A HIGHLY SENSITIVE ELECTROMETER.

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FOR the measurement, and more particularly the detection, of very small potential differences on open circuit a very highly sensitive electrometer was required. The most sensitive hitherto described is the "duant" electrometer of Hofmann[1] which has a capacity of only 5 cm. and may be adjusted to work in a condition approaching instability. It can then give deflections at the rate of 10 mm. per millivolt (scale distance 1.5 meters), but he does not state whether it is steady enough in its action to detect a single 10^{-4} volt unit by a 1 mm. deflection, the only results given from which the steadiness can be judged being for the lower sensitivity of 1 *mm/mv.* This instrument suffers from the disadvantage of requiring a needle of extremely delicate and exact construction, but a more troublesome feature is the complexity of the electrical system used in its operation. The suspension is made conducting and the potential to be measured is communicated to the needle, while the two conductors which take the place of quadrants must be kept at a high potential difference by a constant battery: it is by a careful adjustment of this potential difference that the maximum sensitivity is obtained.

The principle of working with a condition approaching instability has also been used greatly to increase the sensitivity of the gold-leaf electroscope by C. T. R. Wilson, and of the string electrometer by Wulf, but neither of these has the inherent sensitivity of the suspended needle electrometer, of which the most familiar form is of course that of Dolezalek. This instrument, in its ordinary form, can give, with very fine quartz fibers, deflections at the rate of 10 mm. per millivolt, but is then somewhat uncertain and slow in its action. Its capacity is about 50 cm. and probably could not be made less without diminishing its sensitivity to potential differences. The necessity of securing a uniform inducting surface inside the quadrants also makes against a small capacity, for the gaps must be small and the quadrant edges thick.

[1] Ann. d. Phys. [4], 42, pp. 1196–1220, 1913.

THE PRINCIPLE OF THE INSTRUMENT.

The instrument about to be described is a modification of the quadrant electrometer, which does not suffer from these disadvantages, and which by an ability to work in a condition approaching instability can be made very much more sensitive. To a certain extent, however, it loses the good feature of giving a deflection proportional to the potential difference.

The four quadrants are replaced by four sectors arranged in pairs AB, $A'B'$, as in Fig. 1, and the box form of the quadrants is abandoned, the sectors being cut from a single disc of metal .5 mm. thick. In the quadrant electrometer the torsion of the quartz fiber is used as a measure of the force on the needle, and is the only source of its stability: in the present case, however, the stability of the needle is procured by an automatic disposition of electric forces; and the torsion of the fiber is useful only for balancing any disymmetry in the electric forces such as may arise from a slightly uneven mounting of the sectors. In the more sensitive adjustments of the instrument, however, this control by the torsion head is very valuable.

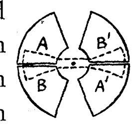

Fig. 1.

As regards the electrical connections, the instrument can be used in exactly the same way as the quadrant electrometer, and the needle can be charged either by a constant battery through a conducting suspension, or by the simpler method of a charging switch.

The chief innovation is that the sectors are mounted on a pair of arms pivoted scissors-like at the center, and that the small gaps between A and B, A' and B' can be varied in width from something very small to about 2 mm. by the action of a micrometer screw. When the gap is small and the sectors are at equal potentials, A and B form a virtually continuous inducing surface opposite the charged needle and the capacity of the system is highest when the needle hangs symmetrically over them: this therefore is its stable position. If a difference of potential is set up between AA' and BB', the needle is deflected, at first nearly proportionally to the potential difference, and then less and less as it approaches the large gaps at the sides. This is the least sensitive way of using the instrument, and gives deflections at the rate of about 3 mm. per millivolt (the scale being 5 meters distant[1]). As the gap between A and B is

[1] It was found possible to use this great scale distance profitably by placing the telescope near the instrument and at an angle. If the plane of incidence of the light on the mirror is horizontal, the scale divisions are blurred owing to reflection at both the surfaces of the mirror glass; but if the plane is vertical, as when the scale is placed high up and the telescope is inclined upwards towards the mirror, this does not occur. The increased sensitivity due to the use of this greater scale distance is valuable in itself, but is not of course a property of

widened, the needle becomes less and less stable in its central position and the sensitivity greater and greater. Just before instability is reached a stable deflection at the rate of as much as 150 mm. per millivolt can be obtained, but it is probably not worth while working with deflections greater than about 40 mm. per millivolt, as will appear later.

It is of interest to notice that when the sectors are very close, and the instrument least sensitive, the sensitivity increases as the potential to which the needle is charged diminishes. This might have been predicted, for, while the deflecting force is proportional to the first power of the charge on the needle, the electrical force giving it stability is more nearly proportional to the square of it. Some values got with an older model, in which the needle was 3 cm. long and the quartz fiber thin enough for its torsion to be almost negligible, are as follows:

Potential of needle in volts	80	40	20	10
Deflection in mm. per millivolt	2.1	3.8	5.3	9

But there is no advantage in using the lower potentials, for the maximum sensitivity attainable is not at all increased, while the period of deflection is greatly lengthened. All the results given in this paper were got with a needle potential of + 80 volts. (The fact that a positive charge is lost to the air less rapidly than a negative one was pointed out in connection with electrometers by Lord Kelvin: the difference cannot be great at 80 volts, however.)

One of the chief advantages of this instrument is that its sensitivity to potential differences is quite independent of the scale on which it is built, for the torsion of the suspension is not a determining factor unless it is altogether too thick. As it is easy to get a quartz fiber .002 mm. thick, which would suit a needle .5 cm. long, it is evident that the capacity can be made very small. Actually, the limiting factor is the smallest mirror with which a scale can be read at a distance of say 1 meter. This is about 2 mm. square and would have too great a moment of inertia for a needle less than about .7 cm. long. In a trial instrument the needle was 3 cm. long, but in the one now to be described it is 1.8 cm., and the disc from which the sectors were cut was 2.1 cm. in diameter, with a .75 cm. hole in its center. The capacity was found to be 9 cm. by a method of induction through a condenser of known and variable capacity.

Constructional Details (Fig. 2).

The most convenient arrangement of parts was found to be given by making a base *A* (carrying the sectors and provided with suitable widely-

the electrometer. To compare with Hofmann's result of 10 mm. per millivolt, for example, which was got at a scale distance of 1.5 meters, the sensitivity values here given should be divided by 3.3. Hofmann used a spot of light instead of a reading telescope and read the scale to .5 mm. only.

spread feet) to which the rest of the instrument (all in one piece) was attached by a spring fit of its cylindrical case B around a flange at C. The case, which is only 5 cm. in diameter and 4.5 cm. high, is made small in order to diminish the effect of air currents within it, even though the electrical capacity may thus be raised by a unit or so.

The micrometer screw and terminal could be made to come up from below; but this would be inconvenient on so small a scale, and hence they are fixed in curved pads D (of brass and vulcanite respectively) which are attached to the base and rest tightly over slots E in the cylindrical case when this is pressed down into position. A good fit here is essential in order to avoid disturbance from air-currents.

For the window, which is 1.5 cm. square, a microscope cover slip was found to be optically satisfactory, although a piece of a slide was not. As the window opening is a possible source of electrical disturbance, it is provided with a divergent metal shade S projecting 2 cm. This has the further advantage of partly protecting the interior from light: it was noticed that the light (or heat) from a 40-watt lamp at a meter's distance, suddenly falling on the interior, gave rise to a very marked disturbance.

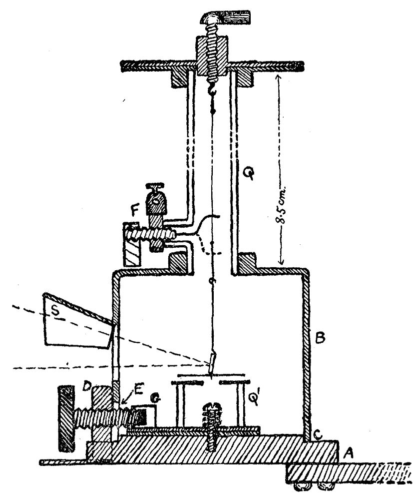

Fig. 2.

The torsion head, which is of any suitable construction, is supported on a quartz tube Q fixed to the top of the case. The use of quartz here serves the double purpose of insulating the torsion head (if this should ever be required) and of reducing to a minimum the effect of temperature changes on the distance between the needle and the sectors. This effect would be expected to give more trouble in the present instrument than in one where the needle hung midway between the upper and lower surfaces of quadrants, but it is not yet certain that the precaution is necessary in practice. Since in the ordinary use of the instrument, the exact potential of the needle is not important, provided it remains constant, the needle is charged by means of a switch F, which comes through a side tube on the quartz column, and by a rotary motion brings a platinum wire into contact with the lower hook (also of platinum) of the suspension. A light metal shield slipped over the lower part of the quartz tube gives electrical protection at this point.

As regards the insulation, the use of sulphur is difficult on so small a scale, but if the interior is kept dry, clean quartz serves the purpose very well (with phosphorus pentoxide in the case, which it should be said was shown in this way to be by no means impervious to moist air, charge was lost at the rate of about 1 per cent. per minute).[1] Two of the sectors are therefore mounted by means of sealing wax on small quartz rods Q' set on one of the scissors arms, and are connected to the terminal by a fine wire which is previously soldered to them and enters the case through a narrow quartz tube. The other two are soldered to short lengths of wire, and not insulated. Quite the most troublesome part of the whole construction was the setting of the four sectors accurately in one plane parallel to the base, and at the right distances apart.

The micrometer screw may operate by a cone and jaws arrangement but in the present case the end of the screw is squared off and works between glass plates G set at an angle on the arms carrying the sectors.

The needle can be made from a single thickness of thin paper rubbed with graphite on both sides, but the use of the drying agent is then liable to alter its shape; so recourse is had to aluminium. It is made very light by using very thin foil and then by thinning the two ends by dipping in hydrochloric acid until they begin to show signs of disintegration. In this way the weight has been reduced to 3 mgm. The weight of the mirror (10 mgm.) is less important on account of its smaller moment of inertia, while that of the platinum stem (17 mgm.) is of course relatively unimportant. As the needle was fixed to its stem by a little sealing wax, it was found essential to secure electrical contact here by a drop of starch paste (covered with paraffin wax to protect it from the drying agent). To obviate any angular play at the hook connections in the suspension, the usual device of making one of each pair of hooks out of the *flattened* end of a fine wire was adopted.

The present instrument requires a quartz fiber .006 mm. thick and 6 cm. long: this could be made thinner and only 1 cm. long or even less with advantage, for the disturbing effect of vibrations would then be lessened. The mirror is 4 mm. by 3.5 mm., and was cut from a thin galvanometer mirror.

The Shape of the Sectors and Needle.

It will be evident from an inspection of Fig. 1 that the smaller the angle subtended by the sectors, the less will be the sensitivity. At the same time the large gaps at the sides should not be too much encroached upon, or the needle will hardly be stable in its central position even when

[1] Most of this must be due to the projecting part of the terminal, which is not kept dry.

the small gaps are made as small as possible. It is found that sectors subtending 70° each give good results.

The shape of the needle is a matter of the greatest importance. The effect of its width and curvature, and of its distance from the sectors, upon what might be called the "angular capacity gradient" of the system for different widths of the sector gap is somewhat complex, and required a good deal of study for its elucidation. It was found that the needle can in general be stable either in the symmetrical position, or in an unsymmetrical position well to one side, and in either case the sensitivity can be adequately controlled by altering the width of the sector gap. But in the case of the unsymmetrical position the suspension must have a permanent twist, and this gives a troublesome "drift" of the needle due to its slow loss of charge; so that attempts to use this were abandoned.

In Fig. 3 are shown curves for the behavior of the needle in its sym-

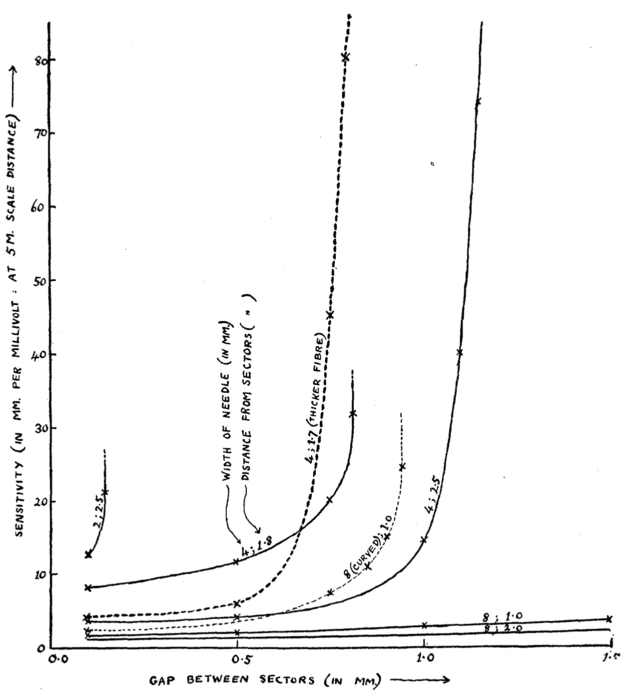

Fig. 3.

metrical stable position (the quartz fiber used being .004 mm. thick): the first number written over each curve gives the width of the needle in millimeters, and the second its distance from the sectors. It may be seen that the sensitivity increases as the needle becomes narrower and as it is brought closer to the sectors. The best needle is obviously flat and about 4 mm. wide: the ratio of the width to length is thus about 1 : 4, and this would no doubt be best for an instrument of any size. It is not so easy to decide upon the best distance from the sectors. With any given suspension, the sensitivity increases as the needle comes closer, and also the period of swing is diminished, but instability arrives more suddenly as the sector gap widens. As, however, the use of a thicker fiber conduces to stability, the best result is obtained by using a relatively thick fiber (.006 mm.) and lessening the distance from the sectors. This plan, which combines the shorter period of swing got at the smaller distance with the flexibility got at the greater, gives the curve shown by the thick dotted line in the figure. (The thin dotted line is for a needle somewhat convex on its lower side.)

The Use of the Instrument.

The torsion head is turned until the needle seems to hang symmetrically, and the latter is then charged. Now the telescope is placed at some convenient position near the window so that the scale can be seen, and the instrument roughly calibrated at this adjustment by a potentiometer. It will usually be found that the region of greatest sensitivity is not exactly at the point of zero potential, so the torsion head is turned until this state is secured, and the telescope moved again if necessary. On increasing the sensitivity by widening the sector gap, the region of greatest sensitivity remains nearly still, and any slight deviation may be corrected by repeating the above process.

Even with the symmetrical adjustment of the system there was often a slight "drift" of the needle, but the use of phosphorus pentoxide inside the case made this practically to disappear. The nature of the remaining drift and of other disturbances that occur will be seen from the following typical results. Runs over the whole scale are given at sensitivities of about 7 and about 40 mm. per millivolt, and also deflections obtained for separate 10^{-2}, 10^{-3} and 10^{-4} volt units.

It will be seen that, whereas the instrument could detect 10^{-6} volt (at a 150 *mm/mv* sensitivity) if it were steady enough, it cannot in practice detect less than about 3×10^{-5} volt, and, with the very efficient optical system used, it does this as well at a sensitivity as low as 7 *mm/mv* as at a higher. If the scale were only 1.5 meters distant, however, it would be best to use a sensitivity corresponding to about 30 *mm/mv* at the 5 meters' distance.

The cause of the unsteadiness is found to lie in an incomplete electrical shielding of the instrument; for, if the sectors are all connected to the case which is then insulated, and the whole is charged to 80 volts, a deflection corresponding to one or two millivolts is obtained. Thus

P. D. in Volts.	Scale Reading in mm.	mm./mv.
.00	573.0	
.05	886.0	
.04	831.0	5.70
.03	772.5	5.85
.02	710.5	6.20
.01	645.0	6.55
.00	575.5	6.95
−.01	505.0	7.05
−.02	439.0	6.80
−.03	378.0	6.10
−.04	320.5	5.75
−.05	266.0	5.45
.00	574.5	

Needle comes to rest in 30 sec.

Detecting 10^{-2} volt.

.00	.01	Δ
577.5	642.0	64.5
578.0	642.6	64.0
577.5	642.0	64.5
578.5	642.0	63.5
579.0	642.5	63.5

Detecting 10^{-3} volt.

.000	.001	Δ
579.5	586.0	6.5
580.0	586.5	6.5
580.0	587.0	7.0
580.0	586.5	6.5

Detecting 10^{-4} volt.

.0010	.0011	Δ
588.2	588.8	between
588.1	588.8	the
588.5	589.3	averages
588.9		+.6

.0010	.0009	Δ
588.9	588.0	between
588.7	588.2	the
588.8	588.3	averages
588.7		−.6
588.8	588.2	

P. D. in Volts.	Scale Reading in mm.	mm./mv.
.000	535	
.010	196	
.008	254	27
.006	319	32
.004	385	34
.002	455	35
.000	538	41
−.002	631	46
−.004	713	41
−.006	785	37
−.008	849	32
−.010	908	29
.000	558*	

Needle comes to rest in 90 sec.

Detecting 10^{-2} volt. (90 sec.)

.00	.01	Δ
558	900	342
558	891	333
556	897	341
565*	895	330
564	894	330
581*	910	331

Detecting 10^{-3} volt. (60 sec.)

.000	.001	Δ
592	630	38
594	632	38
590	625	35
588	623	35
596*	628	32
588	626	38

Detecting 10^{-4} volt. (40 sec.)

.0010	.0011	Δ
633	636	
632	636	between
633	638	averages
638*	639	
636.5	638.5	2.75

fluctuations of only a few volts in the "earth" charge would amply account for the disturbances observed: these fluctuations are inevitable in the neighborhood of electric lighting circuits. The defective shielding is probably due to the presence of the window, since a very good shielding of every other part of the instrument does not remove it. This difficulty will be investigated further.

The instrument becomes dead-beat when the sensitivity is raised to 15 mm. per millivolt. Its period at the higher sensitivities is not nearly as great as the time given for a reading in the table (*e. g.*, 90 sec., 60 sec., etc.), for fully two-thirds of this time is occupied by the final slow "creep" of the quartz suspension. For less accurate work good readings could be got in 20–30 sec., especially since chance disturbances would then be relatively less frequent. Also at the lower sensitivities, the first swing takes only 5 of the 30 sec. required for the needle to come to rest.

The Use of a Floating Needle.

Since the torsion of the suspension is not an essential factor in its operation and stability is secured electrically, it is possible to use a floating needle. This would have the advantages of making the instrument dead-beat at all times and of eliminating the final "creep" which occupies about two-thirds of the time taken for a deflection at the higher sensitivities; but the viscous resistance of the liquid makes the instrument slow in action for needles less than 5 cm. long,[1] and also the advantage of control by the quartz fiber is lost. For the last it would be necessary to substitute an up and down adjustment of one of the sectors or something equivalent. A roughly made trial instrument with no sort of adjusting mechanism, and in which the needle takes up an unsymmetrical and very insensitive position, gives steady deflections at a sensitivity of 1 mm. per millivolt. The needle is in electrical contact with the float tank, which is insulated and kept at 80 volts, and the sectors are above instead of below the needle. The float is made of a small piece of quill tubing, and is kept vertical by a weight about 5 cm. below it. The needle is kept in its central position by the attraction of a cylindrical magnet for a little piece of iron placed on the top of the floating system.

Summary.

An electrometer has been designed which can be constructed to have a capacity as low as 4 or 5 cm.,[2] and in the present model has a capacity

[1] That is, with the most efficient float yet constructed.

[2] Besides this, the capacity could be halved again by omitting one end of the needle and the pair of sectors below it.

of 9 cm. It is of simple construction and operation. Its sensitivity is great enough for the detection of 10^{-6} volt, but it has not been made steady enough as yet to detect an isolated potential difference less than about 3×10^{-5} volt in practice. It is a modification of the Dolezalek electrometer which can, by means of a mechanical adjustment, be made to work in a condition approaching instability. The way in which the stability of the needle is secured makes it possible to place it on a torsionless suspension or a float, but this plan has certain drawbacks.