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A SENSITIVE MODIFICATION OF THE QUADRANT ELECTROMETER: ITS THEORY AND USE.

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Synopsis.

New Quadrant electrometer of high sensitivity, with tilted needle and movable quadrants. *Principle.* If the needle is given a slight tilt about its long axis and one pair of quadrants is raised or lowered a small distance with respect to the other pair, electrical control forces are set up which add to or subtract from the restoring torque from the suspension. *The theory* of these forces is discussed, the equation giving the sensitiveness in terms of the potential of the needle and the geometrical arrangement of the quadrants is derived and the method of utilizing electrostatic control to the best advantage is described. *Advantages:* High sensitivity, nearly independent of the deflection, and quick adjustment of sensitivity through a great range. *Results.* By using a small needle, 4.5 mm. in radius, with a slight tilt, sensitivities as high as 60,000 mm. per volt have been obtained. Adjustments are difficult at these extreme sensitivities, but the electrometer can usually be used up to 15,000 mm. per volt without undue trouble. Practical suggestions are given regarding needles, suspensions and mirrors.

Quadrant electrometer: needles of mica or aluminum. Technique.

Quadrant electrometer sensitivity; summary of elementary theory.

1. Introduction.

If a quadrant electrometer is to be used for the quick and accurate measurement of small electric charges or small potential differences it should be very sensitive, it should be as nearly as possible equally sensitive over all parts of the scale, and the moving parts should come quickly to rest when a measurement is being made. If we consider certain possible means of securing high sensitiveness, we shall see that this may be obtained without unduly sacrificing either the uniformity of the scale deflections or the rapidity with which readings may be taken.

According to the simple theory of the quadrant electrometer, if the needle is at a potential V and the two pairs of quadrants are at potentials

v_1 and v_2 respectively, the angle through which the needle is turned is given by

$$k_2\theta = k_1(v_2 - v_1)\left(V - \frac{v_2 + v_1}{2}\right),$$

where $k_2\theta$ is the torque exerted on the needle by the suspending fibre when twisted through an angle θ and $k_1 = R^2/\pi h$, where R is the radius of the needle and h is the distance from the lower to the upper side of the quadrants. In practice, the term $(v_2 + v_1)/2$ may nearly always be neglected in comparison with V, so that the sensitiveness is directly proportional to the potential of the needle. As long as V remains comparatively small this expression is found to be accurate, but when the potential of the needle is large, another term, which is approximately proportional to $V^2\theta$, becomes of prominence. We have then[1]

$$k_2\theta = k_1 V(v_2 - v_1) - k_3 V^2\theta,$$

and the sensitiveness is

$$S = \frac{\theta}{v_2 - v_1} = \frac{k_1 V}{k_2 + k_3 V^2}. \qquad (1)$$

With a given suspension the quantity k_2 is constant, but it is possible to vary k_3 over a large range of positive and negative values by changing the geometrical arrangement of the electrometer needle and quadrants. When k_3 is positive, the needle is held in more stable equilibrium, and there is said to be a "positive electrostatic control"; when k_3 is negative, the needle is held less firmly in position, and there is said to be a "negative electrostatic control." It is evident that, by adjusting the quantity $k_3 V^2$ until it is opposite in sign and nearly equal to k_2, any desired degree of sensitiveness can be attained.

If, as is usually the case in practice, the two pairs of quadrants are not connected directly to a battery, but one pair is connected to an insulated system whose gain of charge is to be measured, there is another factor, called the "inductional electrostatic control," which has to be considered. This control is due to the difference of potential between the quadrants which is set up when the electrometer needle moves from one into the other. The torque produced by this effect is always in a direction to resist the motion of the needle, and may be written as $- k_4 \cdot V^2/C \cdot \theta$, where the constant k_4 depends on the construction of the electrometer and C is the capacity of the system connected with the

[1] *Cf.*, *e. g.*, R. Beatty, Electrician, 65, p. 729, 1910 and 69, p. 233, 1912; or Makower and Geiger, "Practical Measurements in Radioactivity," p. 6.

insulated quadrants.[1] The sensitiveness in this case is

$$S = \frac{\theta}{v_2 - v_1} = \frac{k_1 V}{k_2 + k_3 V^2 + k_4 \dfrac{V^2}{C}}, \tag{2}$$

where v_2 and v_1 refer now to the potentials of the quadrants before the needle moves from its zero position,—or their potentials if the needle were prevented from turning. Thus the sensitiveness when one pair of quadrants is insulated is always less than when both are at definite potentials. It is still possible to adjust k_3 in such a manner that the needle borders on instability and the sensitiveness becomes very great, but there is now the difficulty that when the insulated quadrants are grounded the term $k_4 \cdot V^2/C$ vanishes and, if $k_3 V^2$ is greater than k_2, the needle becomes unstable. This difficulty need not be serious, however, if it is possible to adjust k_3 quickly over a sufficiently large range. In any case, the sensitivity is increased by the introduction of the "negative electrostatic control" term $k_3 V^2$.

In order to use a quadrant electrometer at its maximum sensitiveness it is therefore essential to be able to vary the electrostatic control readily over wide limits. A number of practical means of obtaining an adjustable electrostatic control have been discussed by Beatty,[2] and one of these has been used by Parson[3] in his highly sensitive electrometer. When the needle of Parson's electrometer is in its zero position it rests over a slit, whose width can be varied at will. The slit has the effect of repelling the needle, so that by widening the slit the needle may be made to approach a condition of instability. The trouble with this arrangement is that the force on the needle, due to the slit, is not proportional to the angle through which the needle has turned, and the sensitiveness therefore varies over different parts of the scale. Thus, while the electrometer is well adapted to "detection" and use in measurements by a compensation or "null" method, it is not so suitable to use in the usual work where deflections are measured.

We have found that an electrostatic control may be obtained by slightly tilting the electrometer needle about its long axis, and at the same time moving one of the quadrants a little above or below the plane of the other quadrants. This type of control possesses the important advantage of giving nearly constant sensitiveness over a large range of deflections and of permitting quick adjustment to any desired amount of control, either positive or negative.

[1] J. J. Thomson, Phil. Mag., 46, p. 536, 1898; Makower and Geiger, *loc. cit.*

[2] *Loc. cit.*

[3] A. L. Parson, Phys. Rev., VI., p. 390, 1915.

2. THEORY.

Let one pair of quadrants be displaced vertically a distance δ with respect of the other. The needle is suspended with its center at a distance p above the horizontal plane of symmetry and is tilted about its long axis so that its slope with respect to the horizontal plane is s. Evidently, as the needle deflects through an angle θ, it approaches the sides a and c (Fig. 1) and recedes from the sides b and d of the quadrants, the effect being to change the capacity of the system and therefore to give rise to forces tending to produce or resist further deflection. The magnitude of these forces, which combine to produce the electrostatic control, we shall proceed to calculate.

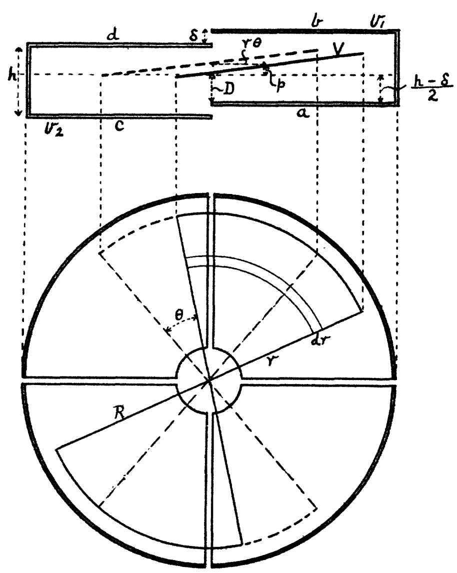

Fig. 1.

Consider first that portion of the needle lying between distances r and $r + dr$ from its center. The distance D between this element and the edge of the side a is

$$D = \frac{h - \delta}{2} + p - sr\theta,$$

where s is the slope $dD/rd\theta$ of the needle and θ is the angle of deflection of the needle from its zero position. The change in the charge induced on the side a by that part of the needle between r and $r + dr$ in turning through an additional infinitesimal angle $d\theta$ is $dq = \sigma r d\theta dr$. The surface density σ is, by Coulomb's law, $\sigma = (V - v_1)/4\pi D$, where V is the potential of the needle and v_1 that of the side a of the quadrant.

Thus

$$\frac{dq}{d\theta} = \frac{V - v_1}{4\pi\left(\frac{h}{2} - \frac{\delta}{2} + p - sr\theta\right)} rdr.$$

The change dW in the potential energy of this part of the system is $dW = \frac{1}{2}(V - v_1)dq$. Thus

$$dT_a = \frac{dW}{d\theta} = \frac{1}{2}(V - v_1)\frac{dq}{d\theta}$$

is the torque exerted on the portion of the needle considered by the side a. The total torque exerted on the needle by the side a is therefore

$$T_a = \int_0^R \frac{(V - v_1)^2 rdr}{4\pi(h - \delta + 2p - 2sr\theta)},$$

which, when integrated, takes the form of the rapidly converging series

$$T_a = \frac{R^2(V - v_1)^2}{16\pi}\left[\frac{4}{2}\frac{1}{(h - \delta + 2p)} + \frac{8}{3}\frac{Rs\theta}{(h - \delta + 2p)^2} + \frac{16}{4}\frac{R^2 s^2\theta^2}{(h - \delta + 2p)^3} + \cdots\right].$$

The torque due to the other faces may be similarly calculated, whence the total torque due to both ends of the needle is

$$T = 2(T_a + T_b + T_c + T_d),$$

which may be written in the most convenient form by grouping separately the coefficients of different powers of θ. Neglecting the term in $(v_2 + v_1)/2$ in comparison with those in V^2 and $V(v_2 - v_1)$, we have

$$T = \frac{R^2}{\pi h}\left\{ V(v_2 - v_1)\left[\left(1 + \frac{\delta^2}{h^2} + 4\frac{p^2}{h^2} + \cdots\right) + \cdots\right] + V^2\left[-\frac{4\delta p}{h^2}\left(1 + 2\frac{\delta^2}{h^2} + 8\frac{p^2}{h^2} + \cdots\right) + \frac{8Rs\delta}{3h^2}\left(1 + 2\frac{\delta^2}{h^2} + 8\frac{p^2}{h^2} + \cdots\right)\theta + \frac{64R^3s^3\delta}{5h^4}\left(1 + 5\frac{\delta^2}{h^2} + 20\frac{p^2}{h^2} + \cdots\right)\theta^3 + \cdots\right]\right\},$$

which may be written

$$T = k_1 V(v_2 - v_1) - k' V^2\delta p - k_3 V^2\theta - k_5 V^2\theta^3.$$

This equation for torque due to electrical forces includes all terms whose influence on the action of an electrometer of the type discussed may be detected. The values of the important constants k_3 and k_5 may be taken to be

$$k_3 = -\frac{8R^3s\delta}{3\pi h^3} \quad \text{and} \quad k_5 = -\frac{64R^5s^3\delta}{5\pi h^5}, \tag{3}$$

and it is to be noted that both must have the same sign.

In equilibrium, this torque must be balanced by that due to the suspension, *i. e.*,

$$k_2\theta = k_1V(v_2 - v_1) - k'V^2\delta p - k_3V^2\theta - k_5V^2\theta^3. \tag{4}$$

The term $-k'V^2\delta p$ is of interest because it shows the cause of the deflection from the zero position generally observed when the needle is charged while the quadrants remain grounded. Other possible causes are contact difference of potential between the quadrants due to solder or imperfect "finish" and a tilt of the needle about its short axis,—this being equivalent, as far as the equation is concerned, to a change of θ. With care in construction these latter causes are not effective. In order to use the electrometer, this zero deflection must be prevented, which can be done by reducing either p or δ to zero. It is advantageous to adjust p rather than δ to zero, for by so doing the values of the constants k_3 and k_5 are not appreciably affected. If the zero shift is thus eliminated for one potential V of the needle, it should not appear for any other needle potential unless one or both of the other causes of zero shift are effective. Therefore, when the height of the center of the needle is adjusted to its position ($p = 0$) of symmetry between the quadrants, as judged by the absence of zero shift, the term $k'V^2\delta p$ of equation (3) vanishes and we obtain for the sensitiveness

$$S = \frac{\theta}{v_2 - v_1} = \frac{k_1V}{k_2 + k_3V^2 + k_5V^2\theta^2}. \tag{5}$$

If δ and s are of the same sign, as in Fig. 1, k_3 and k_5 are negative and the sensitiveness is increased, *i. e.*, there is a negative electrostatic control. Similarly if δ and s are of opposite sign, the electrostatic control is positive. Thus, with a given inclination of the needle, the control can be varied through wide limits by moving one pair of quadrants up and down. In practice we have used three of the quadrants in their position of symmetry, in which case the constants k_3 and k_5 have just half the values assigned in equations (3). With negative control, it is theoretically possible to obtain any sensitiveness between zero and infinity, while with positive control there is, for any given value of the constants, a maximum sensitiveness given by placing the derivative of S with respect to V equal to zero. If we neglect the term in k_5, which is very small and does not take a value until the needle has deflected, we obtain for the maximum sensitiveness under positive control

$$ {}_{+}S_{\max} = \frac{k_1}{2k_2}\sqrt{\frac{k_2}{k_3}} $$

when (6)

$$ V_m = \sqrt{\frac{k_2}{k_3}}. $$

Practical difficulties of a mechanical nature prevent the attainment of infinite sensitiveness under negative control. These difficulties will be discussed later.

When the electrometer is thus made very sensitive a relatively long time is required for the needle to come to its position of equilibrium. While the needle is in motion, the air resistance is proportional to the linear velocity of the needle, to its area, and approximately inversely to the distance between the needle and the quadrants. The torque due to air damping may therefore be written $k_6 \cdot R^4/h \cdot d\theta/dt$, where $d\theta/dt$ is the angular velocity of the needle. If I is the moment of inertia of the needle, the equation of its motion is therefore

$$ k_1 V(v_2 - v_1) - (k_2 + k_3 V^2 + k_5 V^2\theta^2)\theta - k_6 \frac{R^4}{h}\frac{d\theta}{dt} = I\frac{d^2\theta}{dt^2}. $$

By using needles made of thin mica sputtered with platinum (suggested to us by Professor Pegram of Columbia University) or made of thin aluminium leaf, the moment of inertia term may be made negligibly small in comparison with the other terms. In this case the time T required for the needle to return to zero after a deflection is evidently approximately proportional to

$$ \frac{\theta}{\frac{d\theta}{dt}} = \frac{k_6 R^4}{h(k_2 + k_3 V^2 + k_5 V^2\theta^2)} $$

$$ = S\frac{k_6 R^4}{hk_1 V} = \frac{\pi k_6 R^2 S}{V}, $$

by definition of the constant k_1. Thus

$$ T \sim S\frac{R^2}{V} $$

and (7)

$$ S \sim T\frac{V}{R^2}. $$

Equations (7) illustrate the well-known fact that the most advantageous combination of high sensitiveness with short period may be attained with small needles. The lower limit to which the needle may profitably be reduced is limited only by the fact that the needle must turn a mirror of sufficient size to give a well-defined spot of light on the scale. By taking into account the resolving power of the mirror, it can easily be shown that the minimum potential difference which can be detected is proportional to $1/R$ instead of to $1/R^2$, if dimensions of needle and mirror are maintained in a constant ratio. For detecting charge, there is further advantage in reducing the size of the needle and quadrants because the capacity of the electrometer is roughly proportional to the linear dimensions of the needle and quadrants.

3. Design.

Equations (5) and (7) give us information essential to the design of an electrometer to operate in the most satisfactory manner. We have used the electrometer in two sizes, one with a needle of 7 mm. radius and the other with a needle of 4.5 mm. radius. The former is rather easier to operate and adjust, while the latter gives greater sensitiveness for a given period. For very delicate work the size can be profitably reduced still further, and we understand that this has been done by Professor Pegram.

As to the use of the electrostatic control, there are a number of factors to be considered. The presence of the term $k_5 V^2 \theta^2$ in equation (5) shows that the sensitiveness is not the same for all values of θ, *i. e.*, over all parts of the scale, though this term is not important except at very high sensitivities. It always tends to increase the control, whether positive or negative, as the electrometer deflects from the zero position. Thus, with positive control the sensitiveness decreases as the needle deflects from zero, and the needle cannot be put into unstable equilibrium. With negative control the sensitiveness increases as the needle deflects from zero and, if the deflection is too large, the needle may move past the point of instability and turn through an angle of 90° to a new position of equilibrium under positive control. Thus the size of the scale deflection which can be used decreases as the sensitiveness increases. This is a disadvantage, but it need not be serious if the design is guided by the following considerations.

Since these difficulties are due to the term in k_5, they are reduced to a minimum by reducing k_5 in relation to k_3. By equations (3) it is seen that the ratio

$$\frac{k_5}{k_3} = \frac{24R^2s^2}{h^2}.$$

It is therefore advantageous to make the tilt s of the needle small and the height h of the quadrants large. In other words, the desired amount of electrostatic control, given by the term $k_3 V^2$, may be most advantageously obtained with a small tilt s of the needle and a relatively large displacement δ of the quadrant. In an actual case in which k_3 was about ten times larger than k_5, the action of the electrometer was apparently independent of the k_5 term for sensitivities below 15,000 mm. per volt, was not seriously disturbed up to 30,000 mm. per volt for deflections less than 100 mm., while at 60,000 mm. per volt the influence of this term was so serious that the electrometer could only be used as a "null" instrument.

Furthermore it is doubly advantageous to have both k_3 and k_5 small, so that the high sensitiveness arises largely from the term $k_1/k_2 \cdot V$. In the first place the high sensitiveness is then reached with little disturbance from the $k_5 V^2 \theta^2$ term and in the second place the greatest sensitiveness in relation to the period is obtained owing to the larger value of V attainable, as shown by equation (7). It is better, therefore, to use a suspending fiber whose constant k_2 is sufficiently small to permit the attainment of fairly high sensitiveness without electrostatic control and then to attain very high sensitiveness by applying a small negative control than to neutralize the torque of a strong fiber by a very strong control.

It is best, therefore, to use a fairly delicate suspension, to give the needle only a slight tilt and to displace the quadrants only enough to make the electrostatic control important for relatively high potentials of the needle. For example, we usually use a sputtered quartz suspension of such size that the little hook cemented on its end will oscillate with a period between 0.5 sec. and 1.0 sec. The needle is given just enough tilt to be detected by inspection. The movable quadrant is displaced about 0.15 mm. in the direction to produce negative control. Under these conditions extreme sensitivities are reached with needle potentials of 75 or 100 volts. If the electrometer is to be used at high sensitivity for work where the quadrants are to be insulated for considerable periods of time, as in getting a continuous photographic record of an X-ray spectrum, it is better to use a very fine suspension and slight positive control, for the zero position of the needle is then more stable.

The remaining features in the design of an electrometer of this type are obvious: a convenient means of adjusting the height of a quadrant from outside of the electrometer case and a means of adjusting the height of the needle while the potential source is connected with it. Both adjustments must be delicate and free from "lost motion."

4. Typical Results.

Figs. 2 and 3 show the action of the electrometer with various degrees of positive and negative control, respectively. Each represents results obtained with a given suspension and a given tilt of the needle—the various degrees of control being obtained by adjusting the moveable quadrant. If equation (1) is written in the form

$$S = \frac{aV}{1 - bV^2}, \tag{8}$$

the constant b determines the "electrostatic control."

Curves *1*, *2*, *3* and *4* are all coincident at the origin where, obviously, the "control" term vanishes. The straight dotted line represents a

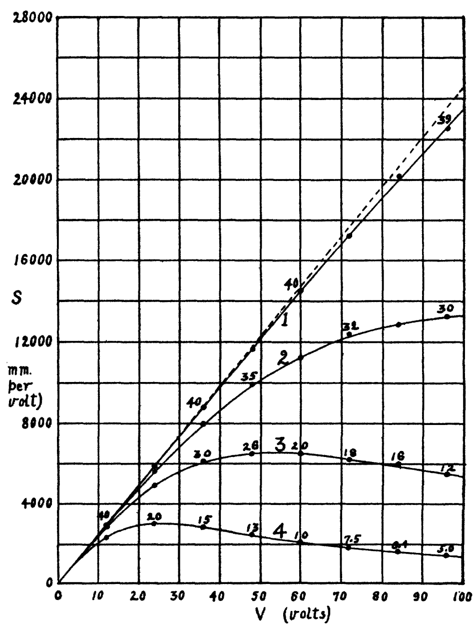

Fig. 2.

condition of zero electrostatic control in which the sensitiveness is strictly proportional to the potential of the needle. This condition was not quite reached in the measurements shown in curve *1*. Curve *2* was obtained by raising the moveable quadrant 0.08 mm., *i. e.*, a quarter turn of the adjusting screw, and readjusting the height of the needle. Curves *3* and *4* indicate further increased amounts of "control." The numbers above the curves represent the period of swing, being the time required to come to within 1 mm. of the resting point after a 50-mm. deflection. It is seen that the period is independent of the sensitiveness when there is no electrostatic control, but decreases as the control increases.

Curves *5*, *6*, *7*, *8*, *9* represent various degrees of "negative control," using a stronger suspension than was used in the experiments on "positive control." In this case curve *5* represents zero control, curve *6* the control obtained by lowering the moveable quadrant 0.08 mm., etc. In each case there is a critical potential V_c above which the needle cannot be kept in equilibrium and near which the sensitiveness is very high. This

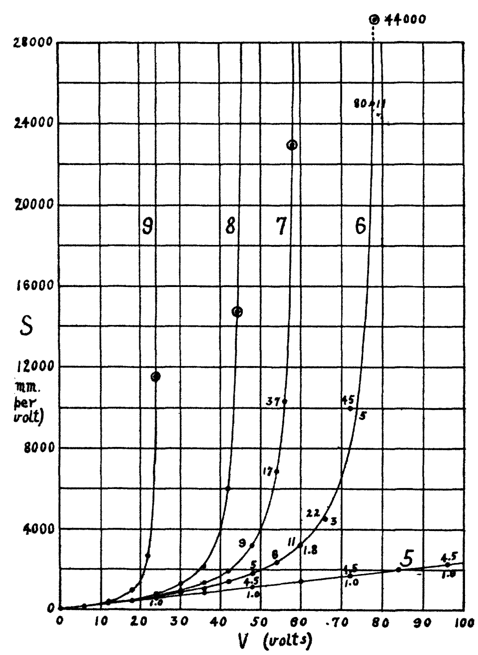

Fig. 3.

unstable condition is approached very rapidly when the control is strong as shown in curve *9*, where an increase of one fourth volt in the needle potential 24 volts would double the sensitivity. In such a condition the needle is very hard to adjust and is sensitive to movements of the support. For this reason also it is best in practice to use relatively small electrostatic control and relatively high needle potentials, as in curve *6*. The highest sensitiveness at which the zero point was sufficiently steady to permit measurements to be made is indicated by a circle in each case. The figures below the curves give the times required to make half the deflection, and show that most of the time of deflection is taken up with the final slow drift.

In both sets of curves the solid curves represent graphs of equation (8), with values of the constants indicated in Table I. The constants were

TABLE I.

Curve.	a.	b.	V_c, Volts.	Curve.	a.	b.	V_c, Volts.
1	245.0	0.000004		6	23.7	− 0.000152	81.2
2	245.0	0.000085		7	23.7	− 0.000279	59.7
3	245.0	0.000355		8	23.7	− 0.000475	45.8
4	245.0	0.001650		9	23.7	− 0.001650	24.6
5	23.7	0.000000	∞				

chosen to give best agreement with the experimental measurements, which are recorded as dots. The needle was of 4.5-mm. radius, in quadrants of 6.5 mm. radius. The capacity of the instrument was 10.4 cm. Exactly similar curves were obtained with a larger instrument with a needle of 7-mm. radius and a capacity of 12.5 cm., except that the periods of swing were somewhat longer.

5. PRACTICAL HINTS.

Needles.—We have used mica and aluminium leaf needles, the former being more difficult to make but more satisfactory in operation because of greater rigidity and less air-damping. The mica needles are cut from the thinnest mica by scratching with a sharp needle around the outline of a brass template, cut to the desired shape and pressed firmly on the mica sheet. The fine wire stem is fastened to the needle with sealing wax and the whole system rendered conducting by sputtering beneath a platinum cathode *in vacuo*. While sputtering, the stem must be supported to prevent its falling over if the wax is softened by the discharge. An alternative procedure is to sputter the needle alone, then mount the stem with a touch of sealing wax, and make conducting contact across the wax by a tiny strip of gold leaf, cemented with india ink. The aluminium needles are easily cut from thin leaf held between a metal template and a flat piece of rubber, such as tire or shoe sole rubber, while a sharp-pointed knife blade is passed around the outline. The stem is mounted with soft wax, and is pressed against the needle so as to insure contact. This mounting and the adjustment of the "tilt" is facilitated by the use of a flat piece of metal which may be heated from underneath and against which the needle, held by the stem in a pair of tweezers, may be pressed. If the needle is irregularly warped, difficulties may be encountered in making adjustments and securing uniform scale deflections.

Suspensions.—Quartz fibers, 1 to 2 cm. long are mounted on platinum or silver hooks with sealing wax, and sputtered to obtain a conducting platinum coat. For use with "negative control," these fibers should be the finest ones that can be drawn in the oxy-gas flame by the bow and arrow method, or the coarsest ones that can be drawn out by the flame itself. For use with "positive control," the very finest fibers may be used, the limit being imposed only by the strength requisite for the support of the needle and mirror. The conductivity of the sputtered coat gradually diminishes and the suspensions usually require re-sputtering after about a year of service. If suspensions break, it is usually at the point of joining to the hook. They may then be easily repaired by dipping the end of the hook several times into india ink and then touching with the wet end the free end of the suspension. They are held together at once, and after drying for two or three minutes the suspension is apparently as strong as ever, and retains its conducting properties.

Mirrors.—When working at high sensitivity, the instrument is so much over damped that the moment of inertia may be made quite large without appreciably increasing the period. Thus the mirrors may be larger than might be supposed. We use mirrors with as much as 10 sq. mm. area on the 4.5 and 7.0 mm. instruments.

Ease of Adjustment.—The most serious sources of difficulty appear to be irregularities in the needle or quadrants and contact difference of potential between quadrants. Thus with some instruments it is easy to reach 10,000 or 15,000 mm. per volt sensitivity and in others difficult to reach 10,000 mm. per volt, due to accidental differences in construction. Among the seven or eight instruments of this type in use in our laboratories we have never had difficulty in obtaining 5,000 mm. per volt at the first trial, and usually count on being able to work between 5,000 and 10,000 mm. per volt without trouble. At higher sensitivities more trouble is experienced with zero drift. Difficulty due to contact difference of potential between quadrants may be identified by the failure to secure identical deflections from the zero, with quadrants earthed, when the sign of the potential of the needle is reversed, for this effect is proportional to the first power of the needle potential while all effects due to lack of symmetry depend on the square of the potential and are therefore independent of its sign. If such contact difference of potential is found to be troublesome, it may be removed by cleaning or compensated by a small potential permanently applied to the "earthed" quadrants.

By taking the precautions suggested in this paper we have been able to employ to advantage sensitiveness as high as 50,000 mm. per volt, at 1 meter scale distance.

Valuable suggestions in the design of the electrometer were made by Professor H. L. Cooke, to whom we are greatly indebted.

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