AN ELECTRICAL MEASURING MACHINE.

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[Selected for Publication with Discussion in writing.]

(I) GENERAL.

End-gauges of length, being of three types, parallel-faced, cylindrical and spherical-ended, a measuring machine of the best kind should be adapted to a great variety of work, namely :—

- (a) Comparison of one gauge, between assigned points, with another gauge, whether of the same or another type.
- (b) Absolute measurement of a gauge, between assigned points (that is, comparison with a line-standard of length).
- (c) Exploration of any gauge. No gauge can be reliable unless its figure is uniform. The measuring machine should have facilities for rotating a gauge into line, holding it there during measurement, and rotating or translating it into any new position for remeasurement.

Commercial measuring machines are used in engineering work for the above processes (a) and (b) and serve well where quickness rather than accuracy is desired. But they are faulty in various respects; for example: (1) Lack of adjustments; (2) Assumption of the truth of certain flat surfaces employed; (3) No provision for

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setting gauges accurately along the line of measurement; (4) The application of considerable forces along the line of measurement.

In consequence of these defects, all such measuring machines fail in the processes detailed above to provide the accuracy now demanded in the standardizing work of a metrological laboratory; and are not good enough for a critical examination of the best modern gauges, notably those of Johansson, of Eskilstuna, Sweden.

The author has developed a method of measuring by electric contact, first described in 1900.* An electric measuring machine founded on this principle was made in 1905.† It has been used in the National Physical Laboratory since 1909. Improvements were made in the machine and have been described with their results.‡

Johansson Gauges.

FIG. 1.

FIG. 2.

The machine proved useful and experience showed that its limitations were due to mechanical design, and not to the new methods employed.

The present Paper describes a new machine founded on the electric contact principle. It has a higher order of reliability than the first machine, while at the same time it is more adaptable to each of the above processes.

The Johansson gauges mentioned above have now attained a unique position on account of their accuracy and adaptability. They are rectangular slabs, as seen in Fig. 1. The true faces

* Phil. Mag., Dec. 1900.

† Proc. Roy. Soc., 1906 A., Vol. 77.

‡ Proc. Roy. Soc., 1910 A., Vol. 84 and 1912 A., Vol. 87.

are about 35 mm. $\times$ 10 mm. and all the slabs on this system have this cross-section. The true faces have repeatedly been proved, both by optical and mechanical tests, to be plane and parallel to a degree of accuracy hitherto unattained in metal.

One peculiarity of this gauge system is that the units can be wrung together and used in combination, so that, given a variety of small gauges, larger ones can be made by simple addition. In Fig. 2 is shown one combination

$$1.000 \text{ in.} + 0.750 \text{ in.} + 0.500 \text{ in.} = 2.250 \text{ in.}$$

Later in this Paper are given the results of tests on these gauges, simple and composite.

(II) DESCRIPTION.

Fig. 3, Plate 10, shows the machine as set up in the works after manufacture. Its appearance when set up ready for use in the laboratory with certain additions is shown in Fig. 5. The complete length over all is 8 feet, height $2\frac{1}{2}$ feet, and the total weight is about 800 lb. It rests on a concrete table built from the foundation. The vertical iron girder seen on the left of Fig. 5, Plate 10, is bolted on the back of the concrete table; this girder carries a reading microscope. The two Figs., not being taken from the same point, show different details.

(1) *Girders*.—At the extreme front and back (see Fig. 4 and Figs. 3 and 5, Plate 10) are girders mounted on cast-iron pillars. These carry the chief weight of the machine uprights A, B, C. The load is conveyed to the girders from the uprights through vertical spring boxes *b* to steel castors *c* fitted with ball-bearings. The girders serve three purposes: (1) to relieve the bed of most of the load of the uprights (about 200 lb.) and so to reduce flexure of the bed; (2) to render the movement of the uprights along the bed easy and smooth; and (3) to reduce the wear on the bed by lessening the pressure of the five feet of each upright on the bed. This device has proved successful, the uprights moving very freely in spite of their weight.

(2) *Bed*.—Inside, but not touching the parallel girders, is the bed of the machine, Figs. 4 and 6, of length 6 feet, height at

FIG. 4.
Section of Bed and Girders.

centre 15 inches, greatest width 8 inches and weight about 500 lb. There are two bow-shaped vertical webs 15 inches deep at the centre and 6 inches at the ends. The thickness of the webs is

1 inch, increased to 2 inches at the edge flanges. The two webs are joined by nine vertical cross-webs, also 1 inch thick. One main web is surmounted by a horizontal plane surface *d*, 2 inches wide. The other web is surmounted by two plane surfaces *e*, *f*, inclined at 90° to one another and at 45° to the horizontal. There are six large holes through each longitudinal web to reduce dead weight. At the bases of the longitudinal webs are two feet, each about one-quarter of the web length from one end. Another foot, about one-quarter of the web length from the other end, lies midway between the webs. Thus the bed is supported on three feet.

FIG. 6.—*Bed. Side View and two Sections.*

There are two "safety" feet on the latter web clear of the table surface by $\frac{1}{4}$ inch. The feet are shown in the sections in Fig. 6.

As regards manufacture, the details of the moulding and casting of the bed were carefully considered; the method of feeding the mould and its position during the setting of the metal being so arranged as to secure a close, fine grain at the surfaces about to be machined. The material of the casting consisted of 60 per cent. best selected heavy scrap iron and 40 per cent. Nottinghamshire No. 4 cylinder iron. When the casting was removed from the mould it was placed in the most vibrational part of the works. After several weeks the three cardinal planes *d*, *e*, *f* were scaled in the planing

machine and the casting again put aside to age for some months. The surfaces were then lightly planed and the bed again put aside. This process having been repeated several times, the bed was ready for scraping eight months after casting. Care was taken during the machining to rest the bed only on its three feet and to hold it down by bolts over its feet only. In the finished bed there are to be three true planes *d, e, f*, two sloped and one horizontal. The imaginary ridge formed by the continuation of the two sloped planes should be parallel with the centre line of the horizontal plane. In order to attain this result a template was made having a large plane to fit the horizontal bed plane *d* and four $\frac{1}{2}$ -inch screw-ends to fit the sloped bed-planes *e* and *f*. First one sloped surface then the other was scraped true to a long surface plate. The large plane surface of the template and the four screw-ends were then scraped true. And finally, the horizontal bed surface was scraped so that the bed fitted the template throughout, whilst the three cardinal bed surfaces remained true as tested by the long surface plate.

Errors arising from defects in the bed are discussed in Section V (page 593).

(3) *Gauge-holder*.—The central upright B, Fig. 3, Plate 10, is shown in detail in Figs. 7 and 8, which are front and side views. This upright will in future be called the gauge-holder, its object being to carry the gauges to be measured and to provide them with translations and rotations necessary to bring them into any desired position. Two gauges are shown in section in the centre of Fig. 7.

Translations.—A surfaced plate L, whose plane is perpendicular to the run of the bed, has three studs $S_1 S_2 S_3$ kept pressed against it horizontally. These studs are fixed to a frame F_1 which carries the gauges to be measured. F_1 is itself carried by another frame F_2 , any desired horizontal motion of the former being produced by a screw W_1 , Fig. 7, moving in a nut carried by the spindle of the screw working in a bearing in F_2 . The weight of F_1 is communicated to F_2 by two basal studs S_4 and S_5 . Again, any desired motion of F_2 vertically is produced

Gauge-Holder.

FIG. 7.—Front View.

FIG. 8.—Side View.

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by a screw W_2 working in a nut fixed in the frame F_2 , the spindle of the screw working in a bearing in P . Four steel pillars $p_1 p_2 p_3 p_4$ connect P rigidly with the base plate B , which is solid with L . F_2 is guided in its up-and-down motion by two rigid V s pressed against p_2 and one V pressed against p_1 by a stiff spring. The three studs $S_1 S_2 S_3$ press against L on its left face, Fig. 3, Plate 10, and Fig. 8. The frame F_1 carries three flanged guiding arms $C_1 C_2 C_3$ which serve the purpose of keeping the studs $S_1 S_2 S_3$ in steady pressure against L . There are three more studs $S_6 S_7 S_8$ kept pressed against the right side of L by spring boxes carried by the couplings. The "surfaced" portion of L consists of three areas, each about 2 inches square, on front and back. These areas are large enough for the utmost run of the studs during the translations. L is $\frac{1}{2}$ inch thick, is solid with the base B , with stiffening buttresses joining the horizontal and vertical parts, and there is a large hole to allow free motion for the gauges.

Thus the principle is to have F_1 "floating." Any up-and-down motion is communicated by screw W_2 through frame F_2 ; while horizontal motions are given by screw W_1 , the nut of which is connected to F_1 by a pivoted link. By this mechanism it is possible to move F_1 to any desired place in a vertical plane strictly parallel with L , while the motion of the screws W_1 and W_2 , even if irregular, cannot move F_1 out of this plane. Provided the surface plate L is true, there would be pure horizontal and vertical motions given to the gauges, clamped in F_1 , when the screws W_1 and W_2 are worked.

L has been scraped on the left face twice, at intervals of several months, since manufacture, and is probably true all over to $\frac{1}{5,000}$ inch. The three studs $S_1 S_2 S_3$ are placed at the angles of an equilateral triangle of side 8 inches, so that the greatest angular movement given to the gauge through error in the surface plate would be about $\frac{1}{5,000} \times \frac{1.7}{2} \times \frac{1}{8} = \frac{1}{50,000}$ radian. The resulting error in the gauge measurement, being a cosine error, would be negligible.

Rotations.—The frame F_1 consists of three parts all lying in one plane, a main plate and two concentric rings. The outer

ring T_1 turns on horizontal axles working in bearings carried by the main plate; while the inner one T_2 (which carries the gauges) turns on vertical axles which lie in bearings carried by T_1 . Adjusting screws are fitted to each ring and serve both to adjust and clamp these. The four axles concerned in these rotations fit their bearings accurately and there are tightening clamps to complete the fit. In this and other respects careful workmanship is required in the manufacture of the gauge-holder, since it is necessary in measuring gauges to perform translatory and rotatory motions in cycles, the gauge being returned at the end of a cycle, with great exactness, to its position at starting. Also, the whole system must be rigid, so that any accidental jar given to it will

FIG. 10.—A Measuring End.

produce no permanent movement. The gauge-holder rests on the bed by five feet ($K_1 K_2 K_3$ are shown), thus having geometrical contact, with only one degree of freedom (that is, along the bed).

(4) *Headstocks*.—The gauges carried by the gauge-holder are measured between micrometer screws carried by the uprights A and C, Figs. 3 and 5, Plate 10. These uprights will in future be called left and right headstocks. The mechanism and connections of the micrometer screws have been fully described in the former Paper (*loc. cit.*). These screws are the only parts of the old machine used in the new one. Though the screws themselves are old, an important modification has been made by the addition of new measuring ends (see Fig. 10). The divided circle of each micrometer is now read by a microscope—a considerable improvement.

The right headstock bears on the Λ of the bed by three studs and on the horizontal surface by two more. This arrangement, which provides a geometrical slide, was chosen in preference to that used in the table gauge-holder merely to save space.

The left headstock is identical with the right except that the former has in addition a long girder support carrying a line-standard. The standard rests on two rollers which can be set and clamped at the Airy points (*see* Fig. 5, Plate 10). Side screws are arranged for setting the standard accurately parallel with the run of the bed. The graduated surface of the standard is at the level of the axis of the micrometer screws. The microscope is never moved nor touched in any way during a measurement; serious error in reading the line standard would arise if the axis of the microscope were to receive even a small rotation on a horizontal axis perpendicular to the standard. Such rotation is liable to occur when, as in most measuring machines, the microscope is mounted on a headstock, the line standard being fixed; for errors in the bed-surfaces will produce these rotations. Or, again, this rotation of the microscope might occur if the microscope were at all loose in its holder in the comparator method of work, where the micrometer eye-piece is handled. In the present method, supposing the line standard be set parallel with the run of the bed (an adjustment easily attained), no error of the first order can arise if the bed-surfaces be even moderately true. This point will be discussed in Section IV.

In order to set the microscope accurately on a line of the standard, there is a jockey-screw placed on the left headstock, the screw of the former engaging in the headstock. This permits of any movement to and fro of the headstock, and scale, along the bed. Instead of, as is usual in measuring machines, using the micrometer eye-piece of the microscope to take up any fraction of a unit of the scale, the micrometer screws of the headstocks are employed. Since Fig. 5, Plate 10, was taken, the measuring ends have been supported by a strong bracket.

(5) *The Measuring Ends.*—The new measuring end is shown in Fig. 10. In the old machine the arrangement was simpler and

contact was made at point p_1 . In the present machine, if point contact is to be made, one either uses the extreme point e or the point p_3 ; in the latter case the end piece MN is pulled off the bar AB. For most purposes p_3 is better than e for point contact. If, on the other hand, we wish to measure with flat ends, the end cap c is pulled off, leaving the lapped flat surface b at the extreme end. The brass tube PQ is coned to fit the screw spindle S, so that when pushed on the latter and the clamp D adjusted the whole forms a rigid system. The invar bar AB is made a true fit in the ebonite bush rings r_1 and r_2 , and is prevented from rotating on its axis by the cross pin n n_2 , which slides in the slotted brass tube. The end of AB is coned, and the coned end of the fitting MN is pushed tight on AB, the two parts being ground to fit. The plate M carries three pillars a (two shown), the far ends of which hold the plate UV. There are three adjusting screws d (two shown) bearing on UV, and the ends of these press against the outer edge of the end block Z. This end block bears in UV by a ball-and-socket joint, so that by means of the three adjusting screws, equispaced round the edge of Z, the end surface b can be brought into any desired plane. The plane actually required is perpendicular to the line of run of the bed. The adjustment of this plane could not be attained with sufficient nicety by the mere motion of the adjusting screws, though these are provided with capstan heads. But the edge of the end piece Z is relatively thin, so that when the three adjusting screws bear tightly on it, a small rotation of one screw produces strain, and fine adjustment is attainable. The whole system, consisting of AB and the end piece MN, is rigid and has one degree of freedom, parallel to the line of the bed. A spring h controls the system and keeps the contact points p_1 and p_2 about $\frac{1}{2}$ mm. apart normally. S is the invar shaft of a micrometer screw; suppose this screw is advanced to cause the end of the system to meet a gauge surface on the extreme right beyond e . First e meets the gauge, then as the screw is farther advanced, contacts p_1 and p_2 are brought together. The meeting of p_1 and p_2 completes an electric circuit consisting of a high resistance (say 5,000 ohms), a cell, switches and telephone. As soon as the telephone sounds,

the observer reads the divided head of the micrometer screw. On reversing the micrometer screw the spring h comes into action, breaking contact $p_1 p_2$ and the telephone again sounds. The general method and precautions used have been explained in previous Papers (*loc. cit.*).

The advantages of the present complex measuring end over the older form are:—(1) Non-metallic bodies can be measured. (2) Heat produced at the contacts is conducted into invar on each side and consequent thermal expansion is small. (3) It is most important to have clear sounds made in the telephone at “make” and “break.” The accuracy of the method rests on this. Any oxide or dust at the contact produces “fuzziness” of sound. Oxide is the principal

trouble, and as the surfaces p_1 p_2 are respectively a bead and plate of iridio-platinum, this trouble is reduced to a minimum. It seems strange that the present system of two mechanical and two electrical contacts should work so much better than the old method which had two electrical contacts only. Accuracy has been gained, even though we have doubled the number of links in the system. (4) It is easy to clean the contacts p_1 and p_2 . A hole (not shown) is made through the tube PQ, so that the rouged or clean leather can be rubbed on the contacts. If the cleaning were performed on the gauge surface, thermal expansion troubles would arise.

(6) *The Switch*.—In Fig. 11 is shown the method of connecting any part of the measuring system in the electrical circuit. A battery, resistance bobbin (say 5,000 ohms), and telephone are joined to points e and f , which are joined to a non-conducting switch-arm, shown joining points a and a' . This arm moves on centre O and so connects in turn bb_1 , cc' , and dd' . Corresponding points a_1 a_1' , etc., are joined up as shown. The gauge G and the right and left contact ends P_2 and P_1 are joined up as shown. It is seen that there are four positions of the switch; the first leaves the circuit open, whereas the other positions join P_1 to G , P_2 to G , and P_1 through G to P_2 .

As a rule, in making a gauge measurement b , b' are connected, and then d , d' , and then left and right micrometers are read; for in that position there is exact electric touch made on each side of G . The switch connections are not complex and when once made need not be changed. No mercury cups are used.

(III) MATERIALS.

The girders are of cast-steel and the bed of cast-iron. Cast-iron is also used in the base plates of all the uprights of the bed, also in the greater part of the micrometer screw supports, the front plate and brackets of these supports being of wrought-iron. The four pillars of the gauge-holder are of steel. All the springs are of hardened steel. Brass is used for the micrometer nut bearings. The

micrometer screws are of silver steel and the micrometer nuts of bell-metal. In order to reduce thermal expansion of the exposed parts of the measuring ends, invar is used on the end of the micrometer screw, also in the greater part of the length of the measuring end as explained in Section II.

(IV) ADJUSTMENTS OF THE MACHINE.

In setting up the machine, first the girders and bed were installed parallel to one another and level each way, as shown by the spirit-level. Then the uprights were mounted on the bed, and the following adjustments made in the order given :—

(1) *To set the Axis of Collimation of a Telescope parallel to the run of the Bed.*—Having levelled the standard carriage lengthwise and crosswise, and set it by eye as nearly parallel to the bed as possible, mount a telescope on the standard rollers, making it rigid by the adjusting screws. Remove the top plate of the gauge-holder and lift out its slides, leaving the base and pillars and the scraped upright plate. Draw a fine black cross on paper, attach it to a wall (about 18 feet away) and illuminate it so that it is clearly seen in the telescope. Focus on the cross; then proceed thus—(a) Run the carriage back 6 inches, the cross, though not quite clear, is easily seen. Set the cross on the cross-wires by moving the paper. (b) Run the carriage forward 12 inches; the cross is again clear enough for setting. Suppose the image of the cross is displaced on account of the last movement, adjust it to the cross-wires by moving the paper. (c) Next run the carriage back 12 inches. If the image is displaced again, rotate the telescope first on a vertical axis and then on a horizontal axis perpendicular to its length to bring the image back. Repeat processes (b) and (c) till no further displacement occurs, when the adjustment is complete. The breadth of the lines on the cross being $\frac{1}{3}$ mm., and the distance from telegraph to cross 500 cm., the angular error in setting is about $\frac{1}{15,000}$ radian, supposing the linear error in setting is the breadth of the line. This angular error is negligible.

(2) *To set the upright Surfaced Plane of the Gauge-holder perpendicular to the run of the Bed.*—Set a good plate mirror against the upright plane, fixing by soft wax three equal steel bicycle balls between the mirror and the plane. In this way we have the mirror surface parallel to the upright plane. Mount a cross formed of white cotton thread on the front of the telescope objective, keeping the threads in place by plasticine and illuminate it by a lamp. Focus the telescope on the image of the cross as given by the mirror. Proceed in the same way as in adjustment (1) until the image remains stationary in the field, the adjustments at the ends of the run being made by (a) screwing in or out the feet of the table and by (b) moving the cotton cross in its own plane.

(3) *To set the run of the Micrometer Screws parallel to the run of the Bed.*—Clamp a microscope tube firmly in the gauge-holder and focus it on some mark on the measuring end which is well illuminated. Now proceed thus—(a) run the screw back 2 cm. and run the gauge-holder forward equally to counteract this. Clamp the gauge-holder and focus again on the measuring end. If a displacement has occurred, so adjust the foot-screws of the headstock base that the displacement is doubled. (b) Now run the screw forward 2 cm. and run the gauge-holder back till focus is again obtained. Adjust the foot-screws of the headstock till displacement, if any, is reduced to nothing. Repeat (a) and (b) till no further displacement occurs.

This adjustment having been made for both micrometer screws, the measuring ends must be brought exactly end to end. This can be done by adjustment of the foot-screws without any attendant rotation, and hence the preceding adjustments are not disturbed.

(V) DISCUSSION OF ERRORS.

In general, absolute measurements are subject to larger errors than comparative measurements. This arises, in great part, from the well-known limitations of the microscope as a measuring instrument, and partly from the large movements given to the measuring apparatus in absolute determinations. Under favourable

temperature conditions two gauges can be compared with an error of, say, 0.1 micron on a single reading; whereas in their absolute measurement the corresponding error might be 0.4 micron. Errors in the measurements will be considered under eight heads:—

(1) *Bed Irregularities*.—Let us first suppose that the three cardinal tooled bed surfaces are true planes. The meeting line caused by producing the two sloped planes is an imaginary ridge. In a perfect bed this ridge would be parallel with the centre line of the third (horizontal) plane of the bed. In reality the ridge diverges from parallelism with the centre line, both in azimuth and inclination. The first divergence produces no angular movement of the headstock when this is moved along the bed, and therefore causes no error; the second divergence, however, does cause rotation on a horizontal axis, but there is no error therefrom in the absolute measurement. Thus if the three surfaces be true planes, no errors arise. Next suppose the three cardinal planes are not true. As the feet of the headstock carrying the standard are given vertical displacements due to bed irregularity, the consequent rotation of the headstock will, in some cases, cause errors in the gauge measurements. Suppose one foot of the headstock when moved along the bed drops distance x from the original plane. If the length of the perpendicular dropped from this foot on the axis of rotation of the headstock be a , the rotation produced $= \frac{x}{a}$.

Resolve the rotation into (1) one on a horizontal axis along the bed; (2) one on a horizontal axis across the bed. The former does not concern us. The latter becomes $\frac{x}{na}$, where n depends on the dimensions of the system. The error resulting from this rotation is a double cosine error; (a) one cosine error being due to foreshortening of the line-standard; (b) the other being due to extra movement of the micrometer screw, acting in the same sense as (a). Suppose the greatest length to be measured is L , we have the error

$$= L \text{ versine } \frac{2x}{na^2}.$$

Suppose the greatest error permissible to be $\mu/10$ (that is, $1/10,000$ mm.), it is found on substituting values for x , n , and a from the apparatus, and taking $L = 1$ metre, that

$$x = \frac{1}{30} \text{ mm.}$$

This result is obtained by supposing a displacement of that foot of a headstock which would produce the greatest value for x . In the other cases no error of the same order occurs.

Thus it appears that bed irregularities must not exceed $\frac{1}{30}$ mm., whether these be of the nature of pits on the surface or of curvature of the bed as a whole. No pits of this depth are likely to occur, at least none would be of such width as the feet of the headstock. But through loading or ageing, the cast-iron bed might conceivably be curved to that extent.

These matters had to be tested. A method of doing this was described by the writer recently.* Any irregularity of a plane surface of more than $\frac{1}{400}$ mm. can be readily detected by two kinds of surface tester described in the above Paper: (1) a small-foot tester for finding out pits or scrape marks; (2) a large-foot tester which has feet too large to fall into any small cups; this form would thus disclose general curvature of the surface. Readings obtained on the three bed surfaces are:—

	A	B
	Small-foot Tester.	Large-foot Tester.
Horizontal Face	144 144 143 142 144 144	58 56 56 55 56 55·5
Near sloped „ .	143 146 144 144 145 144	56 57 56 55·5 55·5 55
Far sloped „ .	144 142 142 144 144 144	57·5 57 55 57·5 55 56
Mean 143·5		Mean 56·0

* Proc. Roy. Soc., Jan. 1912, Vol. 86, page 227.

The unit in this table is $\frac{1}{10,000}$ inch. The numbers in each set are in close agreement, though one set differs from the other because the zeros of the two are different, which is of no importance. The results given in A show that such irregularities and pits as exist in the bed are of no importance.

In the Paper quoted (*loc. cit.*) it is shown that using the large-foot tester we can obtain the reading of the ideal true plane. In the above instrument this reading is 56.5. The greatest departure from the value in Table B is 1.5 unit. But we are considering curvature of the surface, and taking the first line we have consecutive errors +1.5, -0.5, -0.5, -1.5, -0.5, -1.0, adding the last five we obtain a cumulative error -4.0. The first reading shows convexity of surface but the last five are all concave, and the departure from true plane is $\frac{4}{1000}$ mm. = $\frac{1}{100}$ mm.

During the above measurements the heavy left headstock was moved about on the bed and the greatest resulting change in the readings was 1 unit. Thus it is established that there are no pits or curvature of the bed surfaces of any account. No doubt the latter result is attributable to the great strength of the bed and to the action of the side girders.

(2) *The Irregularities of the Surface-plane of the Gauge-holder.*—The Johansson gauges have faces which are truly plane and parallel to about $\frac{1}{100,000}$ inch. This is established by the readings given in Section VI. If the surfaced planes of the gauge-holder were true to the same figure, and also if the translatory movements of the gauge-holder took place without any loose play, we should obtain readings for one face of a gauge which would be regular to about $\frac{1}{50,000}$ inch. But such is far from the case, and the want of regularity gives us an indication of the truth of this upright surfaced plane. Thus, as an example, consider Table 1 (page 604). Plot a curve, Fig. 12, connecting readings at places 1, 2, 3, 4 in column 1 with places on the gauge and obtain curve I. Do likewise for places 5, 6, 7, and again for places 8, 9, 10, 11, and so obtain curves II and III.

The numbers are grouped as above because the members of each group are equispaced on a straight line on the gauge surface (*see* rectangular diagram on Fig. 15, page 606). If the gauge surface and the gauge-holder upright surface were ideal, and if no loose play occurred in the apparatus, these curves would be coincident straight lines which would be horizontal if the setting were perfect. The actual vertical departure from linear is, taking readings three at a time, 0.7, 0.9, 0.5, 0.6, 0.7 micron. Taking the greatest number we find the error to be about $\frac{1}{1.100}$ mm. This is due to defective surfaced plane and loose play (for the small gauge surface has a higher order of accuracy).

The movement of $\frac{1}{1.100}$ mm. by the gauge surface involves an

angular movement of the gauge of, at worst, $\frac{1}{55,000}$ radian. The versine of this angle, which shows the error in measuring the gauge, is a negligible quantity.

Thus no appreciable error arises from defective workmanship on the translatory movements. The irregular appearance of the numbers, in columns 2 and 3, Table 1 (page 604), is misleading, for we read both headstocks, and by adding results, the linear error found above vanishes, while the angular error is, as shown, insignificant.

(3) *Temperature*.—The room in the Metrology Section of the National Physical Laboratory, in which measurements were made, is arranged to have steady temperature. The four walls are separated from the outer walls by air-passages and by rooms,

the temperature of these outer spaces being kept as steady as possible. The glass ceiling also is separated by a large air-space from the glass roof. Under favourable conditions the temperature of the air surrounding the measuring machine would not vary 0.1° C. during the time taken, say 1 hour, in any complete set of measurements. The temperature of the gauges and of the various parts of the machine would lag behind that of the surrounding air; the massive parts especially would be slow in taking up temperature changes. The greater the lag, the less will the errors be due to temperature. The gauges themselves being exposed and relatively small, it is found advisable to wrap them in layers of flannel and insert a thermometer bulb between flannel and gauge; delicate comparative work (e.g. Tables 3 and 4 on the 3-inch gauges, pages 608-9) would be otherwise impossible except with short gauges. A gauge 4 inches long changes length 0.1μ for temperature change 0.1° C.; so that small temperature latitude is allowable ($\mu = \text{micron} = \frac{1}{1,000} \text{ mm.}$). In the extreme case of a 1-metre gauge, change in length 0.1μ occurs for 0.01° C., so accuracy in such a case is impossible as a rule, unless the complete operation of measurement is done in short time. The only exposed parts of the machine itself which are not massive are the measuring ends of the micrometers, and these have invar in some places and felt wrapping in others, so as to render temperature errors negligible.

(4) *Calibration Errors of Micrometer Screws.*—In the previous Paper * is given the process of calibration of these screws by an optical interference method. Over a whole millimetre the greatest departures anywhere from truth of the face value of the readings are $+0.28 \mu$ and -0.20μ . This indicates the order of the possible error in the screw readings. Error of appreciable amount only arises when the run of the screw amounts to several microns. In comparison work, where the lengths compared agree closely, it is negligible.

* Proc. Roy. Soc., 1906 A., Vol. 77, page 351.

(5) *Microscope Readings*.—The microscope used is one of the quality usual in comparator work (magnifying power about 35). The accuracy of the readings depends on the quality of the microscope, and also very much on the smoothness of edge of the ruled lines. For the invar scale and microscope used, five consecutive readings taken on the left micrometer screw were in microns ($= \frac{1}{1,000}$ mm.):—

331·6 332·0 331·2 331·4 331·6

The process in each case consisted in moving the left headstock till a certain line was set under the microscope and then adjusting the measuring end to contact with a gauge surface. In this way the only errors will be due to microscope and scale. The differences above are twice as great as would be the case for a very well-ruled standard.

(6) *Calibration Errors of the Line Standards*.—The lines on the invar standard have been calibrated, and in any absolute work account is taken of these errors. Thus, in determining the absolute length of the 1-foot standard, the error between the lines chosen is about 9 μ .

(7) *Irregularities of the Measuring End Surfaces*.—The faces of the flat measuring ends must be true to a high degree. Scraping is not suitable, but the following dual process is successful. After the “ends” are machined, prepare a brass surface plate. (a) Spread on the brass fine-washed emery having no grit. Rub the “end” on the brass, avoiding tilting movement. Clean the “end” with rouge paper and place on it an optically true glass plate; interference bands will appear. They will be concentric curves if rubbing has been long continued; (b) clamp the “end” in a vice with face up. Take a small rod with chisel end, wrap on it rouge paper, several layers thick, bent up at the end to form a wad. Serve the wad with fine washed emery and oil. Rub the wad on the “end” face, applying equal circular motion to all parts except the edges. Clean the surface with rouge and test with the optical glass. The bands

will, if the process has been long enough, be concentric curves, but in this case the edge is the highest part of the surface. Process (a) tends to make the surface convex, whereas (b) makes it concave, and by using them alternately a flat surface is obtained. In the later stages fine washed rouge free from grit is used in place of emery. The surfaces must be left slightly convex rather than concave, for in the latter case there would be a direct error in certain absolute measurements. The appearance of the rings on the finished ends is given in Fig. 13. The actual colour of the

FIG. 13.—*Measuring Ends.*

centre depends on the size of dust particles which happen to be enclosed between the glass and metal surfaces. It will be seen that while both surfaces are good the right "end" is best, as it has a larger central coloured area. The departure from flat over nearly the whole of the areas of each is $\frac{1}{4}$ wave length, say 0.2 micron at most. The error resulting from this in comparative and absolute work would be negligible as both surfaces are convex slightly.

(8) *Troubles attending the Electric Contact Method.*—It is easy, if precautions are taken, to repeat readings to 0.05μ ; but neglect of

care may reduce the sensitiveness to 0.3μ . If when contact is made the sound in the telephone is faint or ill-defined, the fault generally lies either at the mechanical contact or at the electric contact, and the right procedure is:—(a) clean the electric contacts of iridio-platinum by rubbing with wash-leather served with rouge, and finally with clean cotton fabric; (b) clean the mechanical contacts with clean cotton to remove dust. The contact sounds should now be sharp, the make and break occurring at an interval of not more than 0.1μ . The readings taken may be either always for “make” or always for “break,” but not indiscriminately. “Make” is preferable.

In using flat ends, dust particles may at any time settle. They act as buffers, rendering the contact soft and uncertain. This is inevitable and is one evil of the flat-ended measuring surface, but cleaning is easily done. The presence of dust would not be detected in the ordinary measuring machine; it would be observed at once in the electric machine, a point further to the advantage of the latter method.

(VI) ACTUAL MEASUREMENTS.

In order to show the method of measuring, suppose it is desired to compare two gauges A and B. They are inserted in the gauge-holder and clamped tight with packing pieces, setting the left surfaces to lie approximately in one plane. Wrap the gauges in flannel, insert a thermometer and leave them to attain temperature equilibrium.

Set gauge A thus: bring up the left micrometer contact to touch the near side of the gauge face and take the reading R_1 . Withdraw the contact point, translate the gauge horizontally, make contact on the far side of the gauge face and take the reading R_2 . In general R_2 will differ from R_1 . The object is to make these readings identical. This is attained by means of the adjusting screws (*see* Section II, Part 3, page 584), in the course of a few minutes. Next translate the gauge and make contact on the bottom of the gauge-face and obtain reading R_3 . Translate

vertically, make contact on the top side of the face and obtain reading R_4 . Use the adjusting screws till R_3 and R_4 are equal. Try readings R_1 and R_2 again, to see if that adjustment has been upset, and finally get $R_1 R_2 R_3 R_4$ in agreement within 1 micron of one another. Gauge A is then set. Readings are taken on it as follows:—

Let the rectangular figure represent the left face of the gauge (Johansson in this case). Mark off eleven places on the face regularly spaced as shown. Enter these in column 1, Table 1.

FIG. 14.

Translate the gauge till place 1 is opposite the left contact end. Take a reading there and enter it at the top of column 2 ($157\cdot3$). Bring up the right contact point to the right face of the gauge. Take a reading there and enter it at the top of column 3 ($352\cdot4$). Add the two readings and enter the result at the top of column 4 ($509\cdot7$). Proceed in this way for all eleven places on the gauge face, obtaining the set of numbers in column 4.

Repeat the whole process three times, the outcome of the whole being columns 4, 7, 10, 13. The arithmetic means for each place on the gauge are given in column 14.

On comparing the results, we find the differences ($0\cdot35 \mu$) between results in each column to be greater than the differences between one column and another for the same place on the gauge. As far as columns 4, 7, 10, 13, are concerned, consistency in

a vertical direction implies regularity in the gauge; whereas consistency in a horizontal direction shows accuracy in the measuring apparatus as a whole. From the above figures we see that, at least in this Table, the measuring machine is more regular in action than the gauge is constant in length along different parallel lines. Subsequent tables of measurements support this view. The most irregular results are for place No. 1. They are 509.7, 509.95, 509.7, 509.9. The greatest difference here is 0.25μ . There are several possible contributors to this error:— (1) Backlash of the screw; (2) loose working of the translations or irregular surface of the upright plane, whereby the gauge might receive a small rotation before returning to its starting place; (3) error in reading the contact; (4) thermal expansions in the gauge or in the machine; (5) irregularity of surface. A small depression or pit might occur here and there on the surface. Of these factors experience on the machine shows that (1) and (3) are negligible, whilst (4), if existent, would probably be progressive, which it is not. Thus only factors (2) and (5) remain; the first is due to irregularity of the upright plane, and the second due to irregularity of the gauge faces.

A scraped surface of the first quality would probably have depressions of at least 0.5μ . The error in the gauge length resulting from this would be negligible. A well-lapped surface, such as the face of a Johansson gauge, has very small pits or grooves. It is uncertain how much they would affect present results.

Before leaving Table 1 it may be noticed that the results in column 14 are grouped in brackets; each bracket contains places equispaced in straight lines along the length of the gauge (*see* rectangular diagram, Fig. 14), the numbers are seen to advance in the same sense. Thus the gauge proves to be slightly thicker at bottom than at top and thicker on the far side than on the near side.

Having set and measured gauge A, proceed on the same lines with gauge B. Suppose this is a 1-inch gauge made by wringing together three Johansson components (0.400 m., 0.350 m., 0.250 m.). The results are in Table 2. It will be seen that this

TABLE 1.
1-inch, Johansson.

1 Place.	2 L.	3 R	4 L + R	5 L	6 R	7 L + R	8 L	9 R	10 L + R	11 L	12 R	13 L + R	14 Means.
1	157.3	352.4	509.7	157.65	352.3	509.95	156.9	352.8	509.7	156	353.9	509.9	509.81
2	156.25	353.55	509.8	157.45	352.45	509.9	157.4	352.5	509.9	156.5	353.35	509.85	509.86
3	156.9	353	509.9	157.1	352.70	509.8	157.5	352.3	509.8	157.6	352.1	509.7	509.80
4	155.5	354.5	510.0	157.4	352.5	509.9	157.0	352.9	509.9	156.2	353.75	509.95	509.94
5	154.5	355.5	510.0	154	355.9	509.9	155.5	354.4	509.9	154.6	355.35	509.95	509.94
6	156	354	510.0	156.1	353.9	510.0	157.2	352.7	509.9	156.8	353.2	510.0	509.97
7	156.3	353.7	510.0	157.35	352.65	510.0	157.6	352.4	510.0	157.2	352.8	510.0	510.00
8	154.4	355.6	510.0	155	355	510.0	156.1	353.8	509.9	155.25	354.8	510.05	509.99
9	156.1	354	510.1	155.55	354.45	510.0	156.5	353.5	510.0	155.9	354.1	510.0	510.02
10	156	354.1	510.1	158	352	510.0	156.8	353.2	510.0	155.55	354.5	510.05	510.04
11	154.9	355	509.9	154.6	355.4	510.0	154.6	355.5	510.1	154.45	355.65	510.1	510.02

Readings are expressed in microns ($\frac{1}{1000}$ mm.).

TABLE 2.

1-inch, Johansson $\left\{ \begin{array}{l} 0.400 \\ 0.350 \\ 0.250 \end{array} \right.$

1 Place.	2 L	3 R	4 L + R	5 L	6 R	7 L + R	8 L	9 R	10 L + R	11 Means.
1	359.5	474.65	834.15	362.4	471.6	834.0	357.9	476.2	834.1	834.08
2	357.7	476.5	834.2	360.5	473.45	833.95	356.4	477.8	834.2	834.12
3	360.45	478.8	834.05	364.4	469.5	833.9	359	475.0	834.0	833.98
4	359.75	474.1	833.85	362.5	471.5	834.0	358.8	475.5	833.8	833.88
5	358.8	475.4	834.2	360.8	473.2	834.0	357.5	476.65	834.05	834.08
6	356.3	477.7	834.0	360.6	473.3	833.9	354.65	479.3	833.95	833.95
7	361.25	472.7	833.95	361.4	472.45	833.85	357.8	476.1	833.9	833.90
8	360.85	473.2	834.05	256.25	477.8	834.05	358.15	476.0	834.15	834.08
9	359.6	474.4	834.0	255.2	478.8	834.0	357	477.0	834.0	834.00
10	361.6	472.3	833.9	257.2	476.7	833.9	358.8	475.1	833.9	833.90
11	361.2	472.6	833.8	257.3	476.4	833.7	358.75	475	833.75	833.75

composite gauge, like the simple one, has measurable errors, somewhat larger than for the simple one. The results in Table 1 are expressed graphically in Fig. 15. The vertical line on the extreme left stands for place 1 on the gauge, the readings for which range from 509.7 to 509.95. The next vertical line stands for place 2, the readings ranging from 509.8 to 509.9, and so on. Thus the length of a vertical line is inversely as the accuracy of the machine readings at any place on the gauge. It is evident that, while the errors of the machine average out about 0.13 micron, the errors of the gauge are distinctly greater, namely, 0.24 micron.

Fig. 15.

The mean result in Table 1 is 509.93. It does not indicate the length of the gauge, but is merely the sum of the two headstock readings as these happen to lie on the bed. Again in Table 2 the mean result happens to be 834.00 and was obtained after the two headstocks had been moved from the position for Table 1. Hence there is no correspondence between the results in the two cases.

The results in Tables 1 and 2 can be shown graphically (*see* Figs. 16 and 17). The ordinates are results in microns as given by the last columns of the tables. The abscissæ show different places in the gauge, these being marked on the curves obtained. The results are grouped, as explained above, in three

parts, each part representing readings along a straight line on the gauge face. Thus places 1, 2, 3, 4 are one line, while 5, 6, 7 and 8, 9, 10, 11 lie on parallel lines on the gauge face. For a perfect gauge (presuming no errors in the machine) the three curves would merge into one horizontal straight line. The following conclusions are obtained from an inspection of these curves. (1) The combination gauge is in general more irregular than the simple gauge, the extreme differences being 0.37μ and 0.24μ respectively. (2) The far side of the gauge has smaller values (i.e. the gauge is there longer) than the near side. (3) The centre line (5, 6, 7) is intermediate between the near and far lines. Another set of

FIG. 16.

FIG. 17.

graphs, Figs. 18 and 19 (page 610), is given for the 3-inch gauges (see Tables 3 and 4), simple and composite. The same general features as in the 1-inch gauges are observed.

Consider the errors incident to using Johansson's method of composite gauges. Suppose the three components in the above case are all wedge-shaped by an equal small angle. The composite gauge may have (by a 1 in 4 chance) a trebled wedge angle; whereas the chances are 3 to 1 that the composite gauge is no more wedge-shaped than the components. And so on for gauges wrung from any number of components. But there is a more serious error which arises from dust particles included between the components. It is difficult, after cleaning the parts thoroughly,

TABLE 3.

3-inch, Johansson $\left\{ \begin{array}{l} 2.00 \\ 0.65 \\ 0.35 \end{array} \right.$ (Temp. $19.1^{\circ} C.$).

Places.	L	R	L + R	L	R	L + R	Means.
1	278.1	160.9	439.0	280.6	158.4	439.0	439.0
2	277.85	161.0	438.85	276.7	162.2	438.9	438.87
3	276.0	163.0	439.0	276.75	162.4	439.15	439.07
4	276.5	162.5	439.0	276.6	162.4	439.0	439.0
5	279.4	159.6	439.0	279.3	159.65	438.95	438.97
6	275.4	163.7	439.1	275.5	163.5	439.0	439.05
7	275.75	163.25	439.0	275.8	163.2	439.0	439.0
8	277.0	162.0	439.0	278.1	160.8	438.9	439.0
9	274.45	164.6	439.05	274.6	164.5	439.1	439.07
10	274.65	164.4	439.05	276.1	163.0	439.1	439.07
11	274.8	164.4	439.2	274.6	164.6	439.2	439.2

TABLE 4.
3-inch, Johansson (Temp. 18.2° C.).

Places.	L	R	L + R	L	R	L + R	Means.
1	99.7	481.5	581.2	95.7	485.6	581.3	581.25
2	99.0	482.2	581.2	98.7	482.5	581.2	581.20
3	102.0	479.1	581.1	102.0	479.2	581.2	581.15
4	104.9	476.3	581.2	105.2	476.1	581.3	581.25
5	96.4	484.75	581.15	96.6	484.5	581.1	581.12
6	98.8	481.3	581.1	99.9	481.2	581.1	581.10
7	103.2	477.9	581.1	103.3	477.9	581.2	581.15
8	94.3	486.75	581.05	94.4	486.7	581.1	581.07
9	97.7	483.4	581.1	97.75	483.2	580.95	581.03
10	101.2	479.9	581.1	101.2	479.8	581.0	581.05
11	104.3	476.7	581.0	104.4	476.6	581.0	581.00

to wring together so carefully as to exclude dust. No doubt much dust would prevent wringing together; but a smaller amount included will not prevent the components holding one another strongly. In some cases, one has found a wedge-shaped interval differing in thickness at the ends by $3\ \mu$ or $4\ \mu$, though after more careful cleaning and wringing this difference was reduced to $0.2\ \mu$, which is the probable error in the gauge itself. The ordinary measuring machine is less likely to observe this error than the electrical machine for two reasons: (1) The former is about one-third as sensitive as the latter; (2) The former applies such large

FIG. 18.

3 INCH COMB.^N J.

FIG. 19.

3 INCH J.

forces, say 3 lb. or more, as would, during measurement, flatten out the dust particles; whereas in the electrical machine the pressure used is minute.

In this connection we may observe how the actual length of simple and composite gauges, of the same face value, compare with one another. Whenever this comparison is made the process adopted is to "set" one of them, make a complete test as shown in the above tables, and note last of all the readings for the gauge centre. The other gauge is then set and the readings for its centre noted. In this way it should be possible to avoid temperature errors and obtain comparison accurate to at least $0.2\ \mu$.

Some results follow:—

TABLE 5.

Johansson's Gauges.

Gauges.		L	R	L + R	a - b
4-inch	(a)	182.7	107.5	290.2	} 0.3 μ
4-inch combination $\left\{ \begin{array}{l} 3.00 \\ 1.00 \end{array} \right\}$	(b)	92.0	197.9	289.9	
3-inch	(a)	241.1	480.6	721.7	} 0.45 μ
3-inch combination $\left\{ \begin{array}{l} 2.00 \\ 0.65 \\ 0.35 \end{array} \right\}$	(b)	558.0	163.25	721.25	
2-inch	(a)	101.0	496.6	597.6	} 0.6 μ
2-inch combination $\left\{ \begin{array}{l} 0.85 \\ 0.70 \\ 0.45 \end{array} \right\}$	(b)	131.0	466.0	597.0	
1-inch	(a)	637.8	197.0	834.8	} 0.25 μ
1-inch combination $\left\{ \begin{array}{l} 0.40 \\ 0.85 \\ 0.25 \end{array} \right\}$	(b)	359.25	475.3	834.55	

$$\mu = \text{micron} = \frac{1}{1000} \text{ mm.}$$

As stated before, a greater value of $L + R$ denotes shorter gauge length. Thus the combination gauge is in all four cases longer than the simple one by an amount considerably greater than the experimental error. This difference cannot be attributed to heating during the wringing process, since the latter was performed hours before comparison was made. So one supposes that dust and the included air-film account for the observed differences.

Mr. Budgett* finds that gauges adhere when wrung together on account of the molecular attraction of the liquid film between them. The gauges no doubt touch one another on an area which is a small percentage of the whole face, and this film lies in the gaps left where the two gauge surfaces are not in actual contact. Thus the film, if free from solid particles, has no effect on the point under discussion; it will not add to the total thickness of a composite gauge.

* Proc. Roy. Soc., 1911 A., Vol. 86.

TABLE 6.

English Make. 1-inch (No. 1).

Places.	L	R	L + R	L	R	L + R	Means.
1	461·2	64·5	525·7	445·0	80·9	525·9	525·8
2	461·0	64·7	525·7	444·9	81·0	525·9	525·8
3	461·2	64·7	525·9	445·0	81·1	526·1	526·0
4	461·2	64·7	525·9	445·2	80·8	526·0	525·95
5	461·1	64·5	525·6	445·0	80·7	525·6	525·6
6	448·0	77·5	525·5	447·5	78·2	525·7	525·6
7	447·9	77·8	525·7	447·6	78·2	525·8	525·75
8	446·2	80·2	526·4	446·1	80·4	526·5	526·45
9	447·7	78·5	526·2	448·2	78·1	526·3	526·25

TABLE 7.

English Make. 1-inch (No. 2).

Places.	L	R	L + R	L	R	L + R	Means.
1	249·9	275·3	525·2	249·3	275·9	525·2	525·2
2	251·2	274·3	525·5	251·5	274·0	525·5	525·5
3	252·6	273·5	526·1	252·8	273·4	526·2	526·15
4	253·9	271·1	525·0	253·6	271·7	525·3	525·15
5	255·3	269·6	524·9	255·4	279·6	525·0	524·95
6	258·3	236·9	525·2	253·2	272·1	525·3	525·25
7	256·4	268·6	525·0	251·2	273·9	525·1	525·15
8	254·5	271·2	525·7	249·0	277·1	526·1	525·9
9	255·5	270·8	526·3	250·5	276·0	526·5	526·4

The Tables so far given refer to Johansson gauges. A set of English-made standards, from 1 inch to 12 inches was available. These are bars, square in section with bevelled edges. The ends are coned and then worked down till the required gauge length is obtained. Some tables of comparison of these with one another are given.

The end faces of these gauges are circular and about $\frac{1}{4}$ inch in diameter. The positions of places on the gauge surface are shown in Fig. 20, place 3 being central. The Tables show that in No. 1

FIG. 20.

(1-inch), place 8 has the highest, places 5 and 6 the lowest results; whereas in No. 2, place 9 has the highest, and places 4 and 7 the lowest results. The greatest differences are, for No. 1, 1.2μ ; for No. 2, 1.45μ .

On comparing these two gauges at their centre points (places 3) we find close agreement, the difference being 0.15μ .

Thus, these gauges compare with one another well at their centres and may possibly be accurate, at these places, in absolute length, but the end faces are far from being true parallel planes.

The greatest differences in Tables 8 and 9 amount to 0.4μ for No. 1 and to 1.5μ for No. 2. At the centre points the gauges differ by 0.2μ only.

Comparison was also made between two 12-inch gauges; but in this case only five places were taken, as shown in the Fig. 21,

FIG. 21.

TABLE 8.

English make. 2-inch (No. 1).

Places.	L	R	L + R	L	R	L + R	Means.
1	448·6	331·4	780·0	447·8	332·1	779·90	779·95
2	448·7	331·0	779·7	448·1	331·6	779·7	779·7
3	449·2	330·4	779·6	448·7	331·0	779·70	779·65
4	449·6	330·0	779·6	449·1	330·6	779·70	779·65
5	450·0	329·6	779·6	449·6	330·0	779·6	779·6
6	450·0	329·8	779·8	449·1	330·8	779·90	779·85
7	453·1	326·9	780·0	451·8	328·2	780·0	780·0
8	452·2	327·5	779·7	451·5	328·2	779·7	779·7
9	451·0	328·6	779·6	449·5	330·1	779·6	779·6

TABLE 9.

English make. 2-inch (No. 2).

Places.	L	R	L + R	L	R	L + R	Means.
1	427·2	352·3	779·5	427·3	352·1	779·4	779·45
2	426·6	352·9	779·5	426·5	353·0	779·5	779·5
3	425·8	353·6	779·4	425·6	353·9	779·5	779·45
4	425·3	354·3	779·6	425·1	354·6	779·7	779·65
5	424·2	355·0	779·2	424·0	355·4	779·4	779·3
6	430·0	350·5	780·5	428·5	352·1	780·6	780·55
7	430·2	349·2	779·5	430·7	348·7	779·4	779·4
8	439·8	349·2	779·0	429·6	349·5	779·1	779·05
9	427·2	352·0	779·2	427·6	351·6	779·2	779·2

TABLE 10.—*English make. 12-inch (No. 1).*

Places.	L	R	L + R	L	R	L + R	Means.
1	427·3	121·1	548·4	428·4	120·1	548·5	548·45
2	427·9	120·2	548·1	428·4	119·9	548·1	548·1
3	428·3	119·5	547·8	428·2	119·7	547·9	547·85
4	430·3	117·7	548·0	429·7	118·4	548·1	548·05
5	430·1	117·8	547·9	430·2	117·6	547·9	547·85

Temp. 18·0°

Temp. 18·0°

TABLE 11.—*English make. 12-inch (No. 2).*

Places.	L	R	L + R	L	R	L + R	Means.
1	21·3	527·5	548·8	20·8	527·9	548·7	548·75
2	20·2	529·5	549·2	20·0	529·2	549·2	549·2
3	21·5	527·5	549·0	21·4	527·5	549·1	549·05
4	20·2	528·3	548·5	20·0	528·6	548·6	548·55
5	23·3	525·9	549·2	23·2	526·1	549·3	549·25

Temp. 18·0°

Temp. 18·0°

place 2 being central. In the case of such long bars, special care, *see* Section V, must be taken to reduce temperature errors.

The greatest differences amount to 0.6μ for No. 1, and to 0.7μ for No. 2. These are less than for the 1-inch and 2-inch bars of the same make, but in the cases of the shorter bars nine readings in all were taken, some nearer the edge than in the present instance. This would account for the apparent greater uniformity in the present case. In the case of long gauges, when the faces are

FIG. 22.

Diagram to show how Absolute Measurement can be made with Point Contact.

small, as in this make, it is impossible to obtain the full complement of readings unless the faces are quite perpendicular to the length of the bar. Hence only five are taken in this instance. After all the above readings were taken for No. 1, it was measured at the centre point. No. 2 was then set and immediately it was measured at the centre point. The following Table shows exact agreement between gauges No. 1 and No. 2 within experimental errors :—

—	L	R	L + R
No. 1 . . .	448.8	100.4	549.2
No. 2 . . .	20.0	529.2	549.2

Absolute Length.—After the above readings on the 12-inch gauges one of them was measured absolutely against the line standard as follows. Set the line standard at some line under the microscope, and let the reading be m . Make contact at the centre points of the gauge faces and let the readings of left and right headstocks be L and R . Remove both 12-inch gauges and substitute in the gauge-holder a short Johansson gauge, say 1 inch, having wrung on one face a thin Johansson slip, say 0.1 inch, as shown, Fig. 22. Adjust the face of the slip to be perpendicular to the run of the bed (*see* Section VI). Unclamp the gauge-holder and run it to the right along the bed, till the right contact nearly touches the slip. Unclamp the left headstock and run it along the bed till it is nearly in contact with the slip. Set a line of the line standard under the microscope and let the reading be m_2 . Make contact of the left measuring end on the slip, call the reading a . Make contact of the right measuring end on the slip, call the reading b .

Translate gauge and slip across and take contact reading c . Remove the slip and make contact on the 1-inch gauge, reading d .

Thus the left headstock has moved as a whole ($m_1 - m_2$). Add to this $(L - a) + (R - b) + (c - d)$, and we have the length of the 12-inch gauge. This roundabout way of measuring is necessary (when we use point contacts), since it is practically impossible to be sure that when the right and left measuring ends are run into contact their extreme points meet.

The following results are obtained (the units are microns):—

Set A.	Set B.
$L = 28816.5$	$L = 28816.5$
$R = 29609.4$	$R = 29609.8$
$m_1 = 483000$	$m_1 = 483000$
$m_2 = 181000$	$m_2 = 180000$
$a = 30826.5$	$a = 29826.6$
$b = 29145.9$	$b = 29145.1$
$c = 29133.1$	$c = 29154.5$
$d = 30403.2$	$d = 30424.5$
temp. 18.2°	temp. 18.2°

Length (at 18.2°) = $(m_1 - m_2) + (L - a) + (R - b) + (c - d)$.
 This comes to:—

—								Microns.
Set A	.	.	.	.	.	.	.	304816.6
Set B	.	.	.	.	.	.	.	304815.3
Difference	.	.	.	.	.	.	.	1.3

This example shows that consistency is possible by this method. If the actual length were desired we should apply corrections for the errors of each micrometer screw, also for calibration errors of the scale, also for thermal expansion to reduce to standard temperature.

Later a more convenient method of absolute measurement will be given, but if the measuring ends are points, the above appears to be the simplest accurate method.

In the present machine electric contact is not made (as in the former machine) at the measuring end (*see* Section II); therefore it is easy to measure a non-conducting gauge or other body. A glass plate, whose two surfaces were optically worked and supposed to be parallel, was tested with results following:—

TABLE 12.
A Glass Plate, optically worked.

Places.	L	R	L + R	L	R	L + R	Means.
1	155.2	277.9	433.1	155.4	277.8	433.2	433.15
2	155.1	278.1	433.2	155.0	278.4	433.4	433.3
3	155.1	278.0	433.1	154.9	278.4	433.3	433.2
4	157.0	275.9	432.9	156.4	277.0	433.4	433.15
5	156.8	276.3	433.1	156.6	276.8	433.4	433.25
6	155.3	277.9	433.2	155.7	277.6	433.3	433.25

Measurement with Flat Ends.—All measurements described so far have been made with point contact, which, though the best method for parallel-ended bars, is not convenient in many cases of comparative and in all cases of absolute measurement.

The usual commercial measuring machine has flat measuring ends; but it should be possible to do much better measuring with flat ends in the present machine than in the usual machine for several reasons.

The measuring ends are seen in Fig. 10 (page 587), the end piece MN is ground to fit the bar AB, and so rests firmly in position, while there is a bushed guide-plate *g*, through which, with a close fit, the left end of MN passes.

As *g* is firmly supported by a strong bracket fixed to the headstock the whole projecting measuring end is kept in position.

Before commencing a measurement the flat ends must be adjusted. A contact rod having a rounded point is fixed to the gauge-holder, so as to project towards the flat end. When the translatory movements are given to the table, the contact moves over face *b*, and it is easy by electric contact to observe if this face is "square." If not, the three screws *d* are worked in or out till that condition is attained. Similarly for the other flat end, and thus we have two flat ends set plane and parallel, to known accuracy. The above adjustment is supposed to be made once for all, but when special accuracy is desired it is easy to readjust.

Next, the gauges to be measured are inserted in the gauge-holder clamps and adjusted to squareness, and the actual measurement then proceeds as described before. A few cases follow :—

TABLE 13.

1½-inch Cylinder (Brown and Sharpe).

Places.	L	R	L + R	L	R	L + R	Means.
1	490·0	338·7	828·7	486·9	342·0	828·9	828·8
2	490·2	338·5	828·7	488·0	340·7	828·7	828·7
3	488·4	340·5	828·9	486·0	342·8	828·8	828·85

TABLE 14.
 $1\frac{1}{4}$ -inch Cylinder (English Make).

Places.	L	R	L + R	L	R	L + R	Means.
1	472.1	330.4	802.5	475.3	327.3	802.6	802.55
2	473.0	329.8	802.8	474.8	327.8	802.6	802.7
3	474.9	328.5	803.4	475.5	328.0	803.5	803.45

The few readings given and repeated suffice to show that the same order of accuracy is obtainable as for point contact.

TABLE 15.
Spherical-ended Gauges (Hartmann).

51 mm.

50 mm.

Places.	L	R	L + R	L	R	L + R
1	385.8	83.5	469.3	622.8	847.4	1470.2
2	101.5	364.2	465.7	571.0	900.2	1471.2
3	402.2	65.6	467.8	812.0	660.0	1472.0
4	410.3	58.6	468.9	651.0	818.0	1469.0

The places at which measurements are taken occur on the end face as shown in Fig. 23. The irregularities of the gauges are

FIG. 23.

considerable (as much as 3.6μ). The difference in length between the gauges at their centres is 1.0009 mm., assuming accuracy in the micrometer screws.

Absolute measurements are more easily done with flat ends than with points. The method of procedure is simple and no examples need be quoted.

Nowadays gauges are made with greater accuracy than formerly. Each unit of any gauge system of the cumulative type, like Johansson's, must obviously be made very true, or the composite gauge, of several wrung together, would be useless. Johansson, in Sweden, and some American machinists, manufacture with an accuracy demanding the best obtainable measuring appliances.

The machine which is now wanted is one which is not only sensitive, but also is capable of testing the gauge in all possible positions. The same gauge might be tested on the ordinary measuring machine by skilled metrologists in London, Paris, and Washington, with three results differing by considerably more than experimental errors. The reason is obvious with the ordinary machine; wrong assumptions are made, e.g. (1) the truth of the gauge surface; (2) the truth of the measuring end surfaces; (3) the accurate alignment of the supporting cradle. The author has spent many years developing the present machine, which can claim to be sensitive and free from many of these false assumptions. The measure of success attained is indicated by the consistency of the readings on the best gauges.

The machine was made by Messrs. Manlove, Alliott and Co., Nottingham, who generously undertook the work at cost price. The author's thanks are due to Mr. J. M. C. Paton, managing director, and to Mr. F. Read, manager, for their interest and help in the design and construction.

After manufacture, the machine was set up at the National Physical Laboratory, Teddington. The author wishes to express his appreciation of the kindness of Dr. R. T. Glazebrook in allowing him free access to the Laboratory and all its facilities. Since the machine has been at Teddington, lengthy and exhaustive tests

made by the writer have led to improvements in some details. Dr. T. E. Stanton, head of the Mechanical Department, has been most helpful by readily allowing these alterations to be effected by his highly skilled assistants. Mechanical assistance has also been rendered by Mr. W. S. Linney of the Physics Department, University College, Nottingham.

(VII) SUMMARY.

To summarize the results of this Paper :—

(1) A new measuring machine is described founded on the principle of electric touch. It is applicable to the measurement of regular solid bodies, e.g., cylindrical, spherical, or parallel-faced, whether metallic or non-metallic. The present machine embodies improvements found desirable in a measuring machine described by the author in 1906.

(2) The solid to be measured is firmly held in a clamp. It can be adjusted in azimuth and elevation and so set parallel to the line of measurement. It can also be run into position by movements perpendicular to its length. For comparison, two solids can be clamped side by side.

(3) The unit of measurement is 0.1 micron ($= \frac{1}{10.000}$ mm.), and comparative readings can be relied on to this amount.

(4) The actual length of a solid as compared with a line-standard can be obtained. Whereas it is usual to have the line standard fixed, and the reading microscope moving with the micrometer, in the present case the microscope is fixed, and the scale moves with the micrometer.

(5) The parts of the machine directly involved in the measuring are susceptible of adjustment; and the errors arising in taking measurements can be estimated.

(6) The machine has been chiefly used for testing and measuring engineering gauges. The gauges made by Johansson, of Eskilstuna, Sweden, are so regular in figure that the usual measuring machine cannot detect any irregularity in them. With the present machine, errors of the order 0.2 micron can be proved to exist.

These gauges are commonly used wrung together to form combination gauges; tests have been made on these also. Small errors occur due to dust inserted by accident between the faces of any two members of a combination, sometimes producing a slightly wedge-shaped result.

(7) For flat-ended bodies, exploring is best done with rounded polished points; but for many purposes, notably for absolute measurement, the measuring ends should be flat; and in this machine it is possible to employ pointed or flat ends at will.

The Paper is illustrated by Plate 10 and 20 Figs. in the letterpress.

Discussion.

Mr. S. W. ATTWELL (National Physical Laboratory) wrote that the end-measuring machine described by Dr. Shaw was set up, and was now, at the National Physical Laboratory, and since Dr. Shaw finished his work for this Paper, it had been used on several occasions for exploration of the end surfaces of length gauges. In work of this kind the machine gave very accurately the variations in lengths of the gauge by means of measurements usually made along different axes parallel to the principal axis, and thus indicated the presence of any error in form of the end surfaces. In the case of gauges found to be in error for form, the measurements did not, however, demonstrate to what extent each end separately was in error, since the readings obtained on either headstock included any variations due to irregularity in form of the surface-plate L, Figs. 7 and 8 (page 585), which variations were only eliminated in taking the addition of the readings from both headstocks. For instance, in investigating a spherical-ended gauge, the mean curvature of the two ends was accurately obtained, but the sphericity of either end separately was left indeterminate.

(Mr. S. W. Attwell.)

It might be possible to improve the machine in this respect by some modification in the design of the translation movement of the gauge-holder. At present the difficulty had not been overcome, even at the expense of prolonged investigation. On the other hand, with flat-ended gauges, the accuracy of each end could be tested by means of an optical proof plane, as described on page 599. Measurements made on the machine then gave very valuable information as to the parallelism of the two faces. The author gave the results of measurements on combinations of gauges compared with a single gauge (page 611), and noted that the combination gauge was in each case longer than the single one. But in concluding that differences were due to dust particles, etc., he had not allowed for the errors in the values of the gauges. The gauges used by Dr. Shaw were taken from a set standardized and used at the Laboratory, and on correcting for known errors in the actual length of the gauges the differences became:—

$$\begin{array}{rcl} 3\text{-inch} - 3\text{-inch combination} & = & -0.2\mu, \\ 2 \text{ ,, } - 2 \text{ ,, } & \text{,,} & = -0.3\mu, \end{array}$$

the differences of the other two comparisons remaining unaltered. The above corrections decreased the mean values of the differences to about -0.25μ , only slightly greater than the experimental error. But as in all four cases the single gauge still measured smaller than the combination when corrected for known errors, it was possible that Dr. Shaw's conclusions were not altogether unfounded.

As regards the determination of absolute length of end standards from line standards, the chief difficulty in the way of accurate results seemed to be with the want of control over the temperature of the gauge. It was hoped that the machine would be used for work on these lines at the Laboratory before long, when checks on the accepted lengths of standards would be valuable. In the example given by Dr. Shaw (page 619) it was interesting to note that, after correcting his results for known errors in the scale and for temperature, the mean value deduced from his measurements gave a length within 1μ of the Laboratory accepted value of the

12-inch gauge. This was a good agreement when one considered that there might be small errors in each micrometer screw, and that the difference between the results of the measurements in Set A and Set B was 1.3μ .

Mr. C. HUMPHREY WINGFIELD noticed on page 589 that invar was made use of for a micrometer screw. He knew this metal had been advocated for measuring instruments by some leading mechanical engineers, but he felt sure they were wrong. To take the simplest case—a calliper-gauge used to measure the length of a piece of steel. If both had the same coefficient of expansion, the gauge could be used at all temperatures. For extremely accurate work, as there was a likelihood of the gauge and bar having different coefficients of expansion, it was necessary they should both be at the temperature at which it was known the gauge was accurate.

If invar were used, the bar might be gauged at a standard temperature; in this respect no advantage was apparent. At any other temperature the discrepancy between the gauge and a bar correct at standard temperature would be greater than if invar was not used, since there was no tendency for the gauge to follow up the variations of the bar due to temperature.

It followed that where invar was used, greater inaccuracy would necessarily follow at any temperature other than that selected as standard, while, at the standard temperature, no advantage was gained for its use. It was, in fact, a most unsuitable material for measuring instruments, though valuable for such purposes as clock pendulums.

He had no criticism to offer on the Paper itself, except that, as the distance between p_1 and p_2 , Fig. 10 (page 587), constituted a "constant" amount of play which had to be taken up before a measurement could be made, the value of this distance required very careful and frequent checking.

Dr. SHAW, in reply, wrote that the machine was made to accomplish various measurements diverse in nature. It was an attempt to increase the accuracy of such measurements as the

(Dr. Shaw.)

ordinary machine made, and to add to these functions others which the ordinary machine failed to provide. These uses had been summarized in the Paper. It was true, as Mr. Attwell pointed out, that surface plate L, Figs. 7 and 8 (page 585), being irregular, threw its own errors into the readings of one gauge-face, and that therefore these readings could not be taken to represent the truth of that one gauge-face. It was not claimed by Dr. Shaw, however, for the machine that it would serve this particular use. After much experience in measuring irregularities in scraped and lapped surface-plate* the best surface-plate found had irregularities of 1μ ($= \frac{1}{25,000}$ inch), and an ordinary one had errors of 2.5μ . This being so, the difficulty raised by Mr. Attwell resolved itself into that of giving plate L a surface truer than that of the best commercial surface plates. The one in the machine had inequalities of about 1.5μ (see Table 1, page 604). The best commercial plate of the size required would be liable to error of at least 0.5μ , an error which would be inadmissibly great for Mr. Attwell's purpose. Though this error entered the readings for one face, no error at all due to plate L entered the joint readings of the two faces, the attainment of which was the purpose of the machine.

As regards the difference between gauges single and in combination which the author attributed to dust particles, his results, after Mr. Attwell's deductions for known errors of the gauges, came out in the four cases quoted as 0.2μ , 0.3μ , 0.3μ , 0.25μ . The consistency of these numbers pointed to some common cause, other than, for instance, observational errors, which would not be all plus errors of the same amount. In note (6) of the summary it was stated that a large wedge-shaped error sometimes arose in the combination system. This was distinct from the effect under discussion, and, taken in conjunction with the results obtained after Mr. Attwell's deductions, seemed a confirmation of the author's surmise, and results.

Invar was used in the machine not for the micrometer screws, as Mr. Wingfield appeared to have gathered, but for distance-pieces

* See Shaw, Proc. Roy. Soc., 1912 A, Vol. 86.

in connection with these screws. One understood that invar could not be cut and polished smooth enough for good micrometer screws. If a calliper-gauge made of invar were used to measure, absolutely, any material but invar, errors would exist in the results for any but standard temperature. But suppose one bar after another of steel were being *compared with one another or with a standard scale*, the calliper-gauge made of invar would be more accurate than any other, since it would not itself change in length, thermally, between individual measurements. In the electric measuring machine invar was used for this very reason. As the micrometer screws were enclosed in a massive casting, it and the massive bed of the machine changed in length, thermally—at a very slow rate; but any small projecting part, having a large surface relative to its mass, would be liable to change temperature quickly through radiation and conduction. Hence the small projecting ends were made of invar, and errors occurring in comparative work were reduced to a minimum; for the measuring machine, unlike the calliper-gauge and screw-gauge, only took comparative measurements either between gauge and gauge or between gauge and standard scale. The author had found invar most useful in other apparatus for delicate comparative measurement where temperature changed quickly.

As regards the constant amount of “play” mentioned. Here again Mr. Wingfield would be quite correct if absolute measurements were taken as in a calliper-gauge, but in comparison work no error whatever arose. If any change were to occur in the play between consecutive readings, it would be seen at once in the readings. Such change did not occur in practice.

Fig. 3. Machine Pl. 10.
in the Works.

Fig. 9.
A Measuring End.

Fig. 5. Machine
ready for use
in the Laboratory.