# Sustained Foucault Pendulums

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(Received August 6, 1952)

The time-delay or phase-shift effects crucial to the operation of ordinary doorbells and buzzers can be employed to sustain a Foucault (or other) pendulum in a very simple manner, not involving any electrical contacts. Some new electrical effects as well as the pendulum itself are discussed.

THERE are no forces to rotate the plane of oscillation of a simple pendulum and thus its plane of oscillation will remain fixed even though its support be rotated. The plane of a pendulum on the surface of the earth thus appears to rotate with respect to its surroundings as the earth rotates (rotates the surroundings). It is fairly obvious that, at the poles, the earth will rotate under the pendulum once in 24 hours; at the equator the plane of oscillation will remain fixed; and at intermediate latitudes the process will take times intermediate between 24 hours and an infinite period.

This device not only has historical significance as a direct proof that the earth rotates, but it also makes an excellent demonstration that can be left on display to arouse interest. The only problem is to maintain motion so that the effect can be observed. The first consideration of this problem was given by Foucault himself.[1] It is clear that any drive mechanism must have radial symmetry so that the swing will be equally easy in all directions. There follows the description of a very simple device to accomplish this, as well as a brief discussion of some interesting related schemes.

If one energizes a coil with ac and sets an iron pendulum bob to swinging toward and away from it, changes in current will be observed due to changes in the inductance as the iron moves toward and away from the coil. The current, and attractive force appropriate to that current, will not drop instantly as the bob approaches and will not build up instantly as the iron recedes. (The above variations are, of course, superimposed upon the normal steady increase in force on approaching a magnet.) Thus the iron will "see" a stronger attractive field as it approaches the magnet than it will at the same position in space while leaving. If the circuit looks essentially inductive (has sufficient $Q$) this effect will maintain the pendulum in oscillation. The effect can be made stronger by placing a condenser in series with the coil to resonate it approximately at the line frequency. (With the bob removed the circuit should be slightly inductive.) Thus, by working on the side of a resonance curve one gets larger changes in current for a given change in inductance. This particular effect has been known for some time and has recently received notice twice.[2,3]

It seems appropriate to digress momentarily at this point and mention that ordinary doorbells and buzzers, whose action is almost always misrepresented, could not work if their magnetic fields were not somewhere a double-valued function of armature position. Because of springy contacts and a finite time constant $L/R$, the armature is somewhere accelerated more strongly while moving toward the magnet than it is decelerated while moving away. A buzzer with sufficiently rigid contacts and fast response time could receive no net energy to maintain itself, though its action could be restored by placing a diode backward across the coil; this being equivalent to having a massive springy contact that does not "break" at the same place it "makes." Thus the fundamental action of the pendulum and that of a buzzer are identical in almost all respects.

It is interesting to consider the possibility of this same piece of apparatus being suitable for

[1] *Recueil des Travaux Scientifiques de Léon Foucault* (Publié par Madame Veuve Foucault sa mère, Paris, 1878), pp. 389, 572.

[2] P. F. Bartunek, Am. J. Phys. 19, 57 (1951).

[3] H. P. Knauss and P. R. Zilsel, Am. J. Phys. 19, 318 (1951).

maintaining a nonmagnetic bob (e.g., aluminum or better, copper) in motion. In this case the bob would be repelled (because of induced currents) but, by acting as a shorted turn (transformer action), it would cause an increase in current on approaching. Because of this, and taking into account time lags that are augmented by the shielding of the center of the bob by its outside, the bob would feel a greater repulsive force on leaving than on approaching and this net "kick" in the direction of movement could supply net energy to make up for losses and maintain motion. The forces with nonmagnetic bobs are much smaller, and there is greater magnetic damping, and so it is quite difficult to set up such a demonstration. However, a partial check on this effect can easily be obtained by enhancing it through resonance. For the shorted turns effectively comprising a conducting bob, a coil is substituted. With the help of an external

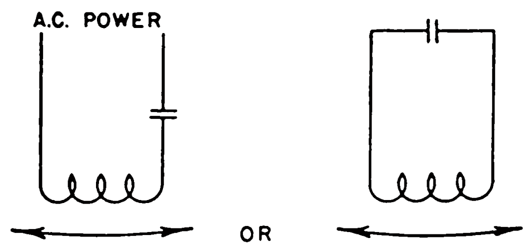


FIG. 1. If the right-hand circuit is tuned to appear inductive (similar to the case of a conducting bob), either coil will maintain the other in motion. If the pendulums are of different lengths, so they do not for long get in step and lose their driving forces, it is interesting to leave both free to swing. In radially symmetrical form this system can be used as a perpetual Foucault pendulum.

condenser the current therein is made larger. The coil might be expected to swing as a pendulum if the circuit is tuned to look inductive, i.e., like a coil. Performance of the experiment (Fig. 1) proved that as long as the right-hand circuit is inductive ($C$ too large for resonance), the force between coils is repulsive and sustained oscillations result. Otherwise an attractive force is produced that will not sustain motion (though, because of changes in $Q$, in all four cases the current in the energized coil drops somewhat on approach while that in the other coil rises).

It might be pointed out that the above results make clear the observation that if the two coils are placed in series directly across the power source, sustained oscillations result. Because of the familiar rule for the total inductance of two adjacent coils, this is true no matter in which sense the two coils are connected, i.e., whether the force is repulsive and the current increases on approach, or both the opposite. As expected,

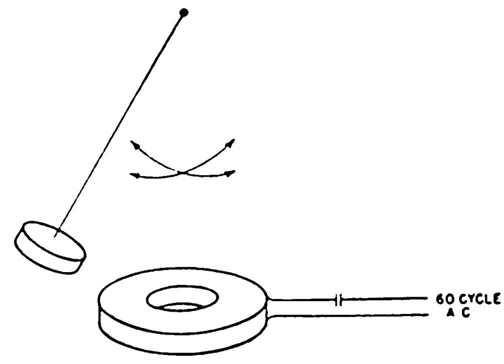


FIG. 2. A coil maintaining an iron bob swinging. The bob can swing equally easily in all directions and thus the arrangement has the symmetry necessary for a Foucault pendulum.

if the circuit includes a condenser, it must be large enough to make the net result inductive if motion is to be maintained in either case.

To maintain any pendulum, one can pull sideways on it at the end of its swing as above, or one can pull downward on it near the bottom of its path. This latter method yields the symmetry necessary to maintain a pendulum that is to swing in all directions. The arrangement is shown in Fig. 2. The pendulum feels a stronger downward and forward force as it approaches the coil than it does on leaving, and the component of this force along the path maintains motion. The response time of such a circuit is essentially the familiar $Q/\pi$ cycles, and we can tell something of desirable geometry by noting that this must be comparable with the time of approach of the bob. The fact is that such an arrangement is not very critical, and hence is rather easy to make work.

The coil first tried by the author (because it happened to be readily available) was wound with number 16 wire and was about eight inches in diameter, two inches thick, and had a two-inch hole. It was found to resonate at 60 cycles with 25 microfarads and, with the application of 10 volts, drove a three-inch iron bob on the first try. Considerably more power was delivered when the magnetic field was altered by laying the coil on a six-inch circle of $\frac{1}{16}$-inch sheet iron.

A larger bob, because of the larger changes in current produced, is more strongly driven without the presence of any fixed pieces of iron. If for some reason one wishes to enhance the effect further, one can insert into the coil a cylindrical

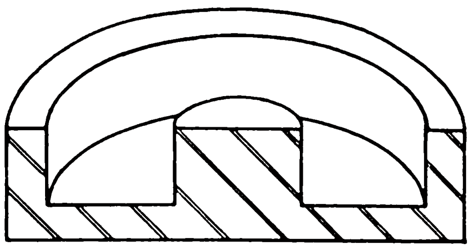

FIG. 3. Section of a core that can be inserted in the coil of Fig. 2 if it is desired to enhance the effect.

powdered-iron core such as is shown in section in Fig. 3.

This drive mechanism is interesting and will pique observers' curiosity, but it can be placed beneath the floor if desired. Sudden changes in the velocity of the bob at the bottom of the path can be obviated by using a heavier bob having more inertia. These changes actually are small because a pendulum loses only a small fraction of its total energy in one cycle (it has a high mechanical $Q$) and so the necessary magnetic forces, even taking into account nonvarying and useless components of the field, can be made much smaller than the gravitational ones. The lower the fields, the smaller the percentage change in downward force at the bottom of the swing, and the more nearly is the result simple harmonic motion.

In this form of the pendulum we see another interesting way of considering the case of a nonferrous bob. The armature of a single-phase induction motor is driven in whichever direction it is originally turning. Similarly a conducting bob should feel small sustaining forces whenever it passes over an energized magnet.

The comparison between a magnetic and a conducting bob might be carried a bit further. The action in the two cases is obviously the same in an ordinary pendulum where the bob is constrained to move in a plane, but now one also has the question of transverse (to the plane of motion) stability during each passage over the magnet. Over a number of cycles any small perturbing force can produce a marked effect on the swing, usually resulting in a slightly elliptical orbit. The "plane of oscillation" of a conical pendulum swinging in an elliptical path will precess in the direction of tracing the ellipse, at a rate roughly proportional to its area. Thus, if care is not taken, a Foucault pendulum can appear to turn at the wrong rate, or even indicate that the earth is turning backward. One might then inquire about the effect of passing through center a little bit to one side of the plane of the major motion. It is tempting to say that the aluminum bob will attempt to go around the "magnetic potential hill" that it "sees"; i.e., it will be deflected to the side if slightly off center, while an iron bob will tend to run through the center of the (varying-height) potential valley that it sees. Thus one might expect that if an aluminum bob is, for any reason, a little off center, on any one trip it will receive a sustained sideward push in the direction of its error, thus increasing it. Actually the exact analysis of the motion in the two cases is an interesting problem in intermediate mechanics. If a fairly heavy bob is used the above has little effect on the crosswise amplitude, and when resonances between the two directions are considered (the period being the same in all), one method seems about as desirable as the other. Interestingly enough, since the motions in the two directions are 90 degrees out of phase and the field changes are controlled by the major one, there is a slight stabilizing tendency to damp out the minor one.

Several of the planetarium museums in this country feature a display of a Foucault pendulum. They are always avidly observed by laymen and scientists alike, and hence are kept in perpetual motion by a relatively involved electronic arrangement that is based on the iron-sheathed ring-magnet shown in Fig. 4. The moving core is attached near the top of the supporting wire and as it swings through the center of its path a phototube or magnetic switch activates the magnet for a short preset interval, thus pulling the core forward in the direction it was going. Besides being a relatively complicated system, it would be subject to criticism on the previous basis except for the unusual radial dependence of its law of force. It can be considered as having a central repulsive force, most of it being exerted near the fixed iron pole piece at the end of the throw where the ellipse and straight line orbits differ little; there being no force at the center.

The matter of perturbing effects warrants further discussion since a small one can cause difficulty when its effect is added cycle after cycle. A comparison of the two methods of magnetic drive might seem to indicate that driving a pendulum at its top would result in minimum sensitivity to asymmetries, but this is not strictly true. A pendulum is less sensitive to asymmetries at its top but similarly it requires a greater driving force there; so it is the percentage asymmetry that is of interest. An air-core coil is especially easy to construct, align, and if necessary, trim up with small metal tabs. It must be said that this simplified drive method does suffer somewhat by comparison in one respect, in that the whole field is not turned on and off to provide useful drive. Specifically, the steady useless component steadily adds in its asymmetry. To this extent the magnet must be made more perfect than in a system in which the field changes the required amount by going fully off. Of course, if one is willing to use a switching arrangement, one can devise systems that use no external field, e.g., magnetically raising and lowering a small mass inside the bob, or periodically raising and lowering the support a short distance, in synchronism with the swing.

Finally it must be stated that the task of setting up a Foucault pendulum is a tedious one. One must achieve absolute symmetry if it is to turn at the correct rate rather than seeking out a preferred direction. Besides the drive mechanism, special care must also be given the clamping of the wire whose bending constitutes the pivot. Absolute perfection can be marred even by the crystal structure of the supporting steel wire. For a demonstration such precision is unnecessary, though certain plastics might provide a simple isotropic support. With reasonable care in alignment the angular velocity should fall within 15 percent of the proper value.

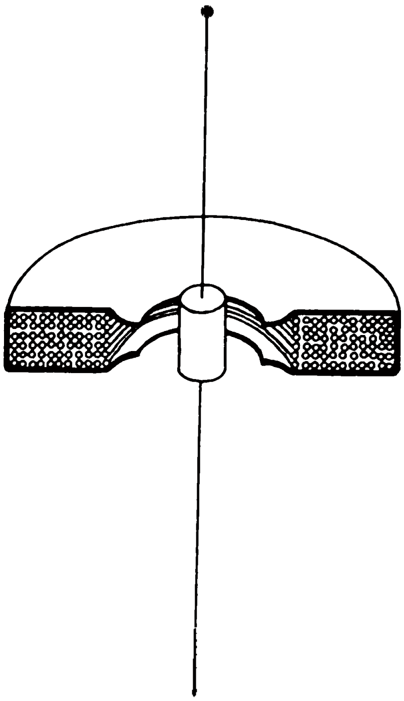

FIG. 4. Iron clad ring-magnet used to maintain a Foucault pendulum. It is electronically energized for a brief (fixed) interval each time the core passes the center.

It is felt that the above will serve as a very simple, uncomplicated and hence reliable, demonstration where achieving the precise rate of turn is quite unnecessary. It is simple enough so that it pays to have an extra smaller pendulum, set up with a rotatable support, to show the principle. Thanks are to be expressed to Mr. Bart Parker for his great help in setting up the displays.

*In one sense, perhaps the technical sense, the life of an adventurer is the practice of the art of the impossible, reserving the word hero . . . to his rationalized, moralized myth. By simple conclusion, then, heroics is in the last resort the practice of the impossible. The capture of the impregnable, the ascent of the unscalable, the logic of the illogical; wild sounding phrases, exactly, for that is just what adventure is.*—WILLIAM BOLITHO.