on the centres and check that the gauge runs fairly true on its centres, using the dial gauge towards each end of the taper gauge in turn. If the run-out is more than a few ten-thousandths of an inch the cleanliness of the centres can be suspected. Although the method of measurement will compensate for eccentricity, accuracy may be impaired if this is too great.

Place the sine bar under the gauge and adjust it to the semi-angle of the gauge, with slip gauges under one roller (Fig. 11). Some trial and error will be necessary in the selection of slip gauges before the correct value is obtained, and this should be done at first with fairly large changes of value, gradually narrowing the field in a similar manner to that used for the measurement of a gap. The gap between the plug gauge and the surface of the sine bar is sighted against the light box. If a light box is not available, quite good results are obtainable by placing a sheet of white paper to give a diffused reflection of an overhead light.

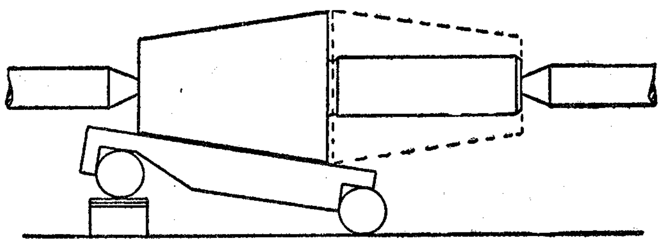


FIG. 11

The sine bar must be aligned with the line of centres for an accurate result to be obtained; the larger the angle of the gauge, the more sensitive is the result to errors of alignment. The angle of the sine bar is a maximum when it is properly aligned and a slight movement will determine this maximum position when near the true value of the gauge.

If the centres used are rather high, it may not be possible for the sine bar to make contact with the gauge. In this case, equal slip gauges can be wrung on to the surface of the bar towards each end so that these will touch the gauge or, alternatively, a good parallel can be placed under the bar. It is also possible to place extra slips under each roller of the bar to increase its total height, but such a set-up is precarious and rather difficult to work with. If no more stable method can be devised, however (always with an eye to the overall accuracy), this latter method will have to be used.

Having obtained the best setting to the angle of the gauge, the slips under the sine bar must be recorded, i.e. the actual slips used should be written down so that their calibrated errors can be applied later. A second determination is made with the gauge rotated 180° on its centres.



The gauge is then reversed on the centres. In doing this, care must be taken to move only one centre so that the relative positions and heights of the centres remain unaltered as far as possible. The same clamping tension should also be used, since variations in this will sometimes alter the height. The reason for this reversal is to eliminate any lack of parallelism between the line of centres and the surface on which the sine bar is placed. Consequently any parallel or other auxiliary support used under the sine bar must remain in the same position and not be reversed, but any slips wrung to the surface of the sine bar in order to increase its effective height can be interchanged with advantage. Having done all this, a fresh determination of the angle of the gauge is made in both the zero and 180° positions of rotation. If time allows, another complete set of observations may be made in a plane at 90° to the first.

### *Observations and Results*

Tabulate the slip gauges used, together with their errors, for each determination. Take the mean value of slips for the four observations; the values used are, of course, the differences between the slips under each roller of the sine bar if any slips have been used under the lower roller. Any error in parallelism between the line of centres and the reference surface will be shown up as a difference between the mean of the two readings when the gauge is one way round in the centres, and the mean when the gauge is reversed. An eccentricity of the gauge on its centres, which differs at each end, will give a difference in values when the gauge is turned 180° on its centres.

The value of the semi-angle of the gauge $\theta$ is given by

$$\sin \theta = \frac{\text{Mean value of slips}}{\text{Length of sine bar}}$$

The length of the sine bar is the distance between the centres of its rollers and will usually be 5 in. If a calibrated value for this length is available, e.g. showing a small error from the nominal value, this calibrated value should be used in the calculations. Use six- or seven-figure mathematical tables for the calculations and estimate the probable accuracy of the measurement. A realistic assessment of accuracy can be made by finding what change in slips can be made before an error in setting is apparent. This change should not greatly exceed 0·0001 in.

## *METHOD II*

### *Apparatus*

Taper Plug Gauge; this must be a small gauge with a small included angle preferably not exceeding 30°.

Sine Bar.

Set of Slip Gauges (with table of errors).

Surface Plate.

Dial Indicator on Stand; the indicator should be of the light contact type; e.g. *Verdict, Victor, Last Word,* etc., if one is available.

### *Method*

The taper gauge must be set up on the surface of the sine bar, with its small end towards the end of the bar which will be raised (Fig. 12). The centre line of the gauge must be accurately aligned with the

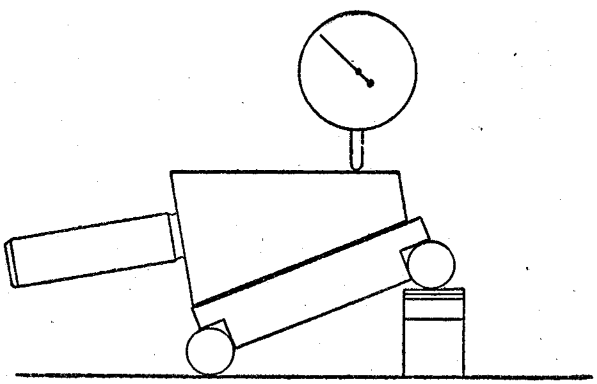


FIG. 12

centre line of the bar, but a setting by eye will do initially. The actual method of mounting will depend on the equipment and materials available; plasticine will be found quite useful, but it must not be allowed to interfere with proper contact between the



gauge and the sine bar and must be carefully cleaned off after use, since it may cause corrosion if left for any appreciable length of time.

It must be remembered that by this method the included angle of the gauge is being measured direct. Place slips under one roller of the sine bar and test with the indicator across the top of the gauge for parallelism with the surface plate. Prior knowledge of the nominal angle of the gauge, or an approximate check, will save time at this stage. The indicator should be passed over the gauge as close as possible to each end, the difference in reading being a guide to the adjustment needed to the slip gauges.

When a zero, or nearly zero, difference is obtained, the alignment of the gauge with the sine bar must be checked more accurately. This may be done by making very small adjustments to the gauge on the sine bar, checking with the indicator and finding the minimum difference between the two ends of the gauge. Care must be taken at all times, and particularly at this stage, to see that the gauge does not 'creep' if mounted with plasticine. This can be detected by taking an indicator reading at one end of the gauge, then at the other, and again at the first end.

If the indicator is sufficiently sensitive, the residual difference less than 0·0001 in. can be noted, particular attention being paid to its direction, i.e. whether the true gauge angle is larger or smaller than that given by the sine bar.

A second determination may be made with the gauge rotated through 90° on its axis.

### *Observations and Results*

Tabulate the slip gauges used, together with their errors for each determination. Calculate the *included* angle of the gauge from:

$$\sin 2\theta = \frac{\text{Value of slips}}{\text{Length of sine bar}}$$

where $2\theta$ is the included angle.

If a residual indicator difference has been obtained, correct this value by an appropriate amount, remembering that an angle of one minute corresponds to a difference of 0·0003 in. over a length of 1 in.

Assess the accuracy of determination by altering the slips by 0·001 in. and noting the difference in indicator readings. Estimate the smallest change in angle which would give the smallest detectable change from the accepted value.

*Conclusions*

Compare the value of angle obtained by this measurement with the nominal value for the gauge. Check the cone surface of the gauge for straightness, using a good flat surface, such as the surface of the sine bar itself. Since this experiment is concerned with the measurement of angle only, it will not normally represent a complete check on the gauge. The diameter at either the large or small end of the gauge can be measured by the method described in Expt. 7, Vol. I. If micrometers and rollers are available, a valuable check on the accuracy of the present measurement of angle can also be obtained. The two experiments performed on the same gauge will provide a useful exercise in the assessment of accuracy of metrological methods.

## *EXPERIMENT 15*

## TO CHECK A FORM GAUGE BY PROJECTION, INCLUDING THE CONSTRUCTION OF THE PROJECTION DRAWING

*Apparatus*

Form Gauge (with drawing showing dimensions).
Profile Projector.
Drawing-board and materials.
Steel Straightedge.
Steel Rule.
Pricker.
Compasses.
Trammels.
Magnifying Lens.
Mathematical Tables (including chords).

It is quite impossible to visualise which of the countless designs of form gauges the student may be asked to check or what type of projector is available. The methods described for drawing and checking the simple example chosen will apply to most form work.

*Materials*

For projectors using an opaque screen, the best general-purpose material is a special type of card consisting of a sandwich of card, aluminium foil and card. This is reasonably stable and provides an excellent surface on which to draw. For more permanent drawings, aluminium sheet, sprayed matt white, is excellent, but the techniques used in this experiment are not entirely suitable for this material. Cartridge paper should be avoided, as it is very unstable. There are also several proprietary materials which vary in their usefulness and particularly in their price.

Projectors using transparent screens (so-called cabinet type) require translucent materials. The simplest of these is tracing or detail paper, but this is extremely unstable and should not be used. Coated glass is the most permanent, but a little difficult to work, as compass points tend to slip. Kodatrace, Ethulon, and Astrafoil are three satisfactory proprietary materials.

A good steel straightedge, not too heavy, with a bevelled edge, is most suitable for drawing straight lines, and the steel rule (also bevelled edge) should be graduated in $\frac{1}{10}$ in. with at least 1 in. subdivided into $\frac{1}{100}$ in. Twelve- and six-inch flexible rules, similarly graduated, are very useful.

The magnifying lens (watchmaker's glass) should be between x5 and x10. The pricker is most essential and can easily be made from a needle in a suitable holder. Many drawing pens have these in the holder of their handle.

The drawing-board requires only to be flat. T-squares, drafting machines, set-squares, protractors, etc., are not used for projection drawings. Use a hard pencil, about 6H, sharpened to a fine point, *not* a chisel point. A fine sandpaper block is useful for doing this. The trammels and compasses should be sturdy and should allow of fine adjustment. The pencil point on these should be a chisel, rounded.

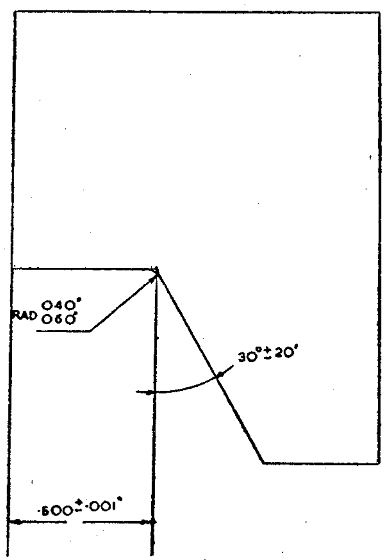



FIG. 13



*Method*

Knowing the magnifications and field available on the projector, and taking into consideration the tolerances and general characteristics of the gauge, decide on the magnification to be used. Remember that high magnification often results in inferior definition. If the gauge is of the plate type, its thickness will affect the definition. Projectors vary considerably as to the amount of depth they can accommodate. If the gauging surfaces are not square to the body of the gauge, difficulty will be experienced in getting a good image. Normally it is the surface nearest to the objective lens which is projected. A good rule is to project the work before making the drawing and find the most suitable magnification, bearing in mind the size of the work and the accuracy required.

In our example (Fig 13), x30 has been chosen. Tabulate the magnified dimensions thus:

| *Actual Size* (in.) | *Size x30* (in.) |
|---|---|
| 0·501 | 15·03 |
| 0·499 | 14·97 |
| 0·06 rad. | 1·8 |
| 0·40 rad. | 1·2 |

Chord for 60° 20′ angle at 20 in. radius = 20·10 in.
Chord for 59° 40′ angle at 20 in. radius = 19·90 in.

*Drawing Methods*

1. Use a light pressure on the pencil and rotate it as it is moved along.
2. Mark off all dimensions with the pricker against the rule and examine the points with the lens to see that they are on the line and at the correct dimension. If the bevel of the rule is thick, it will be found helpful if the rule is tipped on edge in order to eliminate parallax.
3. Prick all intersections of lines, and examine with the lens for accuracy. This is extremely important, because if subsequent lines have to be drawn through these points and fail to intersect accurately, the lines may be erased without destroying the

intersection points. The points must be kept small—just sufficient to hold a compass or trammel-point.

4. Set compasses and trammels against the rule to the required dimension and describe a part of a diameter on a straight construction line. Measure the diameter with the rule and lens and adjust until correct. Residual errors on diameters will, of course, be halved on the radius.
5. Construct all perpendiculars geometrically by the intersection of arcs, using radii large enough to embrace the length of perpendicular required.
6. Construct all angles by the arc-and-chord method. Choose an arc whose radius is at least as large as the length of angular line required and look up the corresponding chord in the tables.

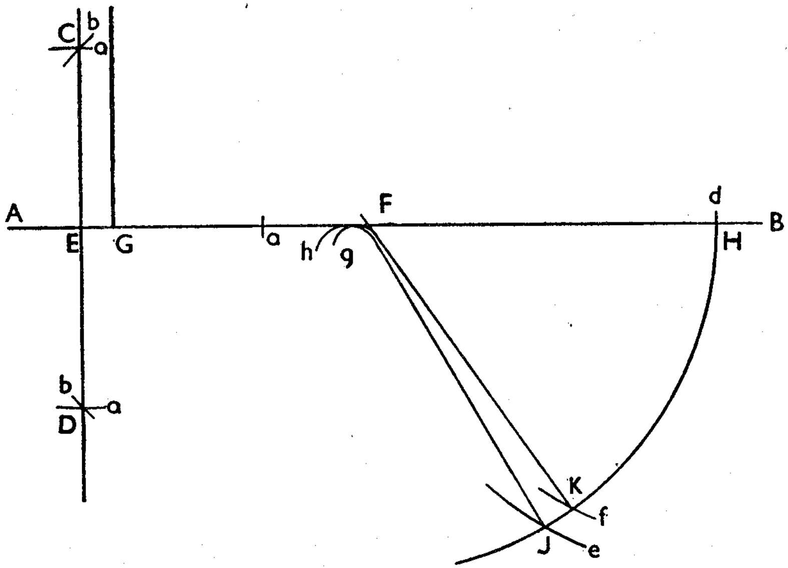



FIG. 14

*Construction of example* (*Fig.* 14)

Draw the line $AB$ about 42 in. long in the centre of the paper.
With centre on $AB$, near $A$, draw arc $a$, radius about 25 in.
With centre at the intersection of arc $a$ with $AB$ and a convenient radius, draw arc $b$ intersecting arc $a$ at $C$ and $D$.



Join $CD$ to cut $AB$ at $E$.
Mark off $EF$ along $AB$=15·03 in.
Mark off $EG$ along $AB$=0·06 in. (15·03—14·97).
Draw the line through $G$ parallel to $EC$, using dividers or compass.
With centre $F$, radius 20 in., draw arc $d$, cutting $AB$ at H.
With centre $H$, radius 20·10 in., draw arc $e$, cutting arc $d$ at $J$.
Join $FJ$ (60° 20′ angle).
With centre $H$, radius 19·90 in., draw arc $f$, cutting arc $d$ at $K$.
Join $FK$ (59° 40′ angle).
With radius 1·20 in. and centre found by trial, draw arc $g$ tangent to $AB$ and $FK$.
With radius 1·80 in. and centre found by trial, draw arc $h$ tangent to $AB$ and $FJ$.

Line in the gauging lines a little more heavily, or, better still, ink them in.

It is a good plan to make the lines quite thick, the edge of the line defining the profile.

The centre of arc $g$ may be constructed by drawing lines parallel to $AB$ and $FK$, 1·20 in. away from them. The intersection of the lines is then the centre. The centre of arc $h$ may be similarly constructed. Experience has shown however, that no accuracy is gained by this method, and the other is much quicker.

### *Projection*

Set up the gauge in the centre of the field, square to the optical axis and with zero rake.

Line the image along $EGF$ so that if the gauge is within limits the angular face lies with $JFK$. The other gauging face should lie between $EC$ and $GL$, and the radius within the limiting profile lines.

### *Observations and Results*

Measure any errors and tabulate them. Angular errors may be conveniently assessed by linear measurement at a known radius. A dimensioned sketch is often useful for identifying local errors.

### *Conclusions*

With care, a projection drawing may be made to an accuracy of 0·01 in. or even better by these methods. Great attention must be paid to accurate pricking of all intersections and measuring lengths.

There is apparatus specially designed for making projection drawings, but this is not likely to be generally available. Projection drawings may also be constructed using marking out methods such as heights gauges, dividing heads, scribers, etc.

Make an estimate of the overall accuracy of measurement that you have obtained.

## *EXPERIMENT 16*

## TO MEASURE THE RADIUS AND ACCURACY OF A PLATE GAUGE OF LARGE RADIUS

### *Apparatus*

One or more Plate Gauges of large radius (several inches).
Surface Plate, preferably having tapped holes in its surface.
Straightedge.
Set of Slip Gauges.
Pair of Standard Rollers (preferably not less than $\frac{1}{2}$ in.).
Suitable clamps for clamping gauge and rollers to surface plate.

The method to be described is intended for a plate gauge of large radius which is too large to be projected on a normal projector and whose radius cannot easily be drawn at an appropriate magnification. The method is suitable for any radius above a few inches, and the exercise will be more valuable if two or more gauges or templates of appreciably different radii are available. One gauge of several inches radius and one of several feet radius could be used.

If gauges or templates of this kind are not available, it will be necessary to make them. This may be done by a method described in the N.P.L. publication *Notes on Gauge Making and Measuring* (H.M.S.O.).*

Since it is necessary to clamp the gauge and the rollers on to the surface plate, it is convenient to use a plate which has been drilled and tapped for clamping screws, usually about $\frac{1}{4}$ in. B.S.F. If such a plate is not available, it should be possible to work across a corner of the plate, using toolmakers' clamps at the edges.

### *Method*

Check first that the true sizes of the rollers and a calibration chart for the slip gauges are available.

Clamp one roller on the surface plate on end and set the other roller at a suitable distance from it with slip gauges. The distance between the rollers should be such that they span a little over half the extent of the radiused edge of the gauge, although, if the gauge

* See also Hume, K. J., *Engineering Metrology*, ch. iv (Macdonald).

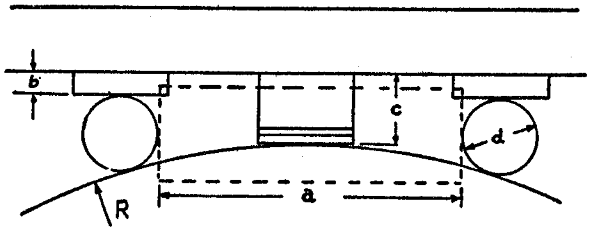



FIG. 15a

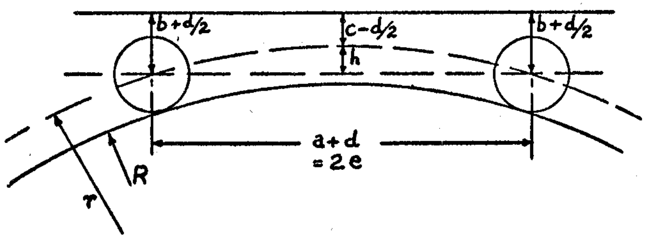



FIG. 15b

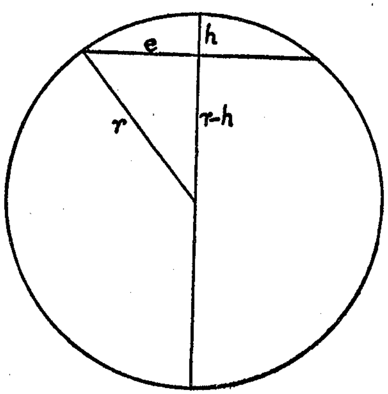



FIG. 15c



is rather long, the distance may be less. The reason for not spanning the whole gauge is to allow the uniformity of profile to be checked by moving the gauge to different positions. The distance can be kept to a round value, but the actual size must be measured when both rollers are clamped.

Lay the gauge on the plate, with its edge in contact with both rollers, starting with one end. Place the straightedge in contact with the other side of the rollers. Both gauge and straightedge may be clamped to the plate, although this should not really be necessary; contact with the rollers must, however, be maintained. There must be sufficient space between the highest point on the gauge and the straightedge for slips to be inserted in order to measure the gap (dimension $c$, Fig. 15). If this gap is too small for the proper manipulation of slips to get the ten-thousandth figure, slips may be inserted between the straightedge and the rollers (dimension $b$, Fig. 15).

Having placed the gauge in position, measure the gap $c$ with slip gauges. A sensitive test for the correct slips is to attempt to rock the straightedge when the slips appear tight; if it will rock at all, the slips are too large. Make similar tests at several positions round the edge of the gauge, say at four or five positions.

Reset the rollers to a different spacing and make a fresh set of measurements. If two or more gauges are to be measured, it may be desirable to use quite different roller settings for each according to its size and radius.

Some difficulty may be experienced in this experiment due to errors in the relative squareness of the faces of the components used. The form of the radius gauges should lie in a plane parallel to the faces of the plate, and it is reasonable to measure it from a surface plate on which it is supported. The end faces of the rollers will be square to their axes if standard gauging rollers are used; the faces may, however, be very slightly convex, but this is not a serious disadvantage. The faces of the larger slip gauges should be square to their sides to an accuracy of about 0·001 in. The same order of error may also occur in the straightedge, and these errors may cause slight differences from the true measured values of gaps.

*Observations and Results*

Fig. 15a illustrates the four dimensions which will have been determined, $a$, $b$, $c$ and $d$. If no slips have been used between the rollers and straightedge, dimension $b$ will, of course, be zero.

It will be seen from Fig. 15b that it is first necessary to calculate the radius of the concentric circle through the centres of the rollers. The roller centres are at a distance $b+\frac{a}{2}$ from the straightedge, and the highest point of the circle is at $c-\frac{d}{2}$. From this the height of the segment $h$ can be found. The distance between the roller centres is $a+d$, and it is convenient for calculation to use half this value, $e$.

Reference to Fig. 15c shows that

$$e^2=r^2-(r-h)^2 \text{ or } e^2=h(2r-h).$$

From this $r=\dfrac{e^2+h^2}{2h}$

The radius of the gauge is, of course, smaller than this by the radius of the rollers.

Tabulate the various stages in the calculations in columns under the following headings:

$a$ $b$ $c$ $d$ $h$ $e$ $r$ Gauge radius.

*Conclusions*

Compare the results obtained on each gauge with the nominal values of their radii, if these are known. For the actual use of such a gauge, direct variations in the profile are of greater significance than figures giving variations in the radius.

Note particularly the effect on the radius value of small variations in measured profile, say 0·0005 in. The larger the radius, the greater will be the effect. If no appreciable variations are actually found in the experiment, calculate the radius for an assumed variation.

The effect on the radius of a small variation in $h$ can also be calculated by differentiating the expression for $r$ previously found. Having calculated the radius for one value of $h$, this method will save further laborious calculation.

Since $r=\dfrac{e^2+h^2}{2h}$

$$dr=\tfrac{1}{2}\left(1-\frac{e^2}{h^2}\right)dh$$

## *EXPERIMENT 17*

### TO CHECK A SINE BAR

*Apparatus*

5-inch Sine Bar.
Set of Slip Gauges.
Set of Slip Gauge Accessories.
Surface Plate (lapped) or Toolmaker's Flat.
Comparator or Sensitive Dial Gauge.
Angle Plate.
Engineer's Square.
Optical Flat or Knife-edge Straightedge.
Feeler Gauges.
Light Box or other type of translucent light.

*Method*

To test a sine bar completely, the following features must be measured:

(1) Equality and uniformity of diameter of rollers.
(2) Distance between axes of rollers.
(3) Parallelism of axes of rollers.
(4) Flatness of gauging surface.
(5) Parallelism of gauging surface with rollers.
(6) Squareness of edge of gauging surface with axes of rollers.

Ideally, it is necessary to remove the rollers from the bar so that their individual diameters may be accurately measured on a comparator. It is unlikely that this will be permitted in a class laboratory exercise and *therefore should not be done* unless specially authorised by the instructor. Sine bars generally fall into two types, illustrated in Fig. 16 (*a*) and (*b*). Type (*a*) will be the easier to measure for diameter of rollers and centre distance, but type (*b*) is the one more commonly used, since its upper end will rest more stably on a pile of slips and, incidentally, is easier to manufacture with a precise distance between the rollers.

The features listed above should be measured in the following ways:

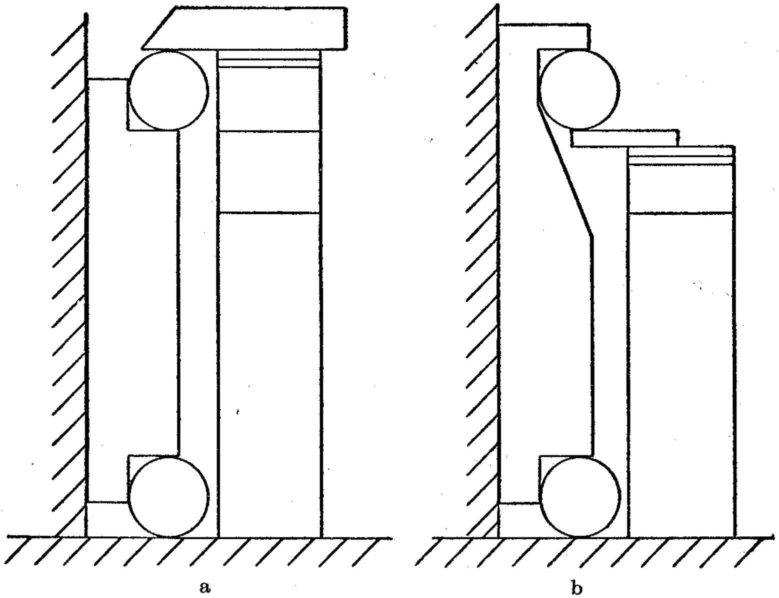



Fig. 16

(1) *Equality and uniformity of diameter of rollers.* It should be possible, with a bar of type (*a*), to compare the rollers on the comparator, using a suitable size of slip gauge as a measuring anvil and holding the bar so that a diameter lying at about 45° to the horizontal can be measured.

This method will not be possible with a bar of type (*b*), and it will be necessary to set up a slip-gauge gap with which to gauge the diameter of the rollers. The diameter of the open roller should be measured with a micrometer; this will save time in finding the exact slip-gauge combination. The gap should be made up, using the small cage from the slip gauge accessories set, together with the thinnest pair of measuring jaws. With care in handling and wringing the slips it should be possible to feel a distinct difference between the gap which goes easily and one which is 0·0001 in. smaller and just binds. Although an experienced observer could estimate the equality of the rollers to 0·00005 in. by this method, it should not be assumed to be accurate to better than 0·0001 in.

Compare and record the values and variations found for each



roller. Aim for an accuracy of 0·00005 in. if the comparator method is used.

(2) *Distance between axes of rollers.* Set up the angle plate or other vertical surface on the surface plate. Set up the sine bar with its gauging surface in contact with the vertical surface and the lower roller resting on the surface plate; if desired, the bar may be held in place with a rubber band (not to be despised) or other form of *very light clamping.*

If the sine bar is of type (*a*), the height over the top of the upper roller must be determined with slip gauges. Build up a pile, with a gauge or jaw from the accessories set protruding at the top, which just goes over the top of the roller. Check from each side of the bar and note any variation between one side of the roller and the other. If the bar is of type (*b*), the height to the under side of the upper roller is determined in a similar manner. In this case it will be essential to use a slip gauge as a protrusion at the top, since its size must be included in the measurement and accessory jaws are not normally calibrated for size. The two methods are illustrated in Fig. 16.

It is obvious that the centre distance of a type (*a*) bar is determined from the dimension over the rollers minus the mean measured diameter of the rollers. Particular care must therefore have been taken in measuring the *actual* diameters as well as *equality* of diameters. The centre distance of a type (*b*) bar will be the actual value of the slips inserted, provided the equality of the diameters is good.

(3) *Parallelism of axes of rollers.* Any error in parallelism of roller axis in one plane will be obvious from variations in centre distance found in the last section, but it is also important to test the rollers for relative twist in planes normal to the gauging surface.

Support one roller along the length of a 0·2 in. slip gauge which should be wrung down on to the surface plate, if possible. The other roller is supported on two similar piles of slips, one at each end of the roller. To make these piles equal, the slips used could be 0·1 in. + 0·1005 in. and 0·1003 in. + 0·1002 in. Either of these piles can be varied if the roller does not rest evenly on them, a condition which can easily be detected if the bar rocks slightly on the slips. It should be possible to detect an error in parallelism of 0·00005 in. by this method if the surface plate is a good one (Fig. 17).

(4) *Flatness of gauging surface.* There are several tests which may be applied for the flatness of the gauging surface. If the surface is

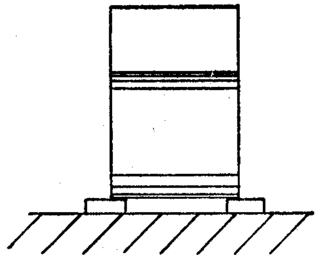


FIG. 17

lapped, an optical flat may be applied, but unless this will cover about three or four inches of the bar an accurate assessment will be difficult. The criterion of flatness with an optical flat is the parallelism of the interference fringes.*

A test which is more generally applicable utilises a precision knife-edge straightedge. One or more of these is usually found in the set of slip gauge accessories, or a larger (8-in.) type may be available. An accurately ground cylinder may also be used as a straightedge. If it is uniform in diameter or uniformly tapered, its own straightness can be checked by using it at various positions round its diameter; any variation in results will indicate lack of straightness of the cylinder.

First hold the straightedge against the gauging face of the sine bar and view against a uniform white light. For this and similar purposes a box may be made up having an opal or ground glass screen and containing several low-wattage lamps. In the absence of a special box an ordinary light can be used, but it is best to look at the shade or opal bowl and avoid looking directly at the bulb.

An error of 0·0001 in. is easily visible, and the gap can be visually calibrated by comparison with an exact gap of 0·0001 in. or more made by wringing two slips end to end on another lapped flat surface. The sizes of the slips differ by the value chosen, and the straightedge is held in close contact with the higher slip. Several values of gap should be tried, as the scale of apparent size is not uniform. A gap of 0·001 in., for example, does not appear to be ten times a gap of 0·0001 in.

The flatness error of the sine-bar surface should not exceed 0·0001 in.

* See K. J. Hume: *Engineering Metrology*, p. 179 (Macdonald).



(5) *Parallelism of gauging surface with rollers.* For this test, the comparator is set up on a surface plate, with its measuring head swung round away from its own table. The sine bar is placed on its rollers on the surface plate, and the comparator head is lowered until a reading is obtained on the gauging face of the bar. Determine carefully the variations in parallelism both along and across the bar, making a sketch map of the errors if they exceed 0·00005 in. or so.

Check the results obtained by turning the bar over and checking the variations over the rollers. Unless the surface plate being used is particularly accurate, some discrepancies are likely to arise and agreement to 0·00005 in. can be considered satisfactory.

(6) *Squareness of edge of gauging face with axes of rollers.* This test is not one of high accuracy but is necessary to ensure that the sine bar may be aligned to work by its edge. The test is best carried out when the bar is mounted vertically for test (2). An ordinary square can be used and held against the side of the bar (Fig. 18). An accuracy

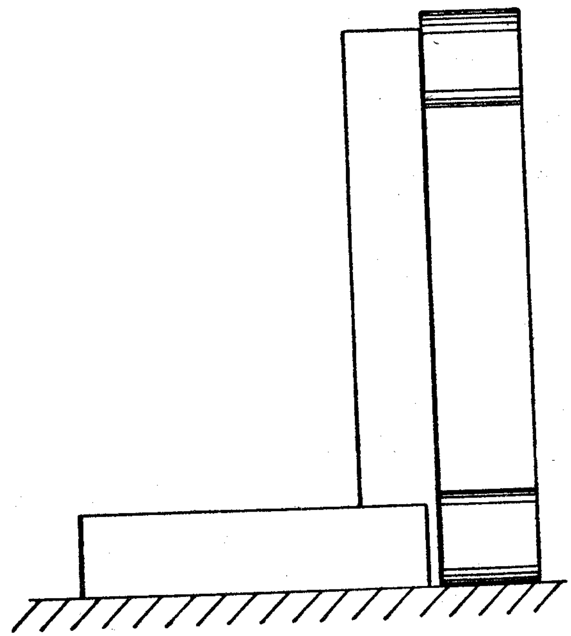


FIG. 18

of about 0·0025 in. is all that is necessary, and a check with feeler gauges will be satisfactory. It should not be possible to insert the 0·0025 in. feeler between the square and the bar.

*Report and Assessment of Results*

When all the measurements have been made, a report on the sine bar should be prepared. The following layout would be suitable for such a report.

REPORT ON A SINE BAR

Serial No. 123

This sine bar has been measured in the Metrology Laboratory of ..................................with the following results.

| | |
|---|---|
| Average temperature during measurements: | 21·5°C. |
| Diameter of rollers: | (i) 0·7500–0·7501 in.<br>(ii) 0·7500 in. |
| Distance between roller axes: | 4·9999–5·0001 in. |
| Parallelism of roller axes: | within 0·0001 in. |
| Flatness of gauging surface: | 0·0001 in. concave. |
| Parallelism of gauging surface with rollers: | within 0·0001 in. (allowing for flatness error). |
| Squareness of edge with roller axes: | within 0·001 in. |

From these results the sine bar can be considered satisfactory for general use. An error of 0·0001 in. in the distance between roller axes will produce an error in angle, when set at about 45°, of 4″. The variation found in this case is therefore negligible. Other values of error would produce proportional errors in angle.

The 0·0001-in. concavity of the gauging surface could give rise to a maximum error of about $\frac{1}{4}'$ This would only occur with a small object making contact with the bar close to one end. The 0·0001 in. parallelism error could produce an error of only 4″.

## EXPERIMENT 18

## THE MEASUREMENT OF A SPUR GEAR TO DETERMINE ITS BASE CIRCLE DIAMETER AND TOOTH THICKNESS AT A GIVEN PITCH CIRCLE DIAMETER

The value of this experiment lies, not so much in the technique of measurement involved, as in the deductions and calculations which can be made from the measurements. The measurements depend on the geometrical principle of the involute gear that the distance between parallel lines embracing several teeth is a constant and is equal to the arc on the base circle intersected by the extreme flanks (see Fig. 19).

This principle will naturally be strictly true only for a gear which is perfect on tooth form, pitch, concentricity, etc.; it is therefore desirable that the gear selected for this experiment should be a precision gear, preferably ground and known to have only small errors in these elements.

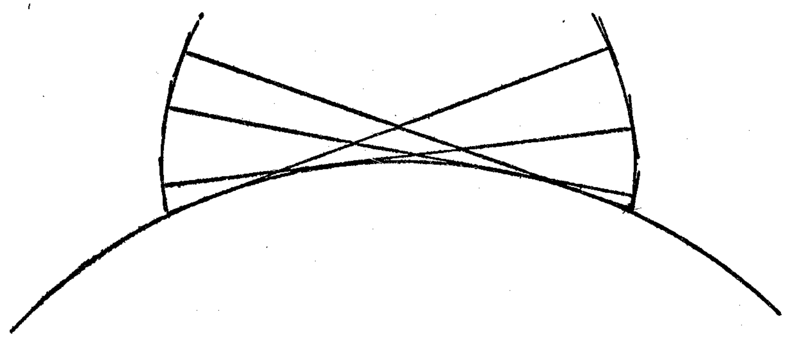


FIG. 19.

*Apparatus*

Suitable Involute Spur Gear.

This should preferably be a gear of 2 or 3 in. diameter with a fairly small number of teeth. An 8 D.P. gear is about the best pitch for mechanical measurement, but considerably smaller pitches on smaller gears are suitable for optical measurement.

Apparatus for measuring across several teeth of the gear between parallel faces.

There are several suitable methods of doing this mechanically, but the two essential features of the equipment are that the measuring faces must be parallel and must be capable of passing into the tooth spaces. Suggestions are:

Slip Gauges, Cage, Projecting Jaws or Extra 0·1 Slips.
Vernier Calliper with Slip Gauges for checking gap.

Specially made Knife-edge Feet for use with a Comparator or Measuring Machine.

If the gear is small it may be measured on a Projector or Measuring Microscope. The gear selected *must*, however, be involute; watch or clock gears are normally cycloidal and cannot be measured by the method of this experiment.

*Method*

The only practical part of the experiment is to measure the distances between parallel faces over two different numbers of teeth of the gear, e.g. over five and three teeth. As previously mentioned, there are several methods of doing this, both mechanically and optically.

(*a*) *Mechanical methods.* The slip gauges in a cage with measuring jaws, or the vernier calliper, are adjusted until the gap will fit nicely over the number of teeth chosen, with no shake and without force. It is not necessary for the body of the slips or the calliper to lie outside the diameter of the gear—the gap can be pushed over the teeth from the side of the gear. If the involute form of the teeth is perfect to any base circle (not necessarily the nominally correct one), it will not matter where the measuring faces make contact with the flanks of the teeth so long as they lie tangentially. Variations, such as tip relief, will give different values as the gap is rotated.

Pitch errors will cause different values to be obtained at different positions round the gear. If such variations, both on the flanks and round the gear, are found, the variations should be noted and a mean value calculated. It is for this reason that an accurate and uniform gear should be used for this experiment.

Care must be taken to see that the gap does not make contact with the corner of the tooth tip or the root. If a vernier calliper is used, the final fit should be checked with the jaw clamped and the gap measured with slip gauges. A gear-tooth-vernier could be used, not in its conventional manner but with the depth slide withdrawn.



If a comparator or measuring machine is used for this measurement it will be necessary to provide knife-edge measuring tips. The parallelism of the contact faces must be adjusted and checked when the machine is set up. A horizontal comparator or measuring machine is the most suitable for this purpose; if the vertical type is used, some difficulty may be experienced in arranging a suitable bottom contact.

(*b*) *Optical methods.* A gear which is too small to measure conveniently by mechanical contact methods may often be measured quite successfully on a projector or measuring microscope. On the projector the distances over the teeth may be measured either between parallel lines drawn on the screen or by setting each side to a single fiducial line by using the stage micrometer; the latter method will be the more accurate. A toolmaker's microscope may be used in a similar manner. As with the mechanical method, care must be taken to see that the measuring line touches the flanks of the gear tangentially somewhere on the involute form and not across the corner of the tooth tip or too near the root.

*Observations and Results*

Having obtained satisfactory values for distances over two different numbers of teeth, taking into account any variations found round the gear, assume that the values are:

$a$ in. over $x$ teeth
$b$ in. over $x+y$ teeth

as indicated in Fig. 20.

*Base circle.* As mentioned already, the distance over a number of teeth is equal to the distance round the base circle intersected by the flanks concerned. Thus the difference between values for two different numbers of teeth is equal to a whole number of pitches round the base circle (base pitches), so that:

$$\text{Base pitch } P_b = \frac{b-a}{y}$$

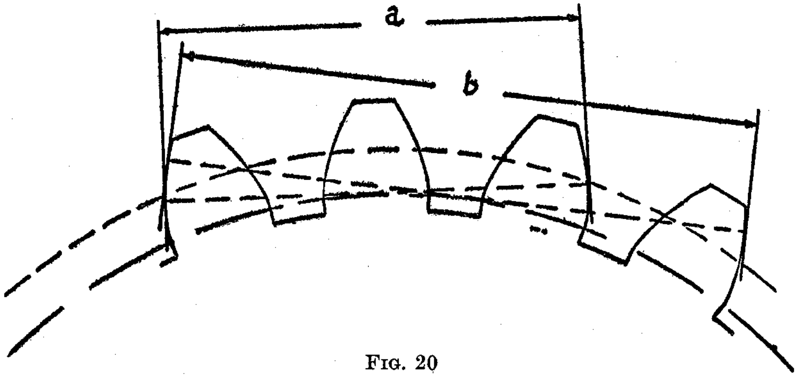



FIG. 20

If $T$ is the total number of teeth in the gear, the circumference of the base circle is $T \times P_b$ and the base circle diameter is $\frac{T \times P_b}{\pi} = D_b$. Calculate this value.

*Pressure angle.* The nominal pitch circle diameter $D$, diametral pitch $P$ or module $m$ of the gear will probably be known.

$$D = mT = \frac{T}{P}$$

Calculate the pressure angle $\psi$ (psi) at this pitch circle diameter from the equation $\cos \psi = \frac{D_b}{D}$.

*Tooth thickness.* Calculate the arc tooth thickness at the base circle $L_b$

$$L_b = a - (x - 1)P_b$$

and calculate also the angle $\alpha$ (in radians) subtended by this arc at the gear centre.

$$\alpha = \frac{2L_b}{D_b}$$

Calculate the involute function (inv$\psi$) for the pressure angle previously calculated:

$$\text{inv}\psi = \tan\psi - \psi \quad (\psi \text{ and inv}\psi \text{ in radians})$$

This angle (inv$\psi$) is the angle between the radii intersecting a flank of a tooth at the pitch circle and base circle (see Fig. 21).



The angle $\beta$ subtended at the centre by the arc tooth thickness at the pitch circle is therefore

$$\beta = \alpha - 2 \text{ inv } \psi \text{ (radians)}$$

and the length of arc on the pitch circle ($L_a$) is:

$$L_a = \beta \times \frac{D}{2}$$

*Conclusions*

It will be possible to draw definite conclusions from these results only if the nominal pitch circle diameter is known or can be calculated and the pressure angle is known or can be deduced. When the actual pressure angle has been calculated from the measurements, its comparison with the nominal value will give an indication of the accuracy of tooth profile. Even if the nominal pressure angle is not definitely known, it is likely to be either 20° or 14½°. If the gear is not of (so called) 'corrected form', the tooth thickness at the pitch circle will almost certainly be slightly less than half the pitch to allow for backlash when in mesh with its mating gear. If, however, the gear is '*corrected*', any deduction of backlash allowance will be impossible unless more data are available. Comment on any of these elements which can be deduced from the measurements.

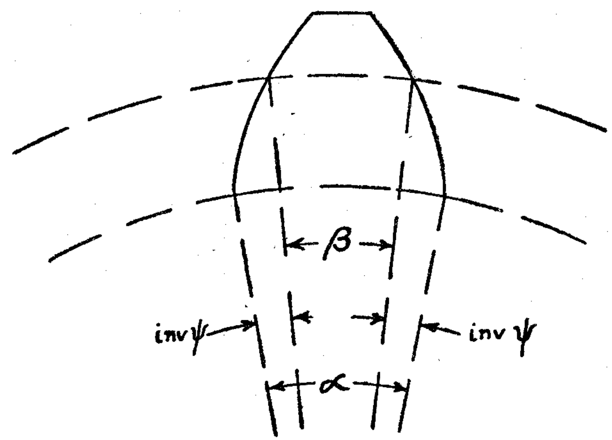



FIG. 21

## *EXPERIMENT 19*

# TO MEASURE THE SIMPLE EFFECTIVE DIAMETER OF A PLUG SCREW GAUGE USING A FLOATING MICROMETER MEASURING MACHINE

*Apparatus*

Plug Screw Gauge.

Two Calibrated Thread-Measuring Cylinders (or wires) to suit the pitch of the thread gauge.

Floating Micrometer Measuring Machine.

Calibrated Cylindrical Standard of approximately the same diameter as the effective diameter of the gauge.

The measuring machine should first be superficially examined. See that it is level. This may be simply checked by giving the floating saddle (carrying the micrometer and fiducial indicator) a gentle push in both directions. If the machine is level there will be no bias to either side. A bias against the indicator can render it sluggish or even inoperative.

Check the micrometer for smooth travel throughout its range—look carefully for eccentricity of the micrometer drum, a sure indication of its having received a knock.

Examine the fiducial indicator. It should move freely under about 8 oz. pressure, and the needle should go well past the fiducial line.

The machine may be fitted with little 'fishing rods' projecting over the centres. They are intended to support the thread wires and prisms by means of cotton threads. Remove them. They get in the way; they can easily bias a measurement by pulling or even bending the wires, and the cottons invariably catch in one's cuffs with disastrous results.

Examine the thread measuring wires. They should be clean and straight. A small amount of bending is permissible in those of very small diameter, but the larger ones should be rolled on a slip gauge and observed against a light to detect any out of straightness. It is assumed that the '$P$' value of the wires is known.

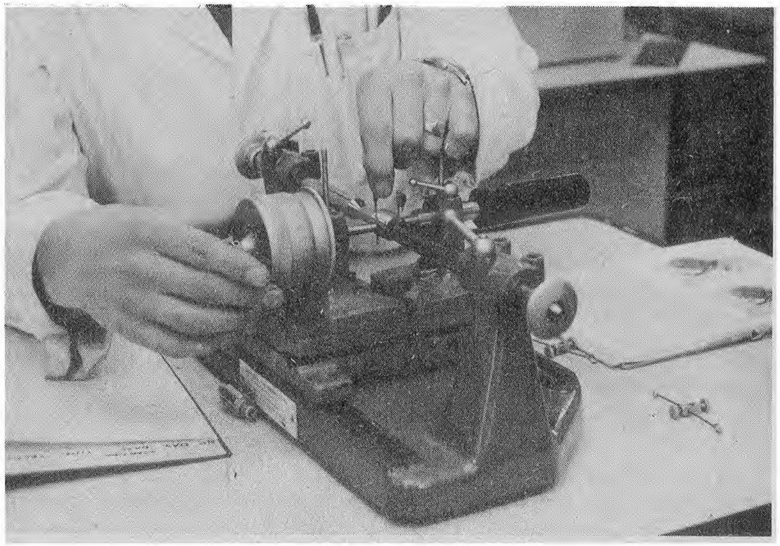


Plate 1. A Floating Micrometer Measuring Machine
See Experiment 19

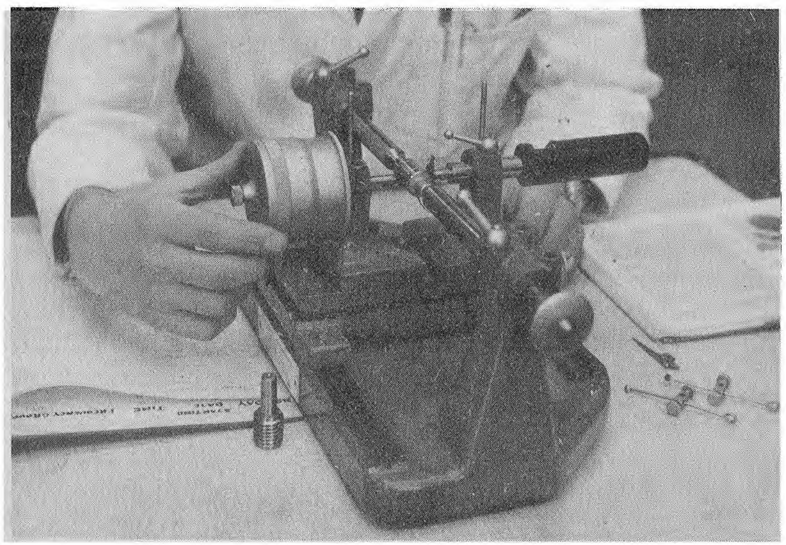


Plate 2. See Experiment 22



The foregoing examination of the diameter machine must not be regarded as a complete check, but rather as an indication that it is still in good working order.

*Method*

Set the machine with the micrometer on the right and adjust the positions of the indicator and the micrometer so that the gauge to be measured is within the range of the micrometer. Put the cylindrical standard between the centres and make sure that there is plenty of movement of the saddle on each side. (The balls on which it moves sometimes jam at one end.)

Holding the saddle lightly with the right hand, insert with the left hand one thread wire between the fiducial indicator and the standard. Keep the wire trapped between the indicator and the standard by biasing the saddle with the little finger of the left hand. Then, with the first finger and thumb of the left hand, hold the second wire between the micrometer anvil and the standard, at the same time advancing the micrometer with the right hand until the indicator is on its fiducial mark. Both wires are now held in position by the indicator pressure. This description may sound rather complicated, but is quite simple in practice (see plate 1).

Move the wires about in order to bed them down and to eliminate any specks of dust which may have settled. Make sure that you are taking the measurement on the operative portion of the wires; they are usually relieved at either end. Finally, leave the wires in a vertical position roughly in the centre of the anvils.

Withdraw the micrometer slightly (not too much or the wires will fall out) and then advance until the indicator needle is exactly on its fiducial mark. Record the reading, $R_B$. After withdrawing the micrometer, remove the wires and the standard.

Put the screw gauge between the centres and, after inserting the wires as before, advance the micrometer until the indicator needle is on its fiducial mark. The two wires should be in the same groove, and again, care should be taken to see that they are bearing on their calibrated diameters.

Gently move the wires about whilst watching the indicator. The reading will probably fall. Leave the wires in the position of the lowest reading and advance the micrometer until the indicator needle is again on its fiducial mark. Again 'waggle' the wires. If the indicator needle does not fall any more, record the micrometer reading $R_B$. The wires should be approximately in the centre of the anvils.

Take three measurements round the gauge in order to check ovality, and at least three along the gauge to check taper. Remove the wires and gauge and take a repeat reading on the cylindrical standard. This should not have changed by more than 0·00002 in.

Readings must always be taken after advancing the micrometer. If the fiducial indicator goes past its mark, withdraw the micrometer and come up to the mark again.

*Observations and Results*

Record results in the manner of the following example:

Type of gauge: ½ in. B.S.F. Screw Plug. Medium fit. 'Go'. General.
Simple effective diameter limits (B.S. 919): 0·4602–0·4606 in.
Thread wires: No. A5625. $P$ value (for 16 t.p.i.) 0·01891 in.
Cylindrical standard size $B$: 0·49985 in.
Readings on standard $R_B$: 0·48500. Repeat: 0·48502. (Mean: 0·48501).

$$\text{Readings on gauge } R_G: \quad \text{ovality} \left\{ \underbrace{\begin{array}{ccc} 0{\cdot}42660 & 0{\cdot}42665 & 0{\cdot}42670 \\ 54 & 59 & 65 \\ 52 & 58 & 63 \end{array}}_{\text{taper}} \right.$$

Simple effective diameter $E$:

$$= B + R_G - R_B + P - c + e$$
$$= 0{\cdot}49985 + 0{\cdot}42660 - 0{\cdot}48501 + 0{\cdot}01891 - 0{\cdot}00005 + 0{\cdot}00003$$
$$= \text{ovality} \left\{ \underbrace{\begin{array}{ccc} 0{\cdot}46035 \text{ in.} & 0{\cdot}46040 \text{ in.} & 0{\cdot}46045 \text{ in.} \\ 29 & 34 & 40 \\ 27 & 33 & 38 \end{array}}_{\text{taper}} \right.$$

The values for the rake correction, $c$, and the compression correction, $e$, may be found in the Appendix (Tables I and II, p. 243). In the numerical example, note that the mean of the two standard readings has been used.

*Conclusions*

Compare the measured sizes of the gauge with the sizes given in B.S. 919,* and decide if the gauge is suitable for use.

*The current issue of B.S. 919: 1953, will be found to refer to 'General' and 'Reference' gauges. It is likely, however, that many of the gauges available for measurement will have been made to B.S. 919: 1940, and for these this issue should be consulted.



This experiment explains the standard method of measuring screw plug gauges and, with care, is extremely accurate. When measuring threaded *work* the corrections $c$ and $e$ may be omitted.

*Alternative Method*

If several gauges of the same size are to be measured it is quicker to set the micrometer on the cylindrical standard and wires to read the actual diameter of the standard $+P-c+e$.

$$R_B = B + P - c + e$$

The subsequent readings on the gauge are then direct values of its effective diameter. The only advantage of this method is that it saves arithmetic, but this is offset by the time taken in setting the micrometer to a specific reading if only a single gauge is concerned.

*EXPERIMENT 20*

## TO MEASURE THE PITCH ERROR OF A SCREW GAUGE (PLUG OR RING)

### *Apparatus*

Plug or Ring Screw Gauge, preferably larger than ½ in. diameter.

Screw Pitch Measuring Machine of N.P.L. 6 in. × 9 in. type, or similar machine of proprietary make.

It will be assumed for the purpose of this experiment that both the gauge and the machine are in inch measure and that the gauge pitch is a standard number of threads per inch. A metric gauge or machine, or both, will not alter the general principles discussed here but will necessarily modify the detailed operations.

The machine will normally be fitted with a micrometer screw of 40 t.p.i. and a number of interchangeable discs will be available for the micrometer drum. One of the discs will be calibrated in the normal way, divided into thousandths and ten-thousandths of an inch. This can be used, in conjunction with the coarser scale of fortieths, for the measurement of any pitch, English or metric, but for normal inch pitches it is more convenient to use the special discs.

These discs are divided into various numbers of equal parts and are marked with the pitches for which they may be used. To illustrate the function of the discs, consider the one divided into seven divisions. A brief calculation will show that single pitches which are multiples or sub-multiples of 7, e.g. 3½, 7, 14, 28, 56, are all represented by an integral number of divisions on the disc. It is thus possible to forget the nominal pitches and the true distances traversed by the micrometer and take direct error readings with the appropriate disc. Details of the method of operation will be given under '*Method*'.

The pitch machine will be found to be supplied with series of different sized styli suitable for various pitches of thread. For external threads the appropriate stylus is fitted directly into the indicator of the machine and engages with the thread under the pressure of the flexible spring strip into which it is mounted (Fig. 22).





As the micrometer is advanced, the stylus rides over the crest of one thread into the next, where it locates between the flanks. At a certain position relative to the flanks the indicator T comes opposite the fixed fiducial line and is brought up to this line in each thread in turn, when the micrometer readings or errors are noted. Each stylus should be identified with a letter or number, and a table should be provided, giving the pitches for which each is suitable. In any case the stylus used should make contact about half-way down the flanks of the thread.

Smaller sizes of stylus with the same identification will be found. Each of these will have the same tip radius as its larger counterpart, but is intended for use in the measurement of internal threads. For this the stylus is fitted into a bar, which is in turn mounted in a flexible strip unit which brings the bar parallel with the machine axis, enabling it to enter the internal thread. A special stylus fitted directly into the indicator engages with a hole in the bar and transmits the motion of the thread stylus to the indicator (Fig. 22).

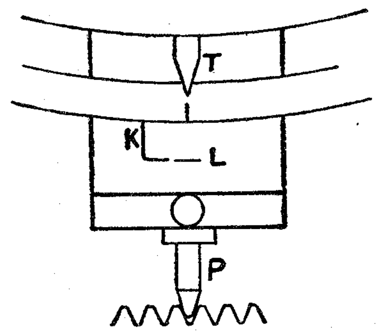



Fig. 22

### *Method*

(*a*) *Plug screw gauge*. Select the micrometer disc appropriate to the pitch of the thread and fit it to the micrometer drum. Since the disc is divided differently on each edge, make sure that the correct edge is adjacent to the fixed drum. Run the micrometer back to a position about one turn before zero, making sure that the indicator carriage does not foul the main casting. Fit the appropriate stylus into the indicator; a table of pitches for each stylus should be provided, but if this is not available select a stylus whose spherical tip will make contact with the thread about halfway down the flank.

Mount the plug gauge between the centres with the threaded end to the left; if it is mounted the other way round it may not be possible to traverse the whole of the thread with the indicator. Operate the longitudinal and transverse adjustments of the indicator carriage to bring the stylus into the first thread space on the left-hand end of the screw. A certain preload is necessary on the indicator, and the correct value is indicated by a small pointer, K, and scribed line, L; precise adjustment of this is not important. Having set this, clamp the transverse slide of the indicator carriage.

Bring the micrometer up to zero on the linear scale and set the disc with one division exactly on the zero of the fixed scale. Using the longitudinal adjustment of the indicator carriage, bring the stylus back into the first thread and continue the movement until the indicator pointer is hard over to its left-hand extremity. No damage will be done to the machine in doing this if the previous instructions have been followed. Clamp the longitudinal adjustment (front clamp) and operate the right-hand wheel carefully to bring the pointer exactly over its fiducial index. If the pointer overshoots, the wheel should be turned back a little way and brought up again. In this way the lead screw of the adjustment will remain in tension throughout the measurement; this may not be essential, but is found in practice to give the most consistent results.

Having checked that the micrometer is still set at zero, rotate the drum fairly quickly so that the stylus traverses two or three threads of the screw gauge. Lift the stylus away from the gauge and return the micrometer just past zero, bringing it forward to zero carefully with the stylus in the thread. It is important to lift the stylus when running the micrometer or longitudinal adjustment backwards, since the thrust on the micrometer spindle is removed and the carriage is liable to jump, being held in contact with the micrometer only by a small weight. If the zero has shifted slightly it will be necessary to reset and run the micrometer again until repetition is obtained. It is sometimes tempting to start a calibration without running the micrometer, an omission which will be greatly regretted if the zero does not repeat at the end of the calibration. The machine is now ready for the calibration run. Readings must only be taken after setting the micrometer in a forward direction.



(*b*) *Ring screw gauge.* A ring screw gauge must be mounted in the chuck or on the faceplate of the machine. In either case it must be concentric and square with the machine axis, and the ground face of the gauge will normally be sufficiently square to its axis for this purpose. The effect of mounting the gauge with its axis tilted will be to give a false lengthening or shortening to the pitch measured.

Select the stylus appropriate to the pitch and size of the gauge, fit it to the bar Q and mount the bar in the internal strip unit. For threads of very small diameter, such as small B.A. sizes, special bars are sometimes supplied with the machine. These are fitted with a stylus as an integral part of their construction.

Mount the adaptor stylus G in the indicator unit. This stylus can be identified by its very blunt tip which engages with the dimple in the stylus bar when the internal strip unit is mounted on the carriage. The bar should not be firmly clamped in the unit until it is seen that all these component parts are in correct relative positions and nothing is unduly strained (see Fig. 23).

Using the longitudinal adjustment of the indicator carriage, engage the stylus with the first thread of the gauge and carry out exactly the same settings, adjustments and test as described for the plug screw gauge. It is even more important with a ring gauge than with a plug gauge, to hold the stylus out of contact when

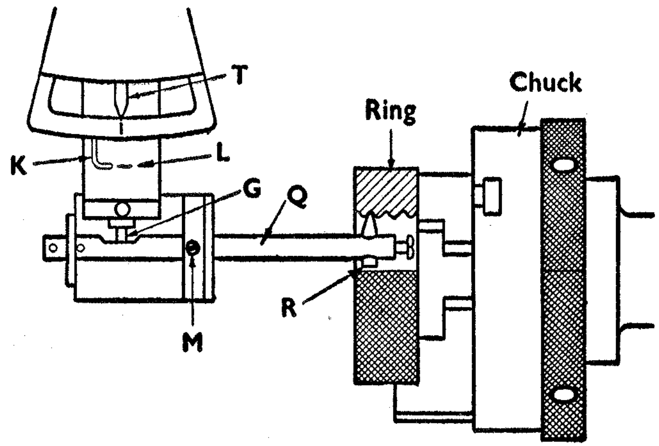



FIG. 23

running back, since there is sometimes more tendency for the stylus to hold in a thread and jump out suddenly.

(c) *Pitch measurement.* Having ensured that all is properly set and that the machine is repeating zero within one tenth division, the pitch measurement can be started. Opinions may vary as to the best method of recording results, whether by tabulating errors or by plotting an error curve direct. In routine work the latter method is nearly always adopted, and if carefully carried out there is little against it. More detail is given under the next heading, where it is assumed that a curve is plotted directly from the readings.

To operate the machine for pitch measurement the micrometer is turned smoothly and fairly slowly for a limited distance. It will help the beginner to calculate the number of turns which will be needed for one pitch so that the next thread is not overrun. As the stylus rides up the flank of the first thread the indicator pointer will move right over to one side and then, as the stylus moves over the crest of the thread, the pointer will swing over to the other side as the direction of pressure on the stylus changes. When the pointer starts to move up to its central fiducial index again the micrometer speed should be reduced and the pointer brought carefully up to its index.

The micrometer reading is then taken, not in full but as an error from zero. If the pitch of the gauge is perfect, a line on the disc will again coincide exactly with zero, but an error will obviously show up as a displacement from zero. In all this use of special discs it is, of course, assumed that the pitch error is considerably less than one division on the rotating disc; with a gauge this should certainly be the case.

Having recorded the error (zero if necessary), move on to the next thread in a similar manner and so on to the end of the gauge or the end of the micrometer run, whichever is reached first. It is possible to measure pitches of longer screws in a number of sections, but the technique of doing this will not be considered here. Return the micrometer to zero, again taking care to hold the stylus away; a jolt at this stage will almost certainly ruin any hopes of good repetition.

If the zero repeats within two-tenths division, make a repeat run and record results as before, again repeating the zero at the end of the run.



Turn the gauge through 180° and take a fresh set of readings. The plug gauge should be rotated on the centres, but the ring gauge must not be removed from the chuck or faceplate which should be rotated as one unit on the machine.

IMPORTANT. All readings on the micrometer must be taken after *forward* rotation. If the micrometer has been run back, at least one whole turn overrun backwards must be allowed before turning forward again.

### *Observations and Results*

Assuming that the pitch error readings are to be plotted directly on to a graph, it will be necessary to have sectional paper with a suitable ruling. If the screw gauge being measured is of a reasonable standard, even though somewhat worn, its pitch error should not exceed one or two ten-thousandths of an inch, and the machine readings can be estimated to the nearest hundred-thousandth. If graph paper with ten squares to the inch is used, each square can represent 0·00002 in.; if millimetre squares are used, each can also represent 0·00002 in. These recommendations are about the largest scale which should be used. Pitches can be plotted at intervals of five squares along the axis.

Having plotted the curve for the first run, plot the repeat readings over the same curve, indicating coincident readings by neatly encircling the first reading. The points of the first run should be joined up before plotting the second run, otherwise the two sets of points will become confused. Full lines can be used to join the first run of points, using dotted lines for the repeat. Plot the measurements made at the 180° position on a separate curve.

If the calibration curve of the pitch machine micrometer is available it should be plotted on each of the curves obtained. Make sure that the figures or curve available represent *errors* before plotting in this way; *corrections to readings* should be reversed in sign before plotting. The true pitch error of the screw under test will obviously be represented by the difference between its curve and the machine's curve. If desired, fresh curves may be plotted after making corrections for the machine. A reference screw with its own official calibration curve provided by the N.P.L. or other authority is usually supplied with the machine, and, if desired, the machine error may be determined directly from this. If this screw is used, make sure to measure along the generator marked on the screw, starting in the correct thread indicated on the calibration curve.

Unless the curves of errors obtained from the screw under test are particularly erratic, draw smooth curves through them and estimate the general tendency over the length of thread.

*Conclusions*

Examine the degree of repetition obtained for each measurement and assess the accuracy of determination. Most of the readings should repeat within 0·00002 in., although an occasional discrepancy of 0·00003–0·00004 in. can be tolerated when it is remembered that the mean will be within 0·00002 in. of either.

Calculate the effect of the maximum pitch error obtained on the virtual effective diameter of the screw. The maximum error used for this purpose should be the value from the smooth curve over the length of the screw or the maximum difference between peaks if the curve is erratic. The virtual effect is equal to the pitch error multiplied by the cotangent of the semi-angle of thread. This factor can be taken as 2 for Whitworth, metric, U.S. or Unified threads without much error; even for B.A. the error will not be significant unless the value of pitch error is large. It should be remembered that the effect is to increase the virtual effective diameter of a male thread and reduce it in a female thread. (See Table IV, p. 245).

## *EXPERIMENT 21*

### TO MEASURE THE FORM AND ANGLE OF A PLUG SCREW GAUGE BY OPTICAL METHODS

*Apparatus*

Plug Screw Gauge.
Profile Projector or suitable Microscope.
Shadow Protractor or Protractor built into the Projector or Microscope.
Thread Form Diagram or Graticule.

The purpose of this experiment is to measure the semi-angles of the thread in order to compute the effect of any errors on the simple effective diameter.

There are many types of projectors and microscopes, with their associated protractors, which are suitable for this experiment. The main requirements of the apparatus are:

(1) Sufficient magnification (x50 is usual).
(2) A means of raking the collimated illuminating beam to the mean helix angle of the thread.
(3) A protractor capable of being read to an accuracy of one minute.
(4) For the greatest accuracy, a precise means of traversing the thread across the projection lens so that diametrically opposite sides of the thread may be examined in turn.

*Method*

*Angle.* Put the cleaned screw gauge in the centres of the projector, or, if this is not possible, clamp the handle securely in a vee block, so that the whole of the gauge may be brought into view by operating the traverse.

With one thread ridge in the centre of the field, throw the projector out of focus by bringing the gauge nearer the projection lens. A blurred pattern will appear round the thread. Move the rake adjustment of the illuminating system until this pattern is symmetrical around the thread image. Re-focus so that the image is well defined.

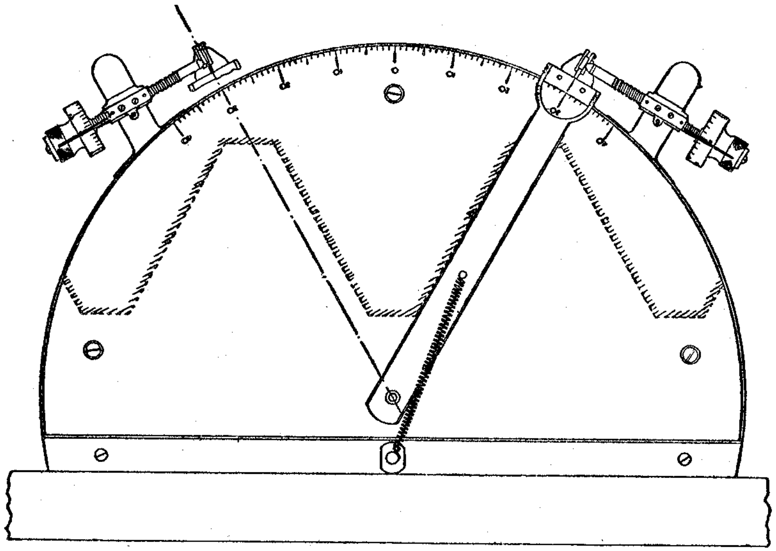


FIG. 24

In the case of the N.P.L. type of protractor (Fig. 24), set the blade parallel to one flank of the image and note the angular reading. Traverse the gauge across the field until the opposite side of the gauge is in the centre of the field. The rake of the beam will now have to be re-set, as before, and the thread focused again.

Without moving the body of the protractor, set the blade parallel to the same flank of the ridge previously measured. This means turning the protractor blade through the included angle of the thread plus or minus any error. Note the reading. If the protractor has a central zero, the mean of these two readings is the true value of one semi-angle with respect to the axis of the thread. Repeat for the other flank of the same ridge.

In the case of a continuously divided protractor (0°–360°) select one cross-line (there are often several lines engraved on this type of protractor) and use it throughout the experiment. Proceed exactly as before. Half the difference between the two readings is the true value of the semi-angle with respect to the axis of the thread.



When setting the blade or line of the protractor against the image of the thread flank, it is preferable to leave a slight gap between them. It is easier to judge their parallelism in this way. Take care to set only on the straight portion of the flank, avoiding the blends of the root and crest radii, if any.

*Alternative Method*

If the projector or microscope is not equipped with a traverse, or the diameter of the thread is too great for the traverse, then the thread angles must be measured with respect to the major diameter. This is not so accurate as the first method, since irregularities of the major diameter will influence the semi-angle values.

Set the gauge up as before, with one side in the projection field. Set the base straightedge of the protractor (if of the N.P.L. type) parallel with the crests of the thread. Swing the blade to each flank of the same ridge in turn. This gives direct values of the semi-angles.

If the protractor is of the continuously divided circle type, select one line and set it parallel with the crests of the thread. Note the angle reading. Swing the same line parallel to each flank of the same ridge in turn, observing the two readings. The differences between these last two readings and the first give the complements of the semi-angles.

The major diameter must be carefully examined for taper, as this will affect the values for the semi-angles. A taper of 0·0006 in./in., on diameter, will introduce an error of 1 min. in each semi-angle, plus on one and minus on the other.

*Form*

The form is examined by lining up the appropriate thread-form diagram or graticule with the projected image. One ridge only, in the centre of the field, should be examined and no attempt made to measure pitch errors by comparison with the diagram. This is because interference by the helix tends to distort the thread form towards the outer parts of the field.

Observe and record form errors of the roundings at crest and root and deformations of the flanks, paying particular attention to possible local interference when the gauge is applied to threaded work.

*Observations and Results*

Record results in the manner of the following examples:

*First method, N.P.L. type protractor*

Type of gauge: Plug screw. ½-in. B.S.F. 'Go'. Medium fit. General.
Form: Whitworth.
Semi-angles: 27° 30′.

| | | |
|---|---|---|
| 1st reading on flank *A* | 27° 42′ | |
| 2nd reading on flank *A*: | 27° 36′ | |
| Mean value for flank *A*: | 27° 39′ | Error = 0·15° |
| 1st reading on flank *B*: | 27° 20′ | |
| 2nd reading on flank *B*: | 27° 10′ | |
| Mean value for flank *B*: | 27° 15′ | Error = 0·25° |
| | | Total error = 0·4° |

Diametral equivalent = +0·00025 in.
Form: Satisfactory.

*First method, continuously divided protractor*

| | | |
|---|---|---|
| 1st reading on flank *A*: | 271° 22′ | |
| 2nd reading on flank *A*: | 216° 4′ | |
| Half difference for flank *A*: | 27° 39′ | Error = 0·15° |
| 1st reading on flank *B*: | 216° 28′ | |
| 2nd reading on flank *B*: | 270° 58′ | |
| Half difference for flank *B*: | 27° 15′ | Error = 0·25° |
| | | Total error = 0·4° |

*Alternative method, continuously divided protractor*

| | | |
|---|---|---|
| Reading on major diameter: | 269° 38′ | |
| Reading on flank *A*: | 207° 17′ | |
| Flank *A* semi-angle: | 90° − (269° 38′ − 207° 17′) | |
| | = 27° 39′ | Error = 0·15° |
| Reading on flank *B*: | 332° 23′ | |
| Flank *B* semi-angle: | 90° − (332° 23′ − 269° 38′) | |
| | = 27° 15′ | Error = 0·25° |
| | | Total error = 0·4° |

*Conclusions*

The first method should be used wherever possible, since it measures the semi-angles with respect to the axis of the thread. The alternative method is very dependent on the accuracy of the



major diameter. Unfortunately, the crests are highly susceptible to damage. Furthermore, the truncation of flat-crested threads is often a separate operation to the thread forming, and, if badly set up, may bear little relationship to the axis of the thread.

The diametral equivalent obtained in this experiment must be added to the value obtained from the pitch error in Experiment 20, and, in the case of a gauge, compared with the values given in B.S. 919. (See Table III, p. 244.)

In the case of threaded work, add the diametral equivalents of both pitch and angle errors to the measured simple effective diameter and compare with the appropriate B.S. listed on p. 253. Note that, with male threads, pitch and angle errors increase the simple effective diameter.

## *EXPERIMENT 22*

# TO MEASURE THE MINOR DIAMETER OF A PLUG SCREW GAUGE USING A FLOATING MICROMETER MEASURING MACHINE

### *Apparatus*

Floating Micrometer Measuring Machine.
'Go' Screw Plug Gauge.
Thread Prisms or Vee Pieces suitable for pitch of gauge.
Cylindrical Standard of approximately the same diameter as the minor diameter of the gauge.

This experiment is very similar to Experiment 19, the measurement of simple effective diameter, and the same technique should be used in handling the machine and prisms.

### *Method*

Examine the prisms. The radiused edge which registers in the roots of the threads is rather susceptible to wear and damage. Lay this edge on a slip gauge and examine against a light-box. Very small errors may easily be seen.

Put the cylindrical standard between the centres of the measuring machine and a prism on either side between the anvils of the fiducial indicator and the micrometer (see Plate 2). This is exactly similar to the set-up in Experiment 19, when taking the standard reading over the wires. Record the reading $R_B$.

Remove the standard and replace it with the screw gauge. Put a prism on either side of the gauge in the same thread groove and advance the micrometer until the indicator needle is on its fiducial mark. Move the prisms about to bed them in and, if the indicator drops, advance the micrometer. Record the reading $R_G$.

Take three readings round the gauge to check ovality and at least three along the gauge to check taper. Remove the gauge and take a repeat reading on the cylindrical standard.

Readings may only be taken after advancing the micrometer. If the fiducial indicator overshoots, withdraw the micrometer and come up to the mark again.





### *Observations and Results*

Record results in the manner of the following example:

Type of gauge: Screw plug. ½-in. B.S.F. Medium fit. 'Go'. General.
Minor diameter limits: 0·4206—0·4196 in.
Diameter of cylindrical standard $B$: 0·40060 in.
Reading over standard and prisms $R_B$: 0·37800. Repeat: 0·37802.

Readings on gauge $R_G$:

| | | | |
|---|---|---|---|
| ovality | 0·39742 | 0·39734 | 0·39738 |
| | 52 | 39 | 46 |
| | 60 | 48 | 54 |
| | taper | | |

Minor diameter $=B-R_B+R_G$
$=0{\cdot}40060-0{\cdot}37801+0{\cdot}39742$ in.

| | | | |
|---|---|---|---|
| ovality | 0·42001 | 0·41993 | 0·41997 |
| | 11 | 98 | 0·42005 |
| | 19 | 0·42007 | 13 |
| | taper | | |

### *Alternative Method*

As when measuring the effective diameter, arithmetic may be saved by making the reading over the standard and prisms equal to the diameter of the standard:

$$R_B=B;$$

the readings on the gauge will then be actual values of the minor diameter. Should the diameter be over 1 in., then, of course, only the decimal part of the size is set on the micrometer.

### *Conclusions*

This is the standard method of measuring the minor diameter of a screw plug. It is independent of the size of the prisms, which only need to have measuring edges straight and parallel to their back faces. The radius of the edge must, of course, be smaller then the root radius of the thread.

Compare the results with the limits given in B.S. 919.*

* See footnote on p. 92.

*EXPERIMENT 23*

# TO MEASURE THE MAJOR, MINOR AND EFFECTIVE DIAMETERS OF A RING SCREW GAUGE OPTICALLY BY MEANS OF A CAST

*Apparatus*

Ring Screw Gauge not less then 1 in. diameter—preferably about 2 in.

Dental Plaster of Paris, OR Rock Sulphur and Powdered Graphite.
Suitable Containers.
Means of melting the sulphur.
Profile Projector or Microscope.
Suitable Thread Form Diagram.
Pair of Standard Rollers.
Box of Slip Gauges, with Table of Errors.
Pair of Parallels (see Fig. 25).

This experiment is not particularly accurate as far as the effective diameter is concerned (about 0·0005 in.) and should only be used

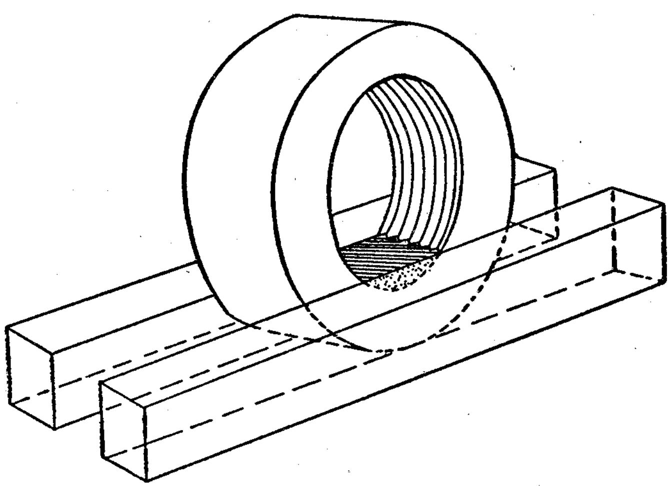


FIG. 25





when an internal effective diameter machine is not available. A cast of an internal thread must be made before the form and angle can be measured, and this experiment is mainly directed towards the method of taking the cast.

*Method*

*Minor diameter*. Measure the minor diameter in a similar method to that described in Experiment 6, Vol. I. Explore for taper and ovality and mark the diameters measured so that they may be related to the casts.

*The plaster of Paris cast*. The ring, scrupulously cleaned and lightly oiled, is set up as in Fig. 25. A thin solution of Vaseline in petrol is ideal for this purpose. It is most important that the segment of the ring flanked by the parallels is considerably less than a semicircle. Since the cast must on no account be screwed out, room must be left to press the cast towards the centre of the ring, thus disengaging the threads.

Mix the plaster with water, stirring constantly, to the consistency of thin cream. Pour the liquid into the segment of the ring and leave to set. This takes only a few minutes—the precise time depends on the consistency of the plaster, atmospheric conditions and the size of the cast. Some experimenting will be found necessary. Remove the cast before it sets really hard.

To remove the cast, take away the side blocks, turn the ring so that the cast is at the top, and press the cast down towards the centre of the ring. It should come away cleanly and the plaster threads appear polished. Several casts should be taken and compared with each other until the technique is mastered.

*The sulphur cast*. Set up the ring as before, but without oiling. (The graphite prevents sticking.) Mix 20 parts of sulphur with 1 part of graphite and heat in a ladle, stirring well together. Be careful not to overheat. As soon as the mixture is fluid, pour into the ring as before, and remove when set.

Either type of cast may now be projected, setting up as described in Experiment 21. The semi-angles are measured as in the alternative method, but using the minor diameter, which has already been measured mechanically, as the datum.

*Major and effective diameters*. Line up the projected image of the cast so that its root (the minor diameter of the ring) is coincident with the nominal outline on the thread form diagram. Adjust the image sideways so that the flanks are symmetrical about the dia gram (Fig. 26).

Measure $x$ and $y$ either by rule or (if available) the built-in micro meter stage. Express these in true diametral errors. Remembe that excess cast means metal missing in the ring and hence a large diameter, and vice versa, and that the measured radial values mus be doubled to obtain diametrical values.

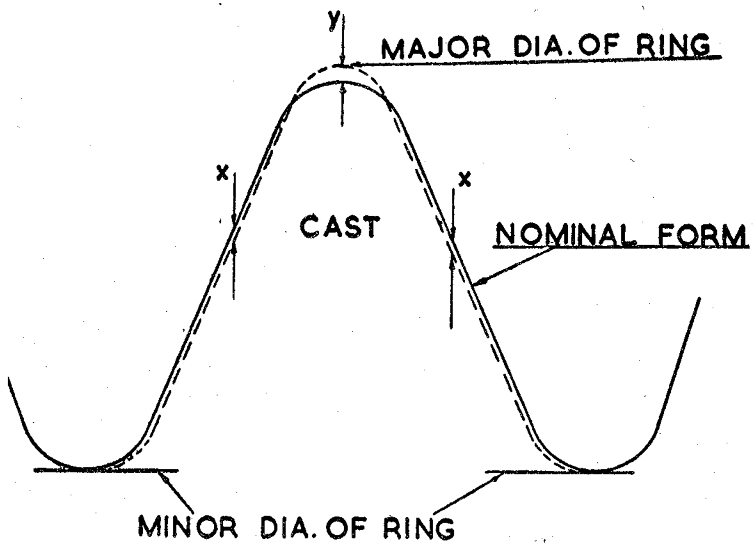



Fig. 26

*Observations and Results*

Record results in the manner of the following example:

Type of gauge: Ring screw. 2 in. × 16 T.P.I. Whit. Medium fit. 'Go'. General.

| *Limits* | (in.) | |
|---|---|---|
| Major diameter: | 2·0004<br>1·9992 | Nominal: 2·0000 in. |
| Effective diameter: | 1·9600<br>1·9592 | Nominal: 1·9600 in. |
| Minor diameter: | 1·9200<br>1.9192 | Nominal: 1·9200 in. |



*Minor diameter* (as Experiment 6, Vol. I)

| | (in.) | | |
|---|---|---|---|
| Mean diameter of rollers: | 0·5002 | | |
| Slips between rollers at position of cast (allowing for slip errors): | 0·9194 | Minor diameter | = 1·9198 in. |
| | | (Error from nominal) | = −0·0002 in. |
| Variation around ring: | 0·9196 | Minor diameters: | = 1·9200 in. |
| | 0·9192 | | = 1·9196 in. |

*Major diameter*

$y$ (at x50): +0·01 in.

$2y$ (actual): +0·0004 in. (with respect to the minor diameter which is −0·0002 in.)

Error of major diameter: = +0·0004 − 0·0002 = +0·0002 in. from nominal.

Size of major diameter: = 2·0002 in.

*Effective diameter*

$x$ (at x50): −0·02 in.

$2x$ (actual): −0·0008 in. (with respect to the minor diameter which is −0·0002 in.)

Error of effective diameter: = −0·0008 −0·0002 = −0·0010 in. from nominal.

Size of effective diameter: = 1·9590 in.

*Angle and pitch*

As in Experiments 20 and 21.

*Conclusions*

The plaster method is perhaps the more accurate though rather messy, and the plaster, once made, may be used only once. Sulphur, on the other hand, may be used again and again. Though the accuracy obtained on the effective diameter is low, it is quite satisfactory for form and angle.

The calculations may appear rather clumsy, but experience has shown that in this experiment it is easier to work in terms of errors from nominal rather than in diameters. Confusion will be avoided if it is firmly borne in mind that the measurements of effective and major diameters are both related to any errors which may be present in the minor diameter.

Both these methods are suitable for threaded rings down to about ½ in. diameter. Below this size dental wax is used and this is described in another experiment.

Compare the results obtained with the appropriate British Standard (see Bibliography p. 253).

### EXPERIMENT 24

## TO TAKE A CAST OF A SMALL RING SCREW GAUGE OR SIMILAR SHAPE

*Apparatus*

2 B.A. Screw Ring Gauge.
Dental Wax.
Needle or Stiff Wire, about 34 S.W.G. (0·009 in.).
Bowl of Hot Water.
Bowl of Cold Water.

This experiment explains how to take a cast of a ring which is too small to cast with plaster of Paris or sulphur.

*Method*

The hot water must be hot enough to soften the wax until it is of the consistency of well-worked putty. Mould a small amount of the wax around the central portion of the needle in the form of a round plug, with more wax on one side of the needle than the other (see Fig. 27). The diameter of this plug must be slightly less than the minor diameter of the ring. By trying the plug in the ring this may be quickly achieved. Put the plug to one side.

Thoroughly clean the ring gauge, being careful to remove the wax that may have adhered to the ring during any previous trials.

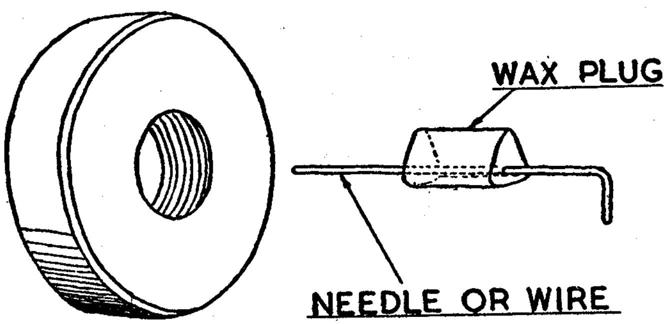



FIG. 27





Immerse the ring in the hot water and leave to attain the water's temperature.

When the ring is hot, immerse the wax plug again and allow it to soften. Remove the ring and stand it on edge on a wooden bench, giving it a sharp tap on the bench to dislodge any water sticking to the upper part.

Insert the wax plug into the ring so that a piece of needle is sticking out on either side, and press lightly upwards into the thread. Lifting the ring and plug together, immerse both into the cold water. It is most important that there is no relative movement between the plug and the ring after they have been pressed together.

When cold, press the plug towards the centre of the ring to disengage the threads and remove. Before projecting the cast examine it visually. The wax threads should appear clean and polished. The commonest faults are:

1. The needle showing through at the root of the cast. This is due to pressing the wax into the ring too hard.
2. Dull and irregular crests of the cast. This is due to insufficient pressure when casting.
3. Thin threads, large angle. This is usually due to movement of the cast relative to the ring before hardening.
4. A broken cast. Usually due to poor distribution of wax around the needle. It may also be caused by rough handling or bad finish of the threads in the ring.

Do not be discouraged if the first few casts break or are faulty for some reason or another. Persevere—they will come out eventually. With some very small gauges, such as 10 B.A. or smaller, the experienced metrologist considers himself lucky if he gets one properly formed thread ridge out of a whole cast.

Remember to wipe all moisture from the gauge, preferably washing it in alcohol or methylated spirit.

*Observations and Results*

The cast is projected and the form and thread angle, major and effective diameters are measured as in Experiment 23. The pitch is measured as in Experiment 20. The minor diameter is measured by pairs of calibrated graded small cylinders.

*Conclusions*

A successful wax cast is just as accurate as a plaster or sulphur cast is for larger work. Wax casts are often used for form work apart from threads such as serrations, splines, undercuts, etc., with considerable success.

## EXPERIMENT 25

### TO MEASURE THE EFFECTIVE DIAMETER OF A RING SCREW GAUGE USING A HORIZONTAL COMPARATOR OR MEASURING MACHINE

*Apparatus*

A Horizontal Internal Comparator or Measuring Machine equipped for internal thread measurement. This is of the type that uses two internal feelers carrying ball-ended styli which register in a single thread groove across a diameter. The instrument may be one of two types. The first has a measuring range of $\pm 0{\cdot}005$ in., the second of 0–4 in. The measuring technique described in this experiment is suitable for either. Another type of machine uses a single measuring probe but the procedure is rather different and will be described in another experiment.

Screw Ring Gauge about 2 in. dia.

Set of Slip Gauges.

*Method*

Mount on the measuring stage the table with longitudinal float (i.e. parallel with the measuring axis). To this table fit the table with free rotation and transverse float. Select the internal arms suitable to the diameter and depth of the ring to be measured and fit them with the ball-ended styli appropriate to the pitch of the thread. Assemble the arms with the tailstock and measuring head of the machine in the horizontal plane. Clamp the ring gauge on to the top table with its thread axis horizontal and at right angles to the measuring axis (Fig. 28). It is often possible, when measuring rings and small work, to dispense with the floating tables, but it is most important that the ring is free to move in all directions in the horizontal plane.

Adjust the height of the measuring stage by means of the vertical control so that the centre line of the ring gauge is approximately level with the thread styli. Close the internal arms together and slide the ring over them. By adjusting the positions of the tailstock and the measuring head, open the arms out until each stylus is

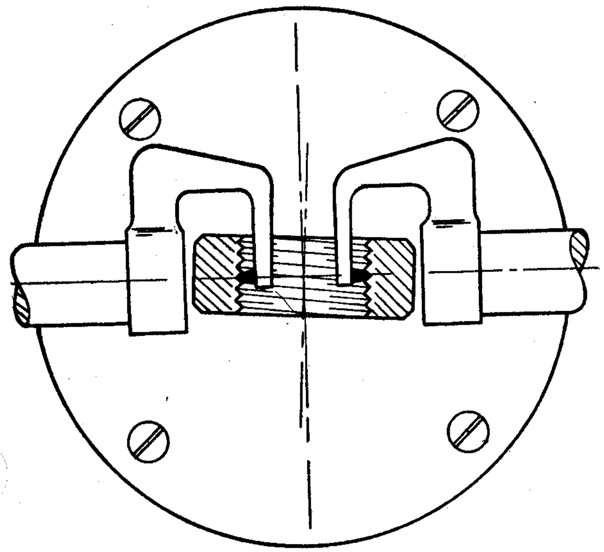


FIG. 28

located in the same thread groove and a reading is obtained in the measuring head. Clamp the measuring head and the tailstock, remembering that there are several clamps to tighten. It is as well to go over this twice and work out a fixed routine for tightening the clamps. One loose clamp is sufficient to spoil the entire experiment.

Watch the scale in the measuring head and move the ring up and down slightly by means of the vertical control. Make sure that a turning point occurs at a maximum reading of the scale. This will represent the maximum chord of the ring which is, of course, the diameter to be measured. Make certain that the ring is free to move in the horizontal plane and, if clamped to the floating table, that there is plenty of float left when the turning point is reached. If the ring or tables do jam, this can usually be detected while obtaining the turning point. When the ring is moved vertically, the scale should move smoothly to a maximum and reverse. Any erratic movement (provided the vertical control is operated smoothly) is a sure sign of something sticking or jamming.

Measuring machines of this type usually have levelling screws in



the base together with a circular level. Don't set the machine dead level, but give it a slight bias so that the work being measured runs against the stylus attached to the tailstock. The reason for this is that though the auxiliary tables float on balls, there is always a certain amount of "sticktion" and, particularly if the job is a heavy one, the measuring head may not be powerful enough to move the work into proper contact with the fixed stylus. The direction of bias has to be changed for external work.

Now that you have made sure that the machine is set so that the ring can be measured and that all the movements are working properly, remove the ring and set up the standard. It may appear at first sight that we are working backwards and that we should have standardised the machine first. Experience shows, however, that all sorts of little movements take place after setting the machine up and that it is better to get these over before actually standardising. Also, nothing is more annoying than to set the machine carefully on the standard and then to find that you have chosen the wrong arms or not left enough room to get the work in.

To set up the standard, select the grooved jaw blades of the appropriate thread angle and pitch range and assemble them in the special carrier provided, separated by slips to the value calculated from the nominal effective diameter of the ring and the jaw blade constant for that particular pitch. Make sure that the slips and blades are truly wrung. Adjust the height of the jaw blades with slips under their rounded ends so that one notch is $\frac{1}{2}$ pitch above the other. This is achieved by putting one slip under each blade, the difference between them being $\frac{1}{2}$ pitch. Clamp this composite standard on the top floating table so that the notches are lying in the same direction as were the thread grooves of the ring. Slide the standard into contact with the stylus after relieving the measuring pressure and again check to see that there is some float left in the tables.

While observing the measuring-head scale, adjust the tilt control of the table to get a minimum turning point. Take care over this, because the bearing area of the notches is small and the styli easily slip out of them. If necessary, adjust the fine tailstock control to bring the reading somewhere in the middle of the scale for the small-range instrument, and clamp. With the 0–4 in. range instrument the reading may be anywhere within the range up to a few thousandths of an inch from either end. Move the measuring-head stylus in and out of contact with the jaw blade once or twice to make sure that the styli are bedding down well. Note the reading.

Remove the standard carefully, after relieving the measuring pressure, and replace the ring as before. Take nine readings: the second thread in from each side and the centre, each at three positions round the gauge. The maximum turning point must be obtained for each reading by operating the vertical control. Remove the ring and take a repeat reading on the standard. The first and second readings on the standard should not differ by more than 0·00005 in.

*Observations and Results*

EXAMPLE:

Ring gauge: $2\frac{1}{2}$ in. × 16 Whit. Go. GEN.
Nom. effective dia.: 2·4600 in.
Jaw blades: 55°. Constant for 16 t.p.i. 0·25632 in.
Slips between jaws: 2·2037 in. Slip error: −0·00004 in.
Slips beneath jaws for $\frac{1}{2}$ pitch offset: 0·132 in. and 0·1008 in. Difference = 0·0312 in.
Effective dia. of standard: Slips between jaws + constant
2·20366 in. + 0·25632 in. = 2·45998 in.
Reading on standard: 2·64782 in. Repeat: 2·64784 in.
Mean: 2·64783 in.

| Readings on gauge (in.) | | | | Size of gauge (in.) | | | Limits (in.) |
|---|---|---|---|---|---|---|---|
| 2·64780 | 75 | 77 | ovality | 2·45995 | 90 | 92 | 2·4600 − 2·4592 |
| 59 | 54 | 56 | | 74 | 69 | 71 | |
| 81 | 74 | 75 | | 96 | 89 | 90 | |
| taper | | | | taper | | | |

Size of gauge = size of standard − reading on standard + reading on gauge.

An alternative method of setting the jaw blades may be used in which the notches are set in line, i.e. the $\frac{1}{2}$ pitch slips are not used. If this method is used, a correction must be subtracted from the measured size of the effective diameter. The value of this correction is:

$$\sqrt{D^2+\frac{p^2}{4}}-D$$

where $D$ = diameter of thread and $p$ = pitch.



This method should only be used where the pitch/diameter ratio is small, i.e. less than 0·05.

*Conclusions*

Assess the accuracy of the experiment and compare the measured size of the gauge with the limits laid down in BS 919. In the example given, the readings are such as might be obtained on a 0–4 in. range instrument.

*EXPERIMENT 26*

## TO SET AND CALIBRATE AN ENGINEER'S BLOCK LEVEL

*Apparatus*

Engineer's Block Level.

Almost any type of precision level is suitable for this experiment, but that most commonly used for precision measurement has a cast-iron body 8 in. or 10 in. long and a sensitivity of about 10 sec. per division of 0·1 in.

Rigid Surface Plate.

This should preferably be mounted on concrete or brick piers but a surface table mounted on a substantial stand directly on a firm floor is quite satisfactory. A small surface plate standing on an ordinary bench should be avoided; but if such a plate is the only one available, great care must be taken throughout the experiment to avoid leaning on the bench or moving it in any way.

Straightedge or Parallel Block.

Tilting Table.

Such a table can take many forms, but will usually have to be specially constructed for the purpose. The table can be made in the form of a light triangular steel framework resting on two ball feet at one end, and on the spherically ended anvil of a micrometer head at the other. The distance $d$ between the axis of the micrometer head and the line of centres of the ball supports can have almost any value, but 20 in. is about the maximum convenient size to handle. About 10 in. is the minimum size to give reasonable accuracy. The separation of the ball feet at the one end can be about 4 in. or 5 in. The form of such a piece of apparatus is shown diagrammatically in Fig. 29. Some means of supporting the level must also be provided, possibly by fastening a flat steel plate to the framework.

Operation of the micrometer head will tilt the table through a small angle and, if the centre distance $d$ is calibrated with a reasonable accuracy, a precise measurement of the angle of tilt can be obtained. A fixed ball foot may be used instead of the micrometer head, and in this case slip gauges of various sizes may be placed under it. This operation is more tedious and there is more





danger of the level moving during the manipulation of the slip gauges.

Adjusting Key.

A suitable key for adjustment of the level should be provided by the makers. If this key is missing, most types of level may be adjusted with an ordinary Allen key.

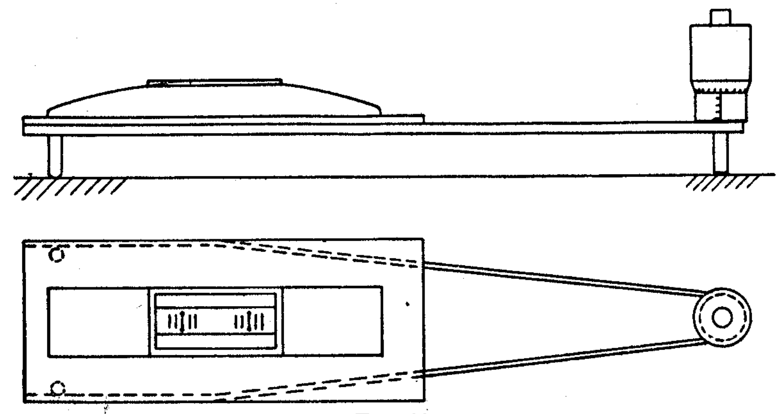


FIG. 29

*Method*

A sensitive level is a precision measuring instrument and is particularly susceptible to changes in temperature. Care must therefore be taken to avoid any violent changes of temperature, and to arrange the experiment in a place free from draughts. Handle the level carefully and as little as possible since unequal expansion of the metal body will upset the readings. The machined base of the level must be cleaned carefully and inspected for burrs, rust marks or other damage. If such damage is present, surfaces should be lightly stoned with an Arkansas stone.

### 1. SETTING THE LEVEL

Unless the level is badly out of adjustment so that a reading cannot be obtained on the scale, it is not always necessary to adjust it to read true when setting on a truly level surface. Nevertheless it is often desirable to set it so that it indicates true level when its bubble is symmetrical within the graduations. To do this, set the level on the surface plate with its edge against the straightedge or parallel. Note the reading of each end of the bubble relative to the central graduation, observing whether it is to the left or right.

Without moving the straightedge, reverse the level end for end and bring to the same position on the table, lying against the straightedge. Again take the reading at each end of the bubble.

A convention of reading must be adopted and adhered to quite strictly. For setting level the best method is to work from the central graduations which are often identified by spots at the ends of the lines. Displacements to the left of these lines can be read as negative, and those to the right as positive. They must be observed relative to a fixed position of the observer, irrespective of any reversal of the level. Each end of the bubble must be read independently.

In taking readings, estimate fractions of a division to the nearest tenth. This is not quite so easy as with a scale and pointer type of instrument, but can be done reasonably accurately with a little practice. In any case an error of $\pm \frac{1}{10}$ div. will not be very serious.

When readings have been taken with the level reversed, it should again be turned to its original position and a repeat of the first reading taken.

Take the mean of the two left-hand readings and the mean of the two right-hand readings. Adjust the level with the key until each end of the bubble comes to its corresponding mean reading. The following example will make this clear, but it must be remembered that all readings are taken relative to a fixed direction in space, *the observer does not rotate his reference axis with the level.* Example:

Convention: + readings to RIGHT
− readings to LEFT

Level readings

| | *LH side* (*div.*) | *RH side* (*div.*) |
|---|---|---|
| First setting | −1·4 | −2·0 |
| Level reversed | +0·2 | −0·4 |
| Adjust to mean | −0·6 | −1·2 |

The deviation of the surface plate from true level is indicated by the mean of these two final readings, i.e. $\frac{-0{\cdot}6-1{\cdot}2}{2} = -0{\cdot}9$ div.—



high towards the left. A truly level surface would read *LH* +0·3, *RH* −0·3—a symmetrical reading on the level.

## 2. CALIBRATION OF THE BUBBLE

Set the block level on the tilting table, taking care to see that its axis is square to the axis of rotation of the tilting table. A slight error in alignment will not be serious, and a careful setting by eye should suffice. If the tilting table has been made so that the platform on which the level is mounted has an edge square to the axis of rotation, no great difficulty will be encountered.

It is most convenient to arrange the tilting table with the micrometer head on the right of the observer. Adjust the micrometer head until the bubble is at the extreme left-hand end of its scale. It is most unlikely that each end of the bubble will read exactly on a division. It is therefore best to calibrate each end of the bubble separately, and take a mean value of the readings at the end. This method will reveal any serious irregularities in the bubble tube.

Taking the left-hand of the bubble first, adjust the micrometer until the bubble reads on the left-hand graduation, and then carefully advance the micrometer to set the bubble on successive graduations, taking the micrometer reading in each position. In order to eliminate backlash in the micrometer it must be rotated only in the one direction when making a setting.

It will be noted that, in this arrangement, screwing up the micrometer will raise the right-hand end of the table, which will cause the bubble to move to the right along the scale. After the last reading, rotate the micrometer a further one or two turns and then carefully turn it back until the bubble reads on the extreme right-hand graduation. Successive readings are taken as the micrometer is unscrewed. This is quite a severe test of the accuracy of operation of the micrometer, and some trouble may be experienced due to irregularities of the backlash. It is, nevertheless, very desirable that repeat readings should be taken with the bubble travelling back to its original position and for this reason it is essential to use a micrometer head which works smoothly.

Repeat this procedure to take readings on the right-hand end of the bubble.

For the purpose of calibration, it will be found convenient to adopt a different convention of reading from that used in setting level. The extreme left-hand graduation should be called "zero", all graduations on the right being positive. This will avoid confusion due to having positive and negative readings as well as positive and negative errors.

*Centre Distance of Tilting Table*

If a calibrated value of this dimension is not available, it will have to be measured. The dimension required is the perpendicular distance from the centre of the micrometer face (assuming it to be spherically ended) to the line of centres of the two balls at the other end.

There are several ways in which this can be done, e.g. measurement of the three sides of the triangle with a vernier calliper or by location of the ball feet against a straightedge and careful scale measurement to a slip gauge in contact with the micrometer spindle. An accuracy of about 0·01 in. should be sufficient.

*Observations and Results*

Record observations in the manner of the following example:

10-in. Block Level No. 1234.

Nominal sensitivity 0·0005 in. in 10 in. (approx. 10 sec per division)

(1) Setting level

The readings and mean values should be noted (see p. 122).

(2) Calibration

(a) *LH* divisions

| *Div from left* | *Tilting table reading (in.)* | | | *Diff. from first rdng.* ($10^{-4}$ *in.*) | *Corres. value over* 10 *in.* ($10^{-4}$ *in.*) | *Nominal* ($10^{-4}$ *in.*) | *Diff. from nominal* ($10^{-4}$ *in.*) |
|---|---|---|---|---|---|---|---|
| | *Raising* | *Lowering* | *Mean* | | | | |
| 0 | 0·50133 | ...131 | 0·50132 | 0 | 0 | 0 | 0 |
| 1 | 215 | ...213 | ..214 | 8·2 | 5·5 | 5·0 | +0·5 |
| 2 | 297 | ...297 | ..297 | 16·5 | 11·0 | 10·0 | +1·0 |
| . | | | | | | | |
| . | | | | | | | |
| . | | | | | | | |
| 12 | 0·51064 | ...062 | ...063 | 93·1 | 61·9 | 60·0 | +1·9 |

(b) *RH* divisions

Record and calculate in a similar manner



The values in the column "Difference from first reading" correspond to a base length of 15·03 in.; the equivalent values for a base length of 10 in. are calculated $\left(\text{multiplying by } \frac{10}{15{\cdot}03}\right)$ and compared with the nominal cumulative values (0·0005 in. per division).

Curves should be plotted for the final column to show variations from a linear calibration.

*Conclusions*

Calculate the average sensitivity per division for a combination of *LH* and *RH* readings and compare the sensitivity of each division with this value.

Compare with the relevant requirements of B.S. 958, which are:

(i) The average sensitivity should not differ from the value marked on the level by more than $\pm 10\%$.
(ii) The maximum deviation of the value of any one division from the average value should not exceed two-tenths of a division.

State whether the level complies with these conditions.

These tests are only part of those necessary to examine a level completely to B.S. 958. Other specifications of accuracy are given under "Finish and accuracy of working parts". These features should also be examined if time and available equipment allow.

## TO COMPARE THE LENGTHS OF TWO END GAUGES ON AN N.P.L. TYPE LEVEL COMPARATOR

*Apparatus*

Level Comparator.

Two End Bars (size about 15 in.) differing in length by 0·00005 to 0·00010 in.

Before starting the experiment make a careful examination of the comparator. If the student is unfamiliar with this instrument he should seek guidance from the instructor as to its use. It is a very sensitive instrument and, although it is quite robust, it could be easily damaged by careless handling. The comparator should be built on to a stout wall or stand on a brick pillar which is isolated from vibration. It should, preferably, have an insulated draught-proof cupboard which will keep the comparator at a uniform temperature as close as possible to 68° F. There should be glass windows to the doors of the cupboard. In some installations, arrangements are made to operate parts of the instrument from outside the cupboard.

A general view of the level comparator with two gauges in position is shown in Fig. 30; the cast-iron base carries a circular steel platen and behind that a pillar on which is mounted the level equipment. On a wall-mounted instrument, the pillar is sometimes fixed independently of the cast-iron base on which the platen is mounted. No particular accuracy attaches to the pillar or the level mounting equipment provided all the actions are smooth and convenient to handle. Apart from the sensitivity of the level, the whole accuracy of the instrument depends on the flatness of the surface of the platen and its ability to rotate accurately in its own plane. It will be seen that the top half of the platen rotates on the lower fixed half and under no circumstances should these two parts be separated by the student.

The level is mounted in a tube which is supported quite loosely in an outer tube. It is the outer tube which is mounted on brackets attached to the column; the whole bracket can be clamped at any



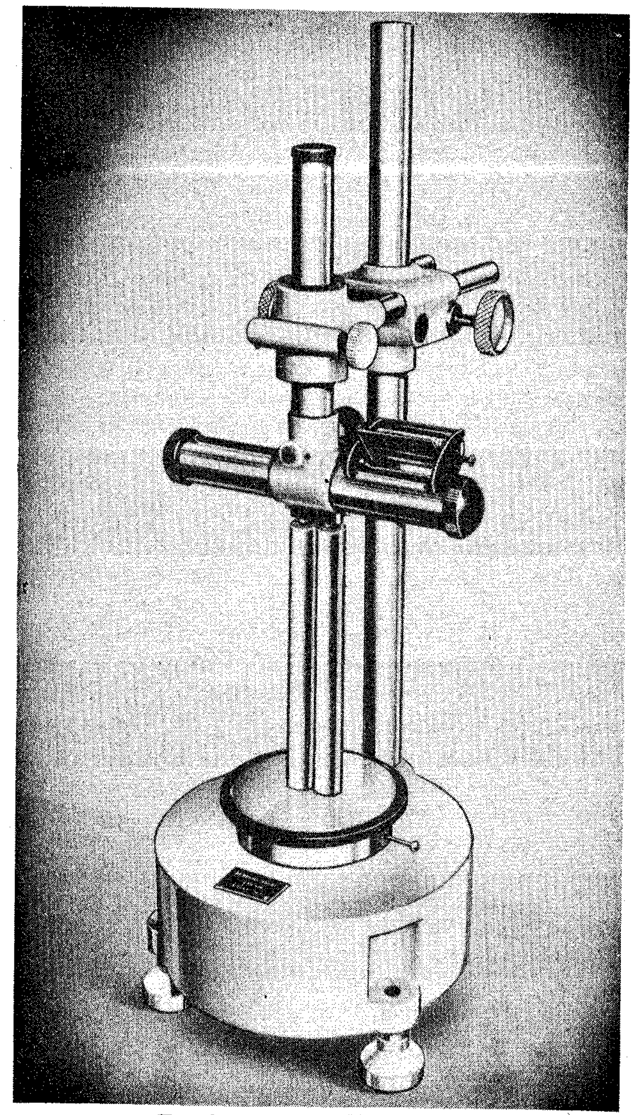


FIG. 30. LEVEL COMPARATOR

position up the column and, in addition, there are smooth adjustments for moving the level unit vertically, back and forward, and sometimes laterally. These movements should be carefully examined. There is a spring adjustment on the bracket to prevent the bracket falling accidentally and this should be adjusted until the bracket just fails to fall under its own weight with the clamp undone. While making this adjustment with one hand, the level unit should be supported with the other hand, so that it does not drop suddenly, with inevitable damage.

Take careful note of the value of the level divisions. This is determined by the sensitivity of the level and separation of the ball feet. On standard instruments the bubble moves about 1·5 in. for a change of relative height of the feet of 0·0001 in. This enables differences of the order of one millionth of an inch to be estimated. Some instruments are of lower sensitivity due to a less sensitive level or a greater separation of the ball feet. The position of one end of the bubble is read against the fixed scale. The scale is not graduated on the bubble tube but is attached vertically behind it. Looking horizontally at the scale, the bubble is observed superimposed on the scale, by reflection in a mirror placed at 45° above the bubble. Two parallel strips of silvering are removed from the mirror so that the scale is observed through the strips of clear glass. To avoid parallax, the distance from the mirror to the bubble is arranged to be the same as the distance from the clear glass to the scale. When the instrument is mounted in a cupboard, final readings may be taken through the glass of the cupboard, ensuring that no temperature disturbances affect the reading. If the value of the level divisions is not marked or recorded, it will be necessary to calibrate the level by taking readings on two slip gauges, differing by 0·0001 in., whose sizes are accurately known. These gauges should preferably be of Calibration or Inspection accuracy and be provided with a chart of errors. The method of calibration is the same as the method of the experiment to be described.

*Method*

Thoroughly clean the platen and the ball feet of the level, polishing off with a clean chamois leather or soft duster. Lower the level assembly carefully to within about one inch of the platen, using the coarse movement on the back pillar. Clamp the main clamp, remembering to support the level unit with one hand when loosening the



clamp. Lower the level, using the fine adjustment, until the ball feet rest on the platen. Continue lowering for another $\frac{3}{16}$ in. so as to make sure that the housing of the level is not preventing the feet from taking up their true position. Wait for several minutes until the level reading has remained constant for at least one minute.

If the instrument is in proper adjustment, the scale readings, when the feet are resting on the platen, should be near the centre of the scale. If these readings are near one end or off the scale, the platen must be levelled by its foot screws. This should be done only with the permission of the supervisor or instructor.

It will be realised that the exclusion of draughts and the avoidance of unnecessary handling are of prime importance. If the instrument is not mounted in a cupboard, it may be necessary to erect temporary screening when making a measurement, if really accurate results are expected. For an extremely accurate calibration the total waiting time may well run into hours but it is unlikely that such time can be spared in the ordinary college laboratory experiment. The maximum accuracy of which the machine is capable (down to millionths of an inch) should not, therefore, be expected if the time available is limited.

While waiting for the comparator to settle, clean and examine the end bars. Check the ends very carefully with an optical flat to make absolutely sure that there are no burrs. It must be appreciated that end bars are relatively heavy and might seriously damage a platen if an attempt were made to wring a burred bar on to it.

When the level reading is constant, take note of it and raise the level by the fine adjustment. Rotate the platen through 180°. Lower the level as before and when the bubble has come to rest, take the reading. If the platen is rotating in a true plane, this reading should be the same as the former reading. If it is not the same, rotate the platen and try to find another position where the 180° movement produces no change in reading. Theoretically, there should be such a position. Consistency within half a division should be obtained but, for the highest accuracy, a method will be mentioned later which will cancel out any error in parallelism or flatness of the platen, provided it is a true error and not due to dirt between the rotating and fixed members of the platen.

Raise the level unit by the coarse adjustment on the vertical bar, until it is high enough to accommodate the length bars. Wring the bars side by side on to the platen, symmetrically about its centre so that each ball foot will rest approximately on the centre of a bar. This setting is shown in Fig. 30. Handle the bars as little as possible and always use a chamois leather to do so. Constancy of temperature is all important because slight variations produce a considerable change in the comparatively large lengths involved. After wringing, the bars must be left as long as possible before taking readings.

Lower the level unit by the main adjustment as before and then, using the fine adjustment, lower the level on to the tops of the bars, making sure that the level casing is free but is not pressing the level down on to the bars. Allow the level to settle and take the bubble reading as before. Raise the level, rotate the platen through 180° and take a repeat reading. After taking this reading, rotate the platen to its original position and take a repeat of the first reading.

If the readings are not taken at a position of no variation, the variation must be compensated for. This is done by taking the first set of readings as just described and then taking a second set of readings after removing the gauges and interchanging their positions on the platen. A little consideration will show that any change in parallelism of the platen will be eliminated if the mean of the two values obtained from these two sets of observations is taken. Again it must be emphasised that this compensation will only apply if the platen behaves consistently, and inconsistency must be watched for.

### *Observations and Results*

Before starting the experiment, identify each gauge carefully. If desired they may be labelled in some way. For the purpose of this description we will call the gauge on the left $A$ and that on the right $B$ when the gauges are in their initial position. Record the bubble readings in the manner shown on the opposite page. The scale may have a central zero or it may have a zero at one end; in any case, it is likely that readings will increase towards the right. Great care must be taken to make quite sure of the value of each level reading. Each division may, for example, correspond to 0·00001 in. change in level between the feet, in which case the final change must be halved. In some cases, however, the scale may be calibrated directly in difference in length of gauges.

### *Conclusions*

Consider the advantages and disadvantages of this method of measurement and its suitability for various purposes. For example,



| *Platen position* | *Gauge position* | | *Level reading (div)* | *Difference (div)* | *Difference* between gauges (in.)* |
|---|---|---|---|---|---|
| | *Left* | *Right* | | | |
| *1st set* | | | | | |
| 0° | $A$ | $B$ | +1·8 | −2·2 | 0·000011 |
| 180° | $B$ | $A$ | −0·5 | $B$ high | $B>A$ |
| 0° | $A$ | $B$ | +1·6 | | |
| *2nd set* | | | | | |
| 0° | $B$ | $A$ | −1·4 | +2·7 | 0·000013 |
| 180° | $A$ | $B$ | +1·2 | $B$ high | $B>A$ |
| 0° | $B$ | $A$ | −1·6 | | |

* These values are calculated on the assumption that one division change corresponds to 0·00001 in. tilt over the distance between the ball feet. A difference between gauges of 0·000005 in. will therefore give 1 div. change on reversal.

would it be suitable for calibrating a set of slip gauges? Note the accuracy obtained if two sets of readings are taken. Consider whether this accuracy could have been improved with more care or improved conditions.

*EXPERIMENT 28*

## TO MEASURE THE INCLUDED ANGLE OF A TAPER PLUG GAUGE USING AN AUTO-COLLIMATOR

*Apparatus*

Taper Plug Gauge, preferably of small included angle and short enough to go in the centres mentioned below. The face at the small end should be flat.

Auto-Collimator of the Angle Dekkor type mounted on a stand adjustable for angle.

Bench Centres, preferably with a working surface immediately below the line of centres.

Grade A Surface Plate large enough to accommodate the Dekkor and the centres.

Set of Combination Angle Gauges or Sine Bar.

Set of Slip Gauges.

The three methods of measuring angles or tapers described in this experiment are no more accurate and often less convenient for simple work than the method described in Experiment 14, Vol. II. On the other hand, one or other of these methods will enable even the most awkwardly placed angle to be measured, such as the cones of large diameter and angle which are often found on large fixtures and components. Tapers that are obscured by shoulder flanges or spigots can also be tackled. For convenience, and so that the results from the three methods may be compared, a small angle cone gauge which will go between centres has been chosen. The end face of the gauge at the small diameter should be flat or slightly concave.

*Method 1*

Select the combination angle gauges to give the included angle of the gauge (see Exp. 32). Clean them carefully, examine them for damage and wring them together, making sure that the side faces are in one plane. Alternatively, set up a sine bar to the included angle. In this case a slip gauge (0·15 in. or 0·20 in.) will probably have to be wrung to its surface in order to give a good reflection. The Angle Dekkor stand incorporates a small surface plate and the angle





gauges or the sine bar are placed on this. Adjust the instrument for angle until a reflection of the scale is obtained in the eyepiece giving a reading about the middle of both scales (see Exp. 29). Ensure that the scale is moving in the plane of the reference angle. Note the reading.

Remove the reference angle and put the cone gauge in its place resting on the surface plate with the angle running in the same direction as the reference angle (Fig. 31). The gauge will tend to roll about, so it will have to be held in position. Don't try to hold it with lumps of Plasticine because these will inevitably get underneath the gauge and give false readings. Metal strips loosely placed on either side of the gauge are much more satisfactory. At this stage, test the balance of the gauge to see that the cone is bedding down firmly on the surface plate. If it is not, stick a strip of lead on the light end. This small precaution can save a lot of false readings. Since the functioning of the auto-collimator depends on a flat, specular (i.e. mirror) reflection of its target scale, the actual surface of the cone is useless. A mirror whose reflecting surface is parallel to its back face must therefore be laid on the cone. The best way of doing this is to stick a slip gauge (0·15 in. or 0·20 in.) on to the cone with a thin smear of Vaseline. In doing this, make sure that the slip is touching the cone roughly along the centre of the slip and not on its edges. Polish the upper surface of the slip. This serves the dual purpose of giving a good reflection and pressing the slip into intimate contact with the cone. Don't use wax, Plasticine or a lot of Vaseline; if you do you will never be sure that the slip is really in contact with the gauge.

Roll the gauge carefully under the auto-collimator whilst observing the eyepiece until the scale comes into view. Since the parallelism of the axis of the cone to the measuring plane of the auto-collimator is unknown, it is necessary to find the maximum angle of the cone. To do this, swing the axis of the cone a little at a time, keeping the reflected scale in view, until a turning point is reached. This takes a little practice because in swinging the gauge it is almost certain to roll and so lose the reflection. Note the angular reading at the turning point and repeat at three positions around the gauge. Remove the cone and take a repeat reading on the reference angle. The gauge should then be checked for straightness in the usual way by laying it on a lapped surface plate or straightedge and examining against a light box.

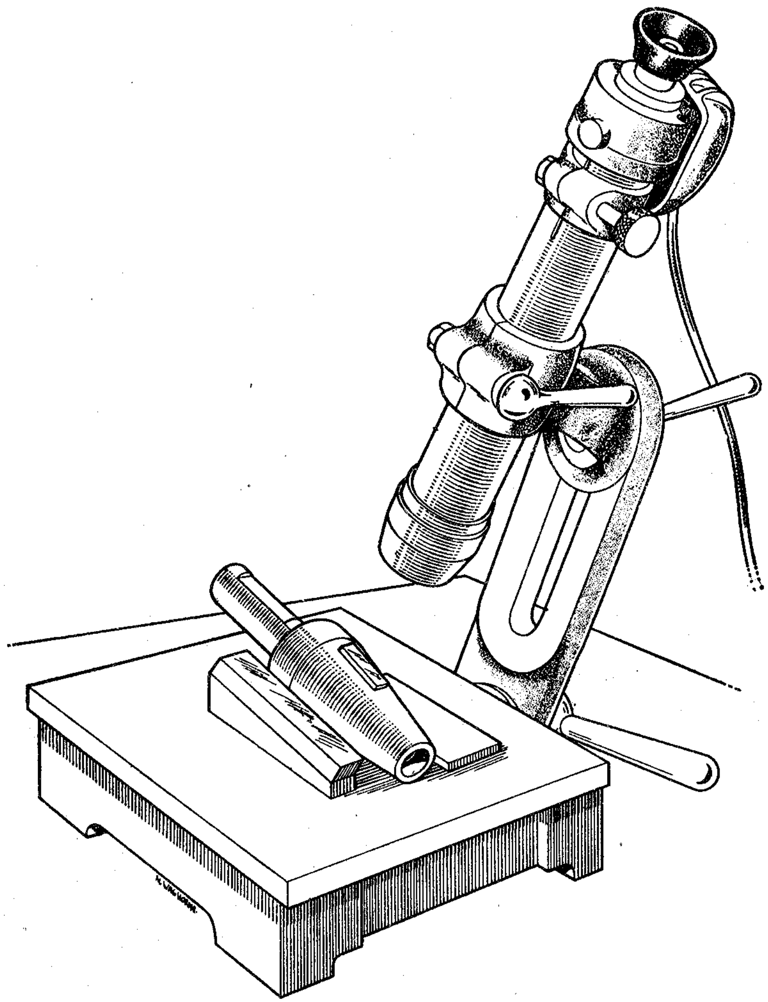


FIG. 31



*Method 2*

This method is rather complicated and can only be used when the cone to be checked can be put between centres. It has its uses, however, particularly for small, repetition work when the accuracy required for determining the angle is greater than can be obtained by projection.

Set the centres and the Dekkor stand on the surface plate with the Dekkor reversed on its arm so that it can overhang the centres (Fig. 32). Put a parallel mandrel of about the same length as the cone gauge in the centres and strap a 0·15 in. slip gauge to it with an elastic band. Adjust the Dekkor so that it is perpendicular to the working surface under the centres, or to the surface plate, by getting a reflection from a slip gauge partly wrung to the plate. Note the reading. Slide the Dekkor over the mandrel and slip and rotate the mandrel until a reflection is obtained. Record the reading. Reverse the mandrel in the centres without rotating it or altering the position of the slip and take another reading. The difference, if any, between the mean of these last two readings and the reading on the surface plate is the error in parallelism of the centres to the surface plate. Reversing the mandrel eliminates a possible error due to taper or eccentricity in the mandrel. Note carefully in which direction any error in the line of centres will affect angle readings on the gauge. This may be ascertained by slipping a piece of paper between one end of the base of the centres and the surface plate and observing how the Dekkor readings change. This test of the parallelism of the centres to the surface plate may be done quite simply by running a sensitive dial gauge over each end of the mandrel (including the mandrel reversed) and translating the linear error into angular error. Since the experiment is an exercise in the use of an auto-collimator, it is probably better to use it.

Make up a reference angle as in Method 1, but this time to the *semi-angle* of the cone, and set up on the surface plate at the side of and parallel to the mandrel in the centres. This may be done by inserting packing slips between the mandrel and the side of the combination angle gauges or the sine bar. Adjust the auto-collimator to get a reflection from the reference angle and note the reading. Remove the mandrel and substitute the cone gauge with a slip gauge strapped to the cone with an elastic band. Slide the auto-collimator over the cone without twisting the base, by sliding it against a straightedge.

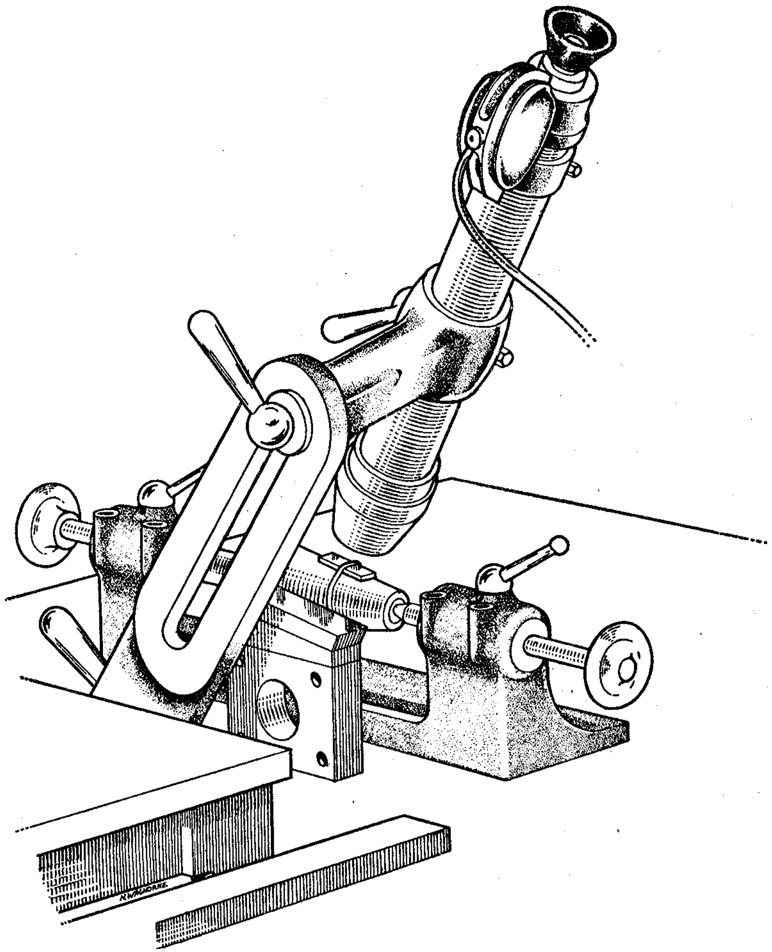


FIG. 32



Rotate the cone gauge until a reflection appears in the eyepiece and note the reading. Remove the slip and replace it at 180° round the cone, rotate the cone and take a second reading. The difference between the mean of these last two readings and the reading on the reference angle plus or minus the error in parallelism of the centres is the error of the semi-angle of the gauge.

It is very much more convenient if there is a working surface directly under the centres because the stand of the Dekkor can then remain in the same position throughout the experiment. The side of the reference angle can be pressed directly against the mandrel and the packing slips and the straightedge may be dispensed with. Unfortunately, the most popular type of bench centres is not like this, so the general case has been included in the experiment.

*Method 3*

This may be used if the base of the cone gauge (at the small diameter end) is flat or slightly concave. It is a little awkward because the auto-collimator has to point upwards at the semi-angle to the horizontal. It is wise, therefore, to set the Dekkor stand well to the edge of the surface plate so that you can still get your eye to the ocular even when it is below the level of the surface plate.

Set the reference angle on the Dekkor surface plate to the semi-angle to the perpendicular. This will mean that the combination angle gauges are wrung to the square block or that the sine bar is set against an accurate perpendicular face (Fig. 33). Adjust the Dekkor to obtain a reading on this angle and note it. Replace the reference angle by the cone gauge standing on its base with a slip gauge strapped to the cone by an elastic band. Ensure that the slip is touching the cone along the centre of the slip. Rotate the cone until a reading in the Dekkor is seen and recorded. Move the slip 180° around the cone, rotate the cone and take a second reading. The difference between the mean of these last two readings and the reading on the reference angle is the error of the semi-angle of the gauge.

*Observations and Results: Examples*

METHOD 1

Taper plug No. 123.
Nominal included angle: 10°

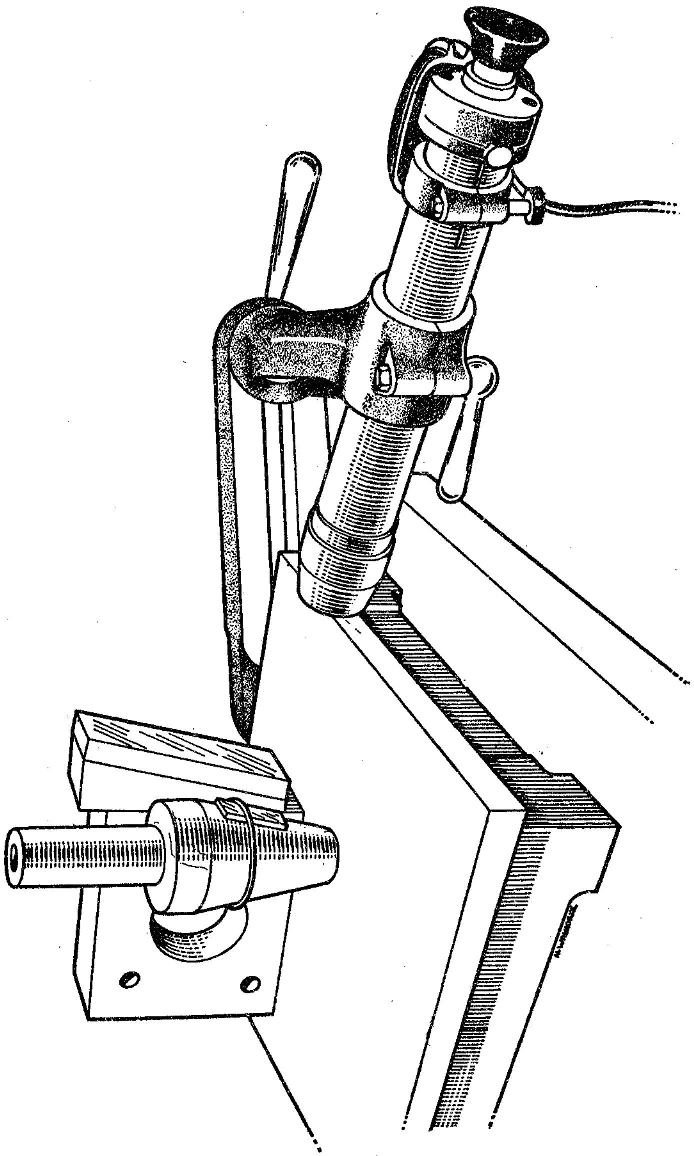


FIG. 33



Combination angle gauges: $9° + 1°$
Or slips used with 5 in. sine bar: 0·8682 in.
Reading on reference angle: 14·4′ Repeat: 14·4′ Mean: 14·4′

| *Readings on gauge (min)* | *Included-angle error (min)* | *Included angle* |
|---|---|---|
| 9·6 | −4·8 | 9° 55·2′ |
| 9·7 | −4·7 | 9° 55·3′ |
| 9·8 | −4·6 | 9° 55·4′ |

METHOD 2

Nominal included angle: 10°
Combination angle gauges
for semi-angle (5°): $9° - 3° - 1°$
Or slips used with 5 in. sine bar: 0·4358 in.
Reading on surface plate: 18·4′ Repeat: 18·4′
First reading on parallel mandrel: 18·8′
Second reading on parallel mandrel: 18·2′ } Mean: 18·5′
Error in parallelism of
centres to surface plate: 0·1′
Correction to angle readings on gauge: −0·1′
Reading on reference angle: 20·4′ Second: 20·6′
Mean: 20·5′

| *Readings on gauge (min)* | *Corrected mean reading on gauge (min)* | *Semi-angle error (min)* | *Included angle* |
|---|---|---|---|
| First 18·4<br>Second 18·0<br>Mean 18·2 | 18·1 | −2·4 | 9° 55·2′ |

METHOD 3

Nominal included angle: 10°
Combination angle gauges
for semi-angle (5°): 90° block − $(9° - 3° - 1°)$
Or slips used with 5 in.
sine bar and 90° block: 0·4358 in.

Readings on reference angle: 24·6′ Second: 24·6′ Mean: 24·6′

| *Readings on gauge (min)* | *Semi-angle error (min)* | *Included angle* |
|---|---|---|
| First 22·9<br>Second 21·5<br>Mean 22·2 | −2·4 | 9° 55·2′ |

*Conclusions*

Several sets of readings should be taken round the gauge and the cone must also be checked for straightness. The use of one of these methods will permit the measurement of angles by an auto-collimator under most conditions. They may be applied, with the exception of Method 2, not only to conical work but also to "angles in the flat". The principles outlined must be adhered to and the most important of these, apart from good common sense in the set-up, are:

1. The plane of maximum slope of the reference angle must lie in, or parallel to, the plane of the angle to be measured. (In the case of a cone, the maximum slope must lie in, or parallel to, a plane which passes through the axis of the cone.)
2. The auto-collimator scale must move in, or parallel to, that plane.
3. Accurate contact between the parallel faced mirror and the work to be measured must be maintained. An elastic band, if practicable, is best for this.
4. The mirror must be truly flat and polished.
5. Always make a test to see in which direction an angle changes for a given scale movement.
6. The datum on which the reference angle is set up must be in a known relationship to the datum to which the angle being measured is referred.

*EXPERIMENT 29*

## TO TEST A STRAIGHTEDGE USING AN AUTO-COLLIMATOR

*Apparatus*

Straightedge.

This may be a straight surface of almost any type. It may be a steel straightedge of the type specified in B.S. 863, a cast-iron straight-edge of the bridge type (B.S. 818), the bed of a lathe or other machine, or other straight surface lying in either a horizontal or vertical plane. The length to be tested should preferably be not less than 24 in., although a shorter length of a precision surface may be used if the auto-collimator is of the sensitive type. Failing an actual straightedge, just as good observations may be made along a line chosen on a surface plate.

Auto-Collimator.

There are two types of auto-collimator in general use; one of low sensitivity, with an accuracy of reading of about 0·2 min, and the other incorporating a micrometer microscope reading to a fraction of a second. The most widely-used low-sensitivity instrument is the Hilger Angle Dekkor. A micrometer eyepiece can be fitted to the Dekkor giving 0·6 sec. There are several instruments of the micrometer type, including those made by Watts, Taylor, Taylor & Hobson, and Precision Tool & Instrument Co.

This method of measurement can be learnt on either type of instrument but, if the straightedge is too accurate, little variation will be detected with a low-sensitivity type. For the purpose of an exercise, therefore, a straightedge with a reasonable amount of error should be used.

In the Angle Dekkor type of instrument, two scales, crossing at right angles, are seen in the eyepiece; one is seen directly on the graticule and the other is reflected from the plane surface being used as a reflector. Thus, angular movement of the reflector about any axis can be measured. In the micrometer type of instrument, the whole telescope can be rotated about its axis to set the micrometer to read in a horizontal, vertical or intermediate plane.

Reflector Carriage.

The carriage which is traversed along the straightedge carries an optically plane reflector to receive and reflect the beam from the auto-collimator. It should take the general form shown in Fig. 34, having two feet on its base spanning a short distance on the straightedge. These feet may be in the form of small precision strips which are wrung to the flat base of the carriage or they may be fixed at a convenient pitch, as an integral part of the base. An optically flat reflector is mounted approximately at right angles to the plane of the base. This reflector may be a separate unit of glass or metal or

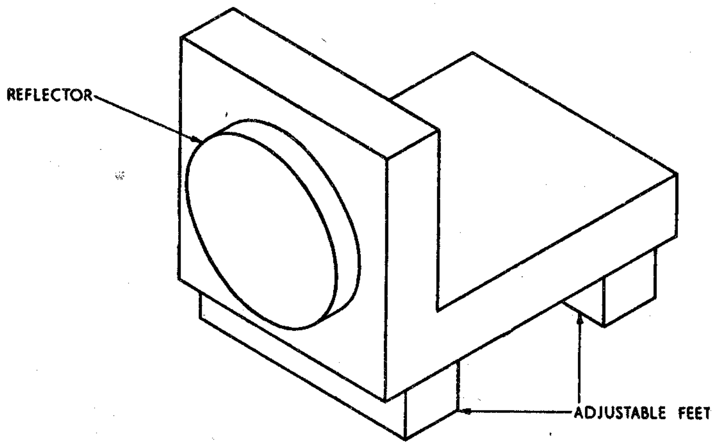



FIG. 34

may be a lapped and polished surface of the block itself. If of glass, it should be coated with reflecting material, generally aluminium or rhodium, on its front face, not on the back.

A slip gauge with a good surface makes a suitable reflector. It must not be a thin one, such as 0·05 in., since this is unlikely to be flat. Something about 0·2 in. or over is most suitable. It may be wrung on to a surface on the carriage or fixed with wax or some form of clip.

A large slip, say 2 in., 3 in. or 4 in., may be used as a complete carriage. Its long edge may be lapped flat or may be relieved to a depth of a few thousandths for most of its length, leaving feet at each end which may be lapped. Naturally such an operation would only



be done with an old gauge, and after any grinding had been done it could be lapped to optical flatness and polished on one or both of its gauging faces. The manufacturers would, no doubt, undertake this.

It is not essential for the carriage to have feet if some other form of suitable carriage or block is available. The precision cube, supplied for use with the Angle Dekkor, is quite suitable for this work, provided that the distance to be traversed is not too great.

It will be seen later that the straightedge may usually be tested lying on its side if desired. In this case, the carriage must be of such a form that it rests on the plate supporting the straightedge and makes contact with two pads on its side. Again, the cube just mentioned is well suited to this arrangement.

Support.

A rigid support is essential for this test. Ideally, the straightedge and auto-collimator should both be supported on the same rigid base, such as a large surface plate. It is not usually satisfactory to stand the auto-collimator on a wooden table, even though the straightedge rests on a surface plate on the same table. Insufficient length in the rigid support might be overcome by placing the auto-collimator at right angles to the straightedge and using an optical square to deflect the beam through a right angle. The optical square is a constant deviation prism often used with an auto-collimator.*

### *Method*

The straightedge may be tested either with its edge uppermost or lying on its side on a surface plate. If on edge, it must be properly supported. If placed straight on the surface plate, the contour of the plate can affect the contour of the straightedge. For minimum deflection, it should be supported at two symmetrical points set at five-ninths of the length of the straightedge apart. It should be most carefully noted that these points are *not*, repeat *not*, the Airy points, which are 0·577 $l$ apart; support at the Airy points brings the ends of the straightedge into a common plane and does not produce minimum deflection, the condition required in the present case. Airy points are used for line standards and end bars only.

If the straightedge is placed on its side, the effects of gravity will be absent and the true free profile of the straightedge can be measured. The whole experiment could be used, if desired, to compare the profile errors of the straightedge using various methods

* See K. J. Hume: ***Engineering Metrology***, **pp. 139 and 196 (Macdonald).**

of support; e.g. on its side, supported at its ends, at positions of minimum deflection, points near the centre, and so on.

The principle of the method is shown in Fig. 35. The carriage is set on or against the straightedge and the auto-collimator is set up in line so that its beam is reflected from the carriage. Assuming that the carriage has two feet, set a certain distance apart as already described, it is first placed at one end of the straightedge and a reading taken on the auto-collimator (in the direction normal to the edge surface of the straightedge).

FIG. 35

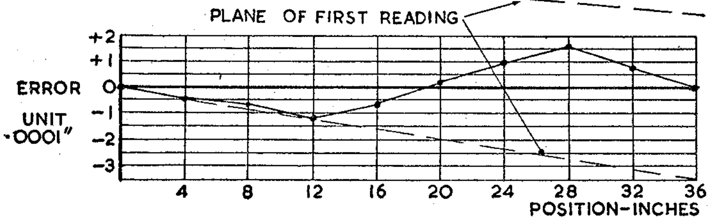



FIG. 36

This first reading represents the angular direction of the first span of the carriage. If the edge were perfectly straight, the same reading would be obtained wherever the carriage was placed along the straightedge. Any errors from true straightness will be shown as angular variations at various positions.

So that these angular variations may be linked up to give a continuous profile curve, the carriage must be moved in steps equal to the pitch between its feet. If a block without feet, such as the cube, is used, the steps must be equal to its length.

If the carriage is on the top of the straightedge, some means must be found of keeping it aligned laterally as it is moved along, so that the reflected beam does not wander horizontally. Two small pegs in the base of the carriage, arranged to run along the side of the straightedge, will serve or some form of fence may be set up against which the side of the carriage slides.

Mark off the straightedge, with a pencil or in some other suitable manner, to show the consecutive positions of the carriage along its length. As mentioned, these marks should be pitched at the separation of the centres of the feet on the carriage or the overall length of a cube or solid block without feet.



Place the carriage in the end position, nearest the auto-collimator. Set up the auto-collimator in line with the straightedge and at such a height or position that its axis is approximately in line with the centre of the reflector. If the instrument is of the micrometer type, see that it is set so that the micrometer reads in a plane at right angles to the surface being measured, i.e. micrometer will be vertical if the surface is horizontal.

The auto-collimator must now be adjusted in position to receive the reflected rays. This may present a little difficulty. In the Angle Dekkor type of instrument, the easiest way is to remove the eyepiece, taking care not to touch the graticule or eyepiece lenses. The instrument may now be manoeuvred until the reflection is seen. This will appear as a flash of light and can be seen over a much wider angular area than the proper image with the eyepiece in place. Get the light roughly central and replace the eyepiece. The image will then not be far away and can easily be centred.

It is not possible to do this with an auto-collimator which incorporates a microscope; the best way is to move the reflector around until the reflected image is seen and judge how much the auto-collimator has to be moved to see the image when the carriage is in its normal position. Having found the image it should be approximately centred in the eyepiece field and a reading taken, either on the graticule or micrometer.

Move the carriage to each of its subsequent positions, taking a reading at each. Repeat each reading as the carriage is moved back along the straightedge. Readings on the Angle Dekkor type of instrument may be estimated to an accuracy of about $\frac{1}{5}$ min and on the micrometer type to about $\frac{1}{2}$ sec. The relative accuracies of the two instruments will therefore be obvious.

Readings on a low-sensitivity instrument are fairly straightforward; the index is simply where one scale crosses the other and it does not matter much whether readings have to be taken on the fixed or the moving scale. The micrometer drum on a sensitive instrument must always be brought up in a clockwise direction when taking a reading and the graticule lines set to straddle symmetrically the image of the target wire. This symmetrical setting may require some practice and it may at first be thought to be an inaccurate method compared with a line-to-line setting. It is, in fact, the most accurate method of visual setting on a line; the eye is far more sensitive to errors of symmetry than it is to a coincidence of two lines. In the Watts instrument make sure that the *reflected image* of the target wires is being used; the wires are also directly visible in the eyepiece but this image does not, of course, move and is only there because it has to be in a central position to provide a long-distance range for the auto-collimator.

It is important to check the direction of reading relative to the direction of tilt of the carriage. This can be done by tilting the carriage slightly by raising one end and noting whether the reading increases or decreases. This direction must be remembered when working up results.

*Observations and Results*

The method of tabulating and calculating results is shown by the example given in the table. It will be noted that a space has been left above the first figures in Columns 1 to 6. This is because each reading represents a *slope* between *two* points, e.g. 0 and 4 in., 4 and 8 in., etc., whereas the final result has to relate the error of each *point* to the first one. The conversion of values in Column 5 to slope differences in Column 6 is done by multiplying each value by the linear value of one second over the span of the feet (or length) of the carriage, 0·00002 in. in this case (0·000005 radian × 4 in.).

The figures in Column 6 are made cumulative in Column 7, after adding another zero at the beginning, as just mentioned. The first two zeros therefore represent the datum line, drawn between the first and second points, from which the errors of the following points are determined. This is shown as a dotted line in Fig. 36. This datum line happens to give a final error of + 3·6 and does not, of course, necessarily represent the best datum.

The most convenient datum, although not necessarily the best, will be the line joining the end points. To refer the errors to this line, the curve must be swung about its zero point until the last point lies on the axis. It will be appreciated that the profile of the curve is not altered in any way by this operation.

Column 8 represents the true straight line between the first and last points and is obtained by taking the final value in Column 7 and dividing it into parts proportional to distances along the straightedge. Differences between Columns 7 and 8 give the final contour errors. Draw a graph of these errors to a suitable scale.



*Conclusions*

Compare the errors found with the relevant British Standard, if a straightedge or surface plate has been used. If a straightedge has been used and tested under different conditions of support, superimpose the various curves to emphasise the variations in profile. A useful reference to this is given in *Gauges and Fine Measurements*, Vol. II, Appendix III, by F. H. Rolt (Macmillan).

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|
| *Position (in.)* | *Auto-collimator reading (sec)* | | | *Difference from first reading (sec)* | *Slope differences in 4 in.** | *Cumulative values* | *True straight line* | *Contour error: Col. 7 minus Col. 8* |
| | *Reading* | *Repeat* | *Mean* | | (*Unit* 0·0001 *in.*) | (*Unit* 0·0001 *in.*) | (*Unit* 0·0001 *in.*) | (*Unit* 0·0001 *in.*) |
| — | — | — | — | — | — | 0 | 0 | 0 |
| 0–4 | 12 | 12·5 | 12 | 0 | 0 | 0 | +0·4 | −0·4 |
| 4–8 | 14 | 13 | 13·5 | +1·5 | +0·3 | +0·3 | +0·8 | −0·5 |
| 8–12 | 11 | 11 | 11 | −1 | −0·2 | +0·1 | +1·2 | −1·1 |
| 12–16 | 16·5 | 17 | 16·5 | +4·5 | +0·9 | +1·0 | +1·6 | −0·6 |
| 16–20 | 16 | 16 | 16 | +4 | +0·8 | +1·8 | +2·0 | −0·2 |
| 20–24 | 20 | 20·5 | 20 | +8 | +1·6 | +3·4 | +2·4 | +1·0 |
| 24–28 | 18 | 17 | 17·5 | +5·5 | +1·1 | +4·5 | +2·8 | +1·7 |
| 28–32 | 10 | 9·5 | 9·5 | −2·5 | −0·5 | +4·0 | +3·2 | +0·8 |
| 32–36 | 10 | 10 | 10 | −2 | −0·4 | +3·6 | +3·6 | (0) |

* 1 sec = 0·000005 in. in 1 in.
= 0·00002 in. in 4 in.

## *EXPERIMENT 30*

# TO CALIBRATE A DIAL GAUGE

### *Apparatus*

Dial Gauge.

This should be a normal type of dial gauge with each main division representing 0·001 in., possibly showing half-divisions. The travel of the plunger is usually about 0·5 in. Other types, e.g. where each division represents 0·0001 in. or 0·01 mm, may be used, but for these different tolerances will apply (see B.S. 907).

Micrometer Head or Slip Gauges.

Surface Plate.

Suitable Mounting Equipment.

Mounting equipment for the dial gauge and the micrometer head can vary considerably. The essential requirement is that it should be quite rigid. The gauge should preferably be supported by the back lug and not by the stem. If it is necessary to support by the stem, it should be fitted into a split bush of substantial diameter in order to avoid any distortion when clamped. The micrometer head may be mounted in a special block or holder or clamped carefully in a small vee block. The gauge and micrometer head are mounted horizontally, opposite each other on the surface plate so that their axes are approximately coincident (see notes under *Method*). It may be found convenient to mount the gauge in the tailstock of a bench micrometer or screw diameter machine. If properly bushed, the gauge will be aligned without further trouble. It must be seen, however, that the micrometer can be adjusted to cover the range of plunger movement.

If a micrometer head is not available, the dial gauge should be mounted vertically above the surface plate or other suitable plane surface so that slip gauges may be placed under the plunger. A comparator stand could well serve for this but, whatever is used, it must be rigid. Many indicator stands and most surface gauges are not!

*Method*

The first thing to do is to ensure that the axis of the dial gauge is aligned to the line of measurement, whichever method of calibration is used. An angle of a little over 1° between the two axes will produce a cosine error of 0·00001 in. over 0·5 in. Visual alignment is therefore not good enough, since the inclination should not exceed 0·01 in. over 0·5 in. Sighting against a straightedge would, however, be adequate. A slip gauge can be held against the side of the dial gauge stem so that it projects alongside the micrometer spindle or both stem and spindle could be "clocked" in both horizontal and vertical planes relative to the surface plate and to a straightedge placed on it. The contact point may be centralised by eye on the micrometer anvil.

If the gauge is set up vertically for calibration with slip gauges, it must be perpendicular to the gauging surface, to the same accuracy. A small block which is reasonably square, e.g. a large slip gauge, will do to check against the side of the stem, again checking in two planes at right angles.

The method of calibration will now be considered under two headings, (a) using a micrometer head, and (b) using slip gauges.

(a) Having set up as already described, see that the range of the micrometer head covers the range of the dial gauge. This is an elementary precaution but it is annoying to find that one is running out of micrometer thread before the end of the range of the gauge. Remember, too, that the micrometer will normally read backwards, decreasing its readings for increasing gauge readings.

Readings on the dial gauge should start somewhere near the 12 o'clock position, the position of the pointer when the plunger is free being between 9 and 11 o'clock. (see B.S. 907).

If possible, adjust the settings so that the micrometer head reads on a 0·1 in. division for the dial gauge zero. Run the micrometer back and forwards several times to check repetition, remembering always to take readings in the forward direction to eliminate backlash.

Take a reading every ten main divisions of the gauge, i.e. at 0·01 in. intervals on a "thousandth" type. Having covered the range, repeat readings may be taken by running back, taking each reading in the backward direction. The success of this depends on the quality and adjustment of the micrometer head. If inconsistent results are found, it may be the fault of the micrometer, of the dial gauge or of both. If the micrometer is in doubt, take these readings also in the forward direction. The lifting lever, when fitted, should not be used for the first calibration but, if time allows, a separate calibration, using the lever at each setting, will provide an interesting comparison.



Read the error on the dial gauge at all settings, a clockwise error always being positive, anti-clockwise negative. Take no notice of plus and minus graduations on gauges working from a central zero. Set the micrometer line-to-line, using a lens for greater accuracy. Record gauge errors to 0·1 division (0·0001 in.).

(b) When checking with slip gauges, the dial gauge should be mounted vertically, as previously described, above a surface plate or gauging surface. Zero setting should be made on a slip gauge placed on the surface, not on the surface itself. A 0·3 in. slip gauge with a 0·1 in. slip wrung on to it will be found convenient. The 0·5 in. range will then be covered in 0·01 in. steps by the slips between 0·3 and 0·8, together with 0·100, 0·110, 0·120, 0·130, 0·140.

The lifting lever will have to be used to insert the slips. If no lever is fitted, the top of the rack plunger must be carefully raised. With this method there is risk of error due to expansion of the slips as they are handled. They should therefore be handled only with a chamois leather or soft cloth and plenty of time should be allowed between each reading for the temperature to settle. It may be possible to wring together several piles of slips in advance, to cover part of the range. For example, the first 0·1 in. could be covered by:

| | |
|---|---|
| 0·300 | 0·350 |
| 0·200 + 0·110 | 0·150 + 0·104 + 0·106 |
| 0·100 + 0·109 + 0·111 | 0·149 + 0·113 + 0·108 |
| 0·101 + 0·114 + 0·115 | 0·148 + 0·125 + 0·107 |
| 0·102 + 0·122 + 0·116 | 0·147 + 0·126 + 0·117 |
| | 0·400 |

These could be left to cool after wringing and be ready to slip under the gauge with a minimum of handling. The next and subsequent 0·1 in. ranges could be covered by similar combinations, although it becomes more difficult to build up larger piles.

*Other Tests*

Calibration is only part of the full test for a dial gauge. Fuller details are given in B.S. 907, and these include requirements for dials, graduations, etc.

Two useful additional tests which concern performance and can be done quite quickly are the tests for repeatability and sensitiveness.

Repeatability is checked by setting up the gauge vertically above a flat surface and passing a cylinder, such as a roller gauge, under the contact point from various directions and at various speeds. This should be done at several positions along the range of the dial gauge. The contact point can also be allowed to rest on a slip gauge and be raised and lowered with varying speeds, using the lifting lever, when fitted.

The other test concerns the ability of the dial gauge to respond to small gradual variations. This sensitiveness is most important since the gauge is often used to check a run or alignment involving only small variations. One method of testing this is to use a mandrel which is eccentric by about 0·001 in. (for testing a 0·001 in. gauge). The exact value of the eccentricity or total throw must be determined beforehand, using a precision comparator, measuring machine or large-drum micrometer.

The mandrel is set up in centres and the dial gauge set against it to read at several positions within its range, in succession. The mandrel is rotated slowly and the exact range of indication is carefully noted. It is most important to mount the gauge *rigidly* for this test. It is surprising to what extent a normal support rod with only a few inches of overhang will deflect before the gauge registers.

Another method of performing this test is to slide an angle gauge under the dial gauge. This is best done on a good scraped or spot-ground surface; a lapped surface will wring to the angle gauge. The one-minute gauge rises 0·001 in. in 3·45 in.

*Warning.* Never oil the plunger of a dial gauge. If it sticks in the stem, oiling is very likely the cause. Stickiness can sometimes be eased by operating the plunger quickly but often can only be remedied by dismantling and cleaning; a job for a skilled instrument mechanic, *not* for the student.

### *Observations and Results*

Record the errors in a table setting out turns in vertical columns and divisions horizontally, as indicated on the opposite page. If two sets of readings are taken, the final figure should be the mean in each case. The unit of error is 0·0001 in.



| | *Divisions of dial* | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 |
| Turn I | 0 | −2 | −3 | −1 | +1 | +5 | +6 | +4 | +3 | +1 |
| Turn II | −1 | 0 | +1 | et | c., e | tc. | | | | |
| Turn III | | | | | | | | | | |
| Turn IV | | | | | | | | | | |
| Turn V | | | | | | | | | | |

Plot the errors continuously on a graph. This will show clearly if there is a periodic error. The first turn in the table above shows a periodic error of 0·0009 in.

Compare the results with the tolerances given in B.S. 907, which for 0·001 in. dials are:

| | |
|---|---|
| Any 0·01 in. . . . . | 0·00025 in. |
| Any whole or half revolution . | 0·0005 in. |
| Any two revolutions . . . | 0·00075 in. |
| Any larger interval . . . | 0·001 in. |

It will be seen that the first turn in the example recorded above exceeds the tolerances for 0·01 in., half revolution and whole revolution.

If the repeatability and sensitiveness tests have been carried out, compare with the tolerances, which are, for 0·001 in. gauges:

| | | |
|---|---|---|
| Repeatability | . . . . . . | 0·0002 in. |
| Sensitiveness | Gradual change of about 0·001 in. accurate to . | 0·0003 in. |

### *Conclusions*

The main conclusions to be drawn from this experiment are whether or not the dial gauge complies with B.S. 907 in the elements checked. Opportunity should be taken to read through the specification and realise that the dial gauge deserves more respect than it usually gets. If the gauge under test has been in use for some time it is unlikely to meet the specification completely. In this case, see which parts of its range can be used with least error and note what this error may be. Note also the errors likely to be introduced if the gauge were used directly to measure distance, e.g. 0·5 in. without reference to other standards, such as slip gauges.

## *EXPERIMENT 31*

# TO MEASURE AN ANGULAR PLATE GAUGE USING AN OPTICAL DIVIDING HEAD

### *Apparatus*

Angular Plate Gauge. This may be almost any form of plate gauge used to check an angle of a component. Most often this takes the form of a gap gauge with angular sides of the type illustrated in Fig. 37. A gauge where the angle is external is just as convenient for the purpose of this experiment.

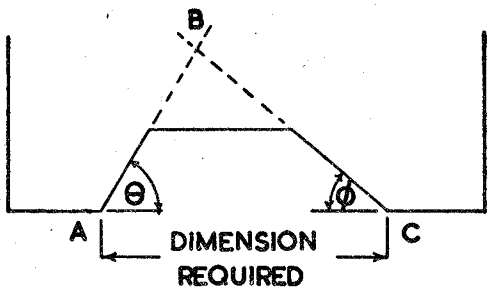



FIG. 37

Dividing Head Mounted on Surface Plate of Suitable Size. The dividing head should preferably be one of the optical type, since the worm and index plate type is generally unsuitable for this purpose. It should be fitted with a faceplate.

A Test Indicator, preferably of the lever type. An ordinary dial indicator may be used, but it will probably be necessary to tilt it from the vertical position. In any case, the indicator must be mounted on a rigid stand which can be moved about on the surface plate.

A Set of Slip Gauges.

### *Method*

It will be assumed for the purpose of describing this experiment that the plate gauge is an angular gap gauge of the form shown in





Fig. 37. The angles $\theta$ and $\phi$ may or may not be equal, but it will be assumed that, for the purpose of checking the gauge, both angles and the dimension $AC$ have to be measured. If a gauge of this form is not available, it may be possible to measure angles only on some other form of plate.

In some gauges of the type illustrated the specified linear dimension may not be $AC$ but the shorter distance defined by the intersection of the angular faces with the upper face parallel with $AC$. The principle of the calculation is, however, exactly the same.

Before starting the experiment, make sure which dimension should be measured. This should be determined either from the drawing or by careful examination of the gauge. Sometimes the finish on the faces (or lack of it) will be a good guide.

The principle of operation is to mount the gauge on the faceplate of the dividing head and rotate the head until each measuring face of the gauge in turn is parallel to the surface plate. The height of the face from the plate is measured.

In theory the gauge can be mounted in almost any position on the faceplate, but if it is too one-sided, considerable difficulty will be experienced in setting each side horizontal and in obtaining an accurate measurement of its height. The best position for the centre of rotation is $D$ (Fig. 38), the intersection of the perpendiculars from sides $AB$ and $CB$ at $A$ and $C$ respectively. The gauge is set up on the dividing head so that point $D$ is as close as possible to the centre of rotation, preferably within 0·02 in.

Having set the gauge as closely as is reasonably possible with its centre in the ideal position, rotate the dividing head until each face in turn is parallel to the surface plate as determined by the test indicator. An effort should be made to get this accurate to 0·0002 in. Measure the height of the face from the surface plate by comparison with a pile of slip gauges, adjusting the value of this pile to within about 0·0001 in. of the actual value. To obtain the greatest accuracy, set each side both above and below the axis of the dividing head. The mean of each pair of values above and below centre will give a value representing the height of the centre of rotation. The accuracy of the experiment may be gauged from the consistency of this value for the various faces.

When the side being measured faces upwards, direct comparison with the slip gauge pile can be made. When it faces downwards, the bias of the test indicator must be altered and an overhanging slip wrung on to the appropriate pile.

Note the angular position of the dividing head when each side is set parallel to the surface plate. Two positions 180° apart should be obtained for each face and this again provides a check on the accuracy of measurement. The actual values of the angles required can be deduced from the readings. No specific formulae need be given since the arithmetic required will usually be obvious but the greatest care must be taken with angles very close to 90° or 180° where the *direction* of an error or small difference may be easily mistaken. The same care must be taken where equal or nearly equal angles are involved.

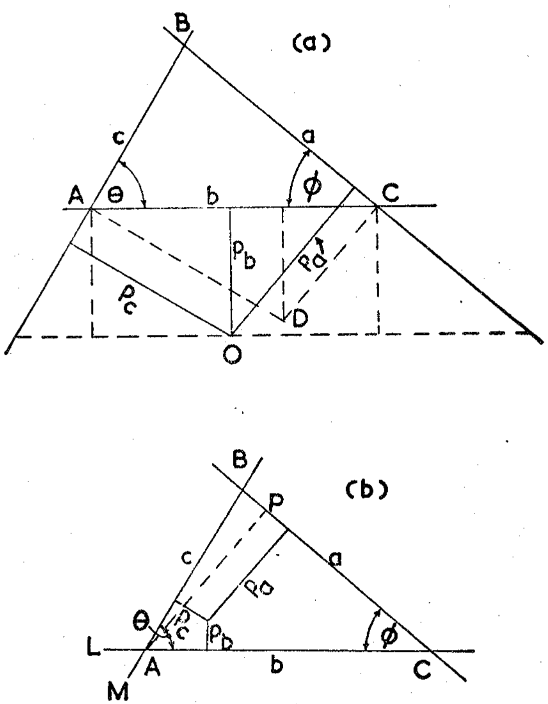



FIG. 38



*Observations and Results*

Referring to Fig. 38*a* the actual centre will be at a position 0 relative to the ideal centre $D$, the perpendiculars are $p_a$, $p_b$, $p_c$ and the angles $\theta$ and $\phi$. The value of $AC$ is given by:

$$p_c \operatorname{cosec} \theta + p_a \operatorname{cosec} \phi - p_b (\cot \theta + \cot \phi)$$

The construction lines have been left in the diagram to indicate the method of arriving at the formula.

Certain types of gauge may require the determination of a perpendicular from one apex to the opposite side, as shown in Fig. 38*b*. To measure the perpendicular $AP$, the best position for the centre of rotation is at the apex $A$, and once again the actual centre is set as close as possible to this. This position will be either within the triangle or in one of the three exterior angles. In any case, the perpendiculars and angles are measured as before, and the values of $p_b$ and $p_c$ are taken as positive if they lie on one side of the lines $AB$ and $AC$, and negative if they lie on the other side. With this convention applied, the value of the perpendicular $AP$ for the position of $O$ shown in the diagram is given by:

$$p_a + p_b (\cos \phi + \cot \theta \sin \phi) + p_c \operatorname{cosec} \theta \sin \phi$$

The actual position of the centre $O$ can be determined by rotating the gauge and determining the height of each side relative to the centre. If a diagram is then drawn showing the centre in its actual position, the appropriate signs to be given to $p_b$ and $p_c$ will be apparent. The following table shows the signs for the four positions of the centre.

| | | |
|---|---|---|
| Centre in angle $BAC$ | $p_b$ positive | $p_c$ positive |
| Centre in angle $LAB$ | $p_b$ positive | $p_c$ negative |
| Centre in angle $LAM$ | $p_b$ negative | $p_c$ negative |
| Centre in angle $MAC$ | $p_b$ negative | $p_c$ positive |

*Conclusions*

This method of measurement is rather elaborate and is seldom used, since more direct methods with slips and rollers will often suffice. It is, however, useful where several gauges of the same type have to be measured and was used quite extensively by the N.P.L..

during the 1939–45 war.* Similar methods were also used for gauges with bores, pins and plugs at compound angles.

It is included here as an example of derived measurement involving some unusual trigonometry. The student should prove the formulae used; the value of the exercise will outweigh the mental strain of the work.

It also provides a number of cross-checks which are useful in assessing the student's practical ability. The student should carefully complete all his observations before cross-checking, and include in his report an analysis of the accuracy of determination,

*See Barnard, C.P.: *Notes on Circular Dividing Apparatus* (H.M.S.O.).

***EXPERIMENT 32***

## TO CALIBRATE A DIVIDING HEAD OR TABLE USING ANGLE GAUGES AND AN AUTO-COLLIMATOR

### *Apparatus*

Dividing Head or Table.

The dividing head or dividing table used in this experiment may be of almost any type since any instrument intended for accurate angular division should be capable of calibration. As an exercise, the experiment may be most useful to calibrate an ordinary dividing head of the worm and wormwheel type. It applies equally, however, to an optical dividing head or table. In the following descriptions the title "Dividing Head" will be used but this will always be taken to include a dividing head or table of either the optical or mechanical type.

The dividing head and the auto-collimator must be set up in some suitable manner on a rigid support, preferably a Grade A surface plate or table. The test can be carried out with the axis of the dividing head in either a horizontal or vertical plane. If a dividing head which has had considerable service in the workshop is used for the experiment it should be checked to see that it functions reasonably well with a minimum of backlash or other fault. In particular, the condition of the faceplate used with it and of taper shanks and other fittings must be good; if necessary the faceplate should be ground to run true before the experiment is carried out. The reason for this is not only to ensure accuracy in the experiment but to safeguard the condition of the angle gauges which will be used.

Angle Gauges.

The angle gauges described here are those invented by Dr. Tomlinson of the N.P.L. and manufactured by Coventry Gauge and Tool Co. Ltd. There are other types of angle gauges on the market and it is quite likely that these could be used just as effectively. The angle gauges described are made of hardened steel and are just over 3 in. long and about $\frac{5}{8}$ in. wide; there are twelve gauges and one square block to the set. The whole secret of the system is the mathematical series adopted for the values of the angles. The twelve angles included in the set are 1°, 3°, 9°, 27° and 41°; 1 min, 3 min, 9 min and 27 min; and 0·1 min, 0·3 min and 0·5 min. In conjunction with the square block it is possible to build up any angle to the nearest 0·05 min, i.e. 3 sec. This is possible with such a small number of gauges because angles can be subtracted as well as added. Angles are made up by wringing chosen gauges together; subtraction of an angle can be carried out by wringing a gauge round the other way—for example, an angle of 5 (either degrees, minutes or seconds) is made up of combination 9 – 3 – 1. The student should be particularly careful when handling these gauges to see that none of the faces becomes damaged; it must be realised that they are considerably heavier than slip gauges and therefore any knock on the edge is much more likely to produce a burr. It is strongly recommended that, if a gauge is accidentally damaged, no attempt is made to stone it or rectify it in any way but that, in the college laboratory particularly, such damage should be reported to the person in charge. For this experiment only the 27° and 3° gauges, together with the square block, are used.

Auto-Collimator.

Either the high-sensitivity or low-sensitivity type of auto-collimator may be used for this experiment. Some notes on both types are given in Experiment 29 (p. 141). If the low-sensitivity type is used, it must be realised that only a limited accuracy will be obtained. If the dividing head is of the ordinary workshop type the low-sensitivity instrument will be quite suitable. On the other hand, if an optical dividing head is being tested it is desirable to have an auto-collimator which incorporates a micrometer microscope and is capable of reading to an accuracy of about 0·5 sec.

*Method*

Set up the dividing head or table on a surface plate, having decided whether to work with its axis vertical or horizontal. Clamp the square block on to the faceplate of the dividing head, having previously made sure that the plate is clean and free from burrs; the face of the plate should also run true within, say, 0·001 in. The square block must be clamped through its centre hole or one of the other attachment holes. It cannot be clamped from outside its faces as each face in turn will be needed for the wringing on of angle gauges. The square block should be reasonably centred on the faceplate; precise centring is not necessary and any attempt to do this is a complete waste of time. Centring within, say, ⅛ in. is quite good enough.



Having set the dividing head to its zero or starting position, set up the auto-collimator in the desired position. For the Angle Dekkor type the most convenient position may be at an angle, so that it is not necessary to stoop or sit down to read the instrument. With the high-sensitivity type, however, it is usually only possible to stand it on its base—that is, with its axis horizontal. The position should be arranged so that the axis of the auto-collimator passes approximately through the axis of the dividing head, in line also, of course, with the gauging surface of the square block.

It will now be necessary to adjust the rotation of the square block on the faceplate so that a reflected image is obtained in the auto-collimator. This may necessitate rotating the whole faceplate on its taper spindle or, in some cases, it may be necessary to rotate the square block on the faceplate itself. If it is not possible, or very inconvenient, to adjust the position of the square block, it would not seriously affect the experiment if the starting point were not the zero reading of the dividing head. The micrometer or scale of the auto-collimator must be set to read in the plane of rotation. When the set-up is complete, rotate the dividing head and make an auto-collimator setting on each face of the square block in turn. The purpose of this is to check whether the gauging surfaces of the block are transversely parallel with the axis. In other words, if the dividing head axis is horizontal, the reflected image on each of the faces must not vary by more than a few minutes from side to side; if it does vary to any extent, the square block is not truly seated relative to the axis. Such an error in setting can lead to quite considerable secondary errors in angular reading.

Having checked that the set-up is correct, the calibration of the dividing head may now be started. Set the dividing head to its zero or starting position and take the first reading in the auto-collimator. If the dividing head is of the worm and wormwheel type, make sure that it is always brought up to a setting in the same direction on every occasion. Make one or two preliminary settings and take readings to see that a reasonable accuracy of repetition is being obtained.

The method of using the angle gauges to give readings at 30° intervals is shown diagrammatically in Fig. 39. To make the 30° angle wring together the 27° and 3° angle gauges. These need not

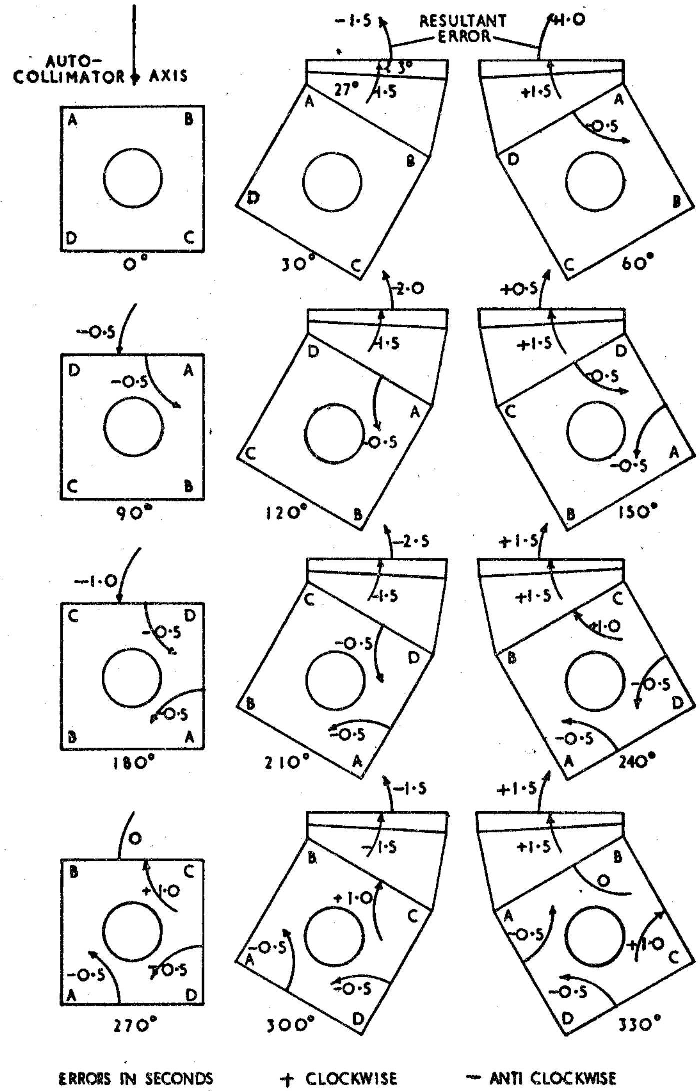



FIG. 39



be separated throughout the experiment. Assuming that the first reading has been taken on face $AB$, the 30° position will be calibrated by wringing the gauges to face $AB$ and taking another reading in the auto-collimator, having first set the dividing head accurately to 30° from zero. For the 60° position the angle gauges have to be wrung to the face adjacent to $AB$, as shown in the third position in the diagram. The 90° position is, of course, taken directly on the adjacent face ($AD$ in the diagram) of the square block and subsequent positions at 30° follow this sequence.

A certain amount of force is necessary to wring the angle gauges on and particular care must be taken not to damage the gauges, not to upset or move the square block or the dividing head itself, and not to heat the gauges unduly by handling. As far as possible the gauges should be handled only through a chamois leather or soft duster. Make sure that, when the gauges are wrung on, their side faces are in one plane with the side face of the square block; an angular error will be introduced if the gauges are skew to any great extent. Do not attempt to slide the gauges on to the face of the square block working from one end to the other. Make sure that all the faces are clean and wiped carefully with a chamois leather and place the angle gauges on the face of the block so that almost all the length of the faces is in contact. The sliding and wringing motion will therefore only have to take place over a short distance but it is important to make sure that the gauges are firmly wrung together and not just adhering rather loosely.

Having completed 360° and taken a repeat reading on zero, a second series of readings should be taken, travelling in the reverse direction if desired. If the worm and wormwheel type of dividing head is being tested, remember to come up to each setting in the new direction of rotation if this has been altered. If time allows, readings may be taken at 90° intervals on the square block alone. These readings will serve as useful checks on the first set of results since it will not be necessary to touch the square block during this calibration. They will provide landmarks for the 30° interval calibration.

### *Observations and Results*

The method of tabulating and calculating results is shown in the table. It is assumed that a sensitive auto-collimator is used and that readings are taken to the nearest 0·5 sec.

| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|
| *Setting (deg.)* | *Auto-collimator reading (sec)* | | | *Difference (sec)* | **Error of angle gauges (sec)* | *Calibration error (sec)* |
| | *Reading* | *Repeat* | *Mean* | | | |
| 0 | 16·0 | 16·5 | 16·5 | 0 | 0 | 0 |
| 30 | 21·0 | 21·0 | 21·0 | +4·5 | −1·5 | + 6·0 |
| 60 | 25·0 | 23·5 | 24·0 | +7·5 | +1·0 | + 6·5 |
| 90 | 21·0 | 22·0 | 21·5 | +5·0 | −0·5 | + 5·5 |
| 120 | 21·5 | 21·5 | 21·5 | +5·0 | −2·0 | + 7·0 |
| 150 | 14·5 | 15·5 | 15·0 | −1·5 | +0·5 | − 2·0 |
| 180 | 15·5 | 16·0 | 15·5 | −1·0 | −1·0 | 0·0 |
| 210 | 12·0 | 11·0 | 11·5 | −5·0 | −2·5 | − 2·5 |
| 240 | 8·5 | 8·0 | 8·0 | −8·5 | +1·5 | −10·0 |
| 270 | 11·5 | 10·0 | 10·5 | −6·0 | 0 | − 6·0 |
| 300 | 11·0 | 11·0 | 11·0 | −5·5 | −1·5 | − 4·0 |
| 330 | 12·5 | 13·0 | 12·5 | −4·0 | +1·5 | − 5·5 |
| 360 | 16·5 | 17·0 | (16·5) | (0) | (0) | (0) |

The mean values at 0° and 360° are the same mean of the four readings.

* The following errors in the square and angle gauges have been assumed: Square: angle *A*, − 0·5 sec; *B*, 0; *C*, + 1·0 sec; *D*, − 0·5 sec.
3° gauge, +1 sec; 27° gauge + 0·5 sec.

Notes: 1. Differences in Col. 5 are + if the gauge face lies at a *clockwise* angle to the plane of the initial reading.
2. Resultant errors in Col. 6 are + if the gauge face lies at a clockwise angle to its nominal position. Errors in Col. 6 are algebraically subtracted from values in Col. 5.

The mean value for 0° and 360° in Col. 4 is the mean of all four values in Cols. 2 and 3.

The direction of auto-collimator reading must be carefully noted. It is most convenient if an *increase* in reading corresponds to an increased angular setting of the dividing head. This condition is assumed in the table. If the instrument reads in the opposite direction—and it is not always possible to prevent this, due to physical set-up conditions—the arithmetic in the table must be adjusted accordingly.

Errors in the angle gauges must be allowed for; the tabulated values should be available with the set. A great deal of care is needed to make sure that the errors are applied in the correct sense for each setting. Since the gauges are used both to increase and decrease angles of the square, the sign of the applied correction will vary.



For example, the 30° angle is a straightforward addition to the initial setting face *AB* and the errors of the 3° and 27° will give the error of the first 30° angle. If the nominal 30° rotation of the dividing head is correct, the gauge errors in the example would give a low reading (−1·5 sec) *and this must be subtracted algebraically from Column* 5, i.e. correction is +1·5.

The 60° angle is quite different. The angle between face *AB* and the upper gauge face is the external right angle formed by *AB* and *DA* produced, minus the 30° gauge combination. The error of *A* must therefore be added to the errors of the angle gauges. In the example the error for 60° will therefore be −0·5 + 1·5 = +1·0 sec.

In the 90° position, face *AD* will not have reached the datum angle after a rotation through exactly 90° if angle *A* is small, as in the example, and the error is *minus* 0·5 sec. Similarly, the error of face *DC* will be −0·5 − 0·5 = −1·0 sec.

Before applying his own corrections, the student is advised to reconcile all the values given in Column 6 of the example with the assumed errors of the square and angle gauges. He should then be able to see quite clearly how to compute his own values. A rough sketch of each configuration is helpful, particularly if the various errors are grossly exaggerated so that the effects are visible.

Plot the final calibration errors and, if they have any appearance of a sine curve (in any phase) try to fit a suitable sine curve to them, using the table in the Appendix. This table is drawn up for a double amplitude of unity but, once the correct phase appears to have been established, a suitable multiplier can be used to match the values obtained.

*Conclusions*

The agreement obtained between the two sets of observations will be an indication of the accuracy of this type of observation. If 90° landmarks are also determined, there should be reasonable agreement between these and the 30° interval calibration. The continued handling of the angle gauges is, however, bound to have an effect on accuracy. The square alone should therefore give the higher accuracy.

This experiment is particularly valuable as an exercise in the logical application of errors in equipment used, since there is not a straightforward formula for their application and the correction at each position has to be reasoned out carefully. It will be found worth while to recalculate these corrections after an interval of a few days or, better still, for two people to work them out independently. The subsequent arguments can be quite an exercise in themselves and will show how easy it is to reason wrongly.

## *EXPERIMENT 33*

### TO CALIBRATE A DIVIDED CIRCLE USING TWO MICROSCOPES

*Apparatus*

The order of accuracy obtained in this experiment will depend very largely on the equipment available. Application of the theory of its operation (the "calliper principle") is, however, more important. It is perhaps best to work with a divided circle which has some appreciable errors, both of division and eccentricity, since errors which are so small as to border on the accuracy of measurement can disguise the principles involved.

Divided Circle.

This may be the circle on or from an instrument, preferably graduated with clean fine lines suitable for observation in a medium power microscope. It is not difficult to prepare a special circle by engraving with a fine scriber, e.g. a well-ground scriber in a set of slip gauge accessories, on the edge of a steel, aluminium, brass or bronze disc. The edge must, of course, have a fine finish and be geometrically accurate. Suitable errors can be artificially injected and the number of divisions for this experiment need not exceed eight (45° spacing). The graduations must be numbered. The circle must be mounted either on its own bearings or on a suitable arbor and should preferably have some means of fine rotational adjustment for setting. A tangent screw on an arm which can be clamped to the circle spindle is quite suitable for this purpose.

Microscopes.

Two microscopes are required. For preference, both should have micrometer eyepieces but the experiment can be performed if one has only a fixed line graticule, provided the other has a micrometer eyepiece or scale graticule. A micrometer is always the more accurate.

The eyepiece graticule, whether micrometer or fixed, should have double lines which will just straddle the line on the circle. It is well known that a symmetrical setting on a line can be made much more accurately than a line-to-line setting.

Suitable rigid mountings must be provided which will enable the microscopes to be set at 180°, 90° and 45° separations round the circle. If a special set-up is constructed for this experiment, the microscopes may be mounted on radial arms which may be moved concentrically with the circle. Perhaps an old spectrometer could be pressed into service, with suitable modifications.

The ideal equipment is the Watts Circular Division Tester, with additional microscope. The only difficulty is that it is not easy to set the microscopes at other than 180° if the axis of the circle is horizontal.

*Method*

(i) 180° INTERVAL

Set the microscopes 180° apart and adjust the circle so that settings or readings may be made on the 0° and 180° lines. Set the fiducial microscope on the 180° line. If this microscope has a micrometer eyepiece, set as close as possible to the chosen zero setting and take several micrometer readings to find the exact position. It is better to do this, and make corrections afterwards, than to try to set a fixed position. Take readings on the 0° line with the other (measuring) microscope.

At this stage it will be as well to investigate the directions of reading of the two microscopes relative to the direction of circle numbering. Preferably, an increase in reading should correspond to the direction of increasing reading on the circle and this will be assumed in the following description. If either microscope reads in the opposite direction, great care must be taken in computing differences. It is easy to check direction by a slight movement of the circle, using the fine adjustment, moving a line in the direction of a higher circle reading. This means that if, say, the 5° line is viewed, the circle is moved in the direction which would eventually bring the 4° line into view. The corresponding change of microscope reading will indicate a *positive* or *increasing* reading on the circle. It is worth while taking a little time to make quite sure of these directions and to be satisfied that this procedure will show the direction of microscope difference if a degree line were in error by a small angle in a *positive* direction, i.e. towards a *higher* circle reading.

Returning to the circle calibration, rotate the circle 180° and set the 0° line on the graticule of the fiducial microscope (without, of



course, moving the microscope bodily). If this microscope has a micrometer, check the setting and allow for any small difference. Take readings with the other microscope on the 180° line. Repeat the setting and readings for the first position.

Consider now the geometry of this operation. Referring to Fig. 40, imagine microscope A is fixed and line 1 is the 180° line. Assume the circle is graduated clockwise. Measuring microscope B is set on line 2 (0°). It is obvious that the interval 2 to 1 clockwise (0° to 180°) is larger than 1 to 2 (180° to 360°). When, therefore, the circle is rotated to set line 2 (0°) at A, the microscope B will not read on line (180°) but its micrometer will have to be adjusted to bring it from position 3 (a position between 179° and 180°) to the position of line 1. By the agreed convention, this will be a positive difference. This means that the interval 0° to 180° is greater than a true 180° by *half* this difference in reading. Calibration of the circle, starting from 0°, will therefore show a positive error for 180°.

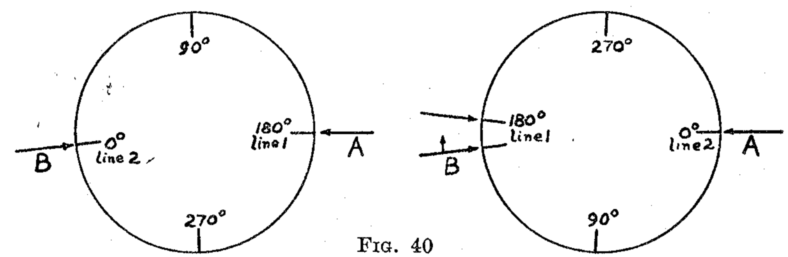



FIG. 40

(ii) SMALLER INTERVAL

Next, adjust the microscopes to a smaller convenient separation e.g. 90°, 45°, 60° or 30°, depending on the total time available for the experiment. The greatest accuracy will be obtained by working progressively down to smaller and smaller intervals, but this consumes a great deal of time. Let us assume that a 45° interval is chosen.

It will be easiest to arrange the microscopes so that the fixed one is on 0°, say, when the measuring microscope is on 45° with its micrometer readings increasing in the same direction as circle readings, as previously described.

The procedure is the same in principle as for the 180° interval. Set the 0° line in the fixed microscope and take the reading on the

45° line. Rotate the circle backwards and set the 45° line in the fixed microscope, taking the reading on the 90° line. Continue for eight 45° intervals and repeat the cycle, if time allows.

(iii) MICROSCOPE CALIBRATION

The calibration of the microscope micrometer must be known in terms of circle division. If this calibration is not already given, some way must be found to check it.

If the field of view covers a whole circle division, perhaps 0·5° or 1° (less likely), it is a simple matter to obtain the angular value of a micrometer division. If two lines cannot be seen in the field of view, means must be found to rotate the circle through a small angle. This might be done by placing slip gauges under the tangent screw, having carefully measured the radius to the contact tip of the screw. It would not be wise to rely on the accuracy of pitch of the screw. Other methods would be to rig up a sine bar device on the circle mandrel, to use a mirror and calibrated auto-collimator or to calibrate against a linear graticule or scale. In the latter case, the radius of the graduated circumference of the circle must be known or measured so that the corresponding linear value of an angle can be calculated. Remember that for each unit of radius:

$$1 \text{ deg} = 0{\cdot}01745$$
$$1 \text{ min} = 0{\cdot}000291$$
$$1 \text{ sec} = 0{\cdot}000005$$

*Observations and Results*

The following table shows typical results for 45° intervals on a circle.

| *Interval (deg)* | *Microscope reading (div)* | *Difference from mean (div)* |
|---|---|---|
| 0–45 | 42·4 | +1·4 |
| 45–90 | 43·8 | +2·8 |
| 90–135 | 40·7 | −0·3 |
| 135–180 | 39·4 | −1·6 |
| 180–225 | 38·6 | −2·4 |
| 225–270 | 40·1 | −0·9 |
| 270–315 | 41·2 | +0·2 |
| 315–360 | 42·0 | +1·0 |

Mean reading 41·0 (to nearest 0·1)



Since the eight 45° intervals *must* total 360°, whatever their individual errors, the mean of the readings in the second column is the reading which would be obtained on an exact 45° interval. Individual differences from this mean are the errors (in divisions) of each interval compared with 45°. It should be particularly noted that these are individual errors of size of angle and do not represent, at this stage a calibration of the circle.

In the following table, three further operations are performed:

(i) The above values are made cumulative, giving the error of each line relative to zero. Note that a zero is added above the first reading since we are now dealing with graduation lines, not intervals.

(ii) Since the cumulative error at 360° *must* be zero, a small progressive correction must be made for the arithmetical error introduced by rounding off the mean reading to the nearest 0·1 division.

(iii) Microscope divisions are converted to angular values according to the microscope calibration.

| *Graduation line (deg)* | *Cumulative error (div)* | *Correction (div)* | *True error (div)* | *True error (min)* |
|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 |
| 45 | +1·4 | 0 | +1·4 | +0·5 |
| 90 | +4·2 | 0 | +4·2 | +1·45 |
| 135 | +3·9 | −0·1 | +3·8 | +1·35 |
| 180 | +2·3 | −0·1 | +2·2 | +0·75 |
| 225 | −0·1 | −0·1 | −0·2 | −0·05 |
| 270 | −1·0 | −0·1 | −1·1 | −0·4 |
| 315 | −0·8 | −0·2 | −1·0 | −0·35 |
| 360 | +0·2 | −0·2 | (0) | (0) |

Calibration of microscope 1 div = 0·35 min

Errors in the final column have been rounded to 0·05 min. Unless really high precision equipment is being used, this will represent the limit of accuracy which can be expected (3 sec). Achievement of even this accuracy can only be obtained with first-class equipment and careful observation.

Although two separate tables have been used for clarity in explaining the steps, they can be combined in one table provided the operations are fully understood.

*Conclusions*

Compare the results obtained from different sets of observations. For example, the 180° error obtained from taking 180° intervals should agree with that obtained from 45° intervals. If observations have also been made at 90° intervals, four "landmarks" will have been obtained.

Generally speaking, these landmarks will be more accurate than the corresponding values found by taking a larger number of smaller intervals. These values may be adjusted to the landmarks by progressive correction; but if there are large discrepancies further investigation is necessary.

Draw a curve of the final results, and if this looks at all like a sine curve (in any phase) superimpose such a curve which is nearest to the general profile.* This sine curve will show errors produced by pure eccentricity of the centre of division to the centre of rotation. Such errors could be eliminated by correct centring of the circle but this is difficult to do completely. Differences from the sine curve represent random errors which can probably not be reduced further by centring.

* See Appendix.

## *EXPERIMENT 34*

### TO COMPARE TWO SLIP GAUGES USING AN OPTICAL FLAT

This method of comparing two slip gauges was originated by the U.S. Bureau of Standards and is included in this volume to illustrate a principle rather than as a useful method for general use. The trouble is that, unless both gauges are flat and parallel to a high degree and their faces are in good condition, the accuracy of measurement is doubtful. In any case it is essential for the reference gauge to be good so that the fringe patterns observed may be interpreted with reasonable accuracy.

*Apparatus*

Slip Gauge for Reference.

This does not have to be Reference *grade* but must have flat and parallel faces (within 0·00001 in.) which must have a good finish.

Slip Gauge for Comparison.

This must be of the same nominal size as the reference gauge but should differ in length from it by several hundred-thousandths of an inch. Its faces need not be so parallel as those of the reference gauge but they must be flat and have a good finish. For this experiment it may well be worth lapping two old gauges to suit these requirements.

Lapped Surface Plate.

This can be a toolmaker's flat or other high-grade lapped surface.

Optical Flat at least 2 in. diameter.

Source of Monochromatic Light.

A suitable source is a mercury or sodium lamp with diffusing screen and filter. If a complete Flatness Interferometer (N.P.L. type) is available so much the better, but in this case the regular optical flat must be swung out of the way since the flat used must actually rest on the gauges.

*Method*

Clean the slip gauges and lapped surface carefully, polishing with a *clean* chamois leather or soft polishing cloth. Wring the gauges to the plate, side by side, separated by a definite distance. The separation and the depth of the gauges must be known and it will be best to gauge the separation with another slip. It will be convenient to make the separation plus the depth of the gauges equal to 0·5 in. The nominal depth (narrow dimension of face) of slip gauges is 0·355 in. in B.S. 888. Allow to cool to the ambient temperature.

Place the optical flat on the gauges, making sure that it is in contact but not wrung on. Try to adjust and balance it to make the interference fringes on the reference gauge lie parallel to the longer edge. Adjust the monochromatic light and filter so that the fringes are clearly seen.

Make a neat and precise enlarged diagram of the fringe pattern on both gauges. Gently press the optical flat outside the edge of each gauge in turn (see Fig. 41) and note carefully what happens to the fringes on each gauge, whether they close up and increase in number or open out and decrease in number. Reverse the gauge being tested, keeping the same end on the plate, and repeat the observations.

Check the flatness of the gauge faces by applying the optical flat to each in turn.

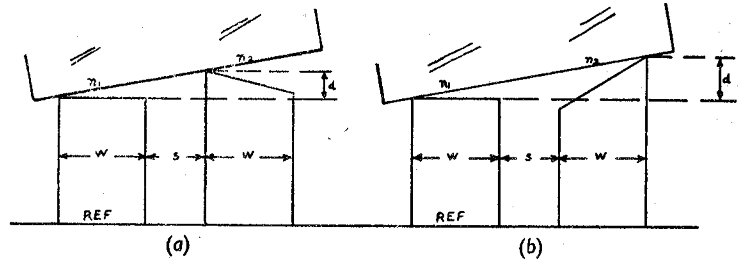
*Observations and Results*

The accurate interpretation of the results of this experiment depends more on an understanding of the principles of simple interferometry than on any hard-and-fast formula.

The four possible basic cases are shown in Fig. 41 and the formulae are given on the assumption that the fringes are parallel to the long edges of the slip gauges. It must be emphasised that reasonable interpretation can only be made if the reference gauge is accurately flat and parallel and that the experiment is not of much use if the gauge being tested is too bad in this respect.

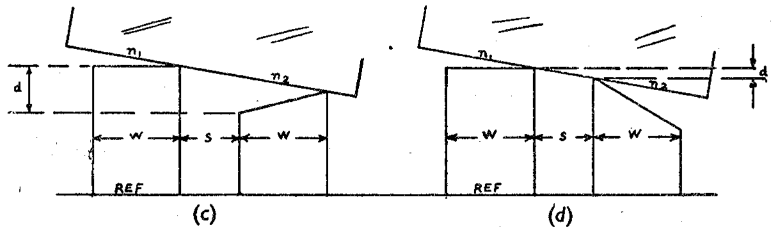
If there is error in parallelism along the face of the gauge, the fringes will not be parallel to the long edge but some of them will intersect it. The number of fringes doing so indicates directly the error in parallelism in half-wavelengths. This also applies if the fringes are curved, indicating a flatness error as well. It will therefore be best to check flatness independently with the optical flat, the curvature of the fringes in terms of fringe separation representing the flatness error in half-wavelengths.

The principle to remember is that each interference fringe represents a contour line along which the optical flat is everywhere




(a) $d = \dfrac{n_1 (w+s)}{w} \dfrac{\lambda}{2}$ Parallelism $(n_2 \sim n_1) \dfrac{\lambda}{2}$

(b) $d = \dfrac{n_1 (2w+s)}{w} \dfrac{\lambda}{2}$ Parallelism $(n_1 + n_2) \dfrac{\lambda}{2}$




(c) $d = \dfrac{n_1 (w+s)}{w} \dfrac{\lambda}{2}$ Parallelism $(n_2 \sim n_1) \dfrac{\lambda}{2}$

(d) $d = \dfrac{n_1 s}{w} \dfrac{\lambda}{2}$ Parallelism $(n_1 + n_2) \dfrac{\lambda}{2}$

$n_1$ = number of fringes on reference gauge
$n_2$ = ,, ,, ,, ,, gauge under test
$\lambda$ = wavelength of light used.

EFFECTS OF PRESSURE IN EACH CASE

| | On right-hand side | | On left-hand side | |
|---|---|---|---|---|
| | Ref. | Gauge | Ref. | Gauge |
| (a) | Fringes open | Fringes open | Fringes close | Fringes close |
| (b) | ,, open | ,, close | ,, close | ,, open |
| (c) | ,, close | ,, close | ,, open | ,, open |
| (d) | ,, close | ,, open | ,, open | ,, close |

In cases (a) and (c), if $n_1 > n_2$, the point of contact is not the highest point on the gauge.

FIG. 41

equidistant from the surface of the gauge. Once the inclination of the flat to the reference gauge has been established, by counting the fringes on this gauge and determining the direction of the tilt, the surface contour of the gauge under test can be found by applying this principle. A good deal of careful thought and reasoning will be needed, however, and this is the main purpose of the exercise.

From the table under Fig. 41 it is seen that the relationship between the two gauges can be qualitatively tested by slight pressure on the optical flat on one side and then the other, watching the behaviour of the fringes meanwhile. Conditions (a) and (c) include the limiting one where the gauge under test is parallel, in which case the number of fringes is equal on each.

A careful measurement of the gauge error after its reversal will check the first results and will help to confirm the direction of error.

Although the light from both mercury and sodium sources contains several discrete wavelengths, these are close enough together, in this experiment, to be taken as a single value.

The true values in millionths of an inch are:

| | |
|---|---|
| Mercury | 21·5 and 23 |
| Sodium | 23 |

It will therefore be seen that if the half-wavelength is assumed to be 0·000011 in. for either source, no significant error will be introduced unless the number of fringes is large, in which case the method is unsuitable anyway.

*Conclusions*

The main conclusion likely to be drawn from this experiment is that, although interferometry is a sensitive measuring technique, it needs a lot of care in use.

By comparing the results of several measurements the general accuracy of the method can be estimated.

## *EXPERIMENT 35*

### TO TEST THE FLATNESS OF A SURFACE PLATE USING A BLOCK LEVEL*

*Apparatus*

Surface Plate to be Tested.

This plate should be B.S. Grade A and should be reasonably large, preferably not less that 3 ft × 2 ft. If it is smaller it will be difficult to obtain enough steps for the level and, in any case, small plates are best tested by other methods. For the purpose of this description, it will be assumed that the plate is 4 ft × 3 ft.

Block Level.

The level should have a sensitivity of not less than 10 sec per division (0·0005 in. in 10 in.) and should not be longer than 10 in. If a small plate is being used, the level may well be shorter. The level may be placed directly on the plate but it is better to provide two feet which can be wrung on to the base of the level to vary the pitch of the points of contact. These feet may be made from hardened steel strips of about 0·5 in. square section and as long as the width of the level base. They must be equal in thickness (to about 0·0002 in) and must be ground and lapped parallel.

The feet may be wrung across the level base so that their centres are at the required separation.

Straightedge.

The straightedge is used only for guiding the level and should, if possible, be long enough to span the surface plate diagonally. A 5 ft steel rule would be most convenient for the plate being considered.

*Method*

The surface plate must be set approximately level so that a reading on the level can be obtained at any point on the plate. The level

*An auto-collimator may be used for this method in a similar manner. Both level and auto-collimator are angular measuring instruments and once the readings have been converted to linear errors along a generator line the method of working out surface errors is exactly the same in both cases. Experiment 29 explains the detailed method of using an auto-collimator for this type of measurement.

must also be set so that its bubble is approximately symmetrical when truly level. The method of doing this is described in Experiment 26.

The plate must be rigidly supported, preferably on a proper stand, on a firm floor. *An ordinary bench is not satisfactory* since it will upset the readings if any additional weight is placed on it; even the weight of the level in different positions could cause variations.

The operation must now be planned by drawing, approximately to scale, a diagram as in Fig. 42. Draw a rectangle $ABCD$, leaving a margin of about two or three inches from the edges of the plate. For the example we are considering (a plate 4 ft $\times$ 3 ft) $AB$ can be 42 in., divided into six parts of 7 in. each, and $AD$ can be 30 in., divided into four parts of 7·5 in. each. It is important that the number of divisions should be even, so that the centre of the rectangle can be an intersection point. The diagonals must also be divided evenly as it is essential that there should be a common measuring point on both diagonals and on the two centre lines. In this case, the diagonal is 51·6 in. and can be divided into six parts of 8·6 in. Mark the ends of each generator line on the edges of the plate.

The method of operation is to move the level along each generator in steps equal to the pitch of the divided parts. Each time the level is moved, its rear foot is placed on the spot previously occupied by the front foot. Thus the angular variation of each division is determined and can be related to the first position and the profile of the plate along the generator can be obtained.

Throughout the experiment, particular attention must be paid to temperature stability. A precision level is very sensitive to draughts and handling; small local changes in temperature will cause changes in reading.

The location of the experiment should therefore be carefully selected and the level should be handled with a chamois leather or a soft duster.

Assuming we are starting with line $AB$ and those parallel to it, set the level feet to a pitch of 7 in. Set the straightedge or rule beside line $AB$ on the plate so that the centre line of the level lies along $AB$ and mark off the straightedge in the divisions chosen. The number of generators and the number of steps chosen will depend to some extent on the time available for the experiment; the principles of the measurement can be learnt with a very few observations.

This type of test always takes a considerable time but it is quite

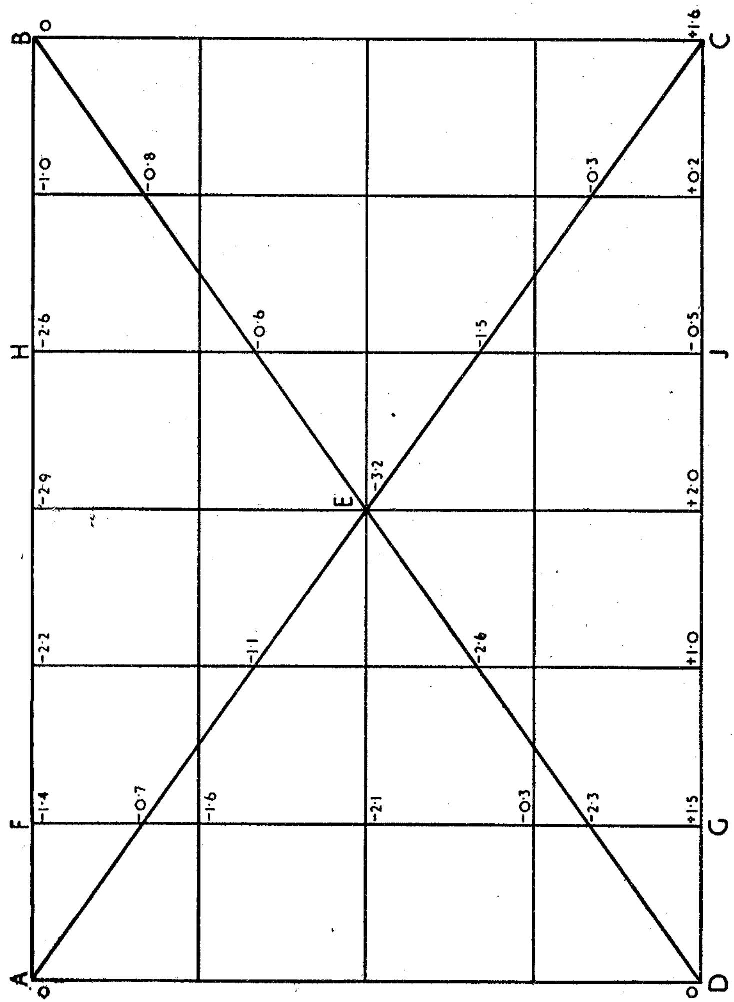



FIG. 42

permissible to split it into several sessions, provided of course the set of readings on any generator is completed at one session. The smallest number of lines which should be used is eight, the four boundaries, the two centre lines and the two diagonals. This will not provide a satisfactory test on the plate but will serve as an exercise in the method of measurement.

Read both ends of the bubble, counting the graduations in the direction $A$ to $B$, the first graduation on the left being zero. It will thus be seen that an increase in the reading from the first value indicates a rise in the contour and a decrease in the reading represents a fall. Readings should be made in the manner described in Experiment 26.

Take readings at each position along $AB$, starting at $A$ and moving the level carefully against the straightedge. If time allows, take repeat readings as the level is moved back along the line. Repeat this procedure on the generators parallel to $AB$; take similar readings on $AD$ and its parallel generators, and also on the two diagonals—after adjusting the feet to the new spacings of 7·5 in. and 8·6 in. respectively.

*Observations and Results*

The method of tabulating and calculating results is shown in Table I for generator $AB$. All the other generators are dealt with in a similar way and the correlation of different generators can be followed from Tables II, III, IV, and V. These Tables are shown in an abbreviated form, omitting level readings and differences, but in practice each table must be recorded in full. It is important, particularly in an experiment of some complexity such as this, that all readings are noted *as they are taken* in a properly prepared book and *not on scraps of paper*. The best type of book for this sort of work is a stiff-backed quarto book, ruled in $\frac{1}{4}$ in. squares. Having such a book is far more important than making fair copies of descriptions of experiments.

In the Tables, leave a space above the first figure in Columns 1 to 6, since in Columns 7 to 8 an additional zero has to be inserted. This is because each level reading indicates a *slope* between *two* points, e.g. 0 and 7 in., 7 and 14 in., etc., whereas the final result has to relate the error of each *point* to the first one. The conversion of values in Column 5 to slope differences in Column 6 is done by multiplying each value by the linear value of one level division over



the spacing of the feet on the level. This spacing is 7 in. in Table I but is 8·6 in. for the diagonals and 7·5 in. for generators parallel to $AD$. All these figures are given solely as examples and, naturally, the actual values used in the experiment must be used for calculation.

The figures in Column 6 are made cumulative in Column 7, after adding another zero at the beginning, as just mentioned. The first two zeros therefore represent the datum line, drawn between the first and second points, from which the errors of the following points are determined. This is shown as a dotted line in Fig. 43.

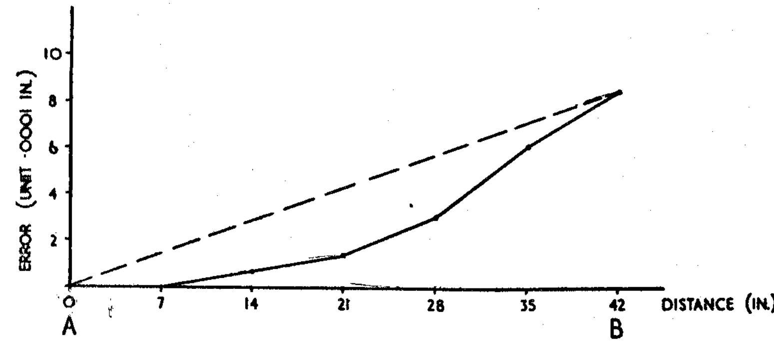



FIG. 43

This dotted line happens to give a final error of +8·6 and does not, of course, represent the best datum. In fact, the datum for each generator has to be related to other generators. In this case the curve is adjusted to a new datum passing through zero at each end.

The operation amounts to swinging the curve about the zero point to give the second curve shown. It will be seen later that other curves have to be swung about other points than zero, to tie down points on the generator being measured to previously determined values of the same points. Adjustments are made by taking the algebraic differences between the two values of each of the two datum points and applying proportional differences for the other points on the curve. The principle of the method will become clear if the examples are carefully followed but the student who is unfamiliar with this type of calculation is warned to proceed cautiously and to justify each step to himself before taking it. It should be fully realised that these adjustments are in no way corrections for erroneous readings. The level readings represent angles only and the overall contour values for each line are related to the direction established by the first level reading on the line, quite a fortuitous datum.

It will be obvious that if errors for the whole plate are to be quoted they must be related to some datum plane. Any convenient plane may be chosen as a datum but it will be most convenient to choose one which passes through three of the points of measurement. The three most convenient points from an arithmetical point of view will be three corners of the rectangle $ABCD$, for example $A$, $B$, and $D$.

The points $A$, $B$, and $D$ will therefore each have to be adjusted to zero without altering the contour curve between them. Point $A$, being the starting point for both $AB$ and $AD$, is zero already. The adjustment to bring $B$ to zero is shown in Table I; $D$ is brought to zero by adjusting the readings along $AD$ in an exactly similar manner.

The next step is to tie the diagonal $BD$ to the zero values for $B$ and $D$ at its ends. If readings along this diagonal were started at $B$, then $B$ will already be zero and $D$ will have to be adjusted to zero as before; if $D$ was zero, $B$ must be adjusted (see Table II). We now have contour lines for the triangle $ABD$, whose corners lie in the chosen reference plane. The fact that this may not be the ideal plane for final reference does not matter at this stage.

So far, no other lines have been tied down; they are waving in the air, so to speak. There is no value for $C$, for example, which will settle the position of $BC$ or diagonal $AC$. But $AC$ passes through the midpoint $E$ of diagonal $BD$ and a value for $E$ will have been established in Table II. Table II has been abbreviated to show the last three columns only, although the whole table will have to be worked out from the actual observations. The importance of making $E$ a measuring point on each diagonal will now be appreciated. Table III (again abbreviated) shows how the values for $AC$ are adjusted to bring $E$ to the previously determined value on $BD$. A properly related value for $C$ is thus automatically obtained and this allows lines $BC$ and $DC$ to be tied down by proportional adjustment to bring point $C$ to this value on each line, as shown in Table IV.

Other generator lines, such as $FG$ and $HJ$, can now be tied to the appropriate end points already determined on $AB$, $BC$, $CD$, and $AD$, as shown in Table V.

If time allows measurements to be made along generators in both directions, i.e. parallel to $AB$ and $BC$, each point inside the rectangle $ABCD$ will have two values for its error. This provides a good check on the accuracy of measurement. With care, values should agree to 0·0001 in.



Mark, on the plan already drawn, the errors obtained at each point and put in the mean values. On another plan draw a contour map by joining points of equal value, rounding the values to the nearest 0·0001 in. (or nearest 0·00005 in. if there are only very small errors).

*Conclusions*

This experiment takes rather a long time to carry out but it need not be tedious and is well worth while doing as an example of systematic observation. All observations should be made before any results are worked out; if obvious errors turn up, rechecks can be made afterwards. It is one of the most rewarding experiences in experimental work to find, after a series of calculations from observations, that good agreement is obtained at cross-check points. If, on the other hand, disagreements are found, the experimenter is made acutely aware of his deficiencies.

The contour results obtained for the plate should be compared with the relevant British Standard B.S. 817. In this Specification, the tolerance given represents the separation of two imaginary parallel planes between which all points on the surface should fall. The surface may, of course, be adjusted to best advantage within the planes. If two points differ in error by more than the tolerance, it is sometimes possible to tilt the surface, algebraically of course, so that all points fall within tolerance.

For example, assuming $AB$ and $D$ to be taken as the zero datum plane, if a point near $A$ were found high and a point near $C$ low, it might be possible to swing the surface about an axis through or near $A$ to bring the low point within the parallel planes without taking the high point outside them. The amount of proportional correction at any point can best be determined from a scale diagram on which radii from the axis of rotation can be measured.

TABLE I

GENERATOR *AB*

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
|---|---|---|---|---|---|---|---|---|---|
| *Position (in.)* | *Level reading (div)* *LH* | *RH* | *Mean* | *Difference from first reading (div)* | *Slope differences in 7 in.** (*Unit* 0·0001 *in.*) | *Cumulative values (contour)* (*Unit* 0·0001 *in.*) | *True straight line* AB *Increments* $\frac{8\cdot6}{6}$ (*Unit* 0·0001 *in.*) | *Contour error: Col. 7 minus Col. 8* (*Unit* 0·0001 *in.*) | |
| – | – | – | – | – | – | 0 | 0 | 0 | *A* |
| 0–7 | 3·4 | 4·0 | 3·7 | 0 | 0 | 0 | +1·4 | −1·4 | *F* |
| 7–14 | 3·6 | 4·2 | 3·9 | +0·2 | +0·7 | +0·7 | +2·9 | −2·2 | |
| 14–21 | 3·6 | 4·2 | 3·9 | +0·2 | +0·7 | +1·4 | +4·3 | −2·9 | |
| 21–28 | 3·8 | 4·6 | 4·2 | +0·5 | +1·7 | +3·1 | +5·7 | −2·6 | |
| 28–35 | 4·2 | 5·0 | 4·6 | +0·9 | +3·1 | +6·2 | +7·2 | −1·0 | |
| 35–42 | 4·0 | 4·8 | 4·4 | +0·7 | +2·4 | +8·6 | +8·6 | (0) | *B* |

* 1 div=0·0005 in. in 10 in.
∴ 1 div=0·00035 in. in 7 in.

Values in Col. 8 are calculated to the nearest 0·1



TABLE II

(showing Columns 1, 7, 8 and 9 only)

GENERATOR *BD* (DIAGONAL)

| 1 | 7 | 8 | 9 | |
|---|---|---|---|---|
| *Position (in.)* | *Cumulative values (contour)* (*Unit* 0·0001 *in.*) | *True straight line* BD (*Unit* 0·0001 *in.*) | *Contour error: Col. 7 minus Col. 8* (*Unit* 0·0001 *in.*) | |
| 0 | 0 | 0 | 0 | *B* |
| 8·6 | 0 | +0·8 | −0·8 | |
| 17·2 | +1·0 | +1·6 | −0·6 | |
| 25·8 | −0·8 | +2·4 | −3·2 | *E* |
| 34·4 | +0·6 | +3·2 | −2·6 | |
| 43·0 | +1·7 | +4·0 | −2·3 | |
| 51·6 | +4·8 | +4·8 | (0) | *D* |

Values in Col. 8 are arranged to bring the final error of *D* to 0. Increments in Col. 8 are $\frac{4\cdot8}{6}=0\cdot8$.

TABLE III

(showing Columns 1, 7, 8 and 9 only)

GENERATOR *AC* (DIAGONAL)

| 1 | 7 | 8 | 9 | |
|---|---|---|---|---|
| *Position (in.)* | *Cumulative values (contour)* (*Unit* 0·0001 *in.*) | *True straight line* AC *making* E=−3·2 *in Col.* 9 (*Unit* 0·0001 *in.*) | *Contour error: Col. 7 minus Col. 8* (*Unit* 0·0001 *in.*) | |
| 0 | 0 | 0 | 0 | *A* |
| 8·6 | 0 | +1·6 | −1·6 | |
| 17·2 | +2·0 | +3·1 | −1·1 | |
| 25·8 | +1·5 | (+4·7) | (−3·2) | *E* |
| 34·4 | +4·8 | +6·3 | −1·5 | |
| 43·0 | +7·5 | +7·8 | −0·3 | |
| 51·6 | +11·0 | +9·4 | +1·6 | *C* |

In Col. 8 the governing value is *E* (+4·7). This makes the error for *E* in Col. 9 −3·2 (1·5−4·7) which agrees with the error for *E* in Table II. Extrapolating +4·7 at 25·8 in to +9·4 at 51·6 in gives the true error for *C* (+1·6) relative to plane *ABD*.

TABLE IV

(showing Columns 1, 7, 8 and 9 only)

GENERATOR *DC*

| 1 | 7 | 8 | 9 | |
|---|---|---|---|---|
| *Position* (*in.*) | *Cumulative values* (*contour*) (*Unit* 0·0001 *in.*) | *True straight line* DC *making* C = +1·6 *in Col.* 9 (*Unit* 0·0001 *in.*) | *Contour error: Col.* 7 *minus Col.* 8 (*Unit* 0·0001 *in.*) | |
| 0 | 0 | 0 | 0 | *D* |
| 7 | 0 | −0·1 | +0·1 | *G* |
| 14 | +0·9 | −0·1 | +1·0 | |
| 21 | +1·8 | −0·2 | +2·0 | |
| 28 | −0·8 | −0·3 | −0·5 | *J* |
| 35 | −0·1 | −0·3 | +0·2 | |
| 42 | +1·2 | −0·4 | (+1·6) | *C* |

Values in Col. 8 are arranged to bring the final error of *C* to +1·6, the value established in Table III.

TABLE V

(showing Columns 1, 7, 8 and 9 only)

GENERATOR *FG*

| 1 | 7 | 8 | 9 | |
|---|---|---|---|---|
| *Position* (*in.*) | *Cumulative values* (*contour*) (*Unit* 0·0001 *in.*) | *True straight line* DC *making* F = −1·4 *and* G = +1·3 *in Col.* 9 (*Unit* 0·0001 *in.*) | *Contour error: Col.* 7 *minus Col.* 8 (*Unit* 0·0001 *in.*) | |
| 0 | 0 | +1·4 | (−1·4) | *F* |
| 7·5 | 0 | +0·8 | −0·8 | |
| 15 | −1·9 | +0·2 | −2·1 | |
| 22·5 | −0·7 | −0·4 | −0·3 | |
| 30 | +0·5 | −1·0 | (+1·5) | *G* |

Values in Col. 8 are arranged to bring the final error of *F* to −1·4 and of *G* to +1·5, the values established in Tables I and IV. Increments in Col. 8 are $\frac{-1\cdot 0-1\cdot 4}{4} = -0\cdot 6$.

## *EXPERIMENT 36*

## TO CHECK THE INVOLUTE PROFILE OF A SPUR GEAR USING A DIVIDING HEAD

### *Apparatus*

Small Spur Gear, preferably with a small number of teeth and of fairly large diametral pitch. The ideal type of gear for this experiment is an oil pump gear, having about ten teeth.

Dividing Head with suitable means of mounting the gear, either on centres or on the faceplate of the dividing head. An optical type of dividing head is best for this purpose, but the worm and wheel type may also be used. The dividing head must be mounted on a suitable surface plate.

Apparatus for Measuring Rack Displacement of the Gear. Various types of equipment may be used for this purpose, but the most convenient is certainly the Watts Microptic type of measuring machine. A special knife-edge foot has to be fitted to the measuring cylinder, and this foot engages with the flank of a tooth of the gear. The measuring face of the knife-edge should be reasonably straight and must lie at right angles to the line of measurement at the point of contact. In principle, the measuring machine or other device takes the place of a rack tooth of zero pressure angle and, in fact, measures the progressive displacement of such a rack as the gear is rotated through known angles. If such a measuring machine is not available, various other devices may be used. For example, a micrometer head may be fitted with a shallow conical disc, as indicated in Fig. 44, and set up to bear on the flank of the tooth with the measuring axis of the micrometer either vertical or horizontal. An alternative to a micrometer head is a knife-edge straightedge resting on varying piles of slip gauges. Another method is to use a lever type test indicator, mounted perhaps on a height gauge. More detailed instructions on the use of each measuring method are given later.

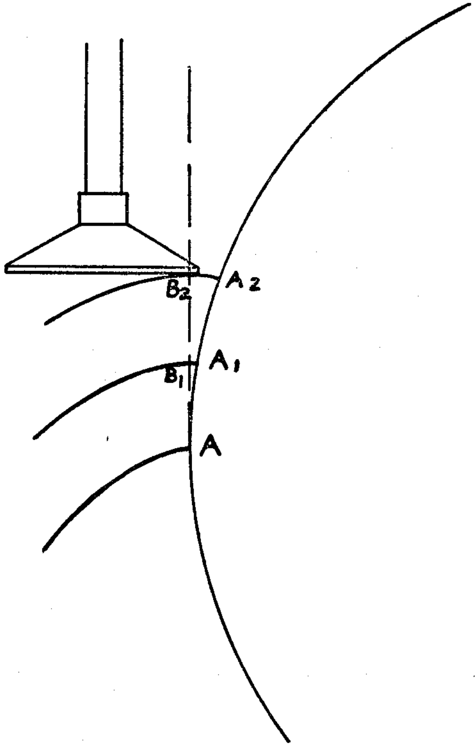



FIG. 44

*Method*

1. USING VERTICAL MEASURING MACHINE

The gear must be set up on a mandrel or in other suitable fashion so that it runs true when mounted on the dividing head. The outside diameter of the gear tooth may give some idea of concentricity, but cannot be relied on. The criterion must be the bore or shaft of the gear which may be assumed to run concentrically when the gear is in operation. The measuring machine should be set up so that the knife-edge foot is in contact with the upper flank of one of the gear teeth, and the height of the measuring head so arranged that as the gear is rotated the point of contact of the foot will move from the root to the tip of the gear.



The point of contact on the knife-edge is constant and its path is tangential to the base circle of the gear. For this reason it must be quite near the tip, which might otherwise foul the root of the tooth.

Build up a pile of slip gauges to the height of centres and set the knife-edge on this pile. Note the reading on the measuring machine. This setting may be made at the back of the knife-edge or, if it is more convenient, a reading may be taken on a different value of slips and the reading at centre height deduced.

Set the knife-edge on a tooth of the gear and rotate the dividing head until the measuring machine reads the centre height value. Note the reading on the dividing head. This operation will only be possible if the root of the tooth lies below the base circle and the involute profile continues right down to the base circle. If this is not so, see footnote.*

From this position, rotate the dividing head to raise the tooth by the pressure angle of the gear. If this angle is not known it may usually be assumed to be 20°. The knife-edge will then be making contact at the pitch circle corresponding to this pressure angle. Rotate the dividing head on either side of this position to determine the total range of contact over the face of the gear. Divide the angular range into eight or ten equal increments; for example, if the range of contact is 40°, each increment may be either 4° or 5°, but there may not be an equal number above and below the pitch line. If necessary, the range should be reduced slightly so that the pitch circle reading falls at one of the increment positions. It will be found that the face of the gear is traversed more quickly above the pitch circle than below it and, if desired, smaller increments may be used over this range.

To start observations, rotate the gear to the first position where contact is made near the root, take the reading of the measuring machine and record the exact setting of the dividing head. Then rotate the gear through the *exact* increment of, say, 5°, and take another reading of the measuring machine. Take similar readings at each increment throughout the range chosen, taking repeat

* If the involute profile does not go down to the base circle, adopt the following procedure:

With the knife-edge making contact somewhere on the flank between root and tip, determine the distance that the knife-edge is displaced for a rotation equal to the pressure angle. If the dividing head is then rotated so that the measuring machine reads this value above the centre height, it will be set on the pitch circle corresponding to the pressure angle.

readings with the gear rotating in the opposite direction, i.e. contact moving from tip to root of the tooth. A similar set of readings should be taken on at least one other tooth of the gear, preferably at a spacing of 180°.

Opposite flanks of teeth may be measured by moving the measuring machine to the other side of the dividing-head axis or reversing the axis of the gear.

### 2. USING MICROMETER HEAD

The micrometer head may be mounted on a suitable stand and used in either a vertical or horizontal position. With certain gears it may be possible to get a fair range of measurement without a special disc on the micrometer head, but this will only apply to a gear with a small number of teeth. Exactly the same principle of operation should be followed as with the measuring machine.

### 3. USING STRAIGHTEDGE AND SLIP GAUGES

Instead of attaching the knife-edge to a measuring machine or micrometer head, it can be placed on a pile of slip gauges, the height being found by trial and error. Alternatively, the tooth may be brought up to discrete positions by the straightedge.

### 4. USING TEST INDICATOR

Another method of measuring rack displacement is to use a lever-type test indicator mounted on a height gauge. In this case the stylus of the indicator must be drawn across the face of the gear tooth from root to tip at each reading. It will be obvious that in this way the highest position of the stylus generates an imaginary straight line parallel to the surface plate, and acts in the same way as the knife-edge on the measuring machine. Approximate readings may be taken from the height gauge itself, but it will be appreciated that these will be accurate to only 0·001 in. or perhaps 0·0005 in. To obtain more accurate readings, settings on appropriate piles of slip gauges will have to be made at each position.

An alternative method with this apparatus is to set the indicator by means of slip gauges at various height values, and take readings on the dividing head. Care must be taken, however, to see that the chosen reading of the indicator is obtained at the highest point on the gear tooth at each setting.



*Observations and Results*

Before dealing with actual results, consider the involute geometry of the measurement (Fig. 44). Assume the first point of contact is at $A$, where the involute rises from the base circle. Successive rotations of this point round the base circle to $A_1A_2$ etc. will displace the knife-edge along the tangent to $B_1B_2$ etc. The fundamental geometry of the involute shows that arc $AA_1 = AB_1$, arc $AA_2 = AB_2$ etc.

This opens up two methods of dealing with the observations. If the gear data are known, the tooth form may be checked against its nominal profile. If the data are not known (or assumed unknown), the actual base circle radius, or the base circle radius best fitting the observations, may be calculated.

Tabulate the readings and extend the table as in the following example (assuming gear data unknown).

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|
| *Angular setting* | *Observed reading (in.)* | *Diff. from P.C. reading (in.)* | *Arbitrary nominal (in.)* | *Diff. from nominal (in.* $\times 10^{-4}$*)* |
| 0° Root | 0·0213 | 0·6406 | 0·6404 | +2 |
| 5° | 0·1815 | 0·4804 | 0·4803 | +1 |
| 10° | 0·3417 | 0·3202 | 0·3202 | 0 |
| 15° | 0·5018 | 0·1601 | 0·1601 | 0 |
| 20° P.C. | 0·6619 | 0 | 0 | 0 |
| 25° | 0·8221 | 0·1602 | 0·1601 | +1 |
| 30° | 0·9822 | 0·3203 | 0·3202 | +1 |
| 35° | 1·1421 | 0·4802 | 0·4803 | −1 |
| 40° Tip | 1·3021 | 0·6402 | 0·6404 | −2 |

The arbitrary nominal values in the fourth column may be any convenient uniform increments which will give small differences in the final column. It is often most convenient to make these the average of the observed increments, 0·1601 in this case. The reason for taking differences from arbitrary linear values is to get sufficient accuracy in plotting a graph on a reasonable scale. If the differences in the third column were plotted direct (as they could theoretically be), a scale would have to be chosen which would not show variations of a few "tenths".

Plot a graph of the figures in the last column and draw the best straight line through the points. The $x$ axis (degrees) represents the arbitrary slope chosen for Column 4 and the best straight line represents a correction to the chosen slope which will make it fit the actual involute values more closely. Obtain a value for the best slope (linear displacement per degree).

Since this is also the arc per degree on the most appropriate base circle the calculation of $BCR$ is quite straightforward.

$$BCR=\frac{\text{Linear displacement per degree}\times 180}{\pi}$$

The graph will show local errors from the true involute to this base circle.

*Conclusions*

If the gear data are known, the true nominals may be calculated for Column 4, but even in this case it is a better exercise for the student if he assumes the data to be unknown.

In the example given, the base circle radius corresponding to the nominal values chosen is 1·8346 in. (arc of 1·2808 in. over 40°). The graph of differences shows a positive general slope of about 0·00035 in. over 40°. The fall away at the tip could be the effect of deliberate tip relief, which is often found. On this basis, the displacement is 1·28115 in. over 40° and this corresponds to a base circle radius of 1·8351 in.

## *EXPERIMENT 37*

# TO CALIBRATE A PRECISION POLYGON (FIRST METHOD)

*Apparatus*

Precision polygon or square from angle gauge set.

A circular or rotatable table with a fine adjustment. This may be an ordinary dividing table or any form of rotating table or face plate, provided there are means of obtaining a fine angular adjustment. No calibration or scale on the table is necessary.

Two auto-collimators. These need not be of the same sensitivity. One may be of the micrometer eye-pièce type reading to within one second, and the other of the Angle Dekkor type, reading only to a fraction of a minute. If two auto-collimators are not available, a set-up of a telescope and collimator may be used in place of one of the auto-collimators. The diagram (Fig. 45) shows the principle of this. For example, it may be possible to press into service the collimator and telescope from a spectrometer.

Suitable surface plate together with suitable mounting equipment, clamps, etc.

*Method*

This method of calibration utilises the calliper principle. That is to say, the polygon is calibrated by intercomparing its own angles, on the principle that, whatever their individual errors, they must add up to 360°. We will assume for the purposes of description that the polygon used has twelve sides. It will also be assumed that the equipment is set up to check adjacent faces whose perpendiculars subtend 30° at the centre. Exactly the same principles may be applied to check between faces subtending 90° and 180° or any other convenient angle. It will, in fact, be best to take a set of readings at, say, 90° positions after a set at 30°. The 90° results can be used as landmarks to adjust the 30° table.

Set up the polygon on the circular table so that it is approximately central, and clamp down if necessary. Clamping must be quite light and the clamps must not interfere with a clear view of any face of the polygon. The centring of the polygon on the table is not critical but it should be centred by eye as closely as possible. What is important, however, is that the faces of the polygon should be parallel with the axis of rotation. Normally the end faces of a polygon will be square to the common axis within a few seconds, and it may be quite sufficient to see that this surface runs true to a few ten-thousandths of an inch.

The best method of checking for this error, which is called pyramidal error, is to set one of the auto-collimators to receive a reflection from the polygon faces with the line of its micrometer or scale parallel to the axis of rotation. If the table is rotated so that each face of the

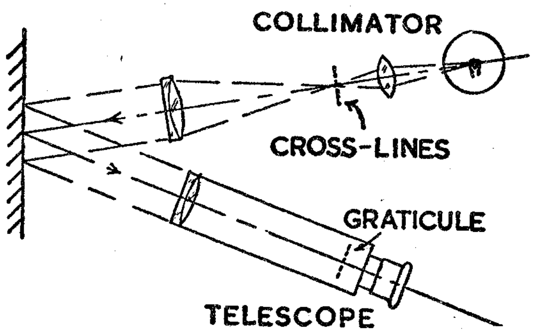



FIG. 45

polygon produces a reflected image, this image will be seen to move up and down unless every face of the polygon is truly parallel to the axis. Even in the best polygon there will be small inherent errors but these are unlikely to exceed a few seconds. If the setting of the polygon on the table is not sufficiently accurate, the plane of the polygon must be adjusted by packing or some other means. If a three-point adjustable levelling table is available, this is probably the best method. Errors from this cause will arise when taking the calibration readings if the target wire or scale of the auto-collimator is tilted relative to the axis of rotation. For example, if the face of the polygon is tilted to the axis of rotation by one minute and the target wire or scale is tilted by 2° the range of error introduced will be over 2 sec. It would be quite possible to have an error of tilt of this amount in setting the auto-collimator unless precautions are taken



to avoid it, so that it will be seen that the polygon must be set up with the greatest care. If such alignment errors are found with the polygon set directly on the circular table, it is perhaps best to set the polygon on three slip gauges so that adjustments in height of any slip may be made to the nearest 0·0001 in.

For the purpose of this description, it will be assumed that the polygon faces are marked *ABCD* . . . *L*, in a clockwise direction on the uppermost face of the polygon. One of the auto-collimators must be chosen as the datum setting and the other as the measuring unit. As shown in Fig. 46, the right-hand instrument is used for setting and this is shown set on face *A*, while the left-hand instrument is used for measuring and is shown set on face *B*. The L.H. instrument should be set to give the higher reading (by 10–15 sec). During the calibration, the circular table with the polygon is rotated anti-clockwise so that at the next setting the datum instrument is set on face *B* and the measurement taken on face *C* and so on right round the polygon.

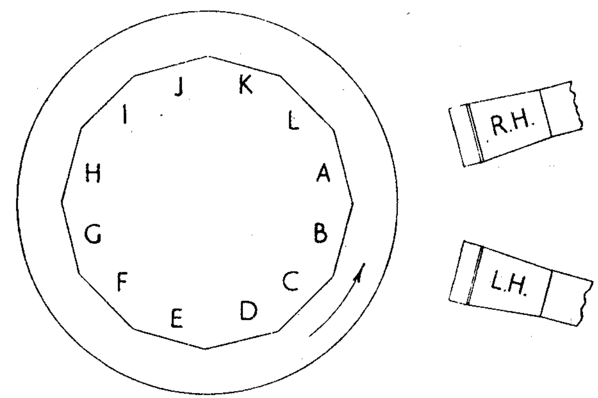



FIG. 46

Before starting the calibration the direction of sign of the measuring auto-collimator must be determined. This can be done by setting the measuring auto-collimator to read on one of the faces and giving the table a slight *clockwise* rotation. Such a rotation would correspond to an *increase* of the subtended angle (or the angle of rotation) between two adjacent faces. The direction of auto-collimator reading for this rotation should be carefully noted and, if possible, the auto-collimator should be set so that this direction of rotation corresponds to an *increase* in reading. This will normally be the case with the Microptic instrument.

Having made this determination and being satisfied that the polygon is rotating accurately, so that its faces are closely parallel to the axis of rotation, the calibration may be started. Set the R.H. auto-collimator on face *A* and take the reading on face *B*. Rotate the table until the same setting is obtained on face *B* and another reading taken on face *C*. If the R.H. auto-collimator has a micrometer, it may be found best to make the setting by actually taking a reading. The accuracy of setting will be improved by this method but any slight variation in reading must, of course, be allowed for, the direction of sign being determined as already mentioned. In such a case it should not be difficult to arrange both the auto-collimators to read in the same direction.

The process is repeated right round the polygon, taking a repeat reading between faces *A* and *B* at the end. If time allows, a second set rotating in the opposite direction should be obtained, the mean of each pair of corresponding readings being found. Again, if time allows, further sets of readings may be taken with the auto-collimators set at 90° and 180°. For 90° readings, only faces *A*, *D*, *G*, and *J* will be used, and for 180° readings faces *A* and *G* only. The table will be rotated 90° and 180° respectively in each case. Unless a much more complicated final analysis is to be made, there is no real purpose in rotating 30° between each setting when the auto-collimators are set at any other angle than 30°, e.g. at 90° or 180°.

### *Observations and Results*

The readings of the two auto-collimators should be recorded in the manner shown below. Each position of the polygon should be set so that the R.H. readings are as uniform as possible.

The grand mean is the mean value of all the differences; round off this value to the nearest 0·1 sec. Since the sum of all the angles of the polygon, whatever their individual errors, must be 360°, the mean value of all differences corresponds to the true angle. Differences from this mean value will give individual angle errors and the cumulative values give the errors relative to face *A*. As usual when values are accumulated, zero must be placed above the first error value to give the errors of individual faces. Values up to this column refer to the angle between *two* faces.



Unit = 1 sec.

| *Faces* | *Readings* | | | *Repeats* | | | *Mean diff.* | *Diff. from grand mean* | *Cumulative* | *Corrn.* | *Error* | *Face* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *R.H.* | *L.H.* | *Diff. L.H.-R.H.* | *R.H.* | *L.H.* | *Diff. L.H.-R.H.* | | | | | | |
| | | | | | | | | | 0·0 | 0·0 | 0·0 | *A* |
| *A/B* | 12·4 | 17·6 | 5·2 | 13·2 | 19·6 | 6·4 | 5·8 | +0·6 | +0·6 | 0·0 | +0·6 | *B* |
| *B/C* | 11·0 | 15·4 | 4·4 | 14·0 | 19·0 | 5·0 | 4·7 | −0·5 | +0·1 | +0·1 | +0·2 | *C* |
| *C/D* | 12·2 | 19·8 | 7·6 | 11·6 | 18·2 | 6·6 | 7·1 | +1·9 | +2·0 | +0·1 | +2·1 | *D* |
| . . | . . | . . | . . | . . | . . | . . | . . | . . | . . | . . | . . | . . |
| *L/A* | 13·0 | 18·4 | 5·4 | 12·6 | 16·8 | 4·2 | 4·8 | −0·4 | −0·5 | +0·5 | (0·0) | *A* |

GRAND MEAN 5·2

Note: The values for grand mean and cumulative values are assumed and have not been obtained arithmetically from the incomplete specimen figures tabulated.

The cumulative errors should end up with zero but there is likely to be a residual error due to rounding off the grand mean. The value of this residual cannot exceed 0·6 sec for twelve sides, if the rounding and other arithmetic has been done correctly. There may be a temptation to take the grand mean value further but this will involve hundredths of a second and, even then, may not be exact. It is much simpler to add a further column of proportional corrections to bring the last reading to zero, again rounding these values to 0·1 sec.

The errors in the polygon determined in this way are errors of *normals* to the faces. These are the errors which have to be corrected for when the polygon is used as a standard of circular division. Errors in the internal angles between faces are opposite in sign. The greatest care should always be taken to work out the logical meaning and sign of final results.

*Conclusions*

Conclusions should be drawn about the accuracy of the experiment itself rather than the accuracy of the polygon which is not subject to any general specification. Apart from calibration, however, the amount of pyramidal error should be noted and, if the image from any face shows inferior definition, an error in the flatness of that face can be deduced.

Comparison of the first and repeat columns of differences will indicate the accuracy of observation. Occasional discrepancies of one or two seconds must be expected; after all, the mean value is only half that amount away from either reading. If an accepted calibration of the polygon is available, the probable overall error can be assessed, although it must still be borne in mind that the accepted calibration may be uncertain by as much as one second. Results should also be compared with those obtained by other methods, such as Experiments 38 and 39, if available.

ALTERNATIVE METHODS

The method of auto-calibration just described, while quite sound theoretically, has certain limitations in practice due to the need to take two separate observations at each position of rotation. This difficulty is reduced and accuracy is increased if photo-electric auto-collimators are used, but there still remains the physical separation



of the two instruments which imposes close temperature control if results closer than one second are required.

A method which requires only one observation at each position and therefore cuts down the time required and reduces the effects of slight temperature variations has been tried experimentally with some limited success and may be worth doing, if only for an interesting exercise. Two variations of the method are possible, one involving a collimator and measuring telescope, and the other requiring one auto-collimator. Both require several auxiliary plane reflectors and are likely to be successful only when using a precision cube whose face will fill most of the aperture of the auto-collimator.

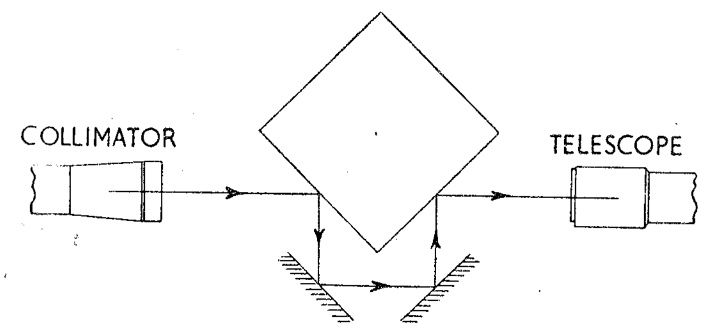



FIG. 47

*First method*

In addition to the cube and the means of rotating it, two plane reflectors are needed. The geometry of the set-up is shown in Fig. 47. The collimator and telescope may each be an auto-collimator but it may be necessary to apply a more powerful light, such as a small projection unit, to the collimator, since four reflections take place and light is inevitably lost at each reflecting surface. The need for good optical surfaces of maximum aperture will be apparent.

The optical arrangement amounts to a constant deviation system and the position of the image in the telescope is independent of the angular position of the cube, within certain physical limitations. It is, however, necessary to adjust this angular position for the best image and rotate the cube fairly accurately through 90° using the scale of the dividing table. Variation of any of the relative angles between pairs of reflectors within the system will vary the reading and hence any variation of the right angle of the cube can be measured.

Thus, an intercomparison of the four angles of the cube can be obtained, the mean auto-collimator reading corresponding to a true right angle. Differences from this value are the errors of individual angles.

*Second method*

This method needs one auto-collimator and three reflectors. The geometry of the set-up is shown in Fig. 48, and from this it will be

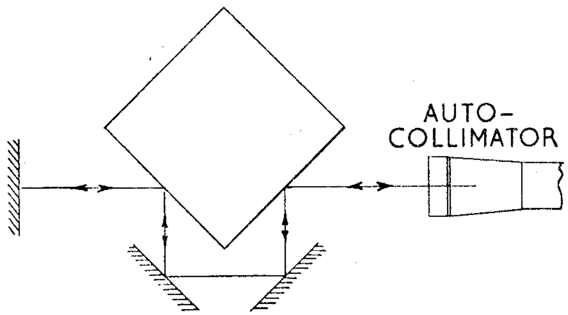



FIG. 48

seen that *nine* reflections are involved. It is true that the sensitivity of the auto-collimator is doubled, but this advantage can easily be offset by the poor quality of the image. Setting up needs great care and much patience. The reflectors must be accurately placed and their full apertures must be utilised. Only good surface reflectors will give any image at all; the best are probably aluminised or rhodiumised glass.

Another special requirement is the illumination of the auto-collimator. The usual lamp is almost certain to be useless and a small projection unit will be needed. Some success has been obtained with lapped steel reflectors and using the projection unit from a dividing head.

Again, only variations in the right angle of the cube will produce variations in reading but the same precautions as in the first method



must be observed. Since the light beam is reflected *twice* in each of the two faces of the cube at each position, variation in angle will produce *twice* the deflection obtained by single reflections. The auto-collimator differences must therefore be halved to give true variations in the angles of the cube.

*EXPERIMENT 38*

## TO CALIBRATE A PRECISION POLYGON (SECOND METHOD)

Experiment 37 dealt with the calibration of a precision polygon or square using two auto-collimators. It may not be possible to obtain two auto-collimators for this and the present experiment provides an alternative method. Unfortunately it still requires some duplication of equipment but this may be more readily available than two auto-collimators. Using a single auto-collimator, the polygon can be calibrated against another similar polygon. The method is still absolute however; calibrations of *both* pieces of equipment are obtained, not just one in terms of the accuracy of the other.

For general class laboratory work, it will be most suitable to use square blocks rather than multi-sided ones. One set of observations has to be produced for each side; a twelve-sided polygon will therefore involve a very long and somewhat tedious experiment, whereas the principles can be learned and practice obtained with four sides only. If both or one of the polygons has more than four sides, only four of the sides at 90° need be used. Thus a polygon and square may be calibrated together. The following description refers to two squares but the method may easily be extended to more sides if required.

### *Apparatus*

Two precision polygons or squares (with lapped optically flat faces).

Auto-collimator, as in Experiment 37.

A circular or rotatable table with fine adjustment; no calibration on the table is necessary.

Suitable surface plate together with mounting equipment, clamps, etc.

### *Method*

The squares are mounted, one on top of the other, reasonably centrally (by eye) on the circular table. The auto-collimator is set





up at such a height that the upper half of its objective covers the upper square and the lower half the lower square. The two squares are mutually adjusted until two distinctly different readings are obtained at the one setting, i.e. the two faces are at a slight angle and produce two images. The separation of the two images is immaterial but should not be greater than necessary. For clarity of description, it will be assumed that the upper square is set to give the higher reading (Fig. 49).

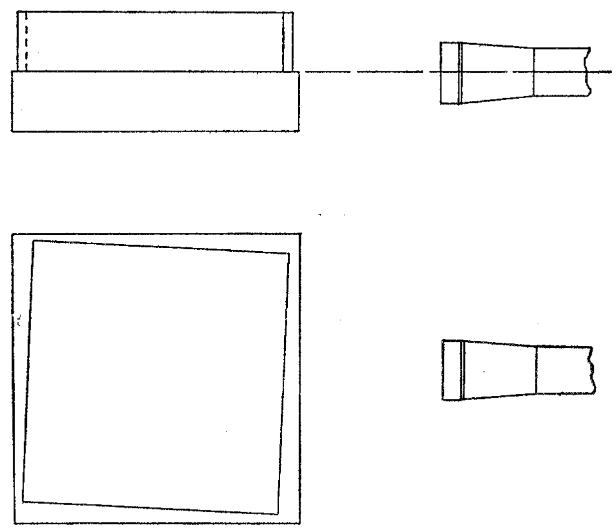


FIG. 49

The images can be identified by masking one face at a time. It will also be assumed that the auto-collimator gives an increasing reading for a clockwise rotation; this is true for the Microptic instrument in its normal position for horizontal reading.

Assume that the lower square has faces $ABCD$ and the upper square has faces $EFGH$, the lettering going anti-clockwise in each case, and that faces $A$ and $E$, $B$ and $F$, $C$ and $G$, $D$ and $H$ are respectively adjacent. Take readings on $A$ and $E$, then rotate the table and take readings on $B$ and $F$, and so on. There is no need to set the same readings each time the table is rotated, although it is best to keep to the same part of the auto-collimator field for convenience and greatest accuracy. It is always unwise to introduce unnecessary variables. Repeat the readings, rotating in the opposite direction. No readings on the dividing table are needed, although these can be useful in setting.

Having obtained one set of readings, rotate the upper square 90° relative to the lower until the next pair of faces is in line, i.e. $A$ and $F$. Take another set of readings, turn the upper square again and so on until four sets have been obtained. Each face on one square will then have been positioned adjacent to each face of the other square.

*Observations and Results*

The four sets of observations should be recorded in the following manner:

TABLE I

Unit = 1 sec.

| *Readings* | | *Diffs.* | *Repeats* | | *Diffs.* | *Mean* | *Second* |
|---|---|---|---|---|---|---|---|
| *Lower* | *Upper* | *E−A etc.* | *Lower* | *Upper* | *E−A etc.* | *diffs.* | *differences* |
| $A$ 10·4 | $E$ 22·6 | 12·2 | 11·0 | 22·4 | 11·4 | 11·8 | −2·4 $d_1$ |
| $B$ 12·6 | $F$ 21·4 | 8·8 | 12·2 | 22·2 | 10·0 | 9·4 | −2·6 $d_2$ |
| $C$ 10·6 | $G$ 18·0 | 7·4 | 10·4 | 16·6 | 6·2 | 6·8 | +2·0 $d_3$ |
| $D$ 11·0 | $H$ 20·4 | 9·4 | 12·0 | 20·2 | 8·2 | 8·8 | +3·0 $d_4$ |

Second differences, $d_1$, $d_2$, etc., are progressive, e.g. $d_1 = 9{\cdot}4 - 11{\cdot}8$ and $d_4 = 11{\cdot}8 - 8{\cdot}8$. They represent differences between corresponding angles of the two squares, upper minus lower. For example, $d_1$ is arithmetically the same as $(F-B)-(E-A)$, and this can be rewritten $(F-E)-(B-A)$, which, if positive, is the amount by which angle $E/F$ is *greater* than angle $A/B$ and, if negative, the amount $E/F$ is *smaller* than $A/B$. All this assumes the condition stated earlier, that the *upper* square $EFGH$ is set to give *higher* readings than $ABCD$.

It should be noted that the errors obtained by this particular arithmetical method represent errors in the angles at the *corners* of the squares. Errors between normals to the faces are opposite in sign. The greatest care should always be taken to work out the logical meaning and sign of final results.



With the squares in their subsequent relative positions, three further tables will be obtained for the following combinations of sides:

| II | III | IV |
|---|---|---|
| $AF$ | $AG$ | $AH$ |
| $d_5$ | $d_9$ | $d_{13}$ |
| $BG$ | $BH$ | $BE$ |
| $d_6$ | $d_{10}$ | $d_{14}$ |
| $CH$ | $CE$ | $CF$ |
| $d_7$ | $d_{11}$ | $d_{15}$ |
| $DE$ | $DF$ | $DG$ |
| $d_8$ | $d_{12}$ | $d_{16}$ |

giving second differences obtained as in Table I.

From these four tables a matrix is drawn up from which can be deduced the absolute errors of both squares:

| | | *Upper square* | | | | |
|---|---|---|---|---|---|---|
| | | $E/F$ | $F/G$ | $G/H$ | $H/E$ | *Sums* |
| *Lower square* | $A/B$ | $d_1$ | $d_5$ | $d_9$ | $d_{13}$ | $s_1$ |
| | $B/C$ | $d_{14}$ | $d_2$ | $d_6$ | $d_{10}$ | $s_2$ |
| | $C/D$ | $d_{11}$ | $d_{15}$ | $d_3$ | $d_7$ | $s_3$ |
| | $D/A$ | $d_8$ | $d_{12}$ | $d_{16}$ | $d_4$ | $s_4$ |
| | *Sums* | $s_5$ | $s_6$ | $s_7$ | $s_8$ | |

In the above matrix, differences are shown between every angle on one square and every angle on the other. Since the sum of all angles on each square is 360°, irrespective of their individual errors:

$$4\ A/B + s_1 = 360° \therefore \text{ Hence, } A/B = 90° - \frac{s_1}{4}$$

Similarly,

$$4\ E/F - s_5 = 360° \text{ and } E/F = 90° + \frac{s_5}{4}$$

and so on with the other sums of lines and columns.

*Conclusions*

As in Experiment 37, the main conclusions to be drawn will relate to the accuracy of measurement and the assessment of experimental error. Accuracy of repetition of readings will be a guide to this. Compare the results with those of Experiments 37 and 39, if available, and estimate the respective accuracies.

## *EXPERIMENT 39*

### TO CALIBRATE A PRECISION POLYGON (THIRD METHOD)

This method adopts the same basic principles as Experiment 38 but can be carried out with only one square or polygon, provided a dividing table or head is available. Instead of comparing each 90° of one square against each 90° of another, four 90° graduations of the dividing table take the place of the second square. The accuracy is, however, likely to be somewhat lower than in the two previous experiments. This need not detract from the value of the experiment.

*Apparatus*

Precision polygon or square (with lapped, optically flat faces).

Auto-collimator.

Circular dividing table or dividing head. Preferably, this should be capable of being read to an accuracy of one second, but, if not, a lower overall accuracy must be expected.

Suitable surface plate, together with mounting equipment, clamps, etc.

*Method*

As in Experiment 38, a polygon or square may be used, but, for class work, it will usually be sufficient to work with a square or use a polygon as a square. A square will be assumed in the following description.

The square is mounted reasonably centrally on the dividing table which is set accurately to its zero position. The square is positioned so that a reflection from one face ($A$) is obtained in the auto-collimator. The table is then rotated through 90° intervals, setting it exactly at each position or setting as closely as possible and taking the actual reading on the scale. The reading of the auto-collimator is also recorded at each position.

Having obtained one set of readings and repeats, the square is rotated 90° on the table so that its first face, which was previously observed with the zero position on the table, is now observed with the 270° reading. Another set of readings is taken, after which the square is moved again and then a third time. Thus, each 90° interval on the dividing table is compared with each 90° angle of the square. It will be seen that the same principle is involved as in Experiment 38.

### *Observations and Results*

As in the two previous experiments, it will be assumed that readings *increase* for clockwise rotation. This applies to both the auto-collimator and dividing table. In the following specimen tables, the table positions are 0°, 90°, 180°, and 270°, and the faces of the square are *ABCD* in the same direction. It is assumed that the table is set to the exact angle at each position.

| *Table posn.* | *Square posn.* | *Auto-collimator (sec.)* | | | *Square angle* | *Diffs. (sec.)* | |
|---|---|---|---|---|---|---|---|
| | | *Reading* | *Repeat* | *Mean* | | | |
| 0° | *A* | 15·4 | 16·8 | 16·1 | *A/B* | +0·8 | ($d_1$) |
| 90° | *B* | 17·6 | 16·2 | 16·9 | *B/C* | −5·1 | ($d_2$) |
| 180° | *C* | 11·0 | 12·6 | 11·8 | *C/D* | +1·8 | ($d_3$) |
| 270° | *D* | 13·2 | 14·0 | 13·6 | *D/A* | +2·5 | ($d_4$) |

The differences in the final column are values of table angles minus angles between *perpendiculars* to adjacent faces of the square or polygon.

From the three subsequent positions of the square relative to table positions, three further sets of four differences will be obtained:

| *Table* | *Square* | | |
|---|---|---|---|
| 0° | *B* $d_5$ | *C* $d_9$ | *D* $d_{13}$ |
| 90° | *C* $d_6$ | *D* $d_{10}$ | *A* $d_{14}$ |
| 180° | *D* $d_7$ | *A* $d_{11}$ | *B* $d_{15}$ |
| 270° | *A* $d_8$ | *B* $d_{12}$ | *C* $d_{16}$ |

From these four tables a matrix is drawn up from which the absolute errors of the square and the dividing table can be found.



| | | *Square* | | | | |
|---|---|---|---|---|---|---|
| | | *A/B* | *B/C* | *C/D* | *D/A* | *Sums* |
| *Table* | 0/90° | $d_1$ | $d_5$ | $d_9$ | $d_{13}$ | $s_1$ |
| | 90/180° | $d_{14}$ | $d_2$ | $d_6$ | $d_{10}$ | $s_2$ |
| | 180/270° | $d_{11}$ | $d_{15}$ | $d_3$ | $d_7$ | $s_3$ |
| | 270/0° | $d_8$ | $d_{12}$ | $d_{16}$ | $d_4$ | $s_4$ |
| | *Sums* | $s_5$ | $s_6$ | $s_7$ | $s_8$ | |

In the above matrix, differences are shown between each angle on the dividing table and each angle on the square. Since the sum of all consecutive 90° angles on the table, and also the sum of angles on the square, is 360°, irrespective of their individual errors:

$$4 \times 0/90 + s_1 = 360°. \text{ Hence, } 0/90 = 90° - \frac{s_1}{4}$$

Similarly,

$$4 \times A/B - s_5 = 360° \text{ and } A/B = 90° + \frac{s_5}{4}$$

and so on with the other sums of lines and columns.

### *Conclusions*

As in Experiments 37 and 38, the main conclusions to be drawn will relate to the accuracy of measurement and the assessment of experimental error. Accuracy of repetition of readings will be a guide to this. Unless the dividing table has a very sensitive setting, the results are unlikely to be as accurate for the square as in the two previous experiments; comments on the comparison should be made if the other results are available.

NOTE. Unlike Experiment 38, in which the 90° *internal* angles of the two squares were compared, values obtained for the angles of the square or polygon by this method refer to angles between *perpendiculars* to the faces or the *exterior* angles between faces.

## EXPERIMENT 40

# TO INVESTIGATE THE MEASUREMENT OF LOBED CYLINDERS

It is now common knowledge to those who make a serious study of dimensional metrology that bodies which appear to be perfectly round when measured on diameter may have an odd number of lobes of quite serious proportions. This experiment seeks to demonstrate this but goes further in showing that similar results may be obtained when elliptical bodies are measured by certain common methods. The same geometrical principles apply to both external and internal measurement, but internal measurement has certain practical advantages for this demonstration.

### *Apparatus*

Three-lobed and two-lobed (oval) internal diameters. Since it is difficult to produce a truly circular bore when it *is* wanted and, perhaps, equally difficult to produce anything but a good round bore when it is *not* wanted, the samples for this experiment will almost certainly have to be specially made ("faked" might be a better word). They can, however, be quite simply produced by grinding bushes of, say, $1\frac{1}{2}$ in. to 2 in. diameter, one in a three-jaw chuck and the other held in two jaws only of a four-jaw chuck. The student will, no doubt, be much more wary of the distortion caused by chucks after this experiment. The amount of tightening will have to be determined by experiment, but variations from roundness of about 0.005 in. should be aimed at. Lobing will, of course, occur only when the specimens are released.

Equipment for measuring the internal diameters will depend on what is available, but it is essential to provide a true diameter measurement, such as on a measuring machine or a bore gauge of the Mercer type, and a three-point internal measurement, such as the type of internal micrometer in which three plungers at 120° are pushed outwards by a cone on the micrometer spindle.

A roundness measuring machine, such as the Talyrond or O.M.T.





instrument, is very useful for the final analysis and confirmation of findings, but is not absolutely essential if not available.

### *Method*

No detailed experimental procedure can be given, since this will depend on the equipment used. In principle, the experiment will consist of measuring carefully the internal diameters of both bushes with both true diameter and three-point systems. Care must be taken to explore the variations to make sure of getting maximum and minimum values in each case.

It will be fairly obvious that the elliptical bore will show its variations in the true diameter measurement and the three-lobed bore will do the same in the three-point measurement. It will also be expected that the three-lobed bore will not show much variation in the true diameter measurement but it may not be so obvious what will happen to the elliptical bore in the three-point measurement.

The whole object of this experiment is to find the reason for the results obtained. No further details will therefore be given at this stage and the student should try to work out his own explanation. A limited geometrical analysis is given in the Appendix; this should give a clue.

If a roundness testing machine is available, charts of the two profiles may be obtained and the errors in roundness shown compared with the results of measurement by the two methods.

### *Observations and Results*

Careful records of all measurements should be made, noting the exact positions on each specimen where maxima and minima occur with each method of measurement.

### *Conclusions*

The conclusions will be the geometrical explanations of the differences found on the two specimens using the two methods of measurement. The type of result to be expected and its geometrical explanation are given in the Appendix. Some remarks on the dangers of attempting to generate circular forms on chucked specimens would be appropriate.

*EXPERIMENT 41*

# TESTS ON A VERTICAL COMPARATOR

*Tests Required*

(a) General inspection.
(b) Rigidity of instrument.
(c) Flatness of table.
(d) Repetition.
(e) Calibration.

*Apparatus*

Vertical comparator.
Set of slip gauges, with calibration chart.
Optical flat.
Accurate cylinder or selected roller.

*Methods*

(a) GENERAL INSPECTION

The instrument and its operating parts should be carefully examined. Operate the clamps on measuring head and table and see whether all the adjustments work smoothly and effectively. Check the effectiveness of the clamps; quite often the fine adjustment to table and/or head may be operated after the coarse adjustment has been clamped. If so, it should operate without too much effort and should have a "stay put" effect, enabling the instrument to be set to a reading to one tenth of a scale division (see B.S. 1054—clause 4). It may be necessary to wring a slip gauge to the table for these tests.

Operate the trigger-raising device if one is fitted and inspect the tip of the measuring plunger. It should have a spherically shaped tip of not less than $\frac{1}{4}$ in. radius; this should be free of appreciable flattening through wear. There should also be some overrun to the plunger movement to avoid damage if it is suddenly depressed. If the instrument is fitted with a mechanical pointer, check that this does not foul the scale or cover glass at any point of its travel.





(b) RIGIDITY

With a slip gauge wrung to the table and the head lowered to give a reading on the scale, make general tests for rigidity. Certain instruments are available with heads of various sensitivities on the same general design. The rigidity, in terms of scale deflection, of a high magnification instrument will not therefore be as good as in one of lower sensitivity.

Placed on a reasonably flat table (not necessarily a surface table) there should be no suspicion of rock. Ideally, the instrument should stand on three feet. The base casting should be adequately webbed and pressure on any part of the base should not cause a deflection exceeding, say, one tenth of one division. Pressure on the top of the column will almost inevitably produce an appreciable deflection, but, on releasing pressure, the pointer should return to its original position within one tenth of a division.

(c) FLATNESS OF TABLE

Check the table carefully with a good optical flat, preferably one which will cover an appreciable area of the surface. Look first for burrs which will be evident by a sudden change in the fringe pattern as the edge of the flat strikes the burr or bruise. Such burrs must be carefully stoned off with a fine stone before proceeding, but students should not do this themselves unless they have been expressly authorised to do so.

Curvature of the table will be shown by curving of the fringes. Curvature amounting to one fringe pitch over the area of the table represents a flatness error of 0·00001 in. The total number of fringes bears no relation to flatness error unless the fringes take the form of complete rings, as is usual on a micrometer face. If the flat is manipulated to produce rings, the number of rings present represents flatness error in units of 0·00001 in.

Tolerance on flatness varies with the magnification of the instrument. Up to $\times 600$ it is 0·00004 in., from 600 to 1000 it is 0·00002 in. and over 1000 it is 0·00001 in. Any error must take the form of a convexity since most wear takes place near the centre of the table, and a concavity could introduce an error when setting on a slip gauge and measuring a smaller object which does not bridge the hollow. If the instrument has had a lot of use, some concavity may show towards the centre, and in such a case the table ought to be relapped.

The difference between convexity and concavity may be detected by pressing the flat near the edge of the table. If the centre of the fringe rings moves towards the point of pressure, the surface is convex. Concavity can best be proved, if suspected, by pressing the centre of the flat and actually distorting it, when the fringes will spread out.

### (d) REPETITION

In B.S.2643—Glossary of Terms, this feature is referred to as "constancy", meaning the reproducibility of a reading over a period of time.

Wring a slip gauge on to the table and adjust to give a reading. Tap the measuring head gently and watch for any change in reading. Roll an accurate cylinder under the measuring plunger from different directions. Variation of reading in either of these tests should not exceed half the tolerance on scale reading shown in Table I. If a trigger-lifting device is fitted, it should be operated when the slip gauge is in place and the slip should then be removed and again slid under the plunger. Variation of reading between these operations should not exceed the whole tolerance in Table I.

### (e) CALIBRATION

B.S.1054 specifies that the comparator shall be calibrated from its zero graduation, first over the positive half of the scale and then over the negative half.

Decide, first of all, on the range of slip gauges to be used to cover the full dial reading and on the intervals at which readings are to be taken. If the range does not exceed ±0·001 in., the selection is quite straightforward. Assuming this to be the case, lay out the 0·1 in. slip and the ten-thousandth series on a surface plate. Great care must be taken to minimise heating effects due to handling both slips and comparator. At the same time, the slips must be well wrung to the table. If a special slip gauge calibration anvil can be fitted, this should be done. Such an anvil sometimes consists of a small diameter face surrounded by an annular face which is about 0·00003 in. lower.

Generally, it will not be necessary to check at every 0·0001 in.; 0·0002 in. intervals would be sufficient over a total range of 0·002 in. Having carefully set zero on the 0·1 in. slip, take readings on the positive half of the scale, using the trigger-lifting device, where fitted. Record errors in units of 0·0001 in. For the negative half, set zero on



the 0·101 slip and work downwards. Repeat each reading, going in the opposite direction.

As an overall check (still assuming the range is ±0·001 in. from zero) use the 0·100 and 0·102 slips.

If the range of the instrument is greater than ±0·001 in., say ±0·005 in., set zero on a higher slip in the thousandth series, e.g. 0·105, and work at 0·001 in. intervals up and down. If time allows, reset zero on 0·1 +0·105 and check at a few intermediate positions using, for example, 0·106+0·1002, 0·107+0·1004, etc., recording these in their appropriate places in the table.

*Observations and Results*

The following method of recording results is recommended:

Comparator type.............. No..............
Slip gauge set no............... Grade............

(a) General inspection
Coarse adjustment
Fine adjustment
Clamping
Trigger operation
(b) Rigidity
(c) Flatness of table
(d) Repetition
Maximum variation (i) on slip — Tolerance $\frac{1}{2}t$
(ii) on roller — „ $\frac{1}{2}t$
(iii) using trigger — „ $t$
For values of $t$ see Table I.
(e) Calibration

The following table is an example of the method of recording calibration observations:

| *Slip (in.)* | *Readings (unit 0·0001 in.)* | | | *Slip error* | *Corrected reading* | *Error* |
|---|---|---|---|---|---|---|
| | *First* | *Repeat* | *Mean* | | | |
| ·100 | 0·0 | 0·0 | 0·0 | −0·05 | 0·05 | 0·0 |
| ·1002 | 2·1 | 2·1 | 2·1 | +0·05 | 2·05 | 0·0 |
| ·1004 | 4·1 | 4·0 | 4·05 | 0·0 | 4·05 | 0·0 |
| ·1006 | 6·0 | 6·2 | 6·1 | 0·0 | 6·1 | +0·05 |
| ·1008 | 7·9 | 8·1 | 8·0 | −0·05 | 8·05 | 0·0 |
| ·101 | 10·2 | 10·1 | 10·15 | +0·05 | 10·1 | +0·05 |

Slip errors are rounded to 0·05 and subtracted from the mean reading. If the comparator scale enables differences closer than 0·00001 in. to be estimated, readings and slip errors should be taken to 0.01.

Continue the table for the negative half of the scale.

TABLE I

TOLERANCES ON SCALE READINGS AS SPECIFIED IN B.S.1054

| *Magnification* Above | *Magnification* including | *Tolerance* t (*Unit* 0·0001 *in.*) | *Magnification* Above | *Magnification* including | *Tolerance* t (*Unit* 0·0001 *in.*) |
|---|---|---|---|---|---|
| 250 | 300 | 0·8 | 1 000 | 2 000 | 0·2 |
| 300 | 400 | 0·6 | 2 000 | 5 000 | 0·1 |
| 400 | 600 | 0·4 | 5 000 | 10 000 | 0·05 |
| 600 | 1 000 | 0·3 | 10 000 | | 0·01 |

The above tolerances are plus or minus.

*Conclusions*

Decide whether the comparator satisfies B.S.1054 or not, detailing any faults or features which are outside tolerance. Assess also the actual accuracy of your observations, particularly the calibration, keeping in mind the effects of any temperature variation and handling of slips.

*EXPERIMENT 42*

## TESTS ON A SCREW DIAMETER MEASURING MACHINE

*Tests Required*

(a) General inspection.
(b) Concentricity and alignment of centres.
(c) Flatness and parallelism of micrometer and indicator faces.
(d) Parallelism of micrometer faces to line of centres.
(e) Calibration of micrometer.
(f) Repetition and sensitivity of fiducial indicator.

The tests and tolerances specified in this experiment are in accordance with the specification of accuracy for this type of machine, laid down by N.P.L. The methods of test which follow are, however, not necessarily those used or recommended by N.P.L. since possible limitations of laboratory facilities have been taken into account. Not all the N.P.L. tests have been included.

*Apparatus*

Screw diameter measuring machine, N.P.L. type.
Surface table or surface plate.
Slip gauges.
Dial indicator, preferably light pressure lever type.
Short mandrel or mandrels which must be straight, parallel and concentric on their own centres within 0·0002 in. total variation. Cylindrical setting standards may be used.
Two thread measuring cylinders (wires) preferably for a fairly coarse pitch, e.g. 10 or 12 tpi.
Optical flat, or a set of special micrometer optical flats.
Various sizes of balls or short rods with balls fixed at each end.
Straightedge (about 12 in.) or a right-angle plate.
Vee block for testing centres.
Projector, if desired, for examining centres.
Lapped surface plate.

*Methods*

(a) GENERAL INSPECTION

Examine the machine carefully without dismantling it. Look for:

Smoothness of float and slide of top and bottom carriages
Smoothness of micrometer traverse and concentricity of drum
Action of fiducial indicator
Condition of micrometer and indicator faces

Take off the top and intermediate carriages, taking care not to lose the balls, and look for:

Indentation of vee ways by balls
Condition of balls—corrosion or flats—diameter should be uniform to 0·0001 in.
Condition of centres—particularly damage on points
Firm clamping of centres and freedom when unclamped

(b) CENTRES

Remove the centres and examine them for straightness against a good surface plate, preferably lapped. Errors in straightness, uniformity and equality of diameter should not exceed 0·0002 in.

Examine concentricity of cone with shank. This may be done by placing a mandrel between centres and rotating each centre in turn with a dial indicator, preferably of the light pressure lever type, measuring movement of the mandrel at the end near the rotating centre. Eccentricity should not exceed 0·0002 in. (0·0004 in. total indicator variation).

If the centres are not within the specified tolerances for straightness and concentricity, the following tests for alignment will not be very reliable as random errors may be introduced. Assuming the centres are satisfactory, replace them in the machine pillars and proceed to test for alignment.

Stand the base casting on a surface plate and check over the shanks of the centres near the pillars with a dial indicator to get the two heights equal above the plate, packing up the base if necessary. Clamp each centre at several positions along its length and check for parallelism with the plate. The measuring axis (micrometer-indicator) should be at the same height as the line of centres within 0·03 in. Carry out similar checks in the horizontal plane by running the indicator base along a straightedge, making sure, of course, that the casting does not move relative to the straightedge. Alternatively, set the base of the casting against a vertical surface, such as an angle plate, and work from the surface table.



Bring the points of the centres together at several positions over the range of adjustment and examine their coincidence with a lens. Finally, mount a short mandrel, or several different lengths of mandrel, between the centres and check for alignment with the surface plate and straightedge. Make sure that the mandrels themselves are parallel, straight and concentric with their centres. Rotate the centres to various positions during these tests.

The foregoing complete tests on centres are fairly lengthy. If it is felt that they take up too much of the time available, the final functional tests with mandrels should suffice to indicate serious errors but will not, of course, be analytical. Alignment errors shown by the mandrels should not exceed 0·0002 in. per inch.

(c) FLATNESS AND PARALLELISM OF MICROMETER AND INDICATOR FACES

Flatness of both micrometer and indicator faces should be checked with an optical flat (Fig. 50). They will normally be slightly convex and must not be concave. The number of interference rings obtained will represent the error in flatness in units of 0·00001 in. Tolerance 0·00003 in.

Parallelism should be checked in several positions within the range of adjustment of the indicator in its pillar and also the range of adjustment of the head and tailstocks (where provided). At small separations, parallelism is conveniently checked with a set of special micrometer testing optical flats, if available, but in any case it should be checked at varying separations to cover positions of rotation of the micrometer, unless it has a non-rotating anvil. At larger separations, larger balls or two balls soldered one at each end of a rod should be used (Fig. 51). These are applied at centre, north, east, south and west positions on the faces and any variations noted. The special micrometer optical flats may also be extended by wringing to suitable sizes of slip gauges. The tolerance on parallelism is 0·0001 in. over the diameter of face. The face of the indicator must be square to the bearing shank to within 0·00003 in. The indicator is best rotated in a vee block, the reflection from its face being

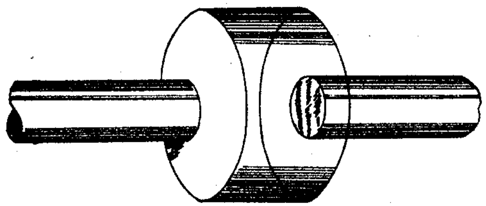


FIG. 50

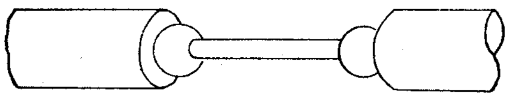


FIG. 51

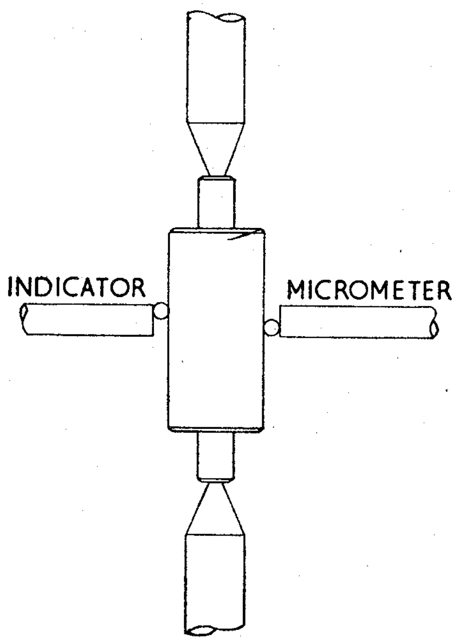



FIG. 52



observed with an auto-collimator. If the micrometer has a rotating spindle, the face must be square with the axis to within 0·00005 in. This may be tested *in situ* in a similar manner.

### (d) PARALLELISM OF MICROMETER FACES TO LINE OF CENTRES

Assuming that previous tests on centres and micrometer faces have shown them to be satisfactory, parallelism of faces with line of centres may be checked quite simply by measuring over wires on to mandrels or cylindrical standards. It is assumed that these have already been tested for parallelism and concentricity. Place one wire between the indicator face and the mandrel, not centrally on the face but near to the edge, either back or front. Place the other wire between the micrometer face and the mandrel near the opposite edge of the face and take a micrometer reading (see Fig. 52). Shift the wires to the other sides of their respective faces and take another reading. Half the difference in readings will be the error in alignment. If time allows, several diameters of mandrel may be used and measurements taken at two or three positions along the traverse of the lower carriage. Alignment error should not exceed 0·0001 in. over the diameter of micrometer face.

### (e) CALIBRATION OF MICROMETER

The micrometer is calibrated in the usual way,* using slip gauges. More care is required, however, than when calibrating an ordinary micrometer, due to the increased sensitivity, and slip gauges must be handled very carefully to avoid heating. The checks on progressive and periodic error should *not* be combined. Progressive error should be checked every tenth of an inch and two separate revolutions should be checked at 0·005 in. intervals for periodic error. The slip gauges must be supported so that they are quite free to align themselves to the anvils. A wooden lever-type clothes-peg, suitably shaped, makes a useful grip for slips and avoids handling them.

Plot the progressive and periodic errors separately. Periodic errors should be inset just above their nominal positions on the main curve but should not be included in the progressive curve. Do not use too large a scale; one inch to represent 0·0001 in. error is more than adequate.

* See Experiment 5.

Tolerances on calibration are:

Progressive error 0·0002 in.
Periodic error ±0·00003 in.

(f) FIDUCIAL INDICATOR

During the calibration of the micrometer, make a repetition check on the indicator and do the same with wires over a cylindrical standard in test (d), placing both wires central on the faces and rocking them back and forward. The tolerance on repetition is 0·00002 in. Check that the indicator plunger, when pushed right in, comes up to a positive stop and does not feel springy.

The sensitivity of the indicator may be checked, if desired, against the micrometer. The distance moved by the pointer may be measured by holding a scale against the window or marking a suitable distance on the window. Calculate the magnification of the pointer movement. It should not be less than 150 times.

The measuring force of the plunger when the pointer is against its index may be checked if means are available such as calibrated spring plungers or a suitable weight loading fixture. It may be necessary to remove the indicator from the machine for this test. The force should lie between 8 oz and 16 oz.

*Report and Conclusions*

Write a concise factual report on your findings under each heading, stating tolerances, and conclude whether or not the machine is satisfactory. Detail any faults which render it unsatisfactory.

*EXPERIMENT 43*

## TO MEASURE SLIP GAUGES ON AN N.P.L. TYPE GAUGE INTERFEROMETER

Before proceeding with this experiment, the student should take careful note of the following points:

(1) The gauge interferometer is capable of measuring the lengths of slip gauges to an accuracy of one millionth of an inch, under suitable conditions.

(2) The most important condition required to obtain this accuracy is constancy of temperature. This should be within one degree of 20°C. and remain constant to 0·1°C.

(3) These conditions are not easily achieved in the class laboratory, even when the equipment is housed in a specially temperature-controlled room. If the number of people in the room changes, the control will be upset. This is difficult to avoid if two or more students are working and the tutor or supervisor has to enter occasionally.

(4) Accuracy of results will therefore be limited and some variations from previously certified sizes of gauges, e.g. on an N.P.L. certificate, are to be expected. Errors can be minimised if small slips are selected for the experiment, say up to 0·150 in.

(5) For maximum accuracy, a second set of observations should be made with the slips turned over and the opposite face wrung on to the platen. There is not usually time for this in a class laboratory period, particularly as further time would have to be allowed after re-wringing for the temperature to become stable.

(6) The educational value of this experiment does not, however, depend entirely on the accuracy of the final results. It provides an excellent example of advanced metrology where a number of interdependent observations have to be accurately made and carefully reduced. In much of the industrial metrology equipment in use today high accuracy is, of necessity, easily achieved and may unfortunately give the student the impression that "there is nothing in it".

(7) The observational procedure which follows is necessarily abridged to be possible within a normal college laboratory period of, say, two hours. While the experienced operator could do much more in the time, the student handling the equipment for the first time will find such a period none too long. Even then, it is a great help if the slip gauges can be set up an hour or so before the student begins the experiment. The room temperature control should also have been operating for at least this length of time.

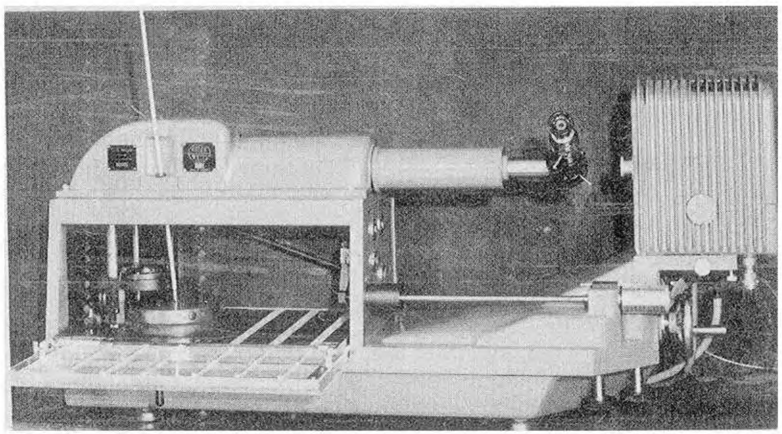


FIG. 53. NLP—HILGER INTERFEROMETER

*Apparatus*

N.P.L. type of gauge interferometer. There are two types of this instrument in general use. One is the simpler pattern which was first developed by the N.P.L. in which the optical system is mounted on an optical bench and the platen stands separately. The whole must stand on a rigid support such as a slate or concrete-topped bench or a heavy surface plate. The whole optical system is open to view and its operating principles can therefore be quite easily seen. A more recent version of this instrument has been developed by Hilger & Watts Ltd. in collaboration with the N.P.L. It is mounted on a rigid base casting, the slip gauge platen and most of the optical system being completely enclosed. Greater accuracy

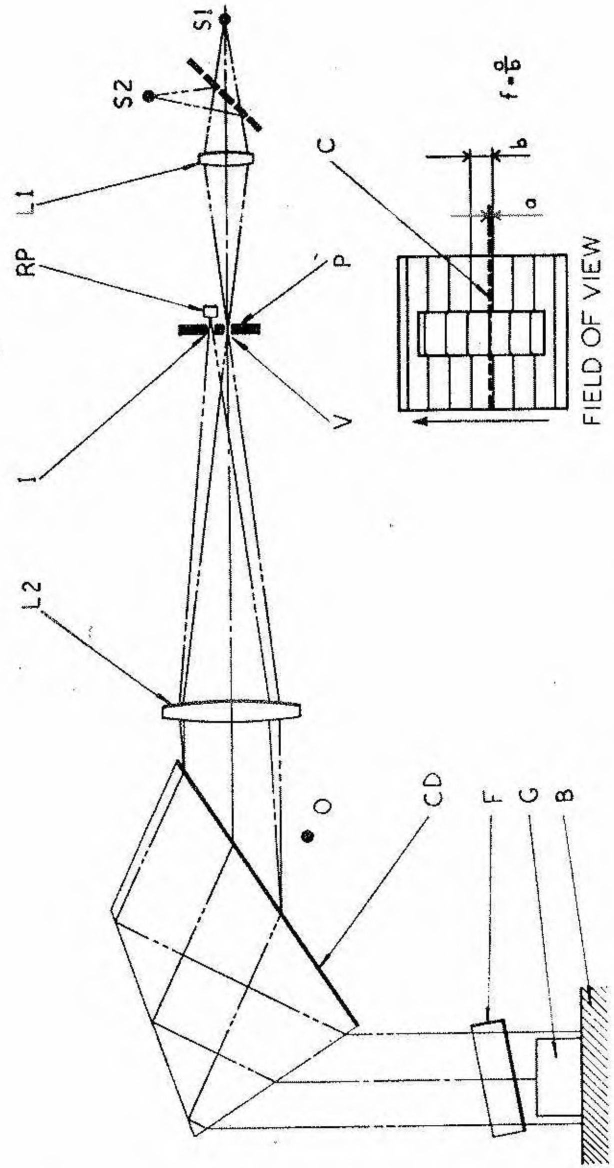



DIAGRAM OF OPTICAL SYSTEM

FIG. 54

P

can be achieved with this instrument but it is not so easy to investigate the working parts. This instrument is illustrated in Fig. 53 and the optical arrangement, which is common to both, is shown in Fig. 54. Other types of interferometer, such as the Kösters-Zeiss, may also be used. The optical system of the latter is different, as are certain of the details of operation, but the actual observations and subsequent calculations are similar. The N.P.L. flatness interferometer is not suitable for this work.

A hot-cathode cadmium lamp is normally supplied and, in addition, a mercury-198 cold-cathode or electrodeless lamp may be provided. The mercury lamp needs a water supply for cooling. Power supply units, to suit the lamp or lamps being used, are required.

Slip gauges for measurement. Several slip gauges, preferably between 0·1 and 0·150 in., should be selected from a set of Calibration or Reference grade (B.S. 888). Inspection, or even Workshop, grade slips could be used but, if so, they should be chosen from the set for a high degree of flatness and parallelism. B.S. tolerances for flatness and parallelism for sizes up to 1 in. are: Calibration and Reference 3 $\mu$in., Inspection 5 $\mu$in., Workshop 10 $\mu$in. Three or four gauges will be enough for a normal experimental period.

Mercury barometer, Fortin type.

Means of measuring vapour pressure, such as a wet and dry bulb thermometer. The aspirated type known as the Assman Psychrometer is particularly suitable as it enables readings to be taken without delay if the wet bulb has to be freshly moistened.*

Celsius thermometer, reading to 0·01 or 0·02°C., preferably certified by N.P.L.

Special slide rule(s) for determining coincidences. Scales are given on pp. 240 and 241 in case a slide rule is not available.

Tables of corrections to barometric pressure for temperature and latitude; corrections for vapour pressure and temperature. Tables of nominal excess fractions for different wavelengths and various gauge sizes. These are normally provided with the interferometer, but tables and scales from which all the above can be calculated are given on pp. 236–241.

*Basic Theory*

Referring to the diagram of the optical system (Fig. 54), it will be seen that the light is focused by a condensing lens $L_1$ on a slit $V$ which is itself in the focal plane of a collimating lens $L_2$. The light from the cadmium lamp, for example, has four lines in its spectrum, red, green, blue and violet, and the parallel beam passes from the collimator to the dispersing prism $CD$ where, due to the different refractive index for each line, it is split into its four constituent wavelengths, each emerging at a slightly different angle. Careful rotation of the prism will bring each beam in turn normal to the lapped platen beneath the prism.

* See note on p. 228.



Before reaching the platen $B$, the beam passes through the optical flat $F$, supported on an adjustable mount, which can be inclined at a slight angle to the platen. Conditions are therefore right for the production of straight interference fringes between the light reflected from the platen and that reflected from the underside of the optical flat. The reflected interfering beam returns along almost the same path and is brought to a focus in a second slit $I$ very close to the first where it is deflected through a right angle into the eyepiece.

If a slip gauge $G$ is wrung onto the platen in the field of view, the interference fringes will cross it. If the length of the slip is an exact number of *half*-wavelengths the fringes will appear to go straight across in unbroken lines. The pitch between fringes represents a difference of one half-wavelength in the wedge thickness between the optical flat and the reflecting surface—platen or slip gauge. Thus, if the length of the slip gauge is a whole number plus a fraction of half-wavelengths the fringes across the slip will be displaced from those across the platen by the same fraction of the fringe pitch (see inset in Fig. 54).

Obviously, we cannot count the whole number of half-wavelengths but we can see and estimate the fraction. If the same length is observed under several different wavelengths, there will generally be a different fraction for each. With, say, four distinct wavelengths a particular combination of excess fractions will occur at only one value of length within quite a wide size range.

The differences between the observed fractions and the calculated fractions for the nominal length give the error in length of the gauge. It is important to realise that the error *could* be calculated from one wavelength only, if the whole number of fringe displacements from nominal size could be known. This is one reason for using several wavelengths in the method of coincidences, but the same certainty could be achieved if the size of the gauge were previously known to 0·00001 in. In addition, of course, the use of four wavelengths provides four determinations, the mean of which will be more accurate than a single reading.

The actual wavelengths of the light vary slightly with the refractive index of the air. This depends on its composition (including the presence of moisture and carbon dioxide) and its density. Hence the need for observing ambient conditions of temperature, barometric pressure and vapour pressure.* In addition to the effect of temperature on wavelength, an accurate determination of the temperature of the slip gauges themselves is essential to relate their measured sizes to sizes at the standard temperature of 20°C. The accuracy of temperature measurement needed for this purpose is far higher than for vapour pressure and barometer correction.

### *Method*

To avoid wasting valuable time in a class laboratory period, it is necessary to set up the equipment about an hour before the experiment is to commence. The slip gauges should be selected and wrung to the platen in radial positions. A few drops of paraffin rubbed over the platen will assist wringing but the gauges must be firmly wrung down. It may be as well to check each gauge for burrs, using an optical flat. This can be done at the same time as the selection of gauges, if they are inspection or workshop grade, for flatness and parallelism.

Adjust the height of the optical flat on the interferometer so that it clears the largest gauge on the platen. *On no account should the undersurface of the flat be touched* or allowed to come into contact with the gauges as it is coated with bismuth oxide to increase reflectivity and this coating is easily damaged. Place the thermometer in contact with the platen (through the aperture provided on the Hilger instrument).

Adjustment of the dispersing prism is usually made with a micrometer head on the open type instrument and a table of the readings corresponding to the various wavelengths should be available. If not, they will have to be determined by trial, but this should be done prior to the class experiment as it may take some time. On the Hilger instrument the wavelength drum is marked with the cadmium and mercury wavelength positions, but a little adjustment

* Neglect of the vapour pressure correction will not normally lead to an error greater than 0·3 $\mu$in. per inch.



from the exact setting may be required to get the best viewing conditions.

It is important to adjust the direction of inclination of the optical flat so that the apex of the wedge is in a known position. It will be realised that the excess fractions must be estimated in a direction leading *away* from the wedge apex, and the following convention of setting and reading should be adopted:

> When adjustment of the optical flat causes the fringes to move *closer together* they should move *downwards*. The direction of reading the excess fractions should then be *upwards*. This is shown in Fig. 54 and corresponds to the direction of inclination shown.

The adjustment is made with the supporting screws of the optical flat on the open instrument and with the two knobs beneath the casting to the right on the Hilger instrument. Settings are best carried out with the cadmium green wavelength as this is the most distinct.

On the Hilger–N.P.L. interferometer, the fringes must close up when the right-hand knob is screwed up. On the open type instrument, the fringes must close up when the central adjusting screw under the prism is turned clockwise to raise the optical flat. If the fringes open out with these operations, the adjustment must continue until the parallel position is passed and the fringes close again.

The observations should be made with the fringes lying across the width of the gauge face. On the Hilger interferometer, the left-hand knob of the two beneath the casting mainly affects the inclination of the fringes. Once they have been set straight across the gauge, the right-hand knob will adjust the spacing without causing any appreciable inclination. The estimation of fractions is, theoretically, independent of the number of fringes across the gauge and this is a matter of personal choice. A balance has to be struck between sharply defined fringes closely spaced or fuzzy fringes widely spaced, but wider spacing does not make it easier to estimate the fraction. Four or five fringes are usually found to be best.

Using each wavelength in turn, estimate the fractional upward displacement of the fringes on the gauge from those across the platen. It will generally be sufficient to use one source of light, either cadmium or mercury; each provides four wavelengths. When using the mercury lamp, however, it is useful to take a reading in cadmium red also. The mercury spectrum covers a smaller range of wavelengths than cadmium but is necessary when measuring longer gauges. Having been through the wavelengths in one direction on the first gauge, turn to the next gauge on the platen, reversing the sequence of wavelengths, and so on. Take a repeat set of readings if time allows and, if further time can be allowed to wring the gauges the other way up and wait for them to settle, a further set may be taken, but this is a refinement necessary only if the calibration is required for permanent future reference.

Before or during the observations on the interferometer the auxiliary readings must be taken. The readings required are:

Barometer
Thermometer on barometer
Vapour pressure (wet and dry bulb thermometer)
Temperature inside interferometer

The barometer should be of the Fortin type and the chamber screw must first be adjusted to bring the surface of the mercury exactly to the tip of the index pointer, i.e. so that the pointer and its reflection just meet. The cursor near the top of the barometer tube is then adjusted so that its front and back edges in line coincide with the top of the mercury meniscus. The barometric height is then read to the nearest 0·01 mm on the vernier scale. The reading of the thermometer on the barometer is also noted.

If a simple wet and dry bulb thermometer is used, the two readings are recorded. If the psychrometer is used, the wick must be wetted, taking care not to saturate it. The fan is then started and readings taken after about one minute.

The thermometer placed in contact with the gauge should be calibrated 0·01°C. and should have been certified by N.P.L. This thermometer must be carefully watched, the range of any temperature variations being noted. Such variations ought not to exceed 0·1°C. if millionth accuracy is to be achieved even with quite short gauges, but such control will not always be achieved under class conditions.

*Observations and Results*

(a) AUXILIARY OBSERVATIONS

Record readings of the barometer (and its thermometer), wet and dry bulb thermometer, and the thermometer in the interferometer in the manner shown in the example following:



Slip Gauge Set No. 12345 Grade: Calibration

AUXILIARY OBSERVATIONS

1. *Barometric pressure*

| | |
|---|---|
| Barometer reading: 746·2 mm at 20·5°C. | |
| Correction for temperature (Table I) | −2·5 mm |
| Correction for latitude 52° (Table II) | +0·4 mm |
| Resultant corrected reading | 744·1 mm |

Any significant correction for barometer calibration should also be applied.

2. *Vapour pressure*

Wet and dry bulb thermometer readings

| | | |
|---|---|---|
| Dry bulb ($t_d$) 20·3°C. | Wet bulb ($t_w$) | 16·2°C. |
| | $t_d - t_w$ | 4·1°C. |

3. *Mean temperature*

Thermometer No. 45678 inside interferometer

| | | |
|---|---|---|
| Reading: 20·36°C. | Correction (N.P.L. certificate) | +0·02°C. |
| | Corrected reading ($t$) | 20·38°C. |

CORRECTIONS TO GAUGE LENGTH

| | | Unit |
|---|---|---|
| 1. *Wavelength correction* | | $1 \times 10^{-6}$ in. |
| (a) for barometric pressure (Fig. 55) | | |
| for 744·1 mm at 20°C. +5·7 | | |
| additional for 20·38°C. +0·35 | Total | +6·05 |
| (b) for vapour pressure (Table III) | | +0·10* |
| 2. *Temperature correction* | | |
| $12 \times (20 - 20{\cdot}38)$ | | −4·56 |
| 3. *Obliquity correction* | | |
| Constant from N.P.L. certificate for interferometer | | +0·11 |
| TOTAL CORRECTION FACTOR | | +1·70 |

* See note on p. 228

The correction to be applied to the observed size of each gauge is therefore:

$$\text{Nominal size of gauge} \times 1{\cdot}70 \times 10^{-6} \text{ (plus)}$$

*Explanation of corrections*

1. The actual wavelength being used at any one time depends on the refractive index of the medium through which the light passes. Standard air for metrology is at 20°C., 760 mm mercury barometric pressure, 10 mm vapour pressure and 0·03% $CO_2$ by volume.

If $\lambda_a$ is the actual wavelength at temperature $t$°C., barometric pressure $h$ mm and vapour pressure $f$, the relationship between $\lambda_a$ and the wavelength in standard air ($\lambda_s$) is:

$$\frac{\lambda_a}{\lambda_s} = 1 + \left[A - \frac{Bh'}{1+\alpha t} + C(f-10)\right] \times 10^{-6}$$

where $\alpha = 0{\cdot}003661$ per deg C
$h' = h(1+\beta_t h)$
$\beta_t = (1{\cdot}049 - 0{\cdot}0157\ t) \times 10^{-6}$

$A$, $B$, and $C$ are constants for the wavelength, but average values of these may be used with sufficient accuracy.

The scale in Fig. 55 and Table III give the arithmetical values of these corrections for a range of conditions of temperature, barometric pressure and vapour pressure. These values are in micro-inches per inch of gauge length.

2. The direct temperature correction to gauge length assumes a coefficient of expansion for steel of $12 \times 10^{-6}$ per deg. C., and the expansion or contraction from 20°C. is calculated in micro-inches per inch.

3. The obliquity correction is a constant for the instrument and is due to the slight separation of the transmission and observational slits. Its value will be given on the N.P.L. certificate for the interferometer and will be about $+0{\cdot}1$ and $+1{\cdot}3$ micro-inch per inch respectively for the Hilger and earlier N.P.L. instruments.

(b) INTERFEROMETER OBSERVATIONS

Record the fractional displacements for the wavelengths used on each gauge measured. The specimen tabulation shown on p. 234 is recommended.



Estimate the fractions to the nearest tenth of the spacing between the fringes as if they were scale lines on an instrument, reading upwards. The advantage of adjusting for fairly fine fringes will be appreciated here.

From each fraction subtract the nominal fraction for the particular wavelength and size of the gauge. These will usually be found in tables supplied with the instrument, but, if not, values must be calculated.

This is done by dividing the nominal size of gauge by the *half*-wavelength and taking the first two decimal places, ignoring whole numbers, in the quotient. Multiplying the size by the number of half-wavelengths per inch (Table IV) has the same effect. Table V gives some key values from which fractions for any size may be calculated.

It is important that the nominal value is always *subtracted* from the observed value even though it may be numerically larger, e.g. ·2 (observed) minus ·65 (nominal) = ·55, the ·2 being regarded as 1·2.

Having obtained a set of differences in four wavelengths for a particular gauge, it now only remains to determine the error in size and apply corrections. Special slide rules enable this to be done quickly and accurately and the scales in Figs. 56 and 57 serve the same purpose.

Since the whole number of half-wavelengths in the error is unknown, the first trial will assume this to be zero. Using the cursor of the slide rule, set to the fractional difference recorded for the longest wavelength $\lambda_1$, and check the readings on the other scales against the respective observed fractional differences.

If the observations have been reasonably accurate, it should be quite obvious whether the right order value has been chosen or whether the next whole number range should be tried. Check in the positive range first, and if this is unsuccessful try the negative range in the same way. There is here one important difference. Negative fractions are *not* read from zero to the left; they are read from left to right so that, for example, minus ·22 is read as $\bar{1}{\cdot}78$, $\bar{2}{\cdot}78$ and so on. This is similar to the use of a negative characteristic in logarithms. In the numerical example given, coincidence is found in the negative range, and a study of the scales will show that the values recorded have been read from left to right from the $\bar{1}$ line. Exact coincidence of all four values on the scales is unlikely to be obtained and the best mean position should be found where the algebraic sum of the discrepancies between differences and scale values is a minimum. A small residual error may be ignored; the nearest 0·5 $\mu$in. should be taken. The error is then read off in micro-inches on the scale. If the unit required is microns (0·001 mm), multiply the micro-inch figure by 0·025; this is accurate to within 2% of error value.

The total correction factor found from the auxiliary observations is then multiplied by the nominal size of the gauge and is added to or subtracted from the observed error. In the example shown, the actual correction is $+1{\cdot}7 \times 0{\cdot}145 = +0{\cdot}24$. This should be rounded to the nearest 0·1 and will therefore be +0·2.

SPECIMEN TABLE OF OBSERVATIONS

| Gauge size: 0·145 in. | | | Marked side up | | |
|---|---|---|---|---|---|
| Lamp: Cadmium | | | Surface errors: 2 $\mu$in. | | |
| | Excess fractions | | | | |
| | $\lambda_1$ | $\lambda_2$ | $\lambda_3$ | $\lambda_4$ | |
| Reading | ·2 | ·0 | ·4 | ·0 | |
| Repeat | ·2 | ·9 | ·4 | ·1 | |
| Mean | ·20 | ·95 | ·40 | ·05 | |
| Nominal | ·54 | ·33 | ·04 | ·46 | |
| Difference | ·66 | ·62 | ·36 | ·59 | Equivalent micro-inch |
| Scale value | $\bar{1}\cdot64$ | $\bar{1}\cdot55$ | $\bar{1}\cdot52$ | $\bar{1}\cdot51$ | −4·5 |
| | | | Total correction | | +0·2 |
| | | | True error | | −4·3 |

Notes:

1. Surface errors of flatness and parallelism are checked in the green wavelength ($\lambda_2$) by observing the curvature and inclination of the fringes across the gauge relative to those across the platen.

2. Note that the difference is always "mean minus nominal", even though nominal is larger, e.g. ·20 − ·54 = ·66.

3. Inspection will show that only the scale values above, corresponding to −4·5 $\mu$in., come near to the observed coincidence of difference values. If other positions are tried, e.g. one half-wave-length on either side, setting to ·65 on $\lambda_1$, the following values are found to coincide:

| | | | | |
|---|---|---|---|---|
| $\bar{2}\cdot65$ | $\bar{2}\cdot29$ | $\bar{2}\cdot19$ | $\bar{2}\cdot14$ | equivalent to −17·1 $\mu$in. |
| +0·65 | +0·82 | +0·87 | +0·90 | equivalent to + 8·2 $\mu$in. |

These obviously do not fit the observed differences, and trials at other positions will show even greater divergences.

4. There will be a similar table for each gauge measured.



### *Conclusions*

The errors found on the gauges measured should be compared, where possible, with an accepted table of errors. This may be found on a certificate issued by the N.P.L. or the gauge manufacturer, or from a previously accepted calibration made in the laboratory. Agreement to one or two millionths should be regarded as satisfactory; too much attention must not be paid to the tenths of a micro-inch shown in the final evaluation. Results may also be compared with the appropriate tolerances for the grade of slips, as given in B.S. 888.

The most important conclusions to be drawn from the experiment are, therefore, the assessment of overall accuracy of measurement and the explanation of any appreciable discrepancies with accepted values. Temperature variation will be the greatest hazard, provided reasonably competent interferometer observations have been made.

It should be remembered that the method described here is somewhat abridged and the tables, graphs and scales are of slightly lower accuracy than those issued with an instrument certified by N.P.L. A few finer points, such as the correction for difference in height between barometer and interferometer and possible variation of phase difference on reflection at different surfaces, have also been neglected.

Reasonable temperature control and a set of observations which give good coincidences should, however, produce an overall accuracy of about one micro-inch for gauges up to 0·2 in.

### TABLE I

CORRECTIONS TO BAROMETER READINGS FOR TEMPERATURE OF BAROMETER

| *Barometer reading* | 650 *mm* | 750 *mm* | 850 *mm* |
|---|---|---|---|
| Temperature (°C) | Corrections (mm) | | |
| 18 | −1·9 | −2·2 | −2·5 |
| 20 | −2·1 | −2·4 | −2·8 |
| 22 | −2·3 | −2·7 | −3·0 |

All corrections are subtracted from barometer reading. Values of temperature and barometer reading may be interpolated or extrapolated.

### TABLE II

CORRECTIONS TO BAROMETER READINGS FOR LATITUDE (Variation in gravity)

| *Barometer reading* | 650 *mm* | 750 *mm* | 850 *mm* |
|---|---|---|---|
| Latitude (degrees) | Corrections (mm) | | |
| 45 | 0·0 | 0·0 | 0·0 |
| 40 or 50 | 0·3 | 0·3 | 0·4 |
| 30 or 60 | 0·9 | 1·0 | 1·1 |
| 20 or 70 | 1·3 | 1·5 | 1·7 |
| 10 or 80 | 1·6 | 1·9 | 2·1 |

The correction is added for latitudes over 45° and subtracted for those under 45°. Values of latitude and barometer reading may be interpolated or extrapolated from the above figures.



### TABLE III

CORRECTIONS FOR VAPOUR PRESSURE

| Temperature (wet bulb) $t_w$°C | Temperature difference $(t_d - t_w)$°C 2 | 4 | 6 | 8 | 10 |
|---|---|---|---|---|---|
| | Corrections $\mu$ in. $C(f-10)$ | | | | |
| 12 | −0·05 | −0·10 | −0·15 | −0·2 | −0·25 |
| 14 | +0·05 | 0·0 | −0·05 | −0·1 | −0·15 |
| 16 | +0·15 | +0·1 | +0·05 | 0·0 | −0·1 |
| 18 | +0·25 | +0·2 | +0·15 | +0·1 | +0·05 |
| 20 | +0·35 | +0·3 | +0·25 | +0·2 | +0·15 |
| 22 | +0·5 | +0·45 | +0·4 | +0·3 | +0·25 |

### TABLE IV

VALUES OF WAVELENGTHS (in standard air)

| | *Wavelength* $\times 10^{-6}$ *in.* | *Number of half-wave-lengths per inch* |
|---|---|---|
| CADMIUM | | |
| Red | 25·348 4398 | 78 900·3195 |
| Green | 20·023 0248 | 99 885·0084 |
| Blue | 18·897 3858 | 105 834·7446 |
| Violet | 18·418 0091 | 108 589·3697 |
| MERCURY 198 | | |
| Yellow (1) | 22·798 0087 | 87 726·9601 |
| Yellow (2) | 22·715 0780 | 88 047·2433 |
| Green | 21·499 1441 | 93 026·9592 |
| Violet | 17·158 9020 | 116 557·5746 |

The above values are based on the international inch, which is exactly 25·4 mm. The mercury 198 values are for a cold-cathode lamp. Values for an electrodeless lamp are slightly different.

### TABLE V

### NOMINAL FRACTIONS FOR KEY VALUES IN SLIP GAUGE SIZE

| *Value (in.)* | CADMIUM | | | | MERCURY 198 | | | |
|---|---|---|---|---|---|---|---|---|
| | $\lambda_1$ *red* | $\lambda_2$ *green* | $\lambda_3$ *blue* | $\lambda_4$ *violet* | $\lambda_1$ *yellow 1* | $\lambda_2$ *yellow 2* | $\lambda_3$ *green* | $\lambda_4$ *violet* |
| 1·0 | ·320 | ·008 | ·745 | ·370 | ·960 | ·243 | ·959 | ·575 |
| 0·1 | ·032 | ·501 | ·474 | ·937 | ·696 | ·724 | ·696 | ·757 |
| 0·01 | ·003 | ·850 | ·347 | ·894 | ·270 | ·472 | ·270 | ·576 |
| 0·001 | ·900 | ·885 | ·835 | ·589 | ·727 | ·047 | ·027 | ·558 |
| 0·0001 | ·890 | ·989 | ·583 | ·859 | ·773 | ·805 | ·303 | ·656 |

The fraction for any value may be obtained by combining multiples of the above values; e.g. 0·145 in. cadmium $\lambda_1$ is computed from:

0·1 = ·032 × 1 = ·032
0·04 = ·003 × 4 = ·012
0·005 = ·900 × 5 = ·5 (actually 4·5, but the whole number is ignored)
Total 0·145 = ·544

As illustrated in the value for 0·005 above, any whole number arising from multiplication or in the sum is ignored. Values of fractions in the table have been given to three places of decimals to minimise errors in the second place when multiplying. The final sum value must be rounded off to the nearest ·01; e.g. ·544 above will become ·54.

The formulae, tables and scales in this experiment have been computed and adapted from data provided by the National Physical Laboratory, to whom due acknowledgment is made. The authors, however, accept full responsibility for accuracy.

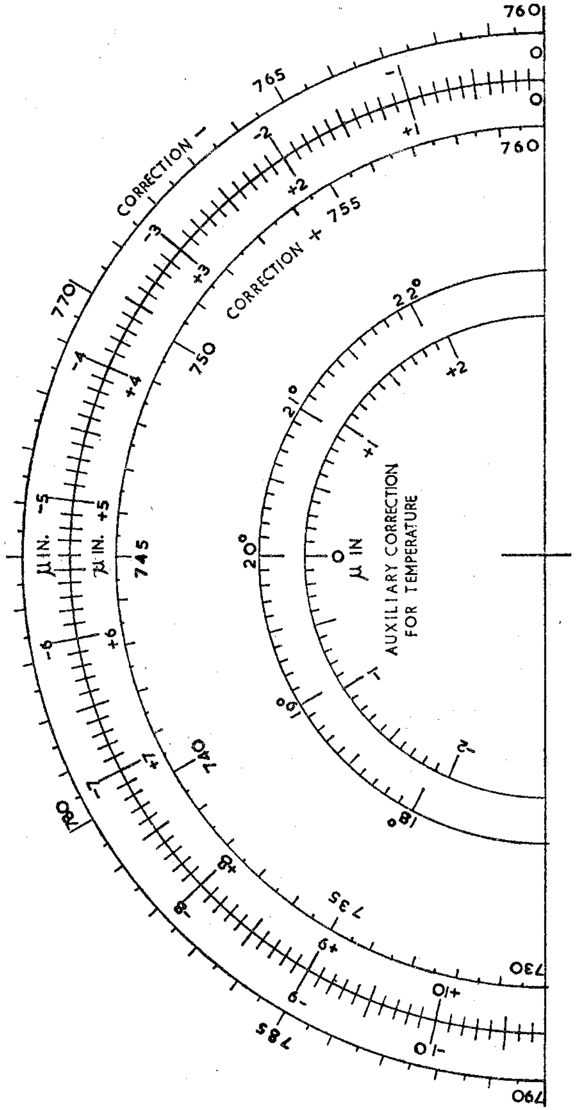
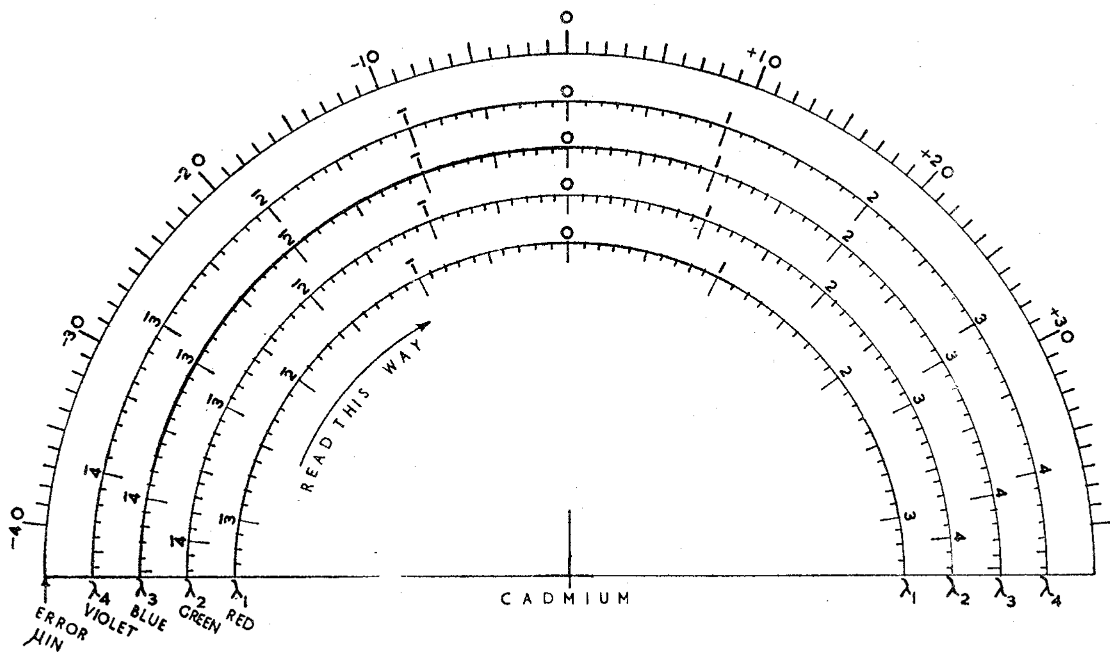
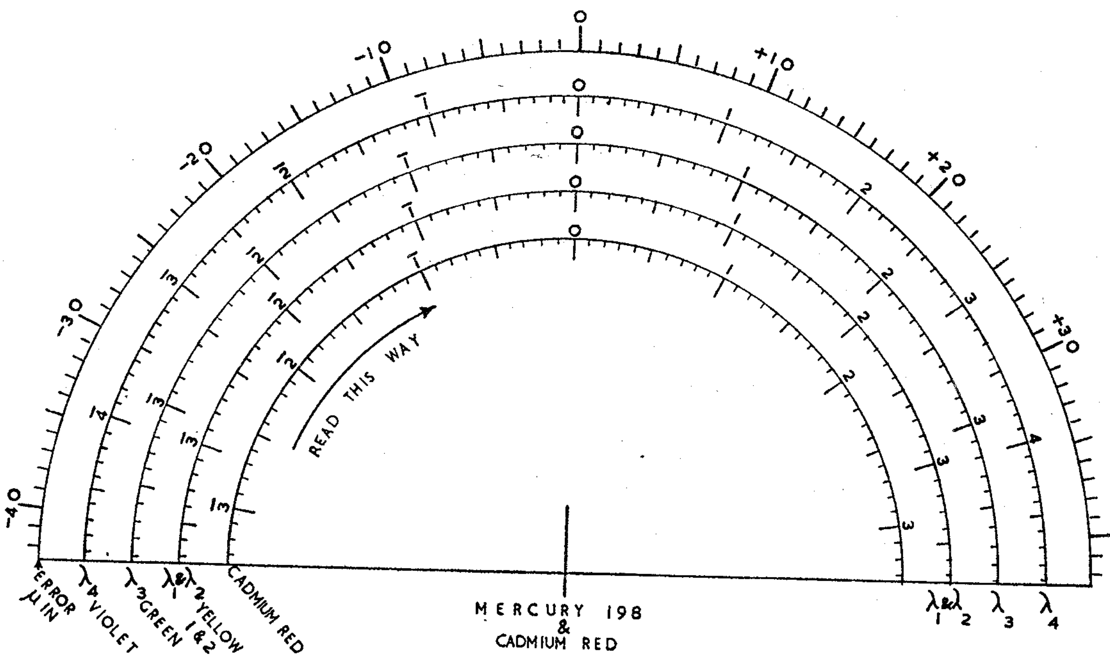



FIG. 55. CORRECTION FOR BAROMETRIC PRESSURE

Using a thread as a cursor passing through the centre, set to barometer reading (corrected for temperature—Table I) and read off correction. Correction is +ve below 760 mm and −ve above. Correction is modified by variation of gauge temperature from 20°C. Read off from inner scale and add algebraically to first correction. *(Copyright reserved)*




FIGS. 56 and 57. COINCIDENCE SCALES FOR FRACTIONAL DIFFERENCES

Using a thread as a cursor passing through the centre, set to the best mean position for observed fractional differences and read off gauge error on the outer scale. Negative, as well as positive fractions must be read in a clockwise direction. (*Copyright reserved*)

# APPENDIX I

The following tables provide data for the various calculations necessary in the measurement of screw threads and include corrections for rake and compression, virtual effects of pitch and angle errors, inch values of metric pitches and limits of size for thread-measuring cylinders.

The tables have been calculated from information given in the N.P.L. publication *Gauging and Measuring Screw Threads*, and the authors are pleased to make due acknowledgement. Students are strongly recommended to consult this publication, where a great deal of information relating to screw threads is to be found in much greater detail than it is possible to give in the present volume.





TABLE I

## RAKE CORRECTIONS

(unit = 0·00001 in.)

| *Diameter of screw* (in.) | *B.S.W.* | *B.S.F.* | *B.S.P.* | *U.N.C.* | *U.N.F.* |
|---|---|---|---|---|---|
| $\frac{1}{8}$ | 6 | – | 2 | — | – |
| $\frac{3}{16}$ | 12 | 5 | – | — | – |
| $\frac{1}{4}$ | 11 | 5 | 3 | 10 | 4 |
| $\frac{5}{16}$ | 10 | 5 | – | 9 | 3 |
| $\frac{3}{8}$ | 10 | 5 | 2 | 9 | 2 |
| $\frac{1}{2}$ | 13 | 5 | 3 | 9 | 2 |
| $\frac{5}{8}$ | 10 | 5 | 2 | 9 | 2 |
| $\frac{3}{4}$ | 10 | 5 | 2 | 9 | 2 |
| $\frac{7}{8}$ | 10 | 5 | 1 | 9 | 2 |
| 1 | 10 | 5 | 2 | 9 | 3 |
| $1\frac{1}{8}$ | 12 | 5 | – | 11 | 2 |
| $1\frac{1}{4}$ | 10 | 5 | 1 | 9 | 2 |
| $1\frac{3}{8}$ | — | 5. | – | 12 | 1 |
| $1\frac{1}{2}$ | 11 | 4 | 1 | 10 | 1 |

NOTES: (1) Rake corrections are *subtracted* from the effective diameter found by measurement.

(2) Rake corrections for B.A. threads may be assumed to vary uniformly from 0·00007 in. for 0 B.A. to 0·00005 in. for 8 B.A.

TABLE II

## COMPRESSION CORRECTIONS

| *Effective Diameter* (in.) | *Compression Correction* | | | | *B.A. No.* | *Compression Correction* | |
|---|---|---|---|---|---|---|---|
| | *55° Threads* | | *60° Threads* | | | | |
| | 8 *oz.* | 16 *oz.* | 8 *oz.* | 16 *oz.* | | 8 *oz.* | 16 *oz.* |
| 0·1 | 5 | 8 | 4 | 7 | 0 | 7 | 10 |
| 0·2 | 4 | 7 | 3 | 5 | 2 | 7 | 11 |
| 0·3 | 3 | 6 | 3 | 5 | 4 | 7 | 12 |
| 0·4 | 3 | 5 | 2 | 4 | 6 | 8 | 13 |
| 0·5 | 3 | 5 | 2 | 4 | 8 | 9 | 14 |
| 1·0 | 2 | 4 | 2 | 3 | 10 | 10 | 15 |
| 2·0 | 2 | 3 | 2 | 2 | 12 | 11 | 17 |

NOTES: (1) Corrections are given in units of 0·00001 in. for two pressures of measurement 8 oz. and 16 oz., for 55° (Whitworth), 60° (Unified, American & Metric), and $47\frac{1}{2}$° (B.A.) threads.

(2) Values for other pressures between 4 oz. and 20 oz. may be taken proportionally.

(3) These values are calculated for *steel* screws.

TABLE III

## VIRTUAL EFFECTS OF ANGLE ERROR

| | Angle Error (min.) | *Virtual Difference in Effective Diameter* (unit 0·0001 in.) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 8 *t.p.i.* | 9 *t.p.i.* | 10 *t.p.i.* | 11 *t.p.i.* | 12 *t.p.i.* | 14 *t.p.i.* | 16 *t.p.i.* | 18 *t.p.i.* | 20 *t.p.i.* | 22 *t.p.i.* | 24 *t.p.i.* | 26 *t.p.i.* |
| Whitworth thread 55° | 10 | 2·0 | 2·0 | 2·0 | 1·5 | 1·5 | 1·0 | 1·0 | 1·0 | 1·0 | 1·0 | 1·0 | 0·5 |
| | 20 | 4·5 | 4·0 | 3·5 | 3·5 | 3·0 | 2·5 | 2·0 | 2·0 | 1·5 | 1·5 | 1·5 | 1·5 |
| | 30 | 6·5 | 6·0 | 5·0 | 5·0 | 4·5 | 4·0 | 3·0 | 3·0 | 2·5 | 2·5 | 2·0 | 2·0 |
| | 40 | 8·5 | 8·0 | 7·0 | 6·5 | 6·0 | 5·0 | 4·5 | 4·0 | 3·5 | 3·5 | 3·0 | 2·5 |
| | 50 | 10·5 | 10·0 | 9·0 | 8·5 | 7·5 | 6·0 | 5·5 | 5·0 | 4·0 | 4·0 | 4·0 | 3·5 |
| | 60 | 13·0 | 12·0 | 10·5 | 10·0 | 9·0 | 7·5 | 6·5 | 6·0 | 5·0 | 5·0 | 4·5 | 4·0 |
| Unified thread 60° | 10 | 2·0 | 2·0 | 1·5 | 1·5 | 1·5 | 1·0 | 1·0 | 1·0 | 1·0 | | 0·5 | |
| | 20 | 4·0 | 3·5 | 3·5 | 3·0 | 2·5 | 2·5 | 2·0 | 2·0 | 1·5 | | 1·5 | |
| | 30 | 6·0 | 5·5 | 5·0 | 4·5 | 4·0 | 3·5 | 3·0 | 3·0 | 2·5 | | 2·0 | |
| | 40 | 8·0 | 7·5 | 6·5 | 6·0 | 5·5 | 4·5 | 4·0 | 3·5 | 3·5 | | 2·5 | |
| | 50 | 10·0 | 9·0 | 8·5 | 7·5 | 6·5 | 6·0 | 5·0 | 4·5 | 4·0 | | 3·5 | |
| | 60 | 12·0 | 11·0 | 10·0 | 9·0 | 8·0 | 7·0 | 6·0 | 5·5 | 5·0 | | 4·0 | |



TABLE III—*continued*

## VIRTUAL EFFECTS OF ANGLE ERROR

| | Angle Error (min.) | *Virtual Difference in Effective Diameter* (unit 0·0001 in.) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 2·5 *mm.* | 2 *mm.* | 1·75 *mm.* | 1·5 *mm.* | 1·25 *mm.* | 1 *mm.* |
| Metric thread 60° | 10 | 2·0 | 1·5 | 1·5 | 1·0 | 1·0 | 1·0 |
| | 20 | 3·5 | 3·0 | 2·5 | 2·5 | 2·0 | 1·5 |
| | 30 | 5·5 | 4·5 | 4·0 | 3·5 | 3·0 | 2·0 |
| | 40 | 7·5 | 6·0 | 5·5 | 4·5 | 3·5 | 3·0 |
| | 50 | 9·0 | 7·5 | 6·5 | 6·0 | 4·5 | 4·0 |
| | 60 | 11·0 | 9·0 | 8·0 | 7·0 | 5·5 | 4·5 |
| | (degrees) | 0 *B.A.* | 2 *B.A.* | 4 *B.A.* | 6 *B.A.* | 8 *B.A.* | 10 *B.A.* |
| B.A. thread 47½° | ½ | 2·0 | 1·5 | 1·0 | 1·0 | 1·0 | 0·5 |
| | 1 | 3·5 | 3·0 | 2·5 | 2·0 | 1·5 | 1·0 |
| | 1½ | 5·5 | 4·5 | 3·5 | 3·0 | 2·0 | 2·0 |
| | 2 | 7·0 | 6·0 | 4·5 | 4·0 | 3·0 | 2·5 |
| | 2½ | 9·0 | 7·5 | 6·0 | 5·0 | 4·0 | 3·0 |
| | 3 | 10·5 | 9·0 | 7·0 | 6·0 | 4·5 | 3·5 |
| | 3½ | | | 8·0 | 7·0 | 5·0 | 4·5 |
| | 4 | | | | 8·0 | 6·0 | 5·0 |

NOTE. Differences for other values of angle error and pitch may be deduced from the above tables by simple proportion.

TABLE IV

## VIRTUAL EFFECTS OF PITCH ERRORS

| Pitch Error | *Virtual Difference in Effective Diameter* | | |
|---|---|---|---|
| | 60° *threads* | 55° *threads* | 47½° *B.A. threads* |
| 1 | 1·7 | 1·9 | 2·3 |
| 2 | 3·5 | 3·8 | 4·5 |
| 3 | 5·2 | 5·8 | 6·8 |
| 4 | 6·9 | 7·7 | 9·1 |
| 5 | 8·6 | 9·6 | 11·4 |
| 6 | 10·4 | 11·5 | 13·6 |
| 7 | 12·1 | 13·4 | 15·9 |
| 8 | 13·8 | 15·4 | 18·1 |
| 9 | 15·6 | 17·3 | 20·5 |
| 10 | 17·3 | 19·2 | 22·7 |

NOTE. No units are specified in this table, since the relative values are the same in any units; e.g. a pitch error of 0·00003 in. on a Whitworth thread gives a virtual difference of 0·00006 in. (to nearest 0·00001 in.), while an error of 0·03 mm. (60° Metric thread) gives 0·052 mm.

### TABLE V

## B.A. PITCHES IN INCHES

| *Thread No.* | *0 B.A. (1·0 mm.)* | *2 B.A. (0·81 mm.)* | *4 B.A. (0·66 mm.)* | *6 B.A. (0·53 mm.)* | *8 B.A. (0·43 mm.)* |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 0·03937 | 0·03189 | 0·02598 | 0·02087 | 0·01693 |
| 2 | 0·07874 | 0·06378 | 0·05197 | 0·04173 | 0·03386 |
| 3 | 0·11811 | 0·09567 | 0·07795 | 0·06260 | 0·05079 |
| 4 | 0·15748 | 0·12756 | 0·10394 | 0·08346 | 0·06772 |
| 5 | 0·19685 | 0·15945 | 0·12992 | 0·10433 | 0·08465 |
| 6 | 0·23622 | 0·19134 | 0·15591 | 0·12520 | 0·10157 |
| 7 | 0·27559 | 0·22323 | 0·18189 | 0·14606 | 0·11850 |
| 8 | 0·31496 | 0·25512 | 0·20787 | 0·16693 | 0·13543 |
| 9 | 0·35433 | 0·28701 | 0·23386 | 0·18780 | 0·15236 |
| 10 | 0·39370 | 0·31890 | 0·25984 | 0·20866 | 0·16929 |
| 11 | | 0·35079 | 0·28583 | 0·22953 | 0·18622 |
| 12 | | 0·38268 | 0·31181 | 0·25039 | 0·20315 |
| 13 | | 0·41457 | 0·33780 | 0·27126 | 0·22008 |
| 14 | | | 0·36378 | 0·29213 | 0·23701 |
| 15 | | | 0·38976 | 0·31299 | 0·25394 |
| 16 | | | | 0·33386 | 0·27087 |
| 17 | | | | 0·35472 | 0·28780 |
| 18 | | | | 0·37559 | 0·30472 |
| 19 | | | | | 0·32165 |
| 20 | | | | | 0·33858 |

### TABLE VI

## METRIC PITCHES IN INCHES

| *Thread No.* | *1 mm.* | *1·25 mm.* | *1·5 mm.* | *1·75 mm.* | *2 mm.* | *2·5 mm.* |
|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 0·03937 | 0·04921 | 0·05906 | 0·06890 | 0·07874 | 0·09843 |
| 2 | 0·07874 | 0·09843 | 0·11811 | 0·13780 | 0·15748 | 0·19685 |
| 3 | 0·11811 | 0·14764 | 0·17717 | 0·20669 | 0·23622 | 0·29528 |
| 4 | 0·15748 | 0·19685 | 0·23622 | 0·27559 | 0·31496 | 0·39370 |
| 5 | 0·19685 | 0·24606 | 0·29528 | 0·34449 | 0·39370 | 0·49213 |
| 6 | 0·23622 | 0·29528 | 0·35433 | 0·41339 | 0·47244 | 0·59055 |
| 7 | 0·27559 | 0·34449 | 0·41339 | 0·48228 | 0·55118 | 0·68898 |
| 8 | 0·31496 | 0·39370 | 0·47244 | 0·55118 | 0·62992 | 0·78740 |
| 9 | 0·35433 | 0·44291 | 0·53150 | 0·62008 | 0·70866 | 0·88583 |
| 10 | 0·39370 | 0·49213 | 0·59055 | 0·68898 | 0·78740 | 0·98425 |
| 11 | 0·43307 | 0·54134 | 0·64961 | 0·75788 | 0·86614 | |
| 12 | 0·47244 | 0·59055 | 0·70866 | 0·82677 | | |
| 13 | 0·51181 | 0·63976 | 0·76772 | 0·89567 | | |



### TABLE VII

## LIMITS OF SIZE FOR THREAD MEASURING CYLINDERS

| *Limits of Cylinder Diameter* (in.) | *Suitable for Threads* | | |
|---|---|---|---|
| | *Whit., U.N. & U.S.* (t.p.i.) | *Metric* (mm.) | *B.A. No.* |
| 0·0680 – 0·0730 | 8 | 3·0 | |
| 0·0540 – 0·0595 | 10 | 2·5 | |
| 0·0495 – 0·0540 | 11 | — | |
| 0·0450 – 0·0470 | 12 & 13 | 2·0 | |
| 0·0385 – 0·0425 | 14 | 1·75 | |
| 0·0340 – 0·0367 | 16 | 1·5 | |
| 0·0301 – 0·0312 | 18 & 19 | — | |
| 0·0271 – 0·0297 | 20 | 1·25 | |
| 0·0243 – 0·0269 | 22 | — | |
| 0·0226 – 0·0247 | 24 | — | |
| 0·0210 – 0·0222 | 26 | 1·0 | 0 |
| 0·0168 – 0·0180 | 32 | 0·75 | 2 |
| 0·0137 – 0·0147 | 40 | — | 4 |
| 0·0111 – 0·0118 | 48 | 0·5 | 6 |
| 0·0089 – 0·0095 | — | — | 8 |
| 0·0072 – 0·0078 | — | — | 10 |

# APPENDIX II

### TABLE OF SINE CURVES

| *Angle (deg)* | *Phase relative to 0° column* | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0° | 30° | 60° | 90° | 120° | 150° | 180° |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 30 | +·25 | +·18 | +·07 | −·07 | −·18 | −·25 | −·25 |
| 60 | +·43 | +·25 | 0 | −·25 | −·43 | −·50 | −·43 |
| 90 | +·50 | +·18 | −·18 | −·50 | −·68 | −·68 | −·50 |
| 120 | +·43 | 0 | −·43 | −·75 | −·87 | −·75 | −·43 |
| 150 | +·25 | −·25 | −·68 | −·93 | −·93 | −·68 | −·25 |
| 180 | 0 | −·50 | −·87 | −1·00 | −·87 | −·50 | 0 |
| 210 | −·25 | −·68 | −·93 | −·93 | −·68 | −·25 | +·25 |
| 240 | −·43 | −·75 | −·87 | −·75 | −·43 | 0 | +·43 |
| 270 | −·50 | −·68 | −·68 | −·50 | −·18 | +·18 | +·50 |
| 300 | −·43 | −·50 | −·43 | −·25 | 0 | +·25 | +·43 |
| 330 | −·25 | −·25 | −·18 | −·07 | +·07 | +·18 | +·25 |
| 360 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

This table gives the values for sine curves with an amplitude of 0·5, i.e. a total "throw" of unity. In applying this to a given curve, the approximate amplitude of the curve should be found by inspection and a suitable multiplier used on the table. The phases shown will be near enough for many cases; but if they are not, more exact figures can be easily calculated.



# APPENDIX III

### GEOMETRY OF MEASUREMENT OF ELLIPSE WITH THREE-POINT GAUGE

Fig. 58 represents the geometrical conditions of a three-point gauging device, first in a true circle, at (a), and in an elliptical bore, at (b). The equilateral triangle $ABC$ is assumed to have the same dimensions in each case. In practice, any variation would be taken up by the micrometer of the three-point gauge.

Radius of circle $=a$

Co-ordinates of $B$ $\left(\frac{-a}{2}, \frac{\sqrt{3}a}{2}\right)$

Co-ordinates of $C$ $\left(\frac{-a}{2}, \frac{-\sqrt{3}a}{2}\right)$

i.e. $BD=\frac{\sqrt{3}a}{2}$

The ellipse in (b) represents a bore with the same mean diameter as the circle but with a variation of $4\delta$ on diameter.

Major axis $=2(a+\delta)$ Minor axis $=2(a-\delta)$

The equation to the ellipse is therefore

$$\frac{x^2}{(a+\delta)^2}+\frac{y^2}{(a-\delta)^2}=1 \quad . \; . \; . \; . \; . \; . \; . \quad (1)$$

and the $y$ ordinates of $B_1$ and $C_1$ are $\pm\frac{\sqrt{3}a}{2}$.

Therefore $$\frac{x_1^2}{(a+\delta)^2}+\frac{3a^2}{4(a-\delta)^2}=1 \quad . \; . \; . \; . \; . \; . \; . \quad (2)$$

Hence $$x_1^2=\tfrac{1}{4}(a^2-4a\delta-20\delta^2\ldots) \quad . \; . \; . \; . \; . \quad (3)$$

neglecting higher powers of $\delta$.

From the diagram $A_1A_2=D_1O+OA_2-D_1A_1$

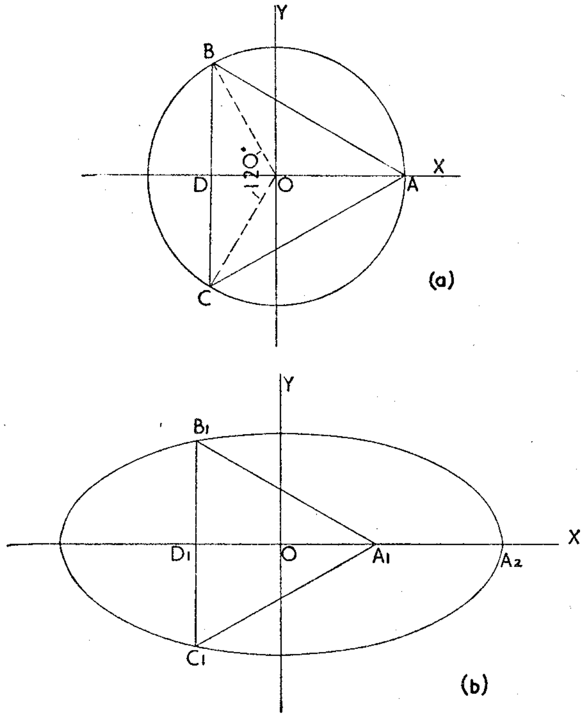



FIG. 58

Therefore $$A_1A_2 = x + a + \delta - \frac{3a}{2} = x - \left(\frac{a}{2} - \delta\right)$$

Multiplying by $\dfrac{x + \left(\frac{a}{2} - \delta\right)}{x + \left(\frac{a}{2} - \delta\right)}$ and substituting for $x^2$ from equation (3)

$$A_1A_2 = \frac{-6\delta^2}{x + \left(\frac{a}{2} - \delta\right)}$$

and, since $x + \left(\frac{a}{2} - \delta\right)$ is very large compared with $\delta^2$ and approximates to $a$

$$A_1A_2 = \frac{-6\delta^2}{a}$$



*Example*

For a bore 2 in. diameter and oval by 0·004 in.

$$a = 1 \text{ and } \delta = 0{\cdot}001$$

Hence $A_1A_2 = 0{\cdot}000\,006$

The significance of such a large variation in diameter being completely missed by a three-point measuring device will be obvious.

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888 Slip or Block Gauges
907 Dial Gauges for Linear Measurement
919 Screw Thread Gauge Tolerances
939 Engineers' Squares
958 Precision Levels
969 Plain Limit Gauges, Limits and Tolerances
1054 Engineers' Comparators
1095 Metric Screw Threads
1580 Unified Screw Threads
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All the above are obtainable from:

The British Standards Institution,
2 Park Street,
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