PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Elasmometer, a New Interferential Form of Elasticity Apparatus

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IV. *The Elasmometer, a New Interferential Form of Elasticity Apparatus.*

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BEING desirous of extending the investigation of the physical characters of the crystals of isomorphous salts to the subject of their elasticity, the question arose as to the best form of apparatus to employ for the determination of the coefficient of elasticity. The most accurate form hitherto devised is that of KOCH ('Ann. der Phys.,' N.F. 1878, vol. 5, p. 251, and 1883, vol. 18, p. 325). It was subsequently employed in the researches of BECKENKAMPF ('Zeitschr. für Kryst.,' 1885, vol. 10, p. 41, and 1887, vol. 12, p. 419), of VATER ('Zeitschr. für Kryst.,' 1886, vol. 11, p. 549), and of NIEDMANN ('Zeitschr. für Kryst.,' 1888, vol. 13, p. 362). The amount of flexure of a thin plate of the crystal was determined by the interference method, sodium light being employed. The plate was laid on the edges of two sloping blocks, and a bending weight applied above its centre, through a point at the end of a hook or a stirrupped knife-edge. The lower surface of the plate, and the upper surface of a totally-reflecting prism supported very closely beneath it, with only a thin film of air intervening, were the two surfaces the light reflected from which was caused to interfere and to produce bands.

A complicated and somewhat cumbersome arrangement for suspending the weight from the hook or stirrup, through a hole in the table on which the instrument was supported, and of regulating and graduating the application of the weight, formed an essential part of the apparatus.

The great convenience and high accuracy of the optical part of the interference dilatometer, which the author has previously described ('Phil. Trans.,' A, 1898, vol. 191, p. 313), suggested the advantage of utilising it as interferometer for the measurement of the amount of flexure of the plate, and many other possible improvements on the apparatus of KOCH also suggested themselves. Eventually the instrument now described was devised. It is applicable to solid substances in general, whether transparent or opaque, and whether polishable or not. It has been constructed by Messrs. TROUGHTON and SIMMS, the makers of the dilatometer.

A general view of the whole apparatus, including the interferometer, is given in fig. 1, as it appears during the progress of an actual determination. The elasticity apparatus is shown in fig. 2, with the three principal parts well detached in order to reveal them clearly.

The Interferometer.

The observing telescope, with its auto-collimator and attached hydrogen Geissler tube, shown in fig. 1 standing on the adjustable pedestal in the foreground, is precisely as described in the dilatometer memoir (*loc. cit.*, p. 324).

The similar pedestal in the background carries the train of two reflecting prisms; these are arranged to direct the particular rays to be employed, those corresponding to the red C-hydrogen line, down the vertically suspended tube, of which the greater

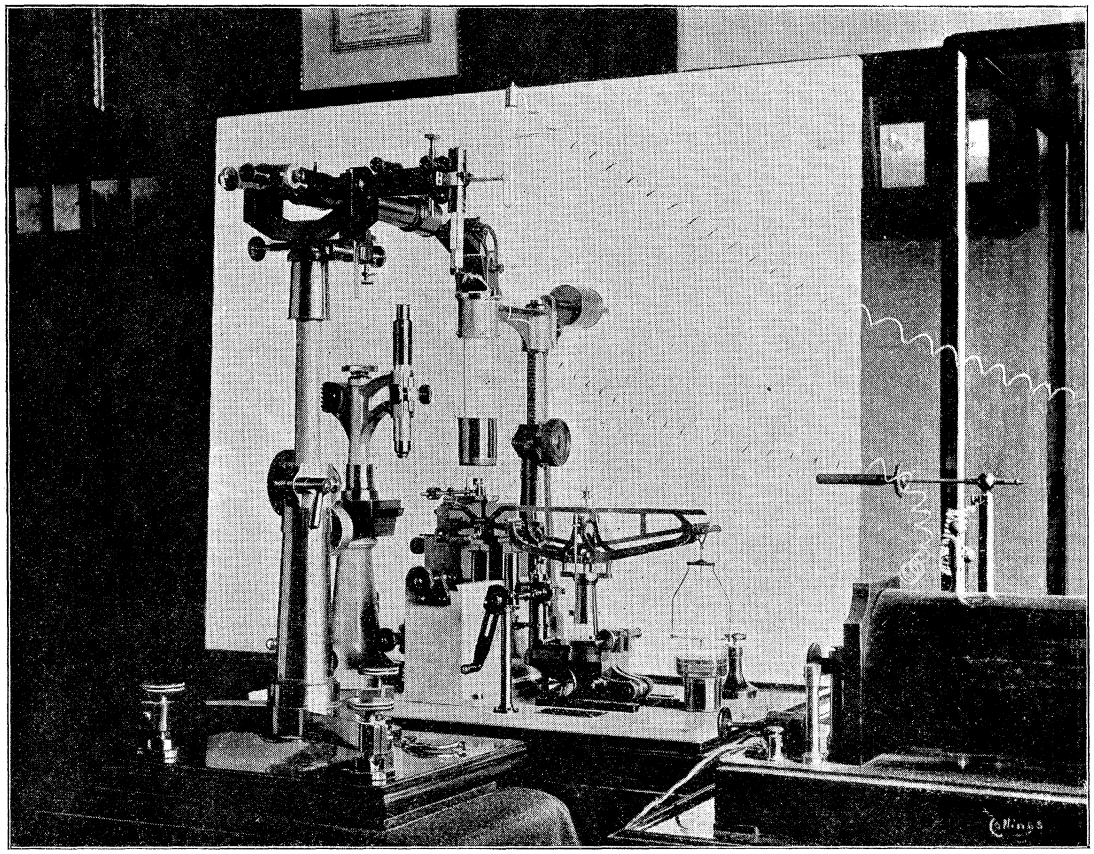

Fig. 1.

portion is of Berlin porcelain, on to the interference apparatus. With the exception of the counterpoise on the backward prolongation of the arm from which the tube is suspended, which experience since the publication of the dilatometer memoir has shown to be a valuable addition, this portion of the apparatus is also exactly as described in that memoir (p. 321) as far as the lower end of the porcelain tube and its short gun-metal continuation.

From the end of the latter the interference chamber of the dilatometer has been removed. The interference tripod is carried by the new apparatus itself, immediately below the end of the vertical tube. As the removed interference chamber carried at its upper end a thick glass disc, which, being equally slightly wedge-shaped (35 minutes) and arranged in the inverse way, corrected for the slight dispersion of the large glass disc of the interference apparatus, a milled cap is provided to contain this correcting disc. The new cap screws on to the lower extremity of the suspended tube; it has the same adequate clear aperture as the removed interference chamber, and is similarly provided with two raised points in its rabbett to tilt the disc to the minute extent required to throw its reflections out of the way of the interfering rays from the interference apparatus.

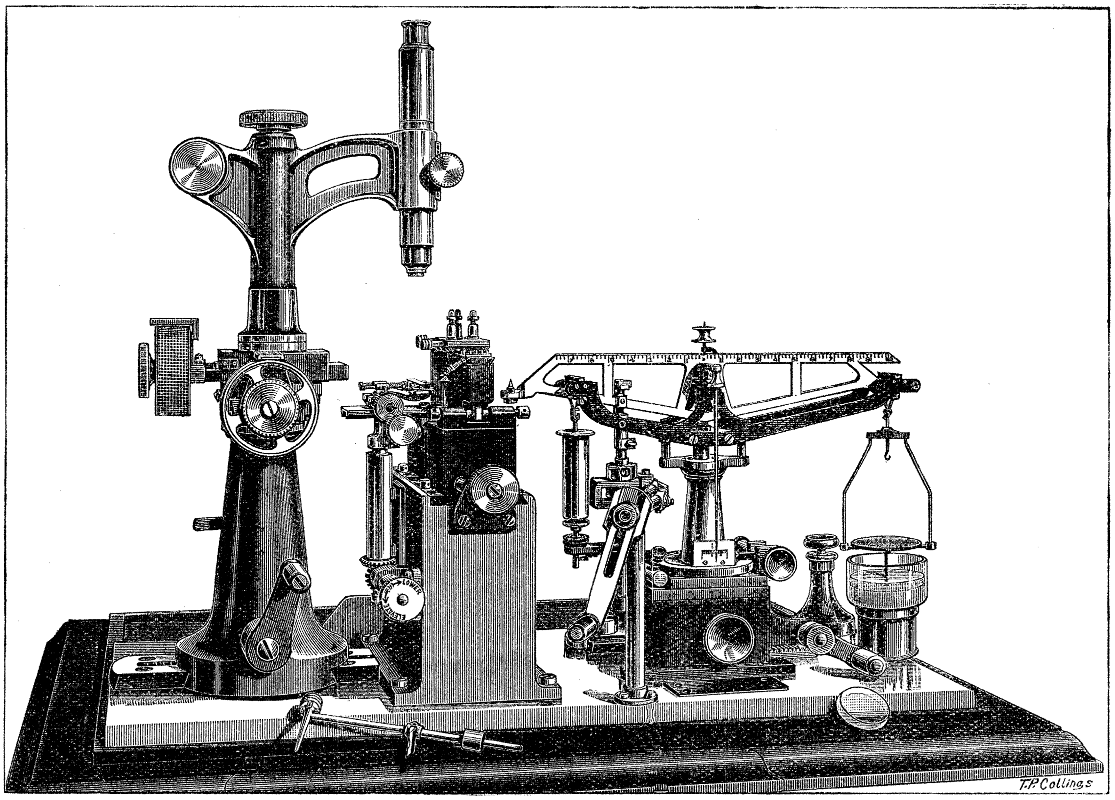

Fig. 2.

The Elasticity Apparatus.

The new apparatus consists of three distinct portions: (1) the apparatus which carries (*a*) the knife-edges, against which the plate of the substance under investigation is to be bent, (*b*) the transmitter of its bending movement, (*c*) the interference tripod, and (*d*) a pair of mechanical "fingers" for adjusting the plate; (2) a delicate balance, through a point at one end of the beam of which the bending weight is applied, and a device for controlling its application; (3) a measuring microscope, reading in two rectangular directions to a thousandth of a millimetre.

The whole of these parts, together with the pedestal of the suspended optical tube

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

of the interferometer, are mounted on a rigid enamelled iron slab, rectangular in its front portion, the front edge being 71 centims. long and the sides 37·5 centims. The slab is continued backwards in the form of a broad arm for a further 22 centims., somewhat to the left of the centre, for the support of the back foot of the pedestal.

The iron base is in turn mounted on a rectangular mahogany base, on the plinth of which fits a glass case with strong mahogany framework, to cover the whole apparatus when not in use. One end of the case is removable, and the latter can then be readily drawn off, the bottom of the frame being covered with cloth to facilitate the sliding.

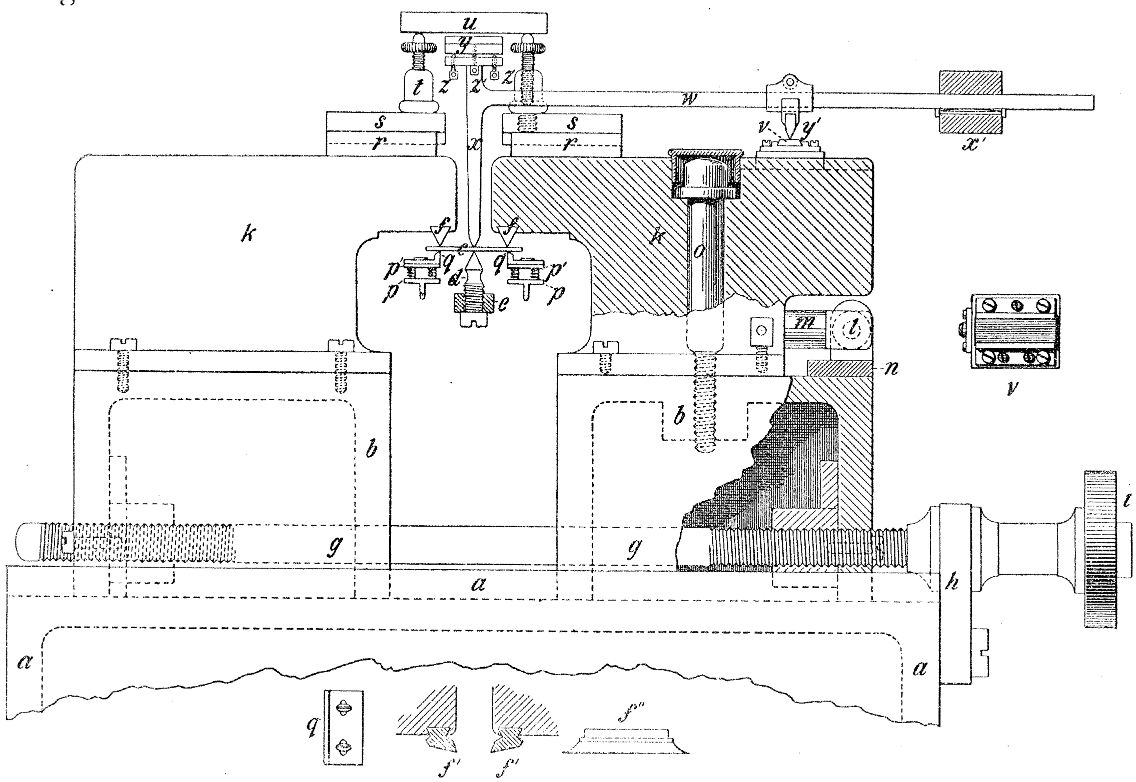

Fig. 3.

The telescope of the interferometer is mounted on a mahogany base 44 centims. by 38 centims., of the same thickness as the main base, to which it is attachable by three pegs fitting in holes in the front edge of the plinth, the outer moulding of which is here detachable to admit it. The smaller base is then continuous with the main base, and brings the telescope up quite close to the top prism of the refracting train, about 5 centims. being the best distance for clear focussing of the silvered reference ring carried at the centre of the large glass disc of the interference apparatus.

The Blocks and Knife-Edges for supporting the Plate.

Somewhat to the left and front of the centre of the iron basal slab an enamelled iron block is fixed (*a* in the accompanying vertical section, fig. 3), with one end facing front and the long edges parallel to the sides of the slab; it is 17 centims. high, 25 centims. long, and 9·5 centims. wide, except at the base, where it is broadened to 14 centims., in order to furnish a flange on each side, through which it is screwed down to the slab. This block carries above it, and sliding in a dove-tailed bed, two gun-metal blocks *bb*, intended to support the plate of the substance under investigation, *c*. The latter is not laid upon the edges of the blocks, as in KOCH's apparatus, but is pressed upwards from below, by a point *d* carried at the end of the balance beam *e*, against two platinum-iridium knife-edges *ff*, arranged edge downwards in the roof of recesses in the blocks.

The amount of movement of the centre of the plate, induced by the bending weight, is observed from above instead of from below, which latter is the method employed by KOCH. The optical arrangements of the author's interferometer are consequently directly applicable, and the totally-reflecting prism carried by the Koch apparatus in the space between the blocks under the plate is eliminated. The plate is brought up to the knife-edges, and also prevented from falling out of position, when the upward pressure of the bending weight is removed, by a delicately adjustable pair of spring supports *pp′q*, which gently press the plate up against the knife-edges without bending it.

The two sliding blocks *bb* are 8 centims. long by 6·2 centims. broad and high, and each is widened at the base into a dove-tail to fit the corresponding guides of the bed. For the purpose of ensuring adequately tight sliding, the left guide is furnished in each case by a stout bevelled rod of gun-metal, let in between an upright flange of the steel block and the dove-tail of the sliding block. Each is fixed by two screws to the steel block, just sufficiently tightly to permit of steady travelling; a third screw, with capstan head and lever handle, is placed mid-way between them, and acts both as an adjusting screw wherewith to modify the tightness of the sliding, and as a clamping screw to fix the blocks in any desired position. The motion of the two blocks is arranged to be equal and opposite on each side of the centre, by means of a long shaft *g* passing through both, having a left-handed screw cut in its hinder portion and a right-handed one in the portion near the front, where it is rotatable in a stout bearing *h* fixed to the end of the iron block. It terminates in a large milled head *i*, rotation of which, in the direction of the hands of a watch, causes the blocks to recede from each other, while rotation in the opposite direction brings them nearer together.

The upper parts *kk* of the blocks which carry the platinum-iridium knife-edges *ff* are separate castings fixed on the top of these sliding parts, and are 5·7 centims. high and 2·1 centims. wide, except at the base, where they are widened to 4·4 centims., to permit of screwing down to the sliding blocks. This is done rigidly by four screws in the case of the hinder block; when they are screwed home the platinum-iridium knife-edge is truly parallel to the basal slab. In the case of the front block, means of adjustment for both azimuth and altitude are provided, to enable the platinum-iridium knife-edge which this block carries to be set absolutely parallel to that carried by the hinder block. The azimuth adjustment is effected about a pivot *o* by two tangent screws *l*, directed horizontally towards each other and against a projection *m*, which they thus press between them, carried in a recess by the upper part of the block; they work in a bearing-piece *n* fixed above the front end of the lower part. The adjustment for altitude is effected by means of three capstan screws, screwing through the basal flanges of the upper block, but not into the lower block, one on the right and two on the left side. After adjustment by these three screws and the two azimuth screws, the upper part of the block can be rigidly fixed to the lower part by means of a strong screw *o* (also acting as pivot) passing as a smooth shaft right through the upper part and screwing into the lower part; its square head is deeply countersunk in a well in the top of the upper block, of adequate size to admit the end of a T-shaped capstan key, wherewith the screw is manipulated. The well is covered with a cap, consisting of a short tube fitting the well and furnished with a flat top, after removal of the key.

The two upper parts of the blocks are 10 centims. long at the top, and they overhang the lower parts at the inner ends by about a couple of centimetres. At 2 centims. below the top at the inner end in each case a recess is commenced, which proceeds horizontally for 2·5 centims., then downwards vertically for about 3 centims., and finally curves outwards again as a basal flange of 0·8 centim., corresponding to the side flanges. It is within the commodious space formed by these two recesses that the balance beam *e* with its pressure point *d* can be introduced, as also the apparatus *pp′q* for supporting and adjusting the plate *c* of the substance under investigation.

The platinum-iridium knife-edges *ff* are fitted in small dove-tail grooves in the under sides of the overhanging parts, as close to the ends as is compatible with rigidity. The platinum-iridium fittings are drawn out to a fine point at each end, the actual knife-edge being the truly straight line joining the two points. The latter project for 6 millims. on each side of the blocks, so that they are visible in the reading microscope when it is arranged over them. Each is labelled with an engraved letter, which is visible in the field of the measuring microscope simultaneously with the point. The left point of the back wedge is marked A and the right one B; the left point of the front wedge carries the letter C and the right point is engraved with D. The lengths of the edges AB and CD have been made equal, and the azimuth adjustment enables AC and BD to be adjusted equal. Two alternative pairs of platinum-iridium wedges are provided. Those shown in position in fig. 3 are of isosceles triangular section, as offering the greatest rigidity of the knife-edge. They are preferable whenever the substance under investigation is of considerable hardness, and good-sized plates of it can be obtained. The alternative pair are shaped as shown at the foot of the main drawing; *f′f′* represents a section through them, and *f″* an elevation of one of them parallel to the edge and as seen from the other. The angle of the wedge is about the same as that of the first pair, but is turned inwards, so as to bring the two sides nearly horizontal and vertical, with the apex (representing the knife-edge) the lowest point and also that nearest to the corresponding section of the fellow wedge. There are three advantages offered by this form, namely, the knife-edge is less likely to cut into a relatively soft substance, a smaller plate of the latter can be employed, and the whole of each edge can be seen in the reading microscope.

The Interference Tripod.

At the top of each block, at the inner overhanging end, a guiding bed *r* is fixed for a sliding table *s* slightly over 3 centims. square, but with the inner corners cut off, so as not to impede the view through the microscope of the platinum-iridium points. The slider on the back block carries, near the middle of its inner edge, a single vertical screw *t* of hard white metal and very fine thread, and furnished with a milled head a few millimetres below its rounded summit, by means of which it can be raised or lowered in the brass columnar nut fixed to the slider. The slider on the front block carries two such screws, arranged also close to the inner edge and with their axes 2 centims. apart. These three screws form a tripod for the support of the colourless glass disc *u*, 4 centims. in diameter, whose lower surface, which has a minute silvered ring at its centre, is to assist in reflecting the interfering light. This disc is shown in the foreground in fig. 2, to the right, leaning against the edge of the iron base. The two sliders can be fixed in the positions found most convenient for supporting the disc, by means of two horizontal clamping screws at their left sides.

The Transmitter.

The front block also carries on the top of its front end a sliding agate table *v*, for the support of the agate wedge of the transmitter. The bevelled agate plate is capable of being accurately levelled by being fitted into a dove-tailed gun-metal setting, which is attached to the sliding table by three levelling and four fixing screws; the guides are grooves cut out of each side of the block, for a length parallel to the top edges of 4 centims. The slider can be fixed in the desired position by means of an oblique clamping screw carried on the left side.

The transmitter consists of a T-piece arranged on its side. It is shown in the foreground, to the left, in fig. 2, resting on the base. Its horizontal stem *w* is a rigid gun-metal rod of circular section and 17 centims. long, which joins perpendicularly the shorter upright cross-piece *x*, 6·2 centims. in length, at a point nearer to the upper than to the lower end. The latter terminates in a platinum-iridium point, intended to rest upon the centre of the plate *c* under investigation, while an agate wedge carried near its middle by the horizontal stem rests on the agate table. At the upper end the vertical rod carries a cylindrical head-piece, 1·5 centim. in diameter and 1 centim. deep, which is made up of three discs, the middle one being slightly thicker than the outer ones, and the parallel surfaces of which are approximately horizontal. The uppermost disc *y* is of black glass; its upper surface furnishes the second of the interfering reflections, and has been ground and polished an optically true plane. The particular disc employed was chosen as the best of six which had been prepared with the greatest possible care, the test being the production of rectilinear and regular interference bands when used, as in the determinations, in co-operation with the silver-ring surface of the large colourless glass disc. The selected disc is cemented by its ground under surface to the somewhat thicker disc of brass. The third metallic disc is rigidly screwed at its centre on to the end of the vertical rod, and upon it the thicker brass disc with its attached glass one is mounted in a manner which permits of adjustment, by means of four capstan-headed screws arranged at equidistant intervals from each other near the circumference. Two zz are situated along the diameter parallel to the horizontal stem of the rocker, and are adjusting screws, screwing only through the third fixed disc and merely pressing upwards against the middle disc; the other pair z', along the diameter at right angles, are fixing screws, and pass loosely through the bottom disc, but screw into the middle one. The black-glass surface can thus be adjusted by the screws zz about that diameter as axis which is perpendicular to the plane of the T-piece. Fine adjustment about the diameter parallel to the stem is afforded by the two fixing screws z', and is roughly provided for in the mode of attachment of the agate wedge y'. This latter tapers to a knife-edge 2·1 centims. long, from which the greater portion of the actual edge about the centre has been hollowed away, leaving only the two end parts with which to rest on the agate plate v. The wedge is mounted in a metallic holder carrying above its centre a split collar, through which the horizontal stem of the T-piece readily slides; a tightening capstan screw, passing through flanges standing up from the split edges, enables it to immovably grip the stem when the agate wedge has been adjusted to its proper position.

Between the agate wedge and the free end of the stem a short cylindrical counterpoise x' is arranged, which is adjustable to the required position for nicely balancing the weight on the other side of the wedge. The stem slides somewhat tightly through the counterpoise on account of a bent spring let into a groove cut along its bore, which serves also the purpose of automatically fixing the counterpoise on the stem after adjustment.

When in position, it will be obvious that the transmitter rests in stable equilibrium, in accordance with three-point contact, with the point of its vertical rod on the centre of the plate under investigation and the two end-points of the agate wedge on the agate plane. The position of the latter can be regulated along its guiding bed so as to suit the particular separation of the blocks, as determined by the size of plate available, so that the wedge shall lie symmetrically along its middle line. The counterpoise can be adjusted so as to regulate the weight with which the platinum-iridium point presses on the plate of the substance down to zero, which, however, it is advisable to stop just short of. The stem lies approximately horizontal and passes with ample room between the two screws of the interference tripod carried by the slider on the front block. The vertical rod passes readily between the two inner overhanging ends of the upper block, and the black-glass surface at its head is at a convenient height about level with the tops of the interference tripod screws when the latter are screwed fairly deeply into their columnar nuts. The black-glass surface can be adjusted absolutely horizontal by the means which have been indicated, and with the aid of a miniature spirit level provided; it is then immediately capable of receiving the rays of light directed down the vertical tube of the optical apparatus, and of reflecting them back again along the same path. The tripod screws can then be adjusted to support the colourless glass disc, so that its lower surface is separated from the black glass by the necessary thickness of air-film to allow for the further approach, without touching, of the black to the colourless glass, which accompanies the bending of the plate. The further fine adjustment required for the production of suitable interference bands, and the measurement of their position with respect to the reference centre of the silver ring, are carried out precisely as described in the dilatometer memoir (p. 339).

Mechanical "Fingers" for Adjusting the Plate.

These are carried by a fitting to the left side of the steel block. The immediate supports of the plate are two gun-metal knife-edges carried on a pair of miniature spring-tables, provided with adjustments for height, mutual separation, and for movement in an out of the recess between the blocks. The fitting consists of a thick plate screwed to the iron block, carrying as part of the same casting a thick-walled cylinder. Within this slides a shaft, on the lower part of which a screw thread is cut, and which is made capable of vertical motion only by the usual slot-and-pin device. The upward or downward motion is effected by rotation of a horizontal bevel wheel, situated near the base of the cylinder and provided within with a screw thread gearing with that of the shaft, so that it acts as a driving nut. This gears with a smaller vertical one mounted at the end of a long axle terminating within easy reach of the observer in a milled head. This axle is supported in two bearings, about which it is flanged, one forming part of the main casting of the fitting and the other being fixed to the iron block near the front end.

The vertical shaft carries a stout head-piece, which terminates above in a grooved bed, for the sliding horizontal in-and-out motion parallel to the front edge of the basal slab; the slider carries a rack beneath, gearing with a strong pinion carried in a hollow of the head-piece and manipulated by a milled head at the front end of a somewhat long axle. The slider in turn carries another horizontal grooved bed at right angles to the first. There are two sliders on this bed, each carrying one of the little supporting tables for the plate under investigation. They are arranged to move equally from or to the centre by means of a right and left-handed screw, carried in the bed and capable of rotation only, and gearing with corresponding nuts fastened beneath the sliders in a way which permits of some adjustment of the centre. The screw terminates in front in a milled head, just above that which effects the in-and-out motion. Each slider carries, flush with and in the middle of its inner edge, a little firmly screwed plate, from which springs a light arm pointing towards the recess between the blocks and suitably curved, carrying a little tabular termination, 2 centims. by 1 centim. (p in fig. 3). Above this is a second similar table, p', the pair being separated by four little spiral springs arranged at the corners, each fixed at its ends to both plates.

Manipulation of the top milled head thus adjusts the two tabular supports as regards their distance apart; the lower one enables the observer to move them into the hollow between the blocks until they come right under the platinum-iridium knife-edges, and out again; and the milled head down below, and in a vertical line with the front edge of the basal slab, enables them to be raised or lowered at will, in order to press the plate of the substance which they support up against the knife-edges, or to remove it from that position.

The two little tables $p'p'$, which may be considered as mechanical finger tips, are all that is necessary for the temporary support of the plate during the preliminary adjustments. But a slight addition is made to each of them to enable them, if desired, to be retenable during the whole determination. The addition consists of a similar table of gun-metal q, carrying a raised knife-edge along the inner side. It is fitted on the permanent table p' in a readily detachable manner, by means of a couple of flat oval-headed screws carried by the table p' near its ends, well out of the way of the plate, corresponding with two similarly shaped holes in q; the two fittings are rigidly attached together when the screws are rotated 90°. The knife-edge side is arranged along the inner side of the table, so that for any given separation of the two knife-edges there is the maximum amount of clear space between the two "finger tips" for the pressure-point end of the balance beam to operate in.

The "finger tips" are to be so adjusted that the gun-metal knife-edges lie precisely under the platinum-iridium edges, and they are then to be raised until the plate laid on the gun-metal edges is gently pressed up into full contact with the platinum-iridium edges. As the gun-metal edges are exactly under the others, no bending of the plate is possible.

If the method of carrying out the determination of the bending of the plate from the initial position of true planeness is adopted, and the gun-metal knife-edges are consequently retained in action, they should only be allowed to exert the minimum pressure. This is easily found, for the instant it begins to be further reduced sudden total derangement of the interference bands occurs. A careful partial turn of the milled head in the reverse direction will then usually suffice to bring the bands again into their former adjusted position, corresponding with the attainment of just full contact of the plate with the platinum-iridium knife-edges.

For the more convenient setting of the long edges of the plate perpendicular to the platinum-iridium knife-edges, a pair of horizontal milled-headed adjusting screws are added to the "fingers," one to each; they are mounted parallel to each other at the level of the plate in small uprights from the sliders, which curve inwards towards the

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

top in order to bring the screws adequately nearer to each other than the knife-edges to enable them to clear the latter. To allow for varying compression of the springs, and consequent variable level of the plate, the screw-ends are expanded into little discs perpendicular to the length of the screws.

The Balance.

A specially constructed form of long-beam balance is employed, designed for maximum strength of beam and to take loads up to 500 grammes. The balance part proper was made by Mr. OERTLING to the author's design, and Messrs. TROUGHTON and SIMMS subsequently mounted it on a movable base and fitted it with the control apparatus. Its general appearance will be gathered from figs. 1 and 2. It is arranged on the right-hand part of the basal slab.

The beam is 35·5 centims. long, has a horizontal top bar graduated as usual for a rider, and is rendered very rigid by four transverse struts. This length of beam was just adequate to admit of the insertion, on the left side, of the control apparatus and a counterpoise for the weight of the pan on the right side.

The central agate fulcrum plane is 3·2 centims. long, and the knife-edge resting upon it, rigidly carried by the beam and about which the latter swings, is 4 centims. long and cut out of a single block; the swinging is consequently exceptionally steady. The central supporting pillar of the balance is shorter than usual, but adequately long for accuracy of the pointer's readings on the ivory scale of the usual kind.

The arrangements at the right-hand side of the column are of the type usually provided by Mr. OERTLING in his most accurate form of long-beam balance for a load of 500 grammes. The thick wire suspending arrangement of the pan is shorter, however, corresponding to the shortened column, and by means of the small hook at its summit the pan is hung from a large inverted stirrup, whose upper horizontal bar is provided with an agate plate by which it rests on the adjustable agate knife-edge of the beam; it is maintained in the proper central position thereon by two small cones carried by the supporting frame, fitting in corresponding conical countersinkings under the bar, until the balance is released from support. This latter is achieved in the usual manner by rotation of a large milled head at the foot of the balance, which pulls down the inner shaft of the column and brings down with it the beam-supporting frame which it carries above; three very rigid guides are provided, one on each side and a larger one behind, which also carries the agate fulcrum plate, to maintain the motion of the frame steady and certain.

The arrangements at the left-hand side of the column are different. The free end of the right half of the horizontal bar of the beam, overhanging the pan-support, has no counterpart on the left half, the beam passing down immediately into the steeply inclined end bar, by which it joins the lower bar. The end is carried out beyond the junction to the same length as on the right side, but the tabular expansion, 18 millims. wide, carrying the agate wedge, in which it terminates on that side, is curtailed in width to 8·2 millims. on the left side. This enables it to be readily inserted not only between the blocks which carry the platinum-iridium wedges, but also between the little spring tables supporting the plate under investigation. At precisely the same distance, on this left side, from the fulcrum knife-edge, as is the pan-supporting knife-edge on the right, an upright agate point, the "pressure-point," is erected. It is mounted at the end of a short screw, passing through the beam-end from underneath, which serves the purpose of enabling it to be adjusted so that its point lies precisely in the same straight line with the agate fulcrum and the pan-supporting knife-edge.

To compensate for the pan and its fittings on the right side of the balance, there is provided on the left, at 5·8 centims. from the pressure-point, a tabular expansion carrying an adjustable agate wedge, over which is suspended a stirrup with agate plate, similar to those on the right; a hollow cylinder is suspended from the stirrup by a short rod terminating in a hook, within which a load can be carried of the extent necessary for perfect compensation. The supporting frame is correspondingly modified on the left, being much shorter and curving upwards so as to support the top bar of the stirrup by a pair of inverted cones as on the right side. A transverse strengthening bar forms the extreme right end of the frame, and a similar bar is inserted on the left side, just before the frame begins to curve upwards. The load within the cylinder is a block of lead, made slightly heavier than required, and subsequently pared until its weight has become exactly such as to bring the total weight on the left side of the balance equal to that on the right. The beam carries above its centre the usual adjustable gravity bob and vane, so that the last trace of adjustment can be effected by the latter.

The balance is mounted on a rectangular gun-metal box which carries the raising and lowering gear of the supporting frame within it, the milled head for working which emerges in front. The box is arranged to be capable of ·5 centims. of motion parallel to the front edge of the basal slab, so that the pressure-point end of the beam may be advanced into or withdrawn from the recess between the blocks. This is achieved by providing the front and back bottom edges of the box with dove-tail flanges, which slide in corresponding guides screwed to the basal slab. The back guide has a clamping slip inserted between it and the flange, which can be driven rigidly against the latter by a strong inclined thumbscrew when it is desired to fix the balance base after adjustment. The motion is effected by means of a strong central rack screwed to the basal slab, and an equally strong pinion borne in bracket bearings projecting from the right side of the box and rotated by means of a winch handle.

The balance is also provided with a fine azimuth adjustment to enable the pressure-point to be placed precisely in the vertical plane half-way between the platinum-iridium knife-edges. This, with the rack adjustment, enables the point to be adjusted with great exactitude under the centre of that portion of the plate of the substance investigated which lies between the knife-edges. The azimuth movement is effected by mounting the central column on a circular dove-tailed base, which rotates in an outer circular guiding bed correspondingly bevelled but not quite so thick, and screwed down to a square basal plinth sufficiently tightly to prevent play; a thumbscrew passing through this outer ring, above which it is flanged, into the square plinth enables the inner rotating base and the column which it carries to be rigidly clamped down to the plinth after the adjustment has been completed. The inner rotating disc carries above it on the right a stout plate, from which projects an arm, the end of which lies between a milled-headed screw and spring piston mounted in uprights from the square plinth. Rotation of the milled head one way or the other thus brings about the desired rotation of the column and all that it carries. A pair of spirit levels are carried along the left and back edges of the plinth.

The height of the balance has been carefully arranged, so that when at rest in its supporting frame the pressure-point is at a level about a millimetre lower than the plane of the platinum-iridium knife-edges. Hence, when a plate is in position under the latter, and the pressure-point is brought under its centre, there is a space of at least one or two-tenths of a millimetre left between the point and the under surface of the plate, supposing the latter about the usual thickness of something under a millimetre. Hence the supporting frame can be left in operation up to the last moment, and when the beam is eventually released it remains practically horizontal during the bending of the plate.

There is one occasion, however, when the beam should be lowered by about a centimetre, namely, when a test is being made for any movement of the knife-edges under the blocks with respect to the interference tripod screws on the top of the blocks. In the form of apparatus now described this movement is practically *nil*, but it is well to have a means of confirming the fact by a direct determination. In KOCH's apparatus it amounts to as much as the equivalent to two interference bands, as the second reflecting surface is not supported by the blocks, but independently. For this purpose instead of a plate a block of glass, 1 centim. thick, has been provided, which may be assumed to be unbendable, and any movement of the interference bands on allowing the weight to act as usual must be due to movement of the parts of the blocks, from knife-edges to tops of screws.

In order to provide for this determination the square plinth is separated from the rectangular basal box by a similar square plate of brass 1 centim. thick, and the fixing screws are long enough to pass through both plates into the box top. When the determination in question is to be made, this insertion plate is removed, and the square plinth fixed directly to the box. The beam will then be at the right height for the experiment.

A support for the pan is provided to prevent it swinging and to remove strain from the beam when not in use. It consists of a short, hollow cylindrical column, with heavy solid base covered underneath with cloth, carrying at its summit a rotatable but vertically immovable nut with milled flange; gearing within is a screw carrying at its head a table of ebonite, hollowed to the shape of the under part of the pan. When the accessory is placed under the pan, the table can be raised to support the latter by rotation of the milled nut.

A removable support is likewise provided for the counterpoise on the left, in the shape of a little table of the diameter of the cylinder, which can be raised to support the latter by means of a similar milled nut carried, however, at the end of a horizontal arm whose other end is a doubly split, and therefore detachable, collar gripping round the column of the control apparatus described in the next section.

The determination of the position of the interference bands at the conclusion of an observation, when the control is removed and the full weight on the pan is operating in bending the plate, is considerably disturbed by flickering of the bands, unless absolute quietude is obtained and absence of all vibration. The difficulty can, however, be entirely overcome by fixing a horizontal disc below the pan and immersing it in oil. A disc of aluminium is provided, of the same diameter as the pan, to which it can be rigidly fixed by means of a stout aluminium rod, 3·5 centims. long; one end of the rod is screwed firmly into the centre of the disc, washers above and below aiding the rigidity, and the other end screws into a little boss fixed permanently underneath the bar on which the pan is mounted. It is thus readily detachable if not required. The disc, when in use, is immersed in oil, cedar oil being found admirable for the purpose, contained in a glass dish with perfectly parallel sides and of a slightly larger diameter than the disc, which, of course, must not touch the glass. The resistance which the oil offers to the vertical motion of the disc effectually steadies the bands, so that the final position can be measured with the utmost accuracy.

Cedar oil possesses the two advantages of not solidifying, and of being so slightly viscous as scarcely to impair at all the sensibility of the balance.

The amount of vertical motion of the beam ends and the pan is so slight, not amounting to a millimetre from first to last if the supporting frame is kept in action up to the moment of beginning the bending, that the amount of the rod which is wetted by the oil is practically constant. It is therefore found sufficient to add to the counterpoise on the left side a weight, previously determined with the greatest care, and made in the form of a platinised disc, which precisely balances the aluminium fitting as immersed in oil. It is laid on the top of the cylindrical compensator, and has a radial notch to enable it to fit round the suspending rod. Any slight remaining inequality of the weights on the two sides of the balance is not more than can be corrected by slight movement of the adjustment vane carried above the centre of the beam.

The Control Apparatus.

About the middle of the lower bar of the beam on the left side a little saddle is fitted, on the top of which is fixed a platinum-iridium cone, the "control-point," similar to the agate "pressure-point." Control of the movement of this point, and therefore of the whole beam with its pressure-point, is afforded by a horizontal agate plate, mounted above the control-point in a fitting capable of extremely fine vertical movement. This fitting is a rectangular double bracket, which envelopes the saddle on three sides, above, behind, and below, the vertical back limb being long enough to leave about 4 millims. space for the bar of the beam to swing in. The agate plate is fitted underneath the top limb. The bracket is carried as part of the same casting at the head of a vertical hollow cylinder of gun-metal 2·8 centims. long, fitted at its lower end with a steel split-collar furnished with a tightening screw, which enables it to be fixed at a convenient height to a vertical shaft, on the upper end of which it slides as far as the bore permits, rotation being prevented by groove and pin. Below the part down which the cylinder can slide the shaft thickens to 1·2 centims., and the whole of the lower portion slides tightly in a gun-metal column 2·8 centims. diameter and 12 centims. long, which is mounted below on a stout bracket fixed to the left side of the rectangular basal box on which the balance is mounted. An exceedingly fine screw thread, whose pitch is one-fourth of a millimetre, has been cut with the greatest possible accuracy on a part of the shaft within the column; rotation of the shaft is prevented by groove and pin, but it can be propelled upwards or downwards by a rotatable but vertically immovable nut, furnished with a correspondingly fine thread within and worm-wheel teeth without. The column is broken to admit the nut at a point 2·2 centims. from the top, and rigidity of the two parts is secured, as well as a suitable support for the bearing of a driving endless screw, by means of a hollow rectangular box-piece, open in front and behind, cast with the two parts of the column. The diameter of the nut is somewhat greater than that of the column, and the peripheral oblique teeth are 72 in number; one revolution of the endless screw rotates it to the extent of one tooth. This corresponds to the vertical movement of the shaft through 0·0035 millim. The bearings of the endless screw are attached to the box by an enveloping double claw, cast as one piece; the front bearing at the crossing is a horizontal cylinder from which the screw shaft emerges. The end of the latter is notched diametrically, to admit of the attachment of either a simple milled head 3·2 centims. diameter, whose short cylindrical stem bears inside its bore a transverse bar fitting the notch, or of a Hooke's-joint arrangement, which brings the manipulating head nearer to the observer without interfering with the movement of the whole balance, and also enables a more delicate mode of rotation than a simple milled head to be employed. It consists of a short tube with similar inner cross-bar, carried at one end of an equally short but thick rod whose other end bears one semicircular fork of the Hooke's-joint; the other fork forms one end of a gun-metal shaft 9 centims. long. The two semicircular forks are rotatable about a pair of rectangular axes, passing through a brass sphere which each fork half encircles. The shaft is loosely supported near its front end in a stout ring carried at the head of a strong gun-metal tubular column, fixed near the front edge of the basal slab. The ring has a short stem rotatable in the bore of the column, but made incapable of vertical motion by groove and pins. The front end of the shaft is notched to gear with the same milled head that fits the head of the endless screw itself. The length of shaft is adequate to permit of the full extent of racking of the balance in or out of the recess between the blocks, so that whatever the position of the balance the control apparatus is equally available.

During an actual determination, after the final adjustment of the pressure-point to the centre of the plate, experience shows that it is of some advantage to the attainment of absolute steadiness in the motion of the bands to substitute for the Hooke's jointed shaft a simple rigid shaft which is also provided; it is fitted with a tightening collar at the end of the barred bore, where it grips the endless screw head, to prevent the slightest chance of slipping. Being twice as long as the jointed shaft, its front end is nearer to the observer, and is supported in a special bearing fixed on the small mahogany base near the telescope pedestal.

In order to render the control still more delicate, so that the bands shall march past the cross-wires with great deliberation, rendering their counting a very easy matter, the milled head can be replaced by a handle at the end of a long radial lever. To the end of a short thick tube, provided with inner cross-bar to fit the shaft notch and also a tightening collar to firmly grip the shaft, a strong plate is fixed, out of the front of which a sliding bed is cut for the lever to slide in; by means of a longitudinal groove in the latter and a clamping screw, the lever can be fixed to the plate in any position, and thus the radius of the circle described by the ebonite handle can be modified as desired. When the lever is at its full length the radius is 10 centims., and the circumference of the circle 63 centims. As one complete rotation corresponds to a rise or depression of the control screw, and therefore of the control point on the beam, of 0·0035 millim., one-tenth of this, namely 0·00035 millim., corresponds to a movement of the handle of 6·3 centims. The pressure-point, however, moves through twice the distance that the control-point traverses, so that a movement of 0·00035 millim. on the part of the pressure-point corresponds to a movement of about 3 centims. on the part of the handle manipulated by the observer. This, however, is a very large amount of movement, of which a tenth part is still a very appreciable quantity.

It so happens that the half-wave-length of the red C-hydrogen light which the author usually employs is 0·00033 millim. As a change in the thickness of the air-film equal to half a wave-length corresponds to the interval between the passage of two consecutive interference bands past the reference spot, it will be clear that the handle has to be turned through a distance of 3 centims. for each transit of a whole band, and therefore that the transit can be controlled with a high degree of delicacy.

In actual practice the control screw is found to work even more admirably than the author anticipated. The bands pass with the utmost steadiness, and their counting is extremely easy.

The Measuring Microscope.

The measuring microscope is mounted, on the left-hand part of the basal slab, on a stout column of circular section, tapering to the summit and expanding at the base to a flange of 14 centims. diameter. The under side of the base is cut with a bevelled groove, by which the column slides over a correspondingly dove-tailed guiding bed of iron, 22·5 centims. long. A strong rack is longitudinally sunk in the bed, and gears with a pinion borne within the lower part of the column, which has here a projection coming out to the flange in front to afford a rigid axle-bearing and permit of the attachment of a winch handle. One half-turn of this handle causes the column to travel rapidly over the rack from left to right or *vice versâ*, so as to bring the microscope over the blocks or remove it out of the way. It can be rigidly fixed in any position on its path by a very strong vertical binding screw, furnished at its head with a lever handle, and screwing through the basal flange, at the back of the column; the screw shaft terminates below in a conical head, which lies within a corresponding conical hole in a bevelled clamping slip inserted against the back guide. Rotation of the handle for half a revolution draws up the cone sufficiently to press the clamping slip tightly against the guiding bed, and so binds the column to the basal slab.

The column is 22·5 centims. high, and carries on its expanded tabular top the two rectangular measuring movements. The guiding bed of the lower one, which is that at right angles to the front edge of the basal slab, and all that it carries is rotatable for about 20° in the horizontal plane about the axis of the column, and capable of a considerable amount of fine adjustment and of eventual rigid fixation at any azimuth within those limits, by means of two opposite capstan-screws directed, through the sides of a rectangular hollow bracket projecting from the back of a collar round the tabular top, against a stud projecting into the hollow from below the guiding bed. This enables the upper right-and-left measuring movement to be set exactly parallel to the fixed platinum-iridium knife-edge AB carried by the hinder block. The thick slider, 8·5 centims. square, which moves over the lower guiding bed carries the guiding bed of this second movement, fixed exactly at 90° to the lower one. The similar slider which moves over this bed carries a vertical column 20 centims. high, from an arm of which the microscope is vertically suspended. The column consists of a fixed conical core and a rotatable outer part, so that the microscope can be swung readily out of the way of the interferometer. The outer rotatable part of the column can be fixed in any position about the core, by means of a washer, with hole to fit a squared part of the core, which projects above the rotatable column, followed by a large milled-headed clamping nut which screws on a thread with which the core terminates.

The column has two curved arms cast with it, on opposite sides of the axis; one bears the microscope and the other a compact counterpoise for the latter. The microscope arm is a double one and the parts are of T-shaped section to give rigidity; it terminates in a vertical hollow cylinder in which the microscope is capable of vertical motion by means of the usual rack and pinion. The magnification provided is about 15 diameters. The eye-piece is carried in an inner sliding tube which affords an adjustment for the focussing of the rectangular spider-lines; the outer tube in which it slides screws into the carrier for the latter, which in turn slides tightly in the main optical tube, and is provided with a flange by means of which the azimuth of the spider-lines may be adjusted.

The rectangular measuring movements have been constructed in a manner which ensures both rigidity of their parts and complete absence of backlash in the working of the screws. The total thickness of the two sliders and their beds amounts to 6 centims. Provision for regulating the fit of the sliders about the beds is made in each case by making one of the guides of the slider take the form of a thick bevelled rod inserted between the correspondingly bevelled side of the bed and an outer flange of the slider provided to contain it, and slightly larger than the gap between them, instead of cutting the bevel out of the slider itself on this side, as is done on the other side. The pressure of the bevelled rod against the bed is determined by two fixing screws and a regulating capstan screw between them. The two capstan screws can also be used to fix the movements in any desired position.

The measuring screws, which lie longitudinally along the centre of the beds and are mounted in closely fitting and very rigid bearings, have been cut with the utmost attainable accuracy. They have a pitch of 1 millim. A finer screw than this was undesirable, in view of the distances to be measured. The length of traverse provided in the case of each screw is about 33 millims., just enough to enable the two end-points of either knife-edge to be brought into the centre of the field of view of the microscope.

In order that there should be no backlash between them and the nuts attached to the sliders which they drive, a special device has been adopted. It consists in making each of the nuts in two parts, which are forced continuously apart by a strong spring. The double nut is cylindrical in shape, with a broad stud projecting above by which it is fixed to the slider. The cylinder has an internal bore of about twice the diameter of the screw, extending from one end along three parts of its length; the remaining quarter forms one part of the nut, being bored and tapped with a screw thread corresponding to that of the screw. The other part of the nut slides like a bored and tapped stopper into the open end of the cylinder, and, being of the same length as the part which is solid with the cylinder, fills up the outer third of the large bore. The outer end of the stopper-nut has two steadying pins projecting radially at the opposite ends of the same diameter, which fit in notches cut to receive them in the cylinder end, so that rotation of the stopper-nut about the cylinder and the nut which is solid with it is prevented. The middle widely bored part of the cylinder accommodates the spiral spring. In fitting the arrangement, the loose or stopper-nut is pressed into its place and compresses the spring; the screw is then inserted. This immediately secures the two sections together, and on removing the finger-pressure the spring exerts its force and pushes the loose nut away as far as any trace of backlash in the fitting of screw and nuts permits. In all positions of the compound nut along the screw, the latter is thus gripped between the two sections of the nut, and all possibility of backlash between the screw and the slider carried above and fixed to the cylinder is eliminated.

The guiding bed of the front-and-back movement carries on the left side a silver scale graduated in millimetres, and that of the right-and-left movement carries a similar one along its front edge. Each slider carries a little silver plate on which the indicating mark is engraved, and which is arranged to slide closely against and partially over the graduations on the scale. The microscope is made to read accurately to a thousandth of a millimetre in each of the two rectangular directions, by a method which entirely avoids the use of an additional micrometer screw. The screw shaft in each case carries, between the bearing from which it emerges and the milled head by which it is rotated, a drum 8 centims. in diameter, fitted with an outer tyre of silver 2·8 centims. broad. This silver cylinder is engraved with eleven equidistant circles parallel to each other and to the cylinder ends, the two outside ones being only a millimetre distant from the latter. The nine inner circles thus divide the cylindrical surface up into ten circular strips 2·5 millims. broad. The two outside circles have each been divided into 100 equal parts 2·5 millims. long, and every alternate division of that edge-circle nearest the bearing has been engraved with its number. The division of these edge-circles has been done so that a line drawn parallel to the shaft axis from any division on one of them would meet the other at a division. A hundred parallel lines have then been drawn obliquely across the cylinder from each division of the numbered circle to the preceding division on the other edge-circle, thus covering the cylindrical surface with 1000 parallelograms. The space between any two divisions of the numbered circle is in this way sub-divided into ten parts by the intersections of the oblique line with the ten other circles, and an indicator in the form of a straight line parallel to the axis of the cylinder, suspended close above the latter, enables the observer to read off directly at which circle the intersection corresponding to the position of the microscope occurs. This indicating straight line is engraved on a glass plate and coloured red to distinguish it from the lines on the cylinder. The glass plate is fixed in a rectangular frame supported horizontally just over the surface of the cylinder, by a bracket standing up from the end of the guiding bed. The red line has numbers from 1 to 10 also engraved against it and coloured red, exactly over the several circles in turn which follow the numbered circle next the bearing. It will be obvious that the position of the microscope at any time, along either of the two rectangular directions, is afforded by taking the reading of the last whole millimetre from the scale on the guiding bed, and then adding the reading for the fraction of a millimetre obtained from the drum; the first two places of decimals are given directly by the numbered circle next the bearing, and the third place is immediately indicated by the red number above the circle whose intersection with the oblique line falls exactly under the red indicating line. In practice this mode of determining the thousandth of a millimetre proves the easiest the author has yet worked with. The fact that a single screw is alone concerned, and one which is absolutely freed from backlash by the double-nut device, renders the method highly accurate.

The microscope is required for the measurement of the free length of the plate of the substance under investigation, that is, the distance between the platinum-iridium knife-edges against which it is bent; also for the measurement of the breadth of the plate. For the determination of the plate's thickness, the thickness measurer which the author has previously described ('Phil. Trans.,' A, 1898, vol. 191, p. 337) is admirably adapted; it affords the thickness with accuracy to the same unit as the measuring microscope, namely, the thousandth of a millimetre.

The most convenient length of plate is from 10 to 20 millims., so as to afford a length between the knife-edges of not less than 8 and upwards of 16 millims. For a 15-millim. plate a breadth of about 3 millims. and a thickness of 0·4 to 0·7 millim. are suitable.

In carrying out the determination of the distance separating the two platinum-iridium knife-edges several series of readings are obtained for the separation of the points A and C, and of B and D, and the mean taken. In case the alternative knife-edges are employed, the actual distance between the centres of the two edges can be read off directly, in addition to the separation of the end-points.

The breadth of the plate is determined for six or seven equidistant points along that portion of the plate which lies between the knife-edges, and the mean taken.

It is convenient to engrave a little cross with a fine needle at the exact centre of the plate while under the microscope, so that the platinum-iridium point of the transmitter can subsequently be readily adjusted precisely at the centre with the aid of a pocket lens.

Instead of the method of carrying out the determinations from the plane of no bending of the plate, by use of the spring tables and their gun-metal knife-edges, it may be more generally preferred to employ the method used by KOCH, of commencing with the plate slightly bent under a constant initial weight, say 50 to 100 grammes, and the apparatus lends itself admirably to this method.

Details of the modes of carrying out the determinations, together with the description of a delicate mode of feeding the balance-pan with the weight employed, are reserved, however, for a subsequent communication describing the work actually carried out with the instrument.

Conclusion.

The advantages which the apparatus now described appears to the author to possess over that of KOCH, with which, however, most excellent work has been done, are as follows :—

(1.) Strictly monochromatic C-hydrogen light is employed, instead of the composite light corresponding to the two sodium D-lines, which are affected by mutual interference. Moreover, the use of auto-collimation ensures greater intensity and parallelism of the illuminating and reflected rays, and consequently greater perfection of interference.

(2.) The transmitter renders the observer independent of the nature of the surface of the plate of the substance investigated, and all necessity in the case of non-polishable and badly reflecting substances for the doubtful device of cementing a small glass plate to it is eliminated. Further, the troublesome alteration in the configuration of the bands, due to the plane surface of the plate being changed to a curved one on bending, or to increase of curvature if already more or less initially bent, is entirely avoided by the use of the transmitter, and bands of maximum excellence, suitable for adjustment between a pair of parallel micrometric spider-lines, are always obtained, owing to the same selected surfaces being employed to reflect the interfering light.

(3.) The employment of the sensitive method of a modified chemical balance for the application of the bending weight affords obvious advantages, not least among them being greater compactness of the whole apparatus, which is entirely above the supporting table, instead of being partly above and partly below.

(4.) The mode of controlling the application of the weight, and of regulating the rapidity of motion of the bands, is much more convenient and accessible.

(5.) The measuring microscope is entirely reserved for the determination of the dimensions of the plate and its setting, instead of also having to be employed for the totally different function of observing the bands. Also, increased accuracy is attained in the two rectilinear measuring movements by the provision of a novel method of eliminating backlash in the mounting of the measuring screws.

(6.) The error due to movement of the blocks supporting the plate, under the bending weight, with respect to the second reflecting surface concerned in the interference, is eliminated, together with all necessity for the application of a correction for it ; the glass disc furnishing this surface, and the knife-edges against which the plate is bent, have a common rigid support, instead of being mounted independently.

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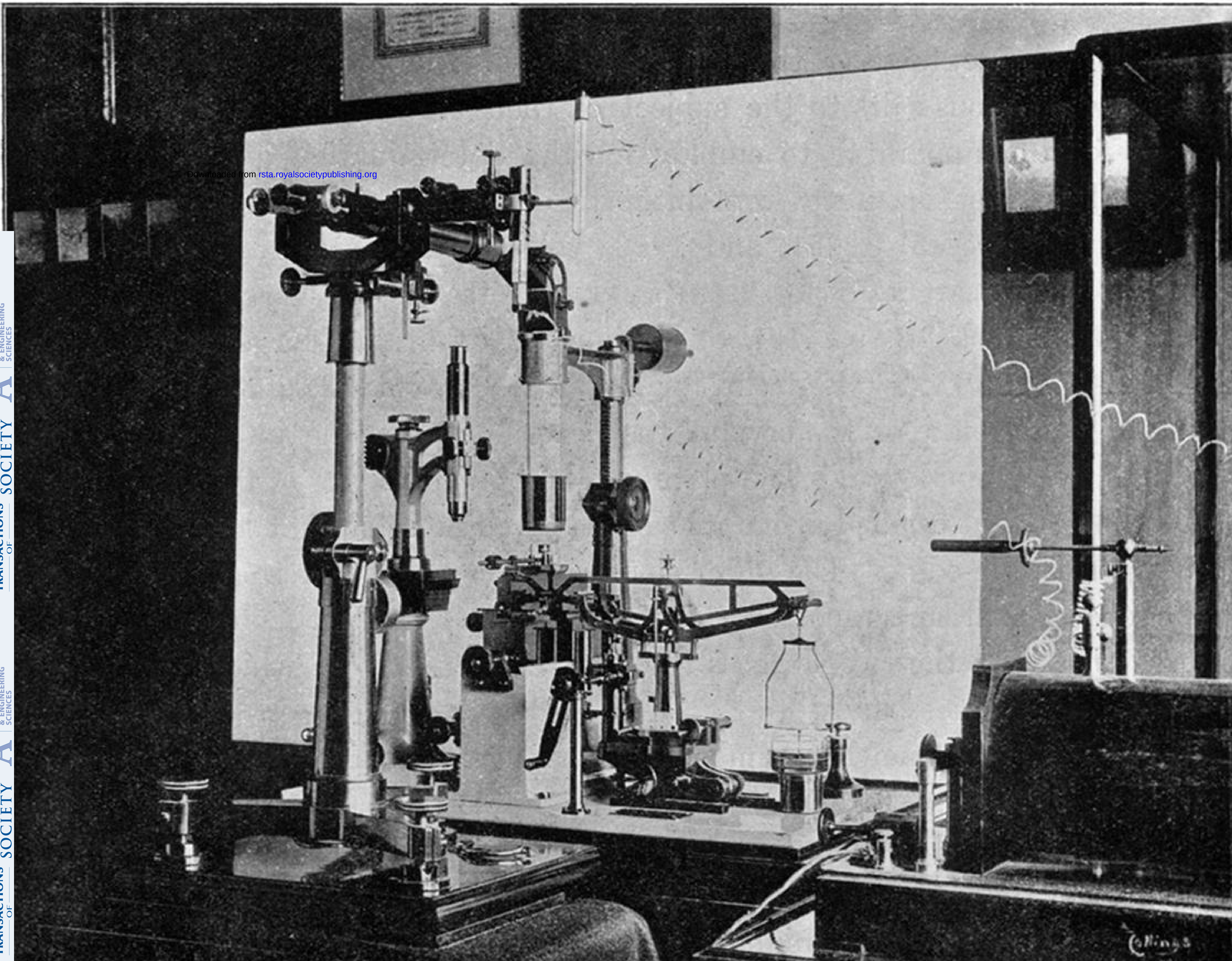

Fig. 1.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES