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The quadrant electrometer

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Another treatment of the brass rods is to burnish by rubbing them together in air or in water. When the rods are uncleaned we get values as at α, β; when cleaned the values are higher as at γ, δ.

The terminal and most interesting points, A, D, H, are emphasized by being in capitals. It may be observed that the same behaviour as to friction is found for glass as for brass. Further investigation will probably show that these effects are general, but vary in degree with all solids.

The method described above, being simple and instructive, makes a useful laboratory experiment. I am indebted to two junior students, Messrs D. Jenkinson and G. H. Perry, for the results in the table given.

II. The operation of obtaining μ is quick, and can be repeated as often as desired. The curves (Fig. 3) show the effect on μ of repeated rubs on *glass*. There are two cases:

(1) (Dotted curves) recently cleaned surfaces require at most one or two rubs to bring up the full and final value of μ.

(2) (Full curves) rods left for many hours in the air, have initial value of μ small; but μ increases as the rubs are repeated and after much friction settles asymptotically to a final high value.

These curves cannot be interpreted, with any assurance, without further detailed investigation, with change of experimental factors: for, not only is the adsorbed layer rubbed aside at each stroke, but in addition the *solid* surfaces themselves are abraded more and more at each rub and we have the changed conditions associated with the Beilby "flow."

The field of friction between solids is clearly a *terra incognita*.

THE QUADRANT ELECTROMETER.

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ABSTRACT. The paper is intended to be an analysis of the principles involved in the practical design of the quadrant electrometer with special reference to its use as a wattmeter for calibration purposes.

It indicates briefly the advantages of the electrostatic method for the measurement of power, and refers to the extreme difficulty experienced in manipulating the early types of instrument.

A description is given of the chief points in the design of the Standard Electrometer constructed at the Reichsanstalt in 1907, and reference is made to the instrument installed at the N.P.L. in 1912.

A list is given of the conditions which are essential to the design of an instrument having a straight line law, and a criticism of some of the devices which have been adopted to conform to these requirements.

In conclusion, a design is given of an instrument suitable for commercial purposes which can be constructed in such a manner as to ensure the maximum degree of accuracy and to provide the minimum number of adjustments.

It is probable that the Quadrant Electrometer arranged as a wattmeter would have entirely displaced the dynamometer type of instrument to-day as a standard for calibration purposes had it not been for the extreme difficulty experienced in manipulating the early types of electrostatic instrument.

This difficulty has been completely overcome by designing the instrument so that it can be constructed with accuracy and adjusted easily without causing too much disturbance to the moving system. An instrument of good design is found to be as simple and rapid in use as a moving coil galvanometer.

The electrostatic method for the measurement of power has several advantages over the dynamometer method, the chief ones for calibration being:

(*a*) A single instrument may be used for currents and voltages of any magnitude.

(*b*) The current taken by the pressure circuit is exceedingly small, being for normal frequencies less than one micro-ampere.

(*c*) The instrument has no frequency error.

(*d*) Its sensitivity can be increased many times when it is used for measurements at very low power factors by increasing the voltage drop across the quadrants.

(*e*) If desirable it can be used as a zero instrument to avoid calibration errors.

Its chief disadvantage is that the deflectional torque is exceedingly small, necessitating a delicate suspension. It must be protected from draughts, dust, and vibration, and is not portable. These conditions can easily be observed in a laboratory. Although the electrostatic method was first investigated by Ayrton and later by Addenbrooke in 1900, the instruments which the latter used were of rather a crude nature, judging by the illustrations of them, and it is probable that the first electrometer designed and constructed upon rational lines was set up at the Physikalisch-Technischen Reichsanstalt and described in *Zeitschrift für Instrumentenkunde*, **27**, 1907, p. 65.

In this instrument every part of the electrical system was made adjustable by a micrometric method. A skeleton diagram showing the arrangement of the various parts is given in Fig. 1. The base is a circular brass ring *a*, mounted on three ebonite pillars with levelling screws. On this is another concentric ring *b* carrying three pillars, and on the top of these is the upper portion of the instrument. The whole quadrant system is adjustable relatively to the base by three levelling screws *c* having divided heads and scales. Each set of quadrants is mounted on a base, the bottom set to *d* and the top set to *e*. Plates *d* and *e* are adjustable relatively to one another (for varying the distance between the quadrants) by three more levelling screws with divided heads and scales *f*. The plates *a*, *b*, *d* and *e* are all accurately constructed and mounted co-axially so that there is no necessity for relative axial adjustment. The plate *g* on top of the main pillars has a flange turned on it, and the tube *h* carrying the suspension and mounted on a framework *k*, *l* can be adjusted axially by three equidistant radial screws. This adjustment is provided so that the suspension can be brought into line with the axis of the quadrant system without disturbing the levelling screws at the base.

The suspension itself is attached at the top to a rod which is capable of vertical and rotational adjustment so as to bring the needle to the correct position relative to the quadrants. An air damper *m* is provided underneath the base, and of course the two plates of this are provided with vertical adjustment. Reference will subsequently be made to details of construction of this instrument.

The next instrument which marked an advance in design was that constructed at the National Physical Laboratory and described in the *Journal I.E.E.* **51**, 1913, p. 294. The advance in this case consisted in a simplification of some of the details of construction—notably the method of attaching the quadrants to their base and the removal of the damping vane and its adjuncts. The latter alteration was rendered possible by a novel construction of the needle, much reducing its moment of inertia and making it possible to obtain sufficient damping from the air friction between needle and quadrants.

The wattmeter which is now in use in the Electrical Measurements Laboratory of the City and Guilds Engineering College was constructed upon similar lines to the N.P.L. instrument and is illustrated in Fig. 2. A few of the details were altered when the drawings of the instrument were prepared. Various difficulties which arose during the construction and adjustment of this instrument have shown that the design might with advantage be still further simplified. Fig. 3 illustrates the essential parts of an electrostatic wattmeter and the connexions for measuring the power supplied to a circuit.

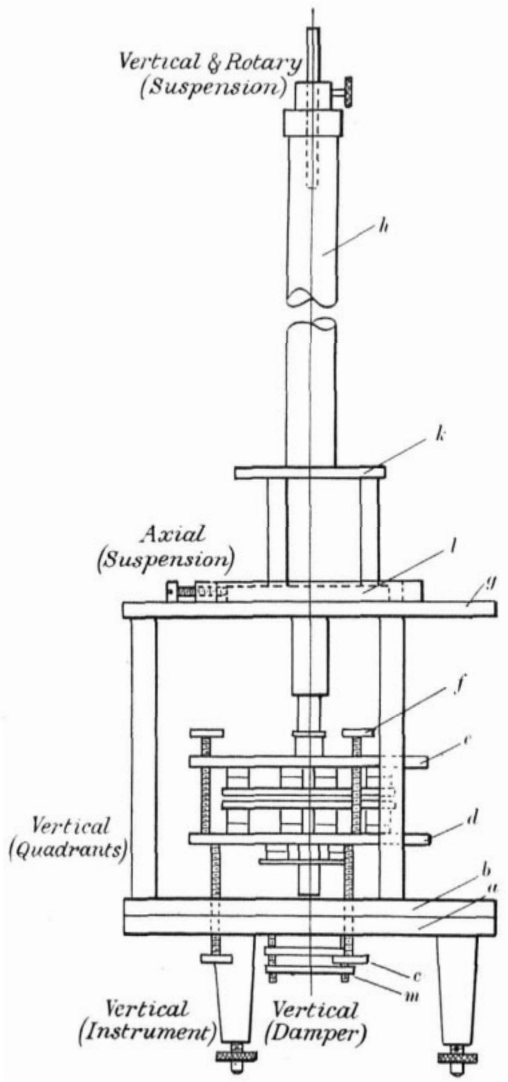

Fig. 1. Skeleton diagram of Reichsanstalt Instrument showing various adjustments

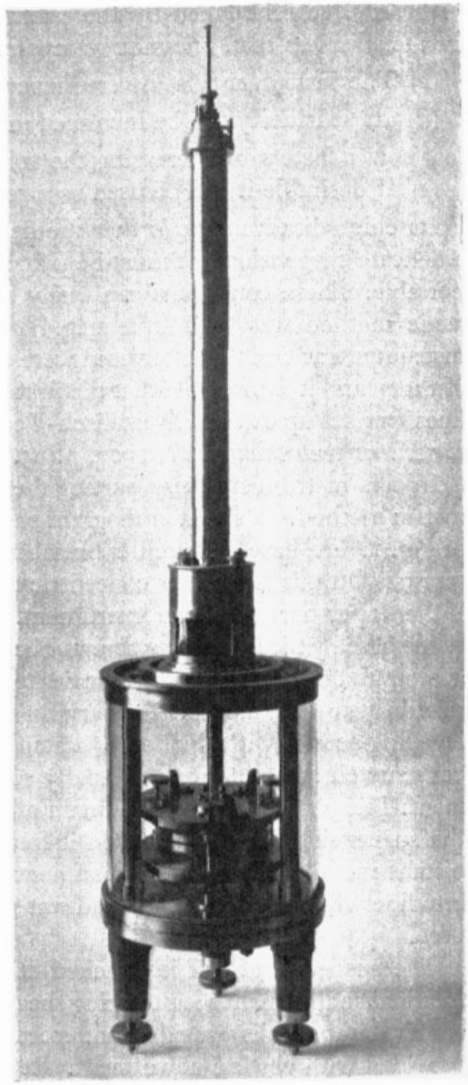

Fig. 2

It is proposed to suggest in what follows a method of construction in which accuracy is obtained with expenditure of less mechanical skill than that needed in the previous instruments, and which also enables the setting up and adjustment of the instrument to be a simple and rapid process.

In the construction of an instrument certain inaccuracies are inevitable, but they may be so small that they can only be discovered by electrical means when the instrument is set up. Therefore provision must be made to counteract the effect of these inaccuracies by special adjustments. In the case of the electrometer, in order to ensure that the deflection shall be accurately proportional to the applied voltages it is necessary that

(*a*) The quadrant surfaces should be flat, co-axial and uniformly conducting.

(*b*) The needle should be flat and accurate in outline, and should move in a plane parallel to the quadrants.

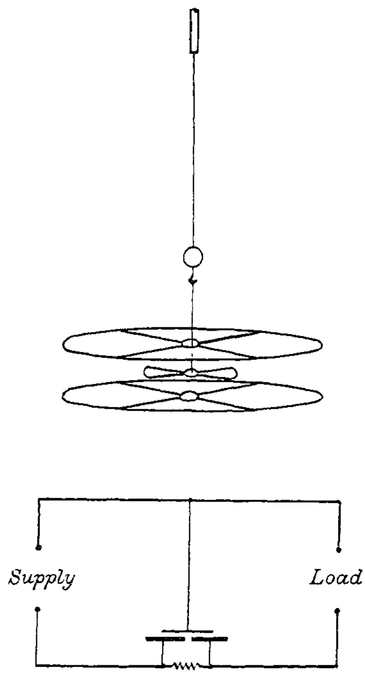

Fig. 3

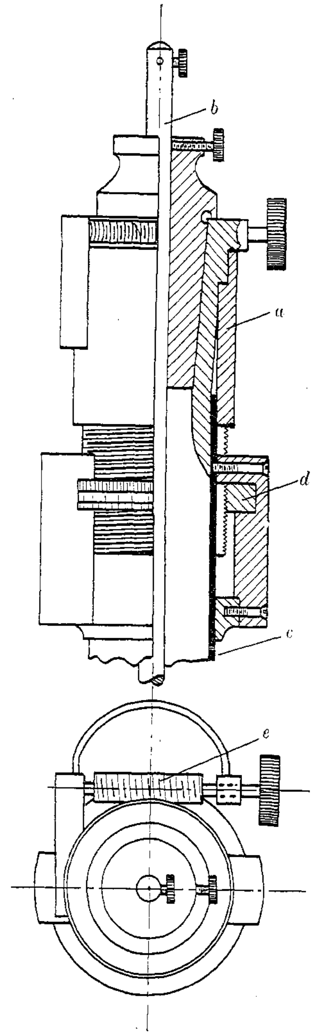

Fig. 4. Suspension fitting on Reichsanstalt Instrument

(*c*) The axis of rotation of the needle should pass through the centre points of the quadrant surfaces.

(*d*) The plane of the needle should be midway between the quadrant surfaces.

The importance of these points increases rapidly as the vertical distance between quadrants is reduced, in the endeavour to obtain the highest possible sensitivity. Condition (*a*) can be fulfilled sufficiently by careful design and construction; the quadrant surfaces being gilded if necessary. Adjustment is not essential. The second part of condition (*b*) and condition (*c*) can be obtained with two adjustments only; tilting the whole instrument on its levelling screws until the needle is co-axial with the quadrants, and then adjusting the level of the quadrant system. This final adjustment can only be carried out when the instrument is connected to a source of supply, A.C. or D.C., with all the quadrants connected together and at a potential of about 100 volts with respect to the needle and case. The level of the quadrants is altered until no deflection of the needle occurs when the supply is switched on or off. The position of the needle when a potential difference exists between itself and all the quadrants connected together is called the *electrical zero*, and in a well-made instrument very little final adjustment is needed to make it coincide with the mechanical zero.

The parts of the instrument which need most consideration in design are (1) the quadrant system, (2) the suspension fitting, and (3) the suspension itself. In the suspension fitting it is necessary that the needle should be capable of coarse and micrometric vertical adjustment, and independent rotary adjustment. Fig. 4 shows approximately the construction

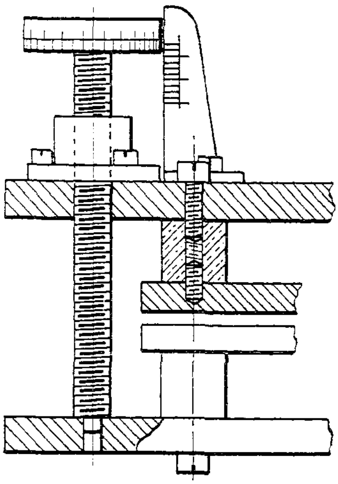

Fig. 5

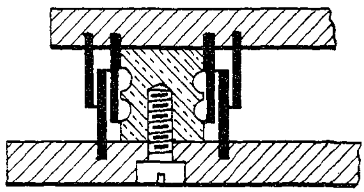

Fig. 6

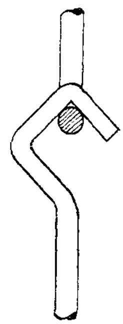

Fig. 7

used in the German instrument. Actually it is rather more complicated than the diagram given, but this is sufficient to show that although its performance may be ideal, it is far too complicated to use in a commercial instrument. (*a*) represents a slotted brass sleeve to give vertical movement without rotation, and (*d*) is the micrometer nut fitted to it; (*e*) is a worm driven rotary adjustment, and the suspension is attached to the rod (*b*) which can be moved up and down, or rotated for coarse adjustment. The construction adopted for the City and Guilds instrument is shown in Fig. 8, and it has been found to work perfectly. It is necessary to have the radial adjusting screw an easy fit or the force necessary to turn it will set the needle in vibration.

The quadrant system shown in Figs. 1 and 6 might be simplified with advantage. It consists of two circular brass disks, each one having four quadrants mounted co-axially upon it. The bottom disk rests on the points of three adjusting screws whose nuts are fixed to the base, and the top disk has three similar adjusting screws whose points rest upon the upper surface of the bottom disk. Thus, in addition to providing vertical adjustment, the screws must be made to serve the purpose of keeping the quadrants co-axial with each other and with the axis of the instrument. In the N.P.L. instrument the hole, slot, and plane

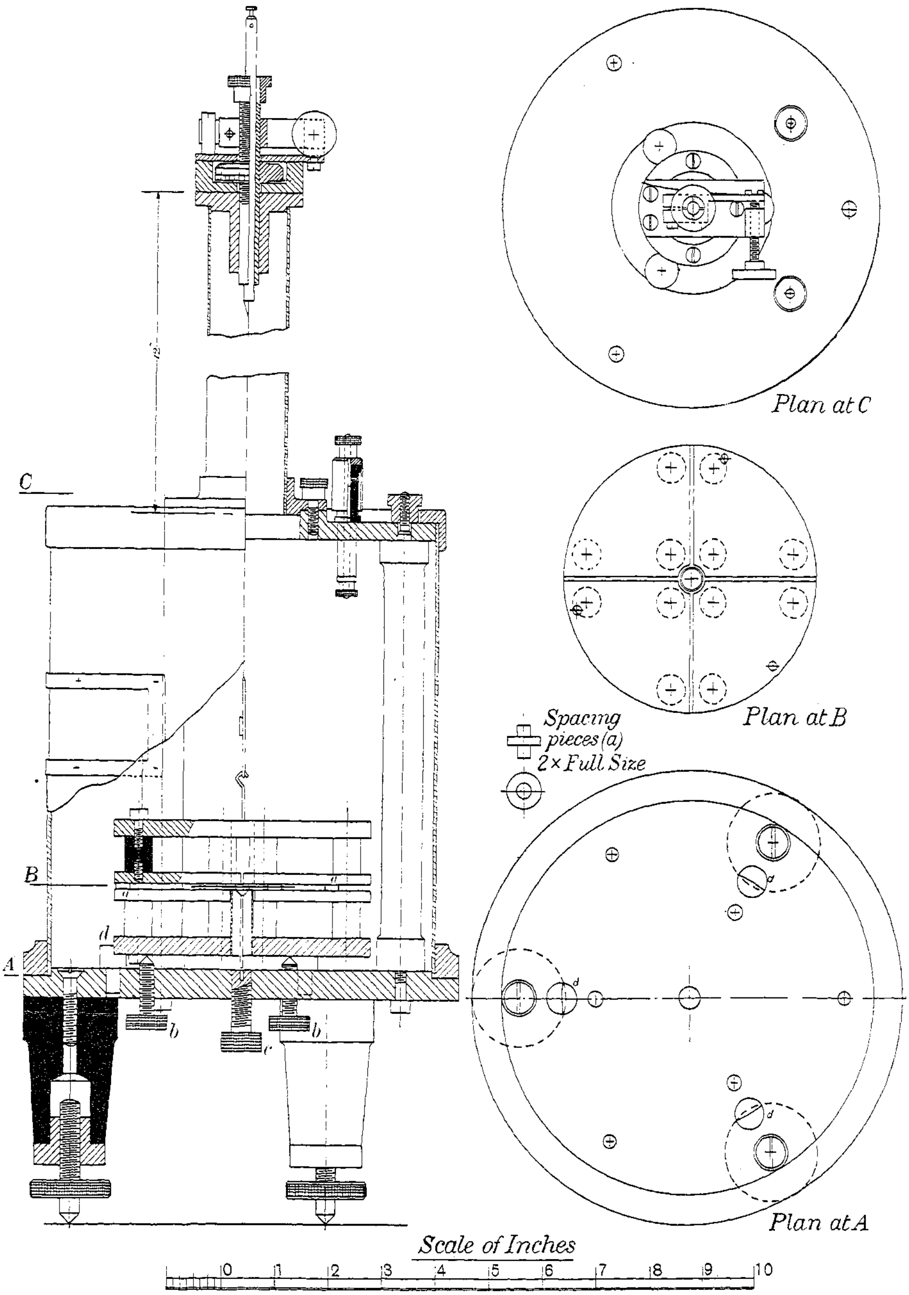
Plan at C
C
B
A
d
b
b
c
a
a
Spacing
pieces (a)
2 × Full Size
Plan at B
d
d
d
Plan at A
Scale of Inches
0
1
2
3
4
5
6
7
8
9
10

Fig. 8

device was used for keeping the disks central, but this is very difficult to mark out and machine accurately, and the slightest irregularity or looseness of the adjusting screw which fits in the hole or slot will cause the disk to move horizontally. An easier and more accurate method is to mark out the two disks together and drill three small holes right through both of them. The holes in the upper disk are then bored out to clear the screw threads and the points of the screws have shoulders which fit over the hole in the lower disk (Fig. 5). With this construction horizontal movement is more restricted since the effect of any irregularity in one screw is reduced by the stability of the others.

Experience has shown that combined distance and locating pieces between the quadrants themselves would be just as good as adjusting screws and would simplify the construction; and for tilting the quadrant system to make the electrical zero coincide with the mechanical zero the arrangement shown in Fig. 8 should be quite satisfactory. The three pegs (*d*) which serve as guides and supports for the bottom disk are driven into the base plate and the slots are turned concentric with it. Tilting is accomplished by means of the screws (*b*) which are thus relieved of a purpose for which they are fundamentally unsuitable—namely, that of keeping the bottom disk concentric with the base. The screw (*c*) is in the centre of the base and is used for taking the weight of the suspension if the instrument is moved and also for centring the needle when setting up the instrument.

The little pillars supporting the quadrants may be made of best quality ebonite if the instrument has a brass case to keep the light from them. It is essential that they are all of exactly the same height and that the tapped holes at each end are co-axial. Fig. 6 shows the construction used in the German instrument. The insulation is ebonite and the object of the shields is stated to be "to prevent any disturbing action of the insulation on the suspension or the needle." They appear to be an unnecessary refinement as the suspension is shielded by the tubes which surround it and which are at the same potential.

It simplifies the construction somewhat to arrange the upper part of the instrument as Fig. 8 instead of mounting the suspension tube on three pillars. The window for the mirror can be made of clear mica.

With regard to the suspension, it is essential that all the parts be made as light as possible, not only to keep down the moment of inertia, but also to reduce the direct stress in the suspension fibre to the minimum. The hook of the needle should be filed to the shape indicated in Fig. 8 to avoid back lash.

The first suspension used on the City and Guilds instrument was phosphor bronze strip 0·006″ × 0·0002″ in cross-section. At unity power factor full scale deflection ($\frac{1}{3}$ radian) was obtained with 100 volts on the needle and 0·2 volt between the quadrants, the latter being $2\frac{1}{2}$ mms. apart, but the zero reading was very unsteady. This was accounted for by the fact that the direct stress in the material was about 5,500 lbs. per sq. inch or nearly equal to the elastic limit. The shear stress due to torsion is quite small and would certainly not be sufficient to cause fatigue. A suitable cross-section to give sufficient sensitivity for most purposes and yet retain a steady zero would be about 0·010″ × 0·0004″. A long suspension is likely to be more satisfactory than a short one as the cross-section can be kept fairly large for a given sensitivity and the direct stress thereby reduced.