The Testing of Plane Surfaces.

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There is only one way of originating a true plane, viz., to make it in triplicate and to work all three surfaces so as to obtain a "fit" between them. In engineering trade practice this is done when a standard plate is required, and any one of the three plates thus obtained can be used as being truly plane (within the limits of the "raddle" process) for the making of further surface-plates.

In many modern exact apparatus, *e.g.*, a standard measuring machine or a Michelson's interferometer, accuracy of measurement directly depends on the truth of the plane "ways" of the bed along which the various parts of the apparatus slide. These ways are made either by scraping or lapping, and it is of importance to know what errors occur from place to place along the bed due to defective workmanship. The bed generally has three worked planes all inclined to one another, and the movable parts rest on these by five contact points, thus allowing only one degree of freedom. These five feet bear on the surfaces below by small areas, and amongst other considerations it is important to know how far these feet rise and fall in and out of the scraping marks if the surfaces have been made by scraping.

Any such rise and fall produces a rocking motion in a movable part as it slides along the bed. In a badly made surface such pits would be wide and deep and the attendant rocking motion considerable. But any surface, whether scraped or lapped, is liable to have constant or variable curvature over a large area due to defective workmanship or due to warping subsequent to manufacture.

It is convenient for present purposes to denote the small local irregularities as *ripples* (only found on scraped surfaces) and the large changes in curvature as *waves*. Any tool used to test for ripples must have small feet, whereas for waves one would need an appliance with feet of such large area as would not fall into scrape marks.

The object of this paper is to indicate ways of measuring these errors in surface-plates. The writer recently had a measuring machine made. Its purpose was to apply to end-standards of length very severe tests as to length and figure; and for this purpose one must be sure that errors of the first order, due to inequalities in the bed, will not enter the results. In the making of the bed more than usual care was taken in casting the bed and in "ageing" it with repeated planing and finally with various stages of scraping.

The principal headstock of the machine has a long base (18 inches). Suppose this headstock is placed on the bed and a sensitive spirit level mounted on it; if it be moved along the bed, then, supposing the three cardinal planes of the bed are true planes, it will move along without rocking and the spirit level will remain at rest. But any error, whether ripple or wave, in the bed would be shown by the level. Very sensitive spirit levels can be made, but exact quantitative results are required, and it would not be easy to calibrate such a device, besides which, if it is sensitive, it must have a very limited range. Moreover it could only be used for a level surface and would not be generally applicable to testing plane surfaces which are often inclined *in situ* to the horizon. So a spirit level device will not serve our purpose.

Again a spherometer will not do, as we have to test a surface which has considerable length but small breadth. In short, there is no apparatus or method in use suitable for the purpose, so one must be invented.

Surface-tester No. 1.—The first device adopted is shown in fig. 1. A stout bar, 20 inches long, of teak is fitted with (1) a micrometer screw in the

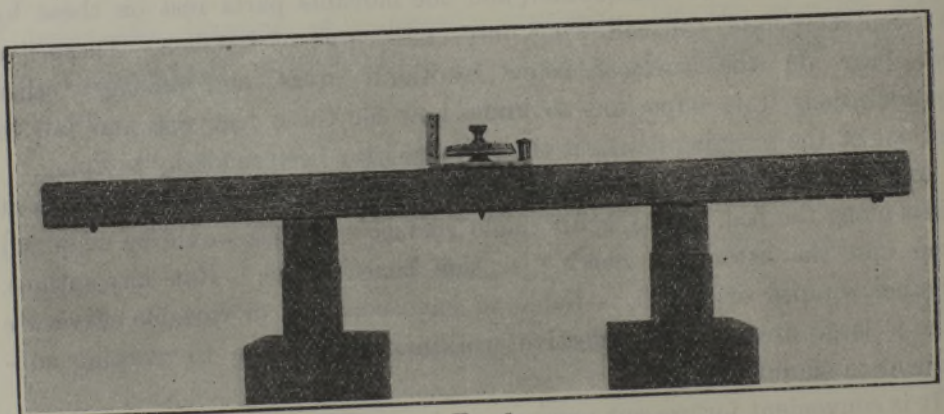

FIG. 1.

centre and with (2) two feet, half an inch apart, set in a line across the bar at one end, and (3) one foot at the other end of the bar.

All the feet are studs just flattened, such as would be found on a rounded foot which has been worked to and fro several times on a flat surface. The micrometer screw being "in," the apparatus, which is akin to a spherometer, would rest stably on a surface plate. There is a binding screw attached to the micrometer. A circuit of a simple cell, resistance box, and telephone receiver is joined to the binding screw and the surface-plate. By working the micrometer "out" electric contact is made when the screw point reaches the surface-plate, and the micrometer is read when the telephone sounds.

Calling the three cardinal surfaces of the bed *a*, *b*, *c*, the following measurements were taken at equal intervals along the length of the bed. The units are 1/10000 inch.

	a.	*b*.	*c*.
	144	143	144
	144	146	142
	143	144	142
	142	144	144
	144	145	144
	144	144	144
	140	144	144
Means	143	144·3	143·5
		Mean of means......	143·6

These surfaces agree, therefore, throughout, to 4/10000 inch for measured lengths of about 16 inches. The rounded mean reading is 143·6. But we have no method, with surface-tester No. 1, of finding the true zero reading. The above surfaces may be all convex or all concave, or the mean reading may be nearly true zero.

The surface-tester was then tried on a new, well-made, scraped surface-plate, the readings being

140 142 140 139 141 142 142 140 140 Mean...... 140·7

If we could assume this plate to be very good, we might take the reading 140·7 to be true zero (*i.e.* the reading which a geometrical plane surface would give), in which case the mean error of the surfaces *a*, *b*, *c*, would be 3/10000 inch in a length of 16 inches. But it is not permissible to assume the truth of any "standard," so the following modification of the above apparatus was made to determine true zero reading.

Surface-tester No. 2.—A stout bar of iron (fig. 2) with a deep vertical web

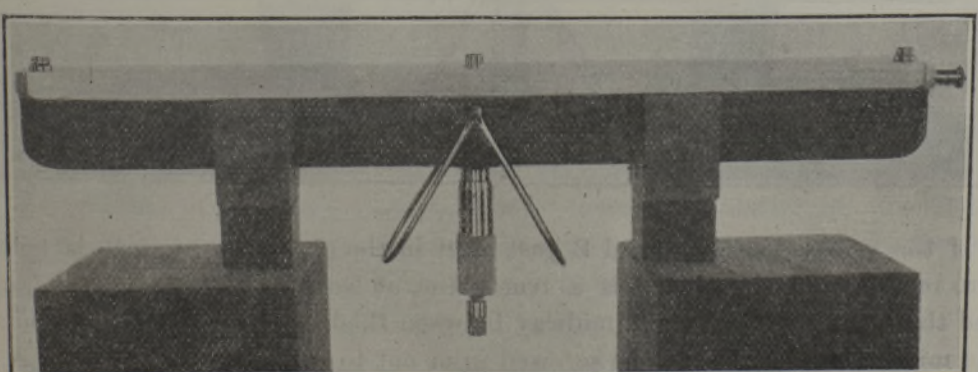

Fig. 2.

has let into its lower face two hardened steel studs with true flat feet of $\frac{1}{4}$ inch diameter. These studs are 12 inches apart. Midway between them is fixed in the bar a Brown and Sharp micrometer screw, whose working end is another true flat surface $\frac{1}{4}$ inch diameter. The studs are bushed, and a binding-screw is let into the bar to enable a circuit to be made just as in tester No. 1. Great care must be taken, when using the testers, that no shocks are received by micrometer and studs. Guards are shown, one on each side of the micrometer. Also, when not in use, the testers are packed away carefully.

This instrument is made in duplicate. Call the two testers A and B. Place A on the surface to be tested. If the micrometer screw is "in," A would rest stably on a flat surface, the end feet touching the latter at places, say d and e. On screwing in the micrometer, contact is made when the latter reaches the surface. Lift the tester from the surface and place it, feet upwards, on a suitable cradle (see fig. 2). Next take the tester B and place it on the surface, its feet resting on places d and e; adjust the micrometer to contact. Take a reading of B; call it B_1. Place B on A as shown in fig. 3.

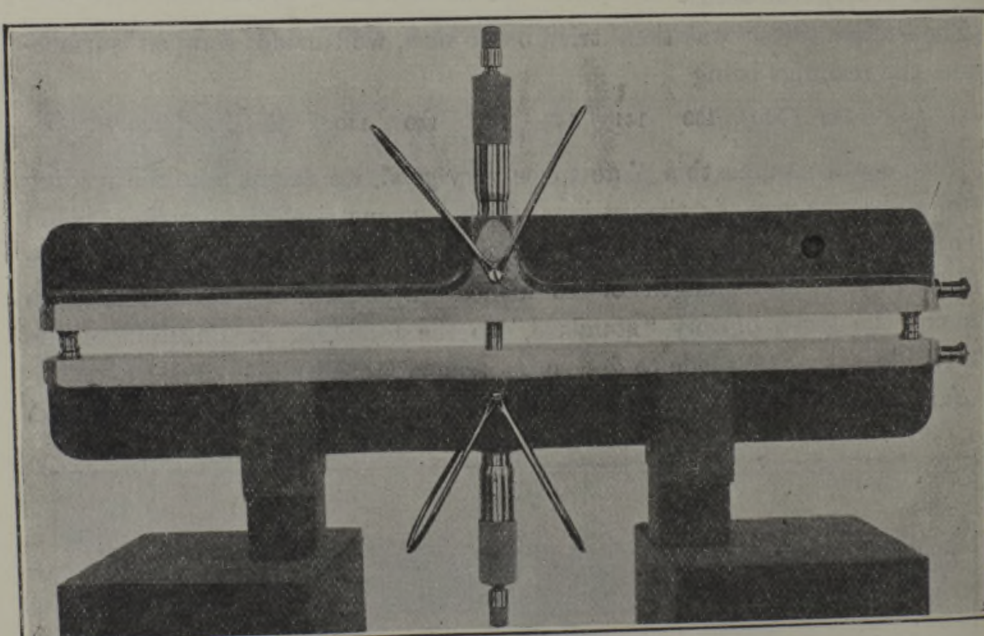

Fig. 3.

If the centre feet of A and B just meet in the above position, B_1 is true zero reading and the surface is a true plane, at least as regards places d, e, and the place on the surface midway between them. If, on the other hand, the micrometer of B has to be screwed in or out to just meet the screw of A, giving reading B_2, we have $\frac{1}{2}(B_1 - B_2)$ as the error of the three places from a straight line. Screwing in shows convexity, and screwing out concavity of the surface. True zero reading is $B_1 + \frac{1}{2}(B_1 - B_2)$.

The process used is akin to the three-surface method mentioned at the beginning of the paper.

A small flexure of the tester occurs, due to its own weight. To avoid this, the supporting blocks under A in the cradle are placed at the Airy points along the bar as shown. Before B rests on A, this arrangement would leave A slightly concave upwards, but when B is placed on A this concavity would be reduced to zero by the weight of B.

For tester No. 2 mechanical contact is simplest, but for tester No. 1 electric contact is more accurate.

In order to obtain true zero reading, we have had to resort to micrometry with flat faces (tester No. 1 would obviously not serve). One great disadvantage of employing flat faces in micrometry is that the errors in truth of these faces enter into the results directly. Surface-tester No. 2 will be of small service unless the highest possible mechanical skill is put into the setting of its three feet in one plane for true zero.

Mr. A. Jenkinson, of the National Physical Laboratory, Teddington, an experienced micrometer maker, undertook to make the two testers No. 2 to meet my requirements, and his work proved very satisfactory. He proceeded as follows :—

Castings were made and were machined and bored roughly to remove casting strains. They were then left for a period in a vibrational place to settle. Machining was repeated. The bottom was scraped true, then clamped to a lathe face-plate and the hole for the micrometer bored out. The holes for the other two feet were reamered to size through a true jig plate. The studs were turned and hardened and were settled in boiling water; they were then pressed into place with bushes. The micrometer was then put into its place and the two other feet lapped by hand till they were true with the micrometer foot. This last process took considerable time and trouble, as on it hangs the accuracy of results.

As examples of the use of the surface-testers the following cases are given :—

I. Hexagon Surface-Plate (2 feet diameter).—Using tester No. 2, nine positions were taken symmetrically round the centre of the plate. In some cases repetition was made to ascertain whether any change due to temperature occurred as the measurements proceeded.

Position.	Reading B_1.	Reading B_2.	Zero reading $B_1 + \frac{1}{2}(B_1 - B_2)$.	Error $\frac{1}{2}(B_1 - B_3)$.
1	17	14	15·5	1·5
2	17	13·5	15·3	1·8
3	17	14	15·5	1·5
4	18	13·5	15·7	2·2
5	18	14	16	2
6	18	13·5	15·7	2·2
7	18·5	14	16·2	2·2
8	17·5	13·5	15·5	2
9	17·5	13·5	15·5	2
7	18	14	16	2
1	17	14	15·5	1·5
			Mean... 15·7	Mean... 1·9 (convex)

As before the unit is 1/10000 inch.

This plate is consistently convex at regions about the centre, the error on a length of 12 inches being on the average about 1/5000 inch.

A set of readings like the above establishes an accurate true zero reading (15·7 in this case). The divergence from this value is at most 0·4/10000 in the table above. This irregularity may be due to defects in the testers or to the impossibility of placing both testers on the same places exactly, or to both causes.

Having discovered true zero for B we need not use A further, for the reading B, together with true zero, gives the error of the surface.

A set of readings taken round the edge of the above surface plate gives us results as below :—

B_1....................	17·5	18	17	16	16·5	16	17	18	16	16
Error, $B_1 - 15·7$...	1·8	2·3	1·3	0·3	0·8	0·3	1·3	2·3	0·3	0·3 (convex)

Thus the mean error near the edge of the plate is less than near its centre, but the plate is more irregular.

Having ascertained the general contour of the surface by tester No. 2 we look for ripples near the centre of the plate by tester No. 1 and obtain readings :—

172 172 172 171·6 171·6 171·6 171·6 172 172·4 Mean...... 171·9

The units are again 1/10000 inch. The extreme readings here differ from the mean reading by about the same amount as when the tester No. 2 was used. So the ripples are a negligible quantity in this plate. In some plates, however, one finds ripples in evidence.

II. Two small surface-plates (10 inches by 8 inches), one lapped and one scraped, were very carefully made, and were tested soon after manufacture. As is seen below they are so good that errors of observation by the micrometer are of the same order as errors of the surface. Probably at present surface-plates are not required and cannot be made as a commercial proposition to higher accuracy. But if such should ever be the case the surface-testers would have to be made more sensitive. This could be done by having a larger divided drum on the micrometer and by using electric contact.

Ten places are chosen and readings repeated at each for each of the above surfaces. True zero for tester A is 56 and for B is 62·7. For the lapped surface both A and B were employed; for the scraped surface A only, further trial being unnecessary. Results:—

Position.	Lapped plate.				Scraped plate.	
	Tester A.		Tester B.		Tester A.	
1	56	56	62	62 ·5	56 ·5	57
2	56	55 ·5	62	62 ·5	56 ·5	56
3	56 ·5	56	62 ·5	62 ·5	56	56
4	56	56	62 ·5	63	56 ·5	56
5	56	56	62	63	56	56
6	56	55 ·5	62	62 ·5	56	56
7	56	55 ·5	62	62 ·5	57	56
8	55 ·5	56	62	62 ·5	56	55 ·5
9	55 ·5	55 ·5	62 ·5	63	56	56 ·5
10	55 ·5	55 ·5	62 ·5	62 ·5	56 ·5	56 ·5
	Mean error ...... 0 ·1		Mean error ...... 0 ·3		Mean error ...... 0 ·2	

The readings on any surface differ by 1/10000 inch only, and the mean errors are only 1/100000 inch, 3/100000 inch, and 2/100000 inch.

The mean error in the lapped plate is a convexity and in the scraped plate a concavity.

The above plates are too small for observation by tester No. 1.

III. Experiments on Plate Glass.—Of all cheap commercial articles this has plane faces with the nearest approach to truth. As regards small areas the two surfaces are so nearly plane that reflection and refraction at them appears, by ordinary tests, to be regular. It is of interest to discover how nearly the surfaces taken on large areas approach truth.

Surface-tester No. 2 is used. Four specimens, taken from the stock of one of the largest manufacturers of plate glass, gave results shown in the following table. A length of plate was placed on two narrow wooden strips so that when the tester rested on the glass its feet would lie vertically over the strips. The strips would take up the weight of the tester and prevent flexure of the plate.

		Reading A_1.	Reading A_2.	Zero.	Mean plate error.
I	Front......	239 242	296 294	267·5 268 } Mean 267·7	27·2 concave
	Back	300 298			31 convex
II	Front......	273 272			4·5 convex
	Back	253 253			15 concave
III	Front......	295 294			26·5 convex
	Back	249 246			20·5 concave
IV	Front......	272 271			3·5 convex
	Back	263 264			4·5 concave

Thus the errors vary from 30/10000 to 3/10000 for these specimens. The fourth specimen has an accuracy which compares well with that of a surface-plate. When once the zero reading (267·7 here) has been found, it is an easy matter to test the plates quickly and pick out a good one.

In all cases the plates are curved as a whole, one side being convex, the other concave.

I am glad to acknowledge that the cost of the apparatus was defrayed by a Government grant from the Royal Society.