A Clock-Controlled Tuning Fork as a Source of Constant Frequency

By J. G. FERGUSON

NOTE: The art of electrical communication employs such a wide variety of methods for the transmission of intelligence that it utilizes alternating currents whose frequencies cover the entire range between a few cycles per second and several million. With the increasing use of these methods, it becomes more and more imperative that determinations of the frequency of any alternating current may be made with extreme accuracy. In particular, recent developments in carrier current telephony and telegraphy over wires have placed exceedingly rigorous limits on the frequency adjustment of certain types of apparatus. It is many times necessary to hold such equipment as oscillators or filters to within 0.1 per cent. of given frequency values under commercial operating conditions. This means that calibrating devices used in the manufacture and maintenance of such circuits must be reliable to 0.01 per cent. and that the primary standard should be good to about 0.001 per cent. or one part in 100,000.

The present paper discusses one of the methods recently developed in the Bell System Laboratory for obtaining a source of practically constant frequency with which other frequencies may be compared. It consists of a clock-controlled tuning fork making 50 vibrations per second and, as is shown, the maximum deviation of its frequency from the mean is less than one part in 50,000.

A study has also been made of means for improving the constancy of the control clock and a new type of clock mechanism consisting of an electrically actuated pendulum, the impulse of which is controlled by a photo-electric cell, is suggested.—EDITOR.

INTRODUCTION

THE art of clock making is of such long standing that there have been few improvements of note in the last fifty years tending to increase accuracy. The average rate of oscillation of a good clock when taken over a sufficiently long period of time as, for instance, a day, can be held constant to about one part in 1,000,000. This accuracy is sufficiently high for all ordinary requirements in the measurement of time, including the field of electrical communication.

However, in electric measurements, the problems which present themselves ordinarily require the accurate measurement of intervals very much shorter than a second which is usually the smallest interval registered by the average clock. In solving these problems, we are therefore forced to the alternative either of designing a clock to have a period very much shorter than those of existing clocks or of using some form of short period oscillator whose uniformity can be controlled by the second impulses from a clock.

The first method has been admirably worked out as described by other members of the staff of this laboratory.[1] In this system a

[1] Paper by J. W. Horton, N. H. Ricker and W. A. Marrison, presented at the annual convention of the American Institute of Electric Engineers, June, 1923.

hundred cycle fork is kept in constant oscillation by a regenerative method, the conditions being so controlled that the mean period of the fork compares favorably with that of a good clock.

The attraction of the second method lies in the possibility of obtaining a sufficiently constant standard of frequency with nothing more than a good clock and standard auxiliary apparatus easily capable of application to any oscillating system. Such an outfit could be made available in cases in which the expense incident to the installation and maintenance of more elaborate equipment would not be justified.

Requirements of a Clock-Controlled Frequency Standard

It is a comparatively simple matter to control or operate a fork, or other oscillating system, by means of periodic impulses from a clock, so that the total number of oscillations will be some definite multiple of the number of impulses from the clock. However, the present requirements are more severe than this. It is necessary to have the oscillator operated so that each oscillation will be sensibly equal in magnitude and duration to every other oscillation. In other words, it is not sufficient that the clock and the oscillator keep in step over a given period of time, but the instantaneous frequency of the fork must not depart appreciably from the mean frequency. This requires a form of control which will not be to any extent discontinuous, but which will change uniformly in proportion to the divergence of the oscillator from the clock. Such a form of control in turn requires that the frequency of the oscillator itself be sufficiently constant when uncontrolled, to reduce all momentary fluctuations and rapid frequency changes to a minimum. This requirement is best satisfied by an oscillating system having a low decrement. Since a mechanical system is usually far superior to an electrical system in this respect, and since the most available mechanical oscillator for the range of frequency in question is a fork, our choice naturally falls on this form of oscillator.

A good fork maintained in continuous operation by some electrical means, such as regeneration, or a make and break contact and a driving magnet, is a comparatively simple system and is capable of a high degree of constancy.[2] It therefore satisfies all of the requirements for our purpose, but there remains the devising of some control which will be proportional to the divergence of the fork from the clock controlling it. In order to use any such control it is practically necessary to integrate the oscillations of the fork so that we may obtain a

[2] H. M. Dadourian, Phys. Rev. 13, page 337, 1919, "On the Characteristics of Electrically Operated Tuning Forks."

time interval equal to the number of cycles of the fork which we desire to make equal to the time interval between successive clock impulses. This is readily accomplished by means of a phonic wheel or synchronous motor operated by the fork. This motor may be connected to any form of gear train in order to get the necessary integration.

The requirements so far outlined do not limit the frequency of the fork in any degree except that we must be able to integrate its periods, and if a mechanical means is used as outlined, this probably sets an upper limit on the frequency at 400 or 500 cycles. However, practical considerations will generally make the most satisfactory frequency considerably lower than this, since it is an easier matter to compare unknown frequencies with a low frequency standard rather than with one of high frequency.

Method of the Control of the Fork by the Clock

The fork used in the system described below is of the same type as that tested by Dadourian. It is operated by a driving magnet and make and break contact, and was originally designed for use in multiplex printer telegraph circuits. It can be adjusted to operate at 50 cycles and is designed to drive a synchronous distributor which rotates once for every 10 cycles of the fork. By means of a 5 to 2 reduction gear and a contact operated by it, an impulse may be obtained once every 25 cycles of the fork. If the fork oscillates at exactly 50 cycles per second, the time interval between the impulses will be exactly one-half second, and this time interval will be shorter or longer, according as the speed of the fork increases or decreases.

The control system used is designed to affect the frequency of the fork in proportion to the difference between half second intervals as measured by the clock and the time required by the fork to complete 25 cycles. Fig. 1 shows the details of this control. Fig. 2 is the schematic diagram. Referring to Fig. 2 the contact marked "Fork" is the contact obtained every 25 cycles from the fork and the contact marked "Clock" is that obtained every half second from the clock. Each of these contacts is adjusted to remain closed for a period of approximately .05 second when operated.

The control operates as follows. When the clock contact closes, the relay operates and locks until the fork contact closes and short-circuits the winding of the relay which then releases. During the time that the relay is operated, the condenser C is charged through the resistance r_1 by the battery B_1. The voltage of this battery is such that when applied to the grid of the vacuum tube, it will just reduce the space current to zero. The condenser C continuously discharges through the resistance r_2. The mean potential on the condenser is thus applied to the grid of the vacuum tube and modifies the space current, which, in turn, is passed through the damping coil

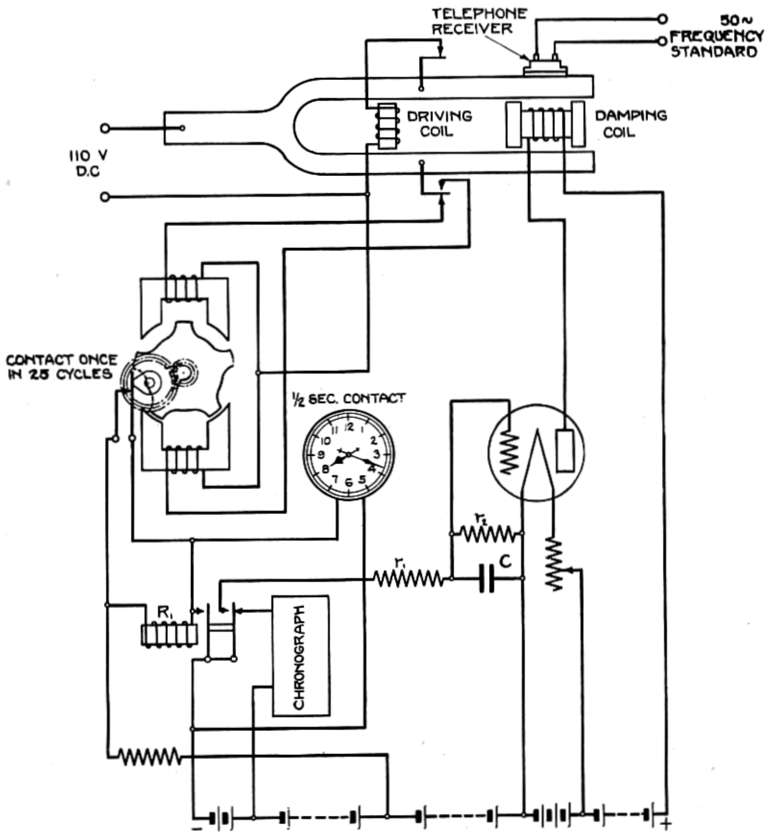

Fig. 1—Clock Control of Fork Frequency

of the fork. A stable condition is reached when the condenser discharge each second is exactly equal to the charge. Any variation in the condenser potential varies the current through the damping coil and changes the frequency of the fork. Now if the period, during which the relay remains operated, increases, the mean potential on the condenser will gradually increase. This will increase the mean negative grid potential, reducing the mean space current through the tube and through the damping winding, thus reducing the damping on the fork and increasing its frequency.

This method of control is slow yet sensitive to very slight changes in frequency.

The method of controlling the frequency of the fork by a damping winding was found to be the most simple and satisfactory method. The amount of variation of frequency which this winding will produce under extreme conditions should be slightly greater than the maximum variation to which the fork is subjected in operation when uncontrolled. This has been found to be about .05%, when temperature

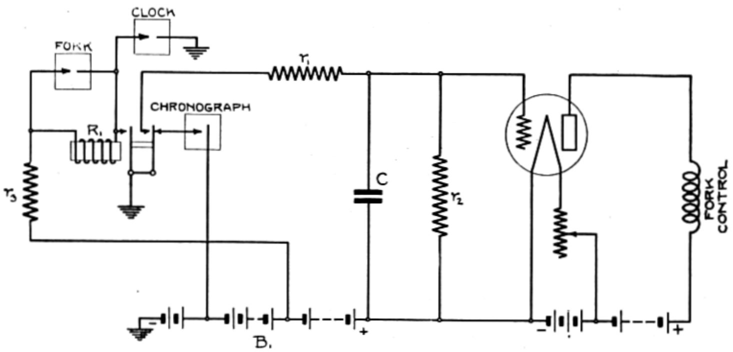

Fig. 2—Clock Control of Fork Frequency. (Schematic Diagram)

variations are held to within a few degrees. The only requirement for the coil is that the current available from the vacuum tube must be sufficient to produce the necessary control. This requirement is easily met. It has been found possible with the equipment described to obtain an effect at least 10 times greater than necessary.

The change in frequency of the fork due to the current in the damping winding is a combination of several effects. The current will increase the decrement of the fork, due to the losses induced in the metal of the fork while vibrating in a magnetic field. This will cause a decrease in frequency. The magnetic force acting on the tines of the fork, even though it be assumed to cause no losses in the fork, is unsymmetrical, having a greater effect at the ends of the swing of the fork. This unsymmetrical force may also be shown to cause a decrease in frequency. Again there is a change in frequency due to the change in amplitude alone. For the type of fork here used this change may be an increase or decrease, depending on the range over which the change occurs.

It is obvious that when the control is operating, the voltage of the condenser and hence the space current of the vacuum tube, will fluctuate each half second. Since it is only the mean value of space current that is used to control the fork, it is important that this fluctuation be reduced to a small amount. This may be done by using a large capacity C or a large resistance R_1. However, the effect of increasing the capacity or resistance is to increase the time required for the control to change, when compensating for changes in the fork frequency. Accordingly the values chosen must be a compromise. If we assume that the control is capable of giving a maximum change in frequency of .1%, and we allow a fluctuation in this control of 5% each half second, this will cause a fluctuation in frequency of 5%, of .1%, or .005%. However, the inertia of the fork prevents it from following such a rapid fluctuation in damping current and hence the actual change in fork frequency is very much smaller than just indicated.

The fact that non-cumulative fluctuations in the control as great as 5% have only a negligible effect on the fork frequency is an important point. Such fluctuations are likely to arise through hunting in the synchronous motor, irregularities in the time of operation of the relay, etc., and since their effects average one another out, there is no danger of their being transferred to the fork.

The ratio of the charging resistance to the discharge or grid leak resistance is not a governing factor, except that the charging resistance must be less than the discharge resistance. The phase position of the fork to the clock under normal conditions is also governed by the relative values of these resistances. For the present circuit r_1 has a resistance one-half that of r_2, and these resistances and the condenser are of such values that it takes approximately 15 minutes for the fork to come into the correct phase relation with the clock when started under the most unfavorable conditions.

While this method of control will hold the fork frequency for an indefinite period in synchronism with the clock, it is possible that the phase relation of the clock to the fork may change. This change may be periodic, that is, it may take the form of an oscillation about the mean phase position, or there may be a gradual change due to changes in the various constants of the control occurring over comparatively long intervals. For instance, any change in the ratio $\frac{r_2}{r_1}$, such as might occur with temperature, will change the phase relation between the fork and the clock.

Chronograph records show that there are no phase changes greater than one cycle of the fork over periods as large as 8 hours. To determine the possibility of hunting, that is, of oscillation of the fork frequency around its mean value, the phase relation was actually disturbed and a chronograph record taken of the readjustment. This will give the period of the oscillation, if any, and the amount of damping.

Fig. 3 shows one of these records. The chronograph was connected in the circuit as shown in Fig. 1 and a record was taken over a period of about 20 minutes after starting the fork. This record shows the length of time in each half second that the control relay was operated. At starting this period is about .11 second. After about 8 minutes it becomes a maximum equal to .2 second and there is no appreciable change over the next 5 minutes, showing a permanent condition has been reached. Accordingly we may conclude from this record that any oscillation about the mean value of the control

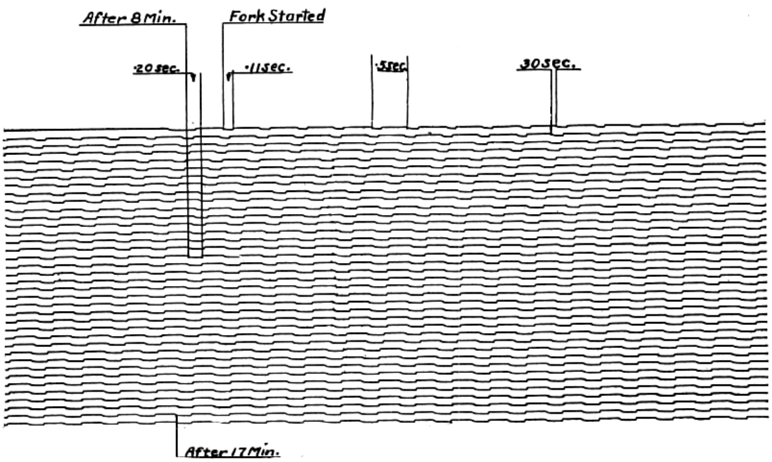

Fig. 3—Chronograph Record of Fork After First Starting

is almost if not quite critically damped. Several other records taken with even greater phase displacements bear out this conclusion. This practically precludes hunting after the phase angle has been once adjusted.

Accuracy of the Clock-Controlled Fork

The accuracy of the fork has been checked in two ways. For long periods of time, chronograph records have been taken at intervals over a period of 8 hours and the maximum variation of the fork from the clock in this period has been found to be less than .02 second, or one cycle. Smaller periods of time cannot be measured accurately on the chronograph used. If we are dealing with periods of time of more than 15 minutes, this gives an accuracy as high as one part in 50,000.

For small time intervals, an entirely different method for measuring the constancy of the fork must be used. Two methods are available. We may either compare the high harmonics of the fork directly with some high frequency which can be held extremely constant over short periods of time, and observe fluctuations in the relative values of these frequencies, or we may compare the fundamental frequency of the fork with a high frequency by some means which will enable us to measure the divergence from an exact integral multiple relation in terms of the higher frequency.

To explain in more detail, we may pick out the one hundredth harmonic of the fork by means of a filter and amplifier and compare it with a 5000-cycle frequency obtained from a constant frequency oscillator by some method of detection which will allow us to count the difference in cycles. By this means we may observe variations in the relative rate of the fork and the oscillator to an accuracy of about one-tenth of a cycle over a period of a few seconds, and this gives us a comparison to an accuracy of 1 part in 50,000. The principal objection to this method is the difficulty involved in separating the higher harmonics of any alternating current wave obtained from the fork. For instance, the separation of the hundredth harmonic from those immediately above and below it would require a circuit so selective that it would probably be very difficult to construct and cumbersome to operate.

If we had means to determine when some high frequency such as 5000 cycles was an exact multiple of the 50 cycles and to measure the difference in terms of the 5000-cycle wave, we would be able to obtain the same results, and avoid the above difficulty.

A device which will allow us to do this is the low voltage cathode ray tube developed by Johnson[3]. The two frequencies to be compared are connected to the two pairs of plates of the tube and the combination of the two deflections causes the luminous spot to trace out a path which repeats itself indefinitely if one frequency is an exact integral multiple of the other, and a stationary figure is produced. In this way any frequency which is a multiple of the fundamental 50 cycles may be accurately determined. As the method of comparison is an electrostatic one practically no power is used.

For the type of tube used, a deflection of about 1 centimeter is obtained for a potential difference of 10 volts between plates, and

[3] J. B. Johnson, *Bell System Technical Journal* Nov. 1922, "A Low Voltage Cathode Ray Oscillograph."

frequencies having ratios as high as 100 to 1 may be readily compared. For ratios of the order of 100 to 1 the lower frequency is preferably stepped up to a high voltage to give an equivalent deflection of as much as 25 centimeters, thus giving a spacing between cycles for the high frequency of approximately 0.5 centimeter. Of course, the whole 25 centimeter deflection is not shown on the screen but this is unnecessary. The value of the ratio cannot be at once determined by this means, there being no appreciable difference between the figure for a ratio of 100 to 1 and 99 to 1, but this ratio may be readily determined by comparing each frequency separately with an intermediate frequency such as 500 cycles.

Having determined the ratio between the high and low frequencies, it is possible, by drawing a reference line across the screen, to determine whether or not they are keeping step with one another. Thus for a comparison of 50 cycles against 5000 cycles, if we get a motion of 2 waves in 10 seconds, this represents a deviation from exact synchronism of 2 parts in 50,000.

Comparisons made in this way between the 50-cycle fork and a vacuum tube oscillator giving a constant frequency of 5000 cycles show no deviation in the mean period of the fork greater than 1 part in 50,000 for observations extending over several minutes. If deviations greater than this were observed, they might equally be ascribed to the auxiliary oscillator but the fact that they do not occur means either that the fork is constant to better than 1 part in 50,000 or that both frequencies vary in exactly the same way which is very improbable.

The above method of comparison does not require a sine wave of current from the fork. In fact it has been found advantageous to have a somewhat distorted wave since an unsymmetrical figure on the luminous screen of the tube is more easily observed. This is due to the fact that one-half of the figure moves across the screen in one direction while the other half moves in the opposite direction. In order not to confuse one half with the other, it is highly desirable that they be dissimilar in shape and this is accomplished by using a distorted wave as the lower frequency. Sufficient distortion is secured by mounting an ordinary telephone receiver in close proximity to one prong of the fork as shown in Fig. 1 and amplifying the e.m.f. thus obtained as much as necessary to obtain the desired voltage.

By means of the simple control system described above, it has been possible to obtain a fundamental frequency so free from fluctuations as to be constant over short or long periods of time to approximately one part in 100,000.

Accuracy of the Clock

So far we have not considered the possibility of error in the clock as a factor. Of course, the fork cannot keep better time than the clock which controls it.

The clock used at present was made by L. Leroy and Co., Paris, electrically driven and beating half seconds. The drive consists of an electric circuit including a single primary cell mounted in the clock, a driving coil and a contact which is closed by the escapement wheel for approximately .1 second in each second. Attached to the lower end of the pendulum is a steel bar which moves into the driving coil as the pendulum oscillates. The electrical impulse is so timed that the driving coil gives the pendulum a slight pull as it is entering the coil. This impulse is sufficient to keep the pendulum oscillating. An additional contact on the clock is used to furnish an electrical impulse for timing purposes.

Time records of the clock have been kept over a period of several months and the rate has been found to be constant to about one-half second a day, which is better than 1 part in 150,000. Since this accuracy is not very much greater than the precision with which the fork keeps in step, any further accuracy will require refinements in the clock itself. With this object in view, an investigation was made of the possibility of obtaining greater accuracy from the existing clock.

Errors are of two kinds. First, if the timing contact is obtained by the operation of the escapement wheel, there may be a cyclic variation in the length of time between successive impulses extending over one revolution of the wheel, (1 minute) even though the pendulum keeps perfect time. This has been found to be the case in some of the best clocks in the country. This error can be overcome by taking the contact direct from the pendulum. The contact we are using at the present time is of this type obtained from the pendulum by means of a photo-electric cell.

The optical system is shown on Fig. 4. Light from the source *A* is concentrated on the mirror, which in turn reflects it on to the photoelectric cell. When the pendulum passes through the center of its stroke, it momentarily cuts off this beam of light. This causes a large increase in the resistance of the photo-electric cell, the change taking place almost instantaneously.

Referring to the diagram of connections on Fig. 4, the potential of battery *B* is divided almost equally between the photo-electric cell and the grid of the tube if the grid leak is made approximately equal to the resistance of the cell when exposed to the light. This gives a negative potential to the grid sufficient to cut off all space current, and the relay R_2 remains unoperated. When the pendulum cuts off the light to the photo-electric cell, the resistance of the cell rises immediately and the grid voltage drops to a very small value. Enough space current will pass now to operate the relay R_2 and a

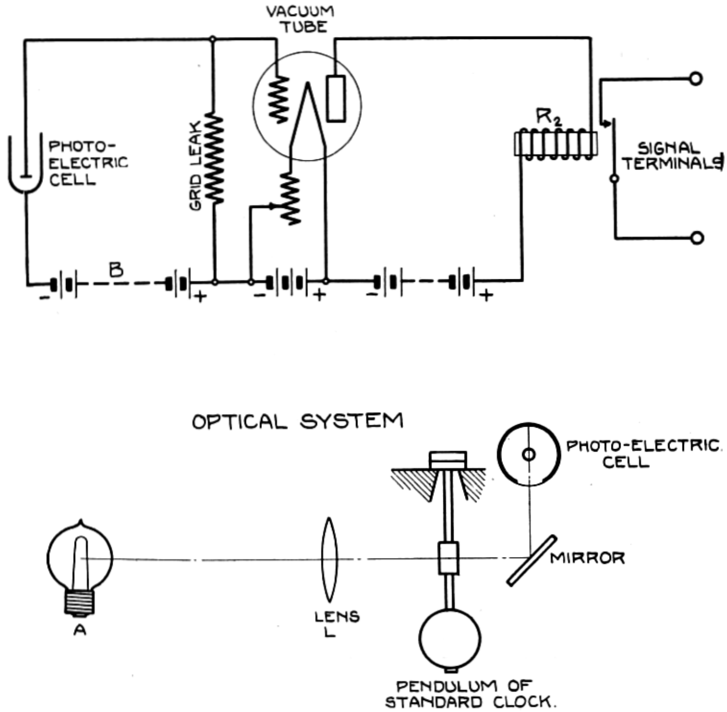

Fig. 4—Circuit for Obtaining Electrical Impulses from Standard Clock Using Photo-electric Cell

signal is transmitted of the same duration as the time the light is cut off the cell by the pendulum. There is no appreciable time lag in the photo-electric cell or vacuum tube.

The principal requirement in setting up this circuit is to obtain a vacuum tube having a resistance between filament and grid including wiring, which is under all conditions considerably greater than the minimum resistance of the photo-electric cell. If this resistance drops much lower, the circuit becomes inoperative even though no additional grid leak is used.

The only irregularity introduced in this system is in the operation of the relay, and as this is a fast operating relay this error will be less than the accidental irregularities in a contact obtained from the escapement wheel even excluding errors due to eccentricity.

This method of obtaining an electrical impulse from a clock is of great value as it may be applied to practically any clock which may not have any other method of producing impulses.

The second type of error is due to variations in the rate of the clock. Two fundamental requirements in the design of an accurate clock are that the impulse delivered to the pendulum be symmetrical about the mid-point of its swing and be not subject to irregularities in magnitude or duration, and that the pendulum be free at all other parts of its swing. These requirements are fairly well met in the

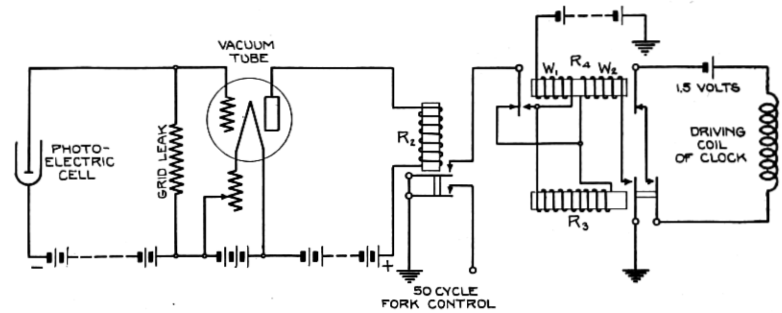

Fig. 5—Circuit of Photo-electric Cell Drive of Standard Clock

present clock. However, the magnitude of the impulse depends on the constancy of the voltage of the driving cell which is a single primary cell of rather small size, and the duration of the impulse may be somewhat variable due to the possible eccentricity of the escapement wheel and due to the method of operation. The pendulum too, is not entirely free from constraint at any part of its swing. These errors may all be avoided or at least considerably reduced by the use of the impulse obtained from a photo-electric cell to drive the clock and by the use of a more constant source of primary voltage.

The use of this type of drive has accordingly been investigated in connection with this clock. It is obvious, since the driving impulse is one of attraction between the coil and the bar carried by the pendulum, that it must be exerted only once per second, that is, when the pendulum is entering the driving coil and not when it is returning. The circuit used is shown on Fig. 5 and operates as follows:

When the relay R_2 operates the first time in the second, it closes the circuit through the winding W_1 of the relay R_4 and through relay R_3. This operates the relay R_3 and closes the circuit through the driving coil of the clock. The current through the one winding of

R_4 is not sufficient to operate it. As soon as the relay R_2 releases, current will pass through all the windings on both relays which in turn closes the relay R_4. This opens the circuit through the driving coil of the clock. The impulse given to the pendulum is, therefore, the duration of the operation of the relay R_2, or the time during which the light is cut off the photo-electric cell during the swing of the pendulum to the left. When the pendulum swings to the right and the relay R_2 operates, R_3 is short-circuited and releases, R_4 being held up by winding W_1. When R_2 releases, it releases R_4 bringing the circuit back to normal. Since the circuit through the driving coil of the clock is closed only when the relay R_3 is closed, and the relay R_4 is released, there is only one impulse per second given to the pendulum.

During a period of operation by this method covering several days the clock gave as satisfactory performance as with the mechanical drive, but while the present gear train is connected to it, no appreciably better performance can be obtained than at present, and accordingly it is proposed to carry out further work along this line with an experimental pendulum having no mechanical connections. By using a good compensated pendulum and mounting it suitably in a constant temperature hermetically sealed case, it appears probable that a photo-electric cell drive would produce a more constant rate of oscillation than the best clocks of existing types. The advantage of this type of drive over other types is the fact that the pendulum is absolutely free from all mechanical constraint at all parts of its swing. The problem of supplying an uninterrupted current for the light and power could readily be solved by the use of duplicate apparatus.

The general method outlined in this paper for synchronizing a fork with a clock has a very wide field of usefulness, and is not limited to the particular application described. For instance, in place of the clock we may substitute another fork and distributor, and we are thus enabled to hold 2 forks with their distributers in exact synchronism by means of an impulse transmitted at a constant time interval of about once every half-second.

By substituting the field coils of a motor for the damping winding on the fork, we are able to hold the speed of the motor in synchronism with the clock, the only requirement being a step down gear on the motor to furnish the desired contact.

The general principle involved is not dependent on the use of a vacuum tube, and if other means of control based on this principle be adopted, very large powers may be controlled in the same way.