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A WATTHOUR METER DEMONSTRATOR

A. D. Moore

Professor of Electrical Engineering

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These are the days when we are asked to dream up teaching aids, and devices to make college and high school students more science-minded. The simple watthour meter demonstrator described here meets both needs. It can be so readily constructed and so satisfactorily operated, that it will appeal to teachers and students alike, at any level.

The watthour meter has no competitor. Energy going to the home, the commercial establishment and the industrial plant, is all measured by this unique and highly developed device. It is the "cash register" of the electric utility business. It deserves more attention than it gets, in the typical electrical engineering curriculum. This writer has long been telling his students that the principles of the watthour meter, together with the implications of its use, permit the claim that it offers a more complete review of the non-electronics part of the electrical engineering curriculum than does any other piece of electrical apparatus.

Electrical engineering instructors wishing to teach some watthour meter theory will find that illustrative problems based on an actual meter are difficult to devise. But the demonstrator can be built, and very realistic problems based on it can be made up.

Any high school or college student can build his own demonstrator. The demonstrator is bristling with physical principles, and it easily lends itself to their demonstration. This paper will be kept on a non-technical level. Thus, instead of scaring the beginner away, it is hoped to coax him into starting a project of his own, in which he can have a lot of fun at learning some rather important things.

The Watthour Meter. The meter's business is to measure energy, or watthours. Its aluminum disk must have a speed proportional to the watts passing through the meter on the way to the load. To achieve this, the meter must meet two requirements: (1) It must have a driving torque proportional to the watts, and (2) it must have a drag or damping torque proportional to the speed.

Requirement (1) is met by the arrangement of coils on the laminated iron core, in a real meter. A "potential" flux is passed through the disk, set up by the potential coil, it being placed across the line. If the meter is to operate correctly at any power factor, this flux must lag behind the line voltage by 90°, and this is arranged for in any meter. There is also a "series" flux passing through the disk, set up by the series coils carrying the load current; it is in phase with the current. Thus the two fluxes are 90° out of phase if the load is purely resistive (load current and voltage being then in phase). A-c eddy currents are set up in the disk surrounding each flux; each set of eddy currents reacts with the other flux, forces are produced, and thus the drive torque is produced.

Requirement (2) is met, in the real meter, by use of damping magnets. Alnico magnets, one or more, are arranged so that their steady flux passes through the disk. If no movement occurs, no force is developed. When the disk rotates, it moves through this damping flux, and those special eddy currents known as Foucault currents, are set up. The emf induced is proportional to speed, and so are the current strengths. The currents interact with the damping flux itself, and thus produce a drag or damping torque, proportional to speed. In the demonstrator, we will at first use a different damping principle.

The Demonstrator Parts. In describing these parts, Figure 1, the first thing to be said is that there is nothing critical about any of the dimensions. The writer built his demonstrator out of whatever happened to be at hand, and using such skills and techniques as were part of his experience. Other builders will do likewise. The design is extremely flexible. We can almost say -- build one of these to your own taste, and it will work.

The 9 x 12 in. plate is plate glass, a little over 0.2 in. thick. Flat window glass could be used. The ring on it is Plastelin®, or plastic modelling compound (used in kindergartens). The ring has a section of 1/4 x 1/4 in., and its internal diameter is 9 in. To make it, some Plastelin was rolled out, and strips were cut from it. These strips were bent around on the plate, joined end to end, and stuck to the plate.

The aluminum disk now resting on the plate, is 8 in. in diameter and 0.05 in. thick. Arts and crafts stores carry such disks, for etching, or to be hammered into trays. If the disk as bought is not quite flat, it can be well flattened by bending it by hand.

Behind the plate are four cylinders of heavy wrapping paper, taped, and stiffened with varnish or Krylon® spray. They are about 4 in. high. Wood or plaster posts would serve equally well.

The two drive coils shown are two-layer coils wound by hand around polyethylene bottles. In use, the bottles are inverted, resting on a plaster foot. The screw cap of a bottle was cast into the foot. Thus, a bottle could be unscrewed and filled with iron particles to increase the flux.

These coils were soon replaced by better coils, now to be described. Each coil was wound by hand, two layers of No. 17 cotton-covered enamel magnet wire, on pieces cut from a heavy mailing tube.

The tube length is about 4 in. A coil, slightly shorter, has 62 turns per layer, and a mean diameter of 1.84 in. The coils were heavily soaked with Glyptal, an electrical insulating varnish. These coils will take 4 amperes indefinitely, and 10 amperes or more, for short periods. Data given later on were taken with these better coils.

It is a simple matter to put bottoms in these coils. Just "borrow" a little dental stone plaster from your dentist. Mix it with water, set the coil on a glass plate, and drop enough plaster down inside so that when jiggled down, the plaster is about 1/8 in. thick. After it sets, wet it to slip it from the plate.

For a centering bearing, the little plaster mound seen at the disk center was formed on the glass plate, with a bearing hole molded into it by use of a nail or something. Make the hole deep enough to keep the bearing pin from ever touching the bottom of the hole. When the plaster sets, wet it to get it loose. After drying, the mound is stuck to the disk center with double-face adhesive material.

At the left of the plate is a brass piece, 1 x 12 in. x 1/16in. thick. A paper clip was opened up and cut so that it rested on the middle of the piece, with one end sticking straight up. Plaster poured over the resting part of the clip, and out over the edges of the piece, securely fixed the bearing pin to the piece. When the piece is inverted, the clip wire becomes a pin, to stick down into the plaster mound's hole. Also shown are two posts, 1 in. high. The brass piece and the posts could be replaced by wood or plaster. This was a bearing made by a man in a hurry. Anyone can think up better bearings.

In front of the plate is a small level, used to level up the plate.

Damping and Supporting the Disk with Water. For years, the writer dreamed of making such a demonstrator, but got nowhere with it because of the bearing problem. A large, heavy disk was desired, to be seen well at a distance. But a heavy disk would call for a rugged bearing with too much friction, or a delicate bearing too easily damaged. Finally, in 1957, he conceived the idea of using surface tension, to float the disk. At one stroke, the bearing problem was eliminated, and damping was obtained by fluid friction. The bearing described above is merely a centering bearing. It is one of the world's worst bearings, but the side forces on it are extremely small.

Fluid friction or "viscous damping" for instruments is, of course, an old idea. And here, we could of course use an aluminum piepan, floating in the ordinary way, and make a demonstrator without using surface tension. But floating the disk with the help of surface tension makes the demonstrator that much more interesting.

The Demonstrator Assembled. Ready for action, the demonstrator is shown in Figure 2. First, 4 oz. of water were poured within the ring, the plate having already been levelled. The disk edge and nearby surfaces have been lightly greased with silicone stopcock grease to make it water-repellant. Before greasing, any roughness of the edge should be smoothed off -- otherwise the disk might sometimes refuse to float. The disk has been placed on the water with one side lowered first, then the opposite side gently lowered. This is to avoid trapping air bubbles underneath. At low speeds, bubbles will stop the disk.

Disk Supporting Forces. This disk weighs 111 gr. or almost 1/4 lb. It depresses the water, causing the water to bulge up all around it.

The surface of the meniscus around the disk curves in and down, being almost vertical where it touches the rim. At first thought it seems that surface tension is doing a miraculous job, to hold up this heavy disk. However, computation shows that surface tension accounts for only about 4% of the lifting force. Hydrostatic pressure accounts for the remainder. The main function of surface tension is to hold the raised water, keep it from encroaching on the disk surface, and enable the water to pile up enough head to exert nearly all of the lift force.

When one sees the floating disk merrily spinning on the water, the effect is indeed striking.

Power Supply. The leads to coil terminals are seen at the left rear, Figure 2. If the coils get a few amperes, with the currents out of phase by a considerable angle, there will be action. To simulate watthour meter performance when its metered load is resistive, we should have coil currents 90^{o} out of phase. This demonstrator is powered from the normal supply: 115 volt, 60-cycle. A variable resistor is in series with one coil. A 100 mf. condenser, varied in steps, is in series with the other. The voltage drop over the coils is very low. Therefore, the currents that flow are very close to being 90^{o} out of phase.

Coil current needs can be changed at will, by going to a different wire size. For example, if No. 23 wire is used instead of No. 17, wire section is 1/4 as much; the coil is given 4 times as many turns; and, at 1/4 the previous current, a coil will produce the same flux, and have the same heating as before. Thus, coil modification can be made at will, to suit the demonstrator to such Variacs® or rheostats, and condensers or inductors, as happen to be available.

Operation. Let the drive coils be placed together as in Figure 2, at a position about 1/3 of the way from disk edge to the center. With about 4 amperes in each coil, a water film thickness of about 0.05 in. under the disk, and with the top turns of the coils about 1/4 in. below the bottom of the plate, the speed is about 3.7 rpm.

Sensitivity. With fluid support, the disk is extremely sensitive to small driving forces. It is illuminating to note that when driven as just above, the power used to turn the disk is of the order of one thousandth of a horsepower. And if the currents are reduced to give a speed of one per cent of the above speed, it takes about one-tenth of one-millionth of a horsepower to drive the disk.

Accuracy. Let one coil's current be fixed, while the other current is changed from low values, to 8 or 10 amperes. A straight-line calibration curve will result: speed is proportional to the varying current. This corresponds, in the watthour meter, to holding line volts constant (therefore, potential flux constant) while varying the load current.

Fluid Damping. The fluid damping or drag torque, is largely due to shear forces in the water film between disk and plate. There is some additional shear force contributed by water in shear outside of the rim of the disk, but this is the smaller part of it. Therefore, if the film is made uniform, and is accurately measured in some manner; if water temperature is taken, in order to look up the viscosity, and if an integration is performed to find the damping torque due to fluid friction, the the drive torque, which is equal to it, can be closely found.

Water can be added or withdrawn with a syringe, during operation. With the film thickness under shear thus changed, corresponding changes in disk speeds are nicely demonstrated.

Viscosimeter. The demonstrator, among other things, is inherently a viscosimeter. For example, when the water was replaced by diluted corn syrup (100 parts of syrup to 60 parts of water) the speed, for the same currents, was 1/30 as much. Thus, the syrup mixture had 30 times the viscosity of water.

Very Low Speeds. At low currents, the demonstrator will operate at speeds of one revolution per hour or less, where movement is barely perceptible.

Coil Positions. Coil position radii, and intercoil spacings, will greatly affect the drive torque.

With the coils together and at equal radii, let them be moved inward from outside of the disk, to where they finally straddle the center. A torque curve will result (as indicated by disk speed) which will have a maximum. Watthour meters are of course designed to take advantage of this fact, with the fluxes positioned to give maximum torque.

If the two coils are placed, say, as in Figure 2, and one is moved away from the other while keeping its radial position unchanged, the torque rapidly falls off.

Another demonstration: starting as in Figure 2, push the pair of coils across to the diametrically opposite position: the disk reverses.

Still another: starting as before, take one coil out, invert it, and hold it above the disk over its previous position: the disk reverses.

Using Iron for Higher Speeds. Anyone playing with a demonstrator will surely want to speed it up. It can be done. Filling the coils with hard cast iron shot increased the speed about 3.5 times. This shot was roughly spherical, and roughly 0.02 in. in diameter. Such shot is made for use with an air blast, to clean castings, and for shotpeening.

Malleabilized cast iron shot, having higher permeability, raised the speed about 6 times.

Disk Thickness. If a disk of half the thickness were obtainable, and operated with the same water film thickness, it would, with the same coil currents, turn half as fast. The resistances of all eddy current paths would have doubled; eddy strengths would be halved; and thus, driving torques would be halved.

The general effect of such a change can readily be shown by replacing the disk with one of the very thin aluminum pieplates, of the kind in which pies now come to the home. Its movement, relatively, will be very slow. No center bearing will be needed for this brief demonstration. (Note: if fluid damping were completely replaced by magnetic damping yet to be described, the above argument about thickness effect on speed, does not hold: the speed would remain independent of disk thickness!)

Magnetic Damping: Foucault Currents. Our millions of watthour meters all have their damping or drag torque produced by movement of the disk through the fixed flux of a permanent magnet (one or more). All of the millions of speedometers in cars and trucks operate on the effect of Foucault currents causing magnetic drag. Unfortunately, nearly all of our electrical engineering textbooks ignore these facts. The indexes of only a few books will include the name Foucault. Thus, our teachers and writers may welcome a chance to become familiar with the principles involved, by working with a demonstrator. If they do, these phenomena may be less widely ignored hereafter.

The Speedometer. The speedometer principle is easily demonstrated. Remove the coils. Make one-way passes close to and across the disk at one side, with a magnet. Sweep the magnet across, lift it on the return, sweep it across again, and repeat. The disk will begin to follow.

If a vertical bar magnet is placed under the plate and moved by hand, to rotate around the center, the disk will follow at its own lesser speed, the speed ratio being constant for a given set of conditions.

In the actual speedometer, an aluminum cup tries to follow the magnet which is turned by the car movement, but is restrained by a spring. The deflection is inherently a measure of the fact that the drag torque is proportional to the speed. Of course, it is actually calibrated in terms of miles per hour.

Using a Magnet to Get Zero Setting. In some experiments, it will be needed to bring the stationary disk's marker precisely to the scale zero. It can be waved there, with a magnet. Simply make slight passes at the disk with a magnet, one way or the other, and the disk is quietly moved by slight amounts without touching it.

Magnetic Damping for the Demonstrator. Suppose we take an Alnico magnet of the U-type, with a bulk of a cubic inch or more, andhold it so that its pole faces nearly touch the top of the rotating disk. If the magnet is strong enough, damping by the magnet will greatly reduce the disk speed: nearly all ofthe damping is then magnetic, and little of it is fluid damping.

Figure 3 shows such a magnet, rigged by clamping it to one side of a wooden bar, the weight of the magnet being counterbalanced by the lump of modelling clay stuck onto the far end of the clamp.

Moving the magnet radially will vary the speed. Thus, an experiment can be run to find magnet position to give maximum damping torque.

Damping due to Driving Flux. The drive fluxes are alternating, and each flux sets up alternating eddy currents around itself, in a pattern of eccentric circles. These drive the disk by virtue of each set of currents interacting with the other flux. These currents do not damp the disk.

But let us go further. To bring out the next point, we recall that with no drive coils in use, a bar magnet whirled around under the disk will make it rotate; and equally, if we fix the magnet, it will cause magnetic drag or damping when the disk is driven by the coils. Now, think of replacing the bar magnet with a coil carrying d-c current, and having constant flux; such a coil alone would turn the disk, if carried around the center as we carried the bar magnet. And, if fixed, its steady flux would damp the disk when the disk is turned.

From all this, we get an idea. Maybe, if we remove everything but one of the a-c drive coils, and carry it around the center continuously, it will set up a-c Foucault currents and start the disk turning. Well, it will. A trial readily shows a small effect. Therefore, we must admit that when the demonstrator is in normal operation, with fluid damping, the a-c fluxes do contribute a little bit of damping, too. Our a-c fluxes in the demonstrator are very weak, and their damping effect is very small. But in the watthour meter, the series flux gets to be large enough at heavy loads, to introduce serious error. In recent years, this "overload droop" error has been almost entirely overcome by a very simple but ingenious means: using magnetic saturation in a certain way, to compensate for the error.

Scale. A scale for observing disk movements is easily applied. An 8-in. circle is drawn on paper, with the circumference divided into 100 units. The graduations are marked outward. This is taped to the under side of the plate, so that one can look down through the water surrounding the disk and see the marks. A bit of paper dropped on the disk near the edge serves as a disk marker. These items are seen in Figure 3.

Exponential Change of Speed. Heretofore, we have considered only constant-speed conditions. Next, we recognize that when power is suddenly applied, the disk cannot start from rest and instantly achieve final speed; and if running when the power is cut off, it cannot instantly stop. We have here in rotational form, the same kind of a case that obtains when a mass is started up with a constant force, but is retarded by a force proportional to the speed (acceleration); or when a mass in motion has the drive force removed, and it is still retarded by force proportional to velocity (deceleration).

It can be shown that under ideal conditions, the speed changes exponentially. In acceleration, if the first time interval T permits the speed to achieve P per cent of final speed, then in the next equal interval T, the speed will gain change P per cent of the speed change remaining to be made, and so on. Deceleration takes place likewise.

Acceleration. Acceleration can be nicely studied when using fluid damping only, to get the greatest action. Starting at rest, we turn on the currents, and time the first revolution, the second, and so on; or, equal parts of a revolution can be timed. If things happen too fast to catch the times all in one run, just time the first revolution on the first try. Start over again, take the time for two revolutions; and so on.

Deceleration or Coasting. This is studied by running at constant speed, suddenly cutting off the currents, and observing disk positions as the disk coasts to a standstill.

An interesting study is developed by first letting the disk coast to rest without timing it, to find the total units through which it will turn for the particular speed used. Suppose it is 100 units. Now put temporary markers on the scale, at 50, 75, 87.5, etc. units from zero. This divides the coasting units into the first half, half of the remaining half, etc. Then start up, achieve full speed, and cut off power as the disk marker passes zero. The intervals as laid out should display equal time intervals. They should, that is, provided our fluid damping behaves perfectly, and gives a retarding torque proportional to speed while speed is changing.

However, perfection is not to be expected here, for inertia of water moving with the disk adds its effect to disk inertia. The water outside of the disk, in particular, will lag in getting into motion; and again, it will have a lag causing overshooting, when deceleration occurs. Therefore, the time intervals mentioned may not check out perfectly.

Short-time Loads: Fluid Damping. Suppose coil currents are adjusted to give one revolution in 10 seconds. Then here is an experiment to try: start from rest, put the currents on for 10 seconds, cut the currents off, and let the disk coast to rest. The disk is accelerating for the on-current time, then coasting afterward. Would we expect the disk to have turned through precisely one revolution? We would want a watthour meter to do just that, for one revolution properly represents the energy that would flow.

However, as brought out above, the outer water lag in fluid damping brings in an imperfection. In one such experiment, the short-time movement was about 20% higher than would have been expected.

Does the Watthour Meter Play Fair with the Customer? Above, the demonstrator over-registered, which means the customer would have been overcharged. Also, anyone can look at his watthour meter, suddenly remove all load, and see that the disk does not instantly stop. One easily gets the idea that on short-time loads, the customer will be charged too much. Nothing of the sort happens.

The meter is equipped with magnetic damping, which faithfully gives a damping torque proportional to speed under any conditions. It can be proved that with this "perfect" damping,the failure of the disk to come up to speed is exactly made up for by coasting when the load is cut off. There is no meter error on loads of reasonable shortness.

The demonstrator will likewise perform correctly, if nearly all damping is magnetic.

Canned Motor Demonstration. The canned-rotor motor, so-called, has the stator and rotor separated not only by the air gap, but also by a thin metal sleeve placed in the gap. Thus, the rotor can be sealed within a fluid pumping or circulating system, as when radioactive fluids must be handled without having seals that may leak.

With the demonstrator running, one can slip a thin aluminum sheet under the plate and over the coil tops. Only a slight reduction in speed will be noted. If the sheet were quite thick, eddy currents induced in it would block more of the flux; but a thin sheet, preferably of high-resistance material, has little effect.

The Demonstrator as a Shaded-pole Motor. With the two drive coils in use, the demonstrator is really an eddy current motor. An even simpler a-c motor which gets along on one drive coil only, is the "shade-pole" motor. Such motors are extremely simple, rugged, and inexpensive. They are widely used. Any number of little gadgets are run by these motors.

Let the demonstrator run normally, then remove a coil. The disk stops. But pick up a piece of copper or aluminum or brass plate, maybe 1/8 in. thick, and perhaps a couple of inches each way (or a heavy metal ring, shown at the right in Fig. 1, can be used). Hold it near the disk, and more or less over the coil, but to one side of it. The disk will turn. Shift to the other side of the coil, and the disk will reverse. You now have a shaded-pole motor. What happens is, that some of the coil's flux goes through the plate or ring, and induces voltage in it. A-c currents flow around the plate, these lagging somewhat behind the induced voltage. The currents set up a flux which is out of phase with the coil's flux. If the ring is held somewhat to one side, then its flux becomes the second of two drive fluxes, and a torque is produced.

Warning: if an overhead brass piece is used to hold the center bearing pin, it may innocently act as a shading member, if the coil gets too close to it. This piece had better be non-metallic.

Using a Coil as the Shading Member. With the two coils placed at the front (near the operator) let the lefthand coil carry a-c current, while the righthand coil is shortcircuited. The disk will rotate clockwise. Remove the "short", leaving the righthand coil open, and the disk stops, provided the coils are empty. But if they are filled with iron shot, the disk will very slowly rotate the other way.

The writer freely admits that when his demonstrator played this foul trick on him, he was sorely puzzled. No light dawned until he stopped thinking about eddy currents in the shot, and began thinking about hysteresis effects.

Circulation of Mercury. If the disk and water are removed, a pound of mercury can be poured into the plate inside the ring. It will form a pool of perhaps 8 sq. in. in area. Now let the two drive coils (filled with iron shot to get full effect) be placed together, and somewhere under the mercury. Very soon, a fairly rapid circulation pattern will be set up in the mercury.

This phenomenon bears on the principles of the electromagnetic pumps now used to move liquid metals in nuclear power reactors.

Warning: mercury is insidious stuff. It is not widely recognized that a serious hazard can develop if it is spilled and allowed to hide under a steam radiator in a small, poorly ventilated room. A physicist known to the writer, working under such conditions, became almost completely paralyzed from breathing the vapor, before the mercury poisoning diagnosis was made. Fortunately, he made a good recovery.

Inverting the Demonstrator Design. The demonstrator described has the advantage of making the disk accessible, and placing it in full view. However, the disk does cover up the coils, and onlookers may not always be sure of coil locations as coils are moved around.

The design can be inverted by placing the plate, with its ring, water pool, and disk, directly on the table. A second glass plate is then rested directly on the ring, and the coils are set on this top plate. Coil positions are always evident.

Disk centering can now be done magnetically. A small piece of iron is fastened to the disk center with double-face adhesive. A small U-shaped Alnico magnet is set on the top plate. The magnet will draw the iron piece to a position under the magnet center, and pretty closely hold it there during operation.

Conclusion. The demonstrator is so versatile, and so adaptable to the direct demonstration of numerous physical principles, that it is a first-class teaching aid. This, it has already proved in the writer's classes.

It is a fascinating thing to operate, and it invariably attracts the attention of all who see it. It is so easily put together that one may hope to have it appear, not only in classrooms and laboratories, but also on display in annual Open Houses.

REFERENCE

1. "Eddy Currents in Disks: Driving and Damping Forces and Torques", A. D. Moore, AIEE Transactions, vol. 66, 1947, pp. 1-11.

Figure 1

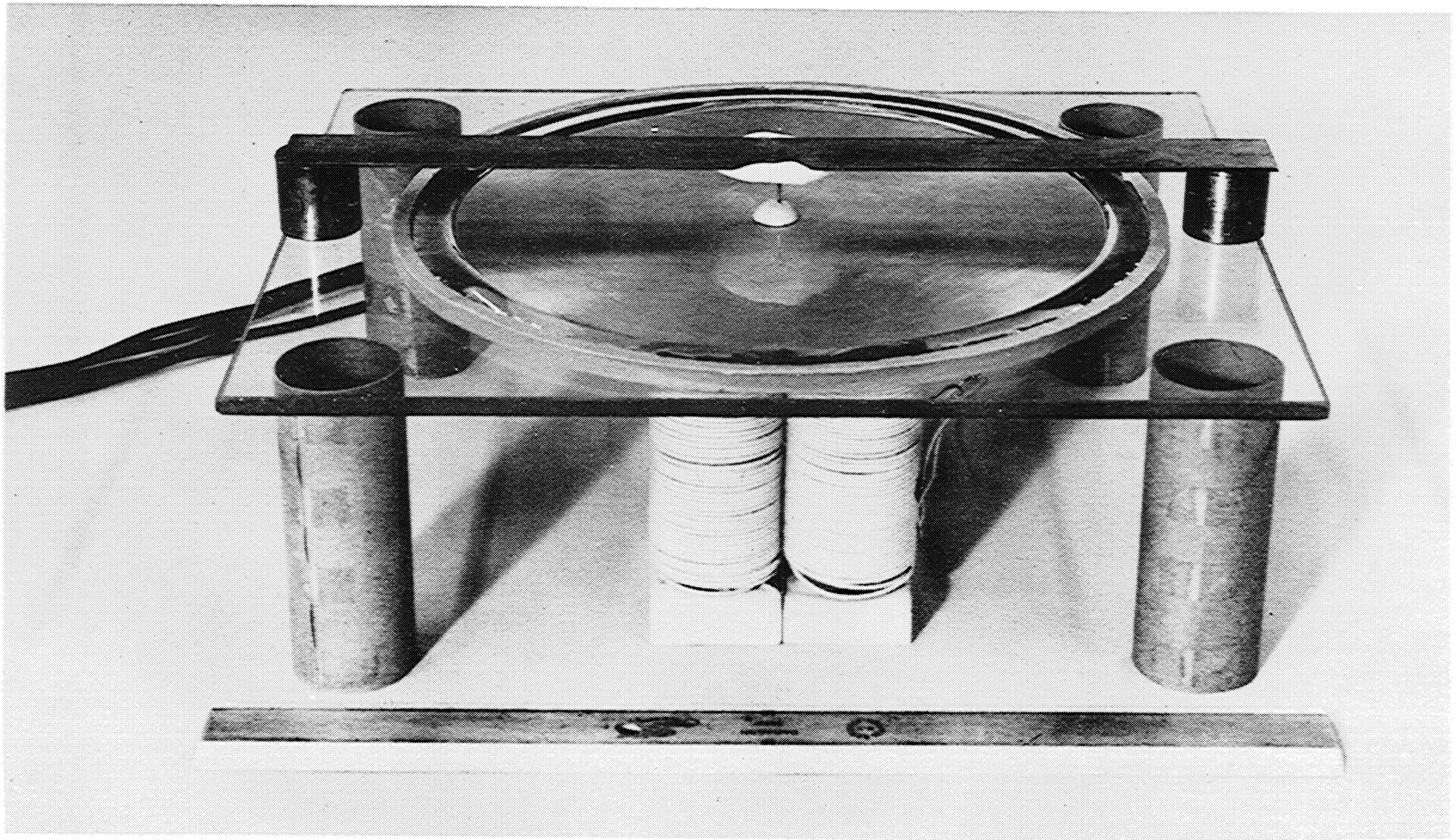

Figure 2

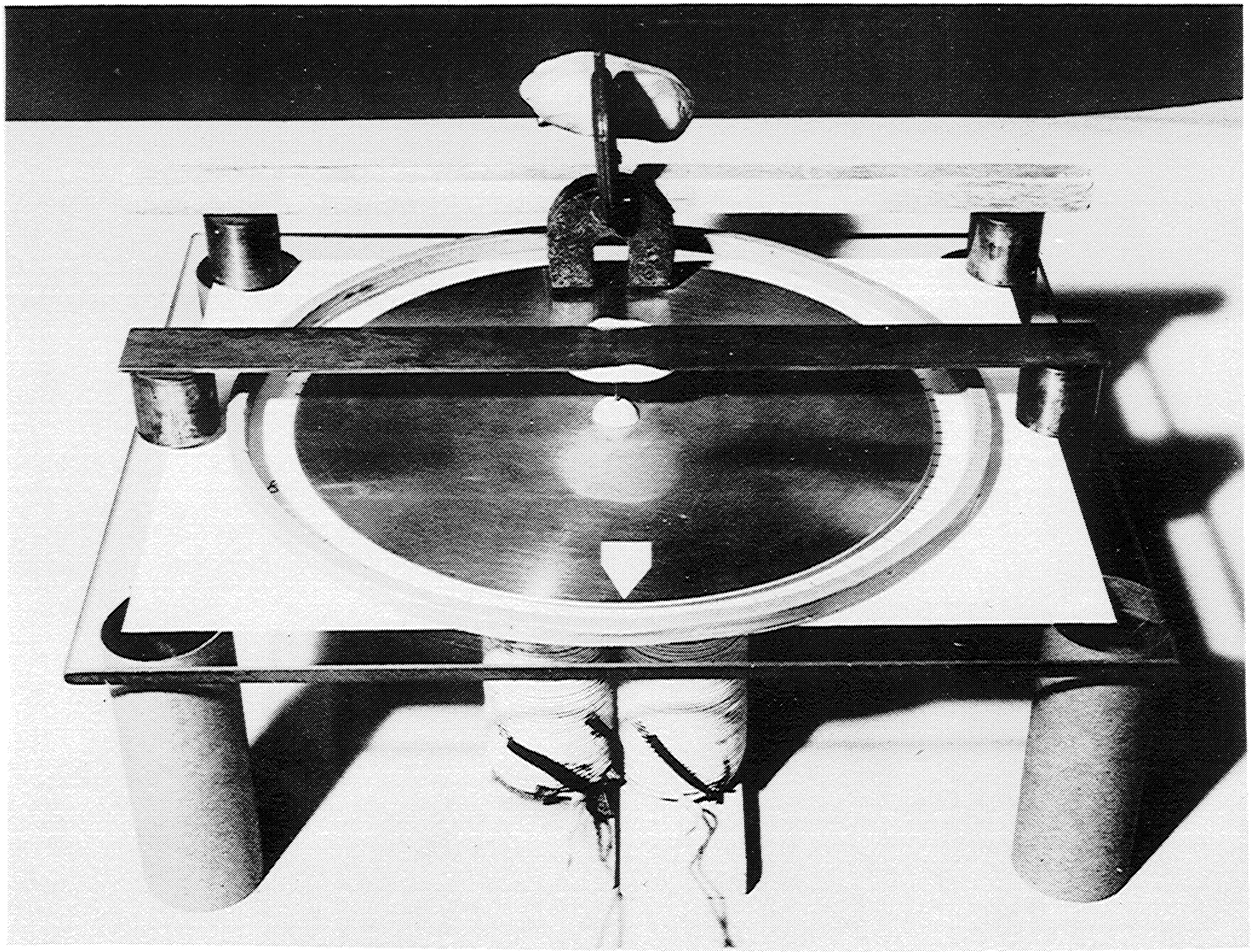

Figure 3