THE PHONIC CHRONOMETER

by

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ABSTRACT. A description is given of an electrically controlled chronometer which is capable of directly indicating time-intervals with an accuracy of one-thousandth of a second. The chronometer is driven by a powerful phonic motor, of novel design, which is controlled by a tuning-fork of adjustable frequency. Methods of eliminating and compensating errors are dealt with and accuracy tests are described.

The chronometers have been used in (A) *the accurate measurement of time in physical investigations, e. g. variation of period of a compound pendulum with amplitude of swing, velocity of sound in the sea ;* (B) *sound-ranging, depth sounding, and in hydrographical survey ;* (C) *psychological measurements—reaction times; etc. ;* (D) *motor-car speed events ;* (E) *electrical investigations involving measurements of quantity* (*current* × *time*).

The instruments are robust in design and permit of simple manipulation of all parts requiring adjustment.

I. Introduction

The above designation has been given to an electrically operated clock which is capable of directly indicating time intervals with an accuracy of the order of one thousandth of a second. The instrument was first conceived with the object of providing a simple and *direct* means of measuring time intervals as an alternative to certain photographic methods then in use in Military and Marine sound ranging. Apart from this possibility, however, it was realized that such a direct-reading chronometer would have a wide application in other fields of investigation where it is desired to measure time-intervals with accuracy.

The accuracy aimed at in the design has been fully achieved. With the chronometer in good adjustment the maximum error for individual observations of a time-interval does not exceed ± .001 second whilst the order of accuracy of the mean of a number of similar observations may reach ± .001 second. Over long periods of time, however, (e. g. of several minutes duration) great care has to be exercised in order to attain such a high degree of accuracy.

II. General Features of Design

Prior to July 1919, when the first of the phonic chronometers now described was constructed, the only high-speed chronometer of any importance was that known as the Wheatstone-Hipp Chronoscope. This instrument is in reality a spring-driven stop-watch with a high frequency escapement (∽ 500 or ∽ 1000 per sec.). The dial mechanism, which is separated from the main clockwork, can be put in and out of gear by means of electro-magnets operating an iron armature. When once started, after rewinding, the clock runs down in less than five minutes. The accuracy of indication when in good adjustment is *on the average* ± .001 second, but individual variations considerably greater than this may occur.

For many purposes, e. g. in sound-ranging such a chronometer has one fatal defect, viz., its short running period. To be of use in sound-ranging the chronometer must be constantly running, so as to be in readiness whenever an explosion occurs. This feature is also desirable for general purposes, especially where the chronometer is required to measure a number of time-intervals in fairly quick succession. The principle of the phonic chronometer is outlined in what follows:

By making use of a device known as a phonic motor — invented by the late Lord RAYLEIGH (*) — a wheel is constrained to rotate *at a constant speed* controlled by an electromagnetically maintained tuning-fork. This wheel *W* (Fig. 1)is employed as the driving wheel of the phonic chronometer. Almost in contact with the rim of this driving wheel is supported a very light dial wheel *w* at the end of an iron armature *R* which is operated by an electromagnet *M*. The spindle of the dial wheel *w* is extended to carry a light pointer *F* which moves over a dial suitably graduated in hundredths or thousandths of a second. Extra gear wheels, not shown in the figure, are provided for indicating the number of complete revolutions of the dial wheel *w*. Normally the rim of the dial wheel presses against an adjustable brake *B* and is just clear of the driving wheel. The electromagnet *M*, operating the iron armature, is wound differentially. When current in either winding is cut off, the armature *R* is attracted and the dial wheel *w* is brought into contact with the driving wheel *W*, returning again to the brake *B* when the current in the second winding of *M* is interrupted.

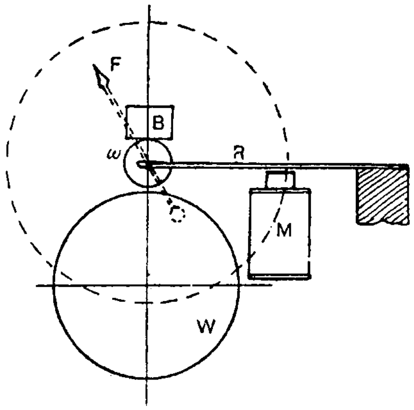

Fig. 1

The duration of contact of the dial wheel with the driving wheel is indicated on the dials. If the indicated time-interval is to be accurate, it is of great importance that the relation between the speed and gear-ratio of the wheels *W* and *w* and the frequency of the tuning-fork should be accurately adjusted. The tuning-fork acts as the escapement and hair-spring of the chronometer. Suppose n is the frequency per second of the fork and N is the number of teeth or bars on the phonic motor, then the armature of the latter makes n/N revs. per sec. If also the gear-ratio of the driving and dial wheels is m, the latter will make nm/N revs. per sec. For example, if $n = 25$, $N = 10$, and $m = 4$, the speed of the dial wheel will be 10 revs. per sec., *i. e* each revolution will correspond to 0.1 second. With 100 subdivisions per revolution

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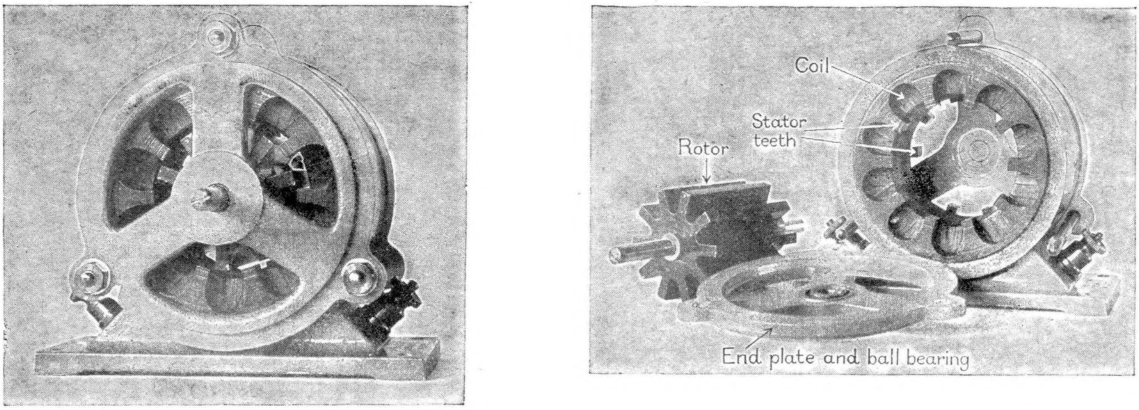
(*) *A complete description of the first phonic motor and its mode of action is given by the late Lord RAYLEIGH in* Nature, 18 (1878) III; *also* Scientific Papers, I 355.



a) b)

Fig. 2

PHONIC MOTOR — *a)* assembled ; *b)* in parts
MOTEUR PHONIQUE — *a)* assemblé ; *b)* démonté
Coil — Bobinage
Stator teeth — Dents du Stator
End plate & ball bearing — Flasque et roulement à billes

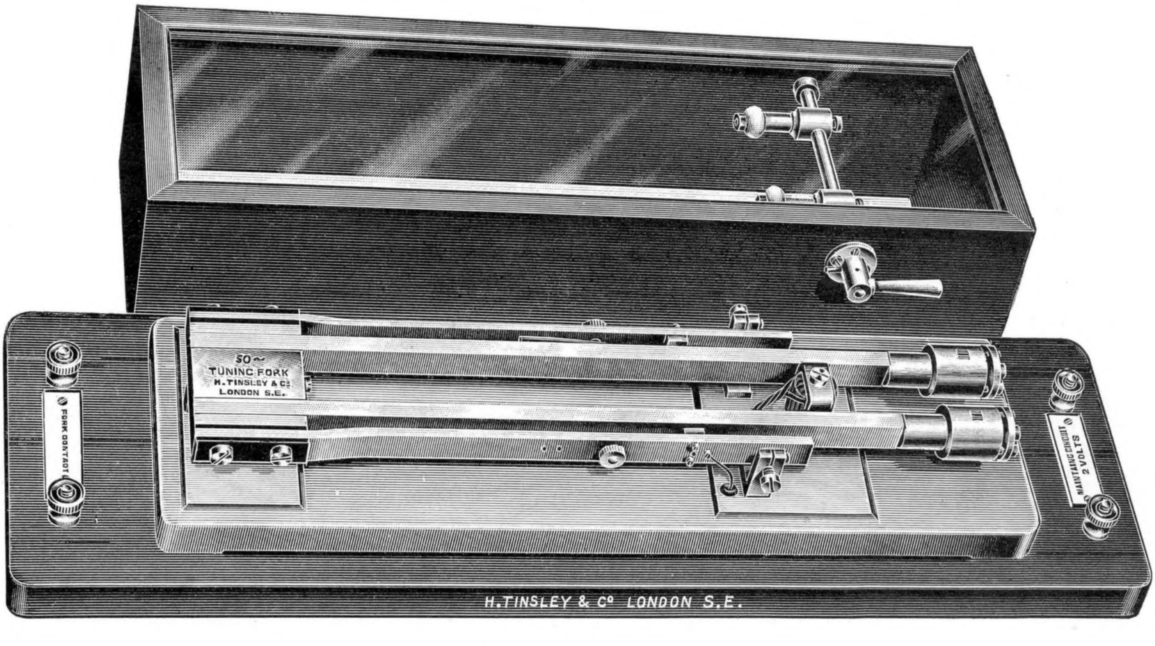


Fig. 4

the clock will indicate thousandths of a second. If the gear-ratio m is not an exact integral number, the difference can be compensated by a suitable adjustment of N, the frequency of the fork.

III. Details of Design

(i) *The Phonic Motor*

A simple toothed-wheel type of phonic motor, until recently in general use, was constructed in 1918 to drive a recording chronograph. This motor was difficult to start up and had barely sufficient torque for the purpose of driving the recording drum. In addition to this, it suffered from the serious defect of transverse vibration of the shaft — this being due to the unbalanced intermittent radial pull of the exciting electromagnet. Various improvements in the design were made by the writers with the object of eliminating these defects, the final form now being known as the "ironclad type" of phonic motor (*). This simple and robust type of phonic motor is shown in Fig. 2, and it is hoped that this may be described in detail in a future paper. The magnetic circuit of this motor is remarkably good, even moderate exciting currents producing a large driving torque. The rotor, mounted on ball bearings, is made up from a single bar of soft iron with ten slots machined longitudinally, leaving ten radial bars outstanding. The stator consists of two similar parts, each with ten teeth corresponding to the ten bars of the rotor. The exciting coil is a single former-wound coil which lies inside the shell of the stator and completely surrounds the rotor.

The performance of these ironclad phonic motors is very satisfactory. They have a large torque for small exciting currents and are easily started. They are silent when running and are quite free from troublesome mechanical vibrations. With these features this type of phonic motor has been found eminently suitable for incorporation in phonic chronographs and chronometers. When fitted with a moderately heavy fly-wheel such as the driving wheel of the chronometer the ironclad motors show no perceptible tendency to "hunt". Phonic chronometers have been constructed with mercury-filled fly-wheels, to counteract "hunting", but these have not been proved superior to ordinary solid fly-wheels. In both cases the "hunting", if it exists, is negligible.

(ii) *Driving Wheel, Dial Wheel, and Brake*

Numerous experiments have been made to discover the most suitable type of wheels and brake for the chronometer. Although toothed wheels, with brake rack to correspond, offer obvious advantages, particularly as regards accuracy of gear-ratio, these advantages have in practice been outweighed by other considerations which have ultimately led to the choice of a friction drive. It is not proposed to discuss the relative merits of toothed and friction drives. Suffice it to state that chronometers have been constructed with both types of drive with equally satisfactory results. Since the friction type is more simple to construct and gives less trouble in use, this form has been chosen, and what follows relates to this type of chronometer unless otherwise stated.

It is essential, of course, that the driving and dial wheels should run "true". Any sign of "wobble" would introduce errors due to varying gap between the rims of the wheels. With careful workmanship the required accuracy is easily obtained. The gear-ratio, in this case the diameter-ratio, of the wheels should also be accurately known, but in general for single-dial chronometers, any slight inaccuracy in gear-ratio can be compensated by adjustment of the tuning-fork frequency (see later Section IV (*a*) iii).

It is essential that the moment of inertia of the driving wheel and rotor of the phonic motor be very large compared with that of the dial wheel, and that the torque on the shaft

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(*) *These motors are now manufactured separately by Messrs H. TINSLEY & C°, who also manufacture the phonic chronometers described in this paper.*

of the driving wheel be so large as to be unaffected by the contact pressure between the dial and driving wheels. With a heavy driving wheel and very light dial wheel, a thin rim of metal with light stiffening spokes, these conditions are easily attained. In chronometers now in use the diameters of the driving and dial wheels are 80 mm. and 20 mm. respectively, the moments of inertia being approximately 3500 and 7 gramme cm.^{2} respectively. Both wheels are made of stainless steel to prevent surface tarnishing, and a light pad of chamois leather is fitted so as to rub on the driving wheel to keep the rims of the wheels clean.

Various spring shock-absorbing devices have been tried to reduce the shock at contact of the stationary dial wheel with the revolving driving wheel and at contact of the revolving dial wheel with the brake. It is considered, however, that the slight improvement observed when such devices are used does not justify the added complication to the design. Comparative tests of geared and friction drives show that the "slip" error in the latter case is negligible. Observations indicate that the "positive" slip at starting on the driving wheel can be exactly compensated by the "negative" slip at stopping on the brake. The slip, if any, when running is undetectable.

The lower bearing of the dial wheel is carried at the top of the moving armature operated by the electromagnet, the upper bearing being fixed in the dial plate of the chronometer. Since the spindle of the dial wheel has to permit of a small angular movement when the electromagnet attracts the iron armature, it has been found an advantage to employ swivel bearings. Ordinary solid bearings have been found to give good results, but owing to the rather heavy side pressures developed when the driving and dial wheels are held in contact, the wear is rather serious and the bearing becomes slack.

Chronometers have been constructed having three sets of dials driven from a common phonic motor (see Fig. 5). With these triple-dial instruments three time-intervals can be measured simultaneously or in very rapid succession. It is important with these instruments, however, that the wheel ratios are known with great accuracy, for the tuning-fork method of compensating error in gear-ratio cannot be applied in this case, unless all the gear-ratios happen to be in error by exactly the same amount.

(iii) *Electromagnet and Armature*

The choice of a suitable electromagnet and armature is of considerable importance, since the accuracy of the indications of the chronometer depends to a large extent on the behaviour of these components. It is essential, of course, that the operation of the armature should be as rapid as possible so that very little time is lost in moving the dial wheel from the brake to the driving wheel. Fortunately any such delay can be compensated by an approximately equal delay in the reverse process when the dial wheel returns to the brake. Thus we are permitted a certain margin of lag in operation without introducing a serious error in the resultant indicated time.

For quick action of the armature three factors are of supreme importance: (*a*) the attractive force of the electromagnet displacing the armature must be considerably in excess of that actually required to bring the dial and driving wheels into contact; (*b*) the inertia and displacement of the moving armature with its load, the dial wheel, must be as small as possible consistent with mechanical strength; (*c*) electrical lags, due to inductance, hysteresis and eddy current effects, must be reduced to a minimum.

Earlier chronometers were constructed with an armature consisting of a soft-iron reed clamped at one end and bridging the poles of the electromagnet near the free end. On account of certain peculiarities observed in its behaviour, however, the clamped reed was finally abandoned in favour of a simple pivoted spring-controlled armature. Phonic chronometers fitted with this type of armature have given very satisfactory results.

With regard to the electromagnet, this must be powerful enough to operate the armature with great rapidity. A large magnet with many turns has a considerable inductance, e. g. in one chronometer in use the self-inductance of one of the windings is 1.09 henries, the D. C. resistance being 204 ohms. Thus the time constant L/R is 0.0053 sec., this being the time required at make of circuit for the current to reach 0.632 of its maximum value. By using a large series resistance, a metal filament lamp of about 1500 ohms, however, and applying a correspondingly high voltage to maintain the required operating current the time constant is reduced to something less than 0.001 sec. Since the conditions at "make" of circuit are entirely different from the conditions at "break", it was considered desirable to operate the chronometer on two successive breaks rather than on a make and a break. This method was to some extent necessitated by the sound-ranging conditions for which the chronometer was first designed. It also becomes possible, on the double break method of operation, to use low voltage circuits on the chronometer magnets without appreciable loss of accuracy. In these circumstances the electromagnet is constructed with two differential windings. When equal currents flow through both windings, the magnetic effects neutralize and the armature is not affected. If, however, current through either winding is broken, the magnetic effect of the other coil attracts the armature and brings the dial wheel into contact with the revolving driving wheel. Breaking the circuit of the second winding restores the armature to its initial position and brings the dial wheel into contact with the brake. In this method of operation mutual induction effects are minimized by the use of series resistance. Such effects might be entirely removed by the use of two independent electromagnets acting in opposition on the same armature. Such a complication has in practice been found unnecessary.

To reduce hysteresis and eddy current effects to a minimum, the cores of magnets should be made of laminated soft iron. Good results have been obtained, however, with solid cores of soft iron having a radial saw-cut.

(iv) *Tuning-Fork Control*

The success of the chronometer depends, of course, on the constancy of frequency of the tuning-fork which controls the motor. The prongs of this fork drive two (sometimes four) pairs of contacts, one pair of which is used to maintain the vibrations of the fork whilst another pair controls the phonic motor. It was found that with ordinary spring contacts, as commonly used in electrically maintained forks, considerable variations of frequency (of the order of 1 per cent.) were observed as the amplitude of vibration was varied. As a consequence of such observations a complete investigation was made of the factors involved in these variations. Amongst other factors likely to produce changes of frequency with amplitude the following have been examined:

(1) Pressure of contact springs;

(2) Variation of time constant L/R of the circuit containing the electromagnet exciting the fork;

(3) Damping of the fork by the spring contacts;

(4) Exciting current of the electromagnet.

Temperature variations are also a source of small changes in frequency of ordinary steel tuning-forks, the change of frequency being mainly determined by the change in elastic constants of the materials of the fork.

The writers are informed that Mr. Dye of the N. P. L. has recently constructed a fork of "Elinvar", invented by M. Guillaume, with a temperature-coefficient of about one-tenth that of ordinary steel. Such a fork would be free from these objectionable variations. Unless extreme accuracy of tuning is required over comparatively long periods, several minutes for example, ordinary steel forks are found to be quite satisfactory.

As a result of the experiments referred to above it was considered desirable to employ an entirely new design of fork contact in which the movement of the spring contact is perfectly definite and easily adjustable. This type is illustrated in Fig. 3. In this design there is no possibility of "overshoot", so common with ordinary spring contacts, the return movement being limited by a flange on the upper end of the plunger on which the contact spring presses. Other improvements have also been made. These contacts are superior to any previously used, the fork running smoothly for long periods without the slightest trouble. The frequency of the fork is also remarkably constant within a small range of amplitude variation.

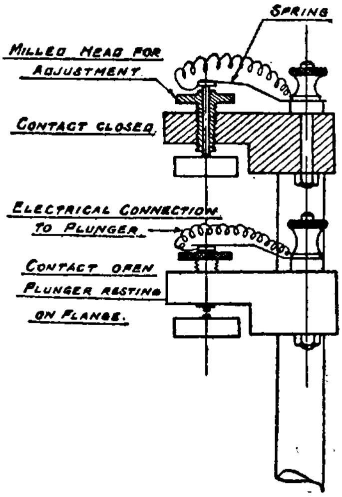

Fig. 3. Tuning-fork contacts

Using a phonic motor with the bars in the rotor the best results have been obtained with a tuning-fork of 25 periods per second. With this arrangement the driving wheel revolves 2.5 times per second and the dial wheel 10 times per second. At higher speeds than this there is increased danger of slip between dial and driving wheels, whilst at lower speeds the dial divisions become rather small and there is increased risk of "hunting" effects.

As we have already mentioned, when a single dial chronometer is used, a slight error in gear-ratio of the friction wheels can be compensated by means of a small adjustment of the frequency of the fork. In this case the fork functions as the escapement and hair-spring of the chronometer, If the latter gains or loses, when compared with a standard of time, it is a simple matter to correct the error by means of the adjustment on the tuning-fork. For this purpose adjustable loading weights are screwed near the tips of the prongs and clamping screws are provided to fix the position of the weights when their final position has been decided upon. A photograph of the adjustable tuning-fork is shown in Fig. 4.

(v) *Adjustments — Mechanical and Electrical*

For the satisfactory compensation and elimination of errors due to mechanical and electrical inertia, etc., it is essential that various controlling influences should be capable of suitable adjustment. We shall confine ourselves here to a mere reference to these adjustments. Provision has been made in the design for the following adjustments:

(1) Gap between armature and pole face of magnet;
(2) Gap between rims of driving wheel and small dial wheel;
(3) Pressure between brake and dial wheel;
(4) Tension of spring controlling armature;
(5) Current operating electromagnet;
(6) Time constants of electrical circuits;
(7) Frequency of fork, to compensate for error in gear-ratio in single dial chronometers.

These adjustments are to a certain extent interdependent and of course depend also on the type of chronometer used. It is essential that the gap between the armature and pole face of the magnet should be small, say .05 of an inch, whilst the gap between the rims of the driving and dial wheels should be reduced to a few thousandths of an inch.

(vi) *Electrical Circuits*

These consist essentially of two parts:

(*a*) Phonic motor and tuning-fork circuit, and
(*b*) Electromagnet or chronometer circuit.

(*a*) *Phonic Motor and Tuning-Fork Circuit.* One tuning-fork contact is used to maintain the fork vibrations in the usual manner by means of an accumulator and rheostat in series with the exciting magnet. The rheostat is important, since it serves to control the amplitude of the fork, which to a slight extent affects the frequency.

The amplitude of the fork is kept constant by means of a V and cross-line diagram painted on the end of a prong. The pattern made by the vibrating diagram changes with amplitude and thus serves as an indicator when the working amplitude has been reached.

A second contact on the fork controls the phonic motor. A suitable battery (depending of course on the winding of the motor), rheostat, and ammeter are connected in series with the winding of the motor, and the rheostat is adjusted until the current indicated by the ammeter is about 1/5 to 1/3 of that obtained on short circuit of the fork contact. It has been found that the motor runs most satisfactorily under these conditions. Although variation of current in the motor circuit has no detectable influence on the "hunting" of the rotor, it is desirable to limit the current to as low a value as possible consistent with sufficient torque for driving the chronometer mechanism without risk of stopping.

(*b*) *Electromagnet or Chronometer Circuit.* As we have already stated, the general practice has been to measure time-intervals between a pair of "breaks", the windings of the electromagnets being connected differentially. Chronometers have been constructed to operate on any voltage from 6 to 200 volts, the windings of the electromagnets of course being varied accordingly. With a 200-volt chronometer, lamps of about 1500 ohms resistance are used in series with each winding ($R = 200$ ohms, $L = 1$ henry), a current of about 0.12 amp. flowing through the main circuit. The contacts which break the circuits may take any form most convenient for the purpose in view, but it is necessary to observe that the contact which opens first and starts the chronometer should not re-set until the second contact is broken and the main voltage cut off. A reversing switch for reversing the main current supply between successive observations is desirable.

(vii) *General Remarks on the Design*

In the phonic chronometers so far constructed, the maximum time-interval directly indicated is 100 seconds, but if required of course additional gear wheels could be introduced to indicate up to any desired maximum. As we have already mentioned, triple-dial chronometers have been utilized for measuring three time-intervals simultaneously or in quick succession as in sound-ranging. The single-dial pattern is, however, quite serviceable for most purposes.

The question of fitting a re-setting mechanism, e. g. a "cam" or heart-shaped fitting, to the fingers of each dial unit has been considered, but this has not been done in the majority of instruments so far constructed. The present procedure is to read the dials before and after each observation, or to re-set the fingers to zero by actuating the electromagnet which gears the dial and driving wheels, and rotating the driving wheel by hand. For general purposes these methods have proved quite satisfactory. In circumstances where a re-setting mechanism is necessary, a slight addition to the standard design is all that is required.

With a multiple contact tuning-fork a number of phonic chronometers may be controlled from the same fork.

IV. COMPENSATION AND ELIMINATION OF ERRORS. ACCURACY TESTS

Brief reference has already been made to certain possible errors in the indications of the chronometer and the means of their elimination. It is necessary, however, to refer to others and to deal with them in greater detail. We shall classify the more important errors as follows:

(*a*) *Mechanical Errors*, involving
  (i) the lag due to inertia of moving parts;
  (ii) "slip" at starting, stopping, and running;
  (iii) gear-ratio;
  (iv) eccentricity of wheels.

(*b*) *Electrical Errors*, involving
  (i) electrical lag in the electromagnet circuit;
  (ii) possible variable effect due to residual magnetization of magnet core.

(*c*) *Tuning-Fork and Phonic Motor Errors.*

(*a*) *Mechanical Errors. Measurement and Compensation*

(i) *Lags due to inertia of moving parts.* It is obvious that a certain amount of time is lost when the dial mechanism is started. Fortunately this lag of the armature can be compensated in a very simple manner, for it will be observed that the armature takes time to leave the pole face on removal of the magnetic field, and the dial wheel on leaving contact with the driving wheel will continue to spin until stopped by the brake. Neglecting for the moment the possible effects of slip, it is clear that this extra spin can be controlled by varying the gap between the friction wheels. Consequently the loss of time at starting can be compensated by the extra time at stopping. It has been found in practice that this compensation can be made perfect with a considerable margin of adjustment in either direction. The total lag at starting amounts to a few thousandths of a second only, so that an approximate compensation will involve only a small fraction of this as error.

(ii) "*Slip*" *between friction wheels.* It is probable that a certain amount of slip occurs at the instant when the friction wheels are brought into contact, for the driving wheel is rotating with considerable peripheral speed, about 2 feet per second, whilst the dial wheel starts from rest at the instant of first contact. Again it is fortunate that this time lag is also automatically compensated, for an equal slip occurs at stopping when the dial wheel, with peripheral speed now 2 feet per second, comes into contact with the stationary brake. Since both slips are probably small, the difference must be negligible. An outstanding error, if any, can be compensated by including under (i) above.

The possible errors involved at starting and stopping have in practice been observed and corrected by two simple methods. The first of these methods depends for its accuracy on the time of fall of a heavy steel ball, under the action of gravity, past two very lightly pivoted contacts which it breaks in its fall. Using this falling ball apparatus it was found easily possible to adjust the chronometer to indicate 0.100 ± .001 second. With this adjustment other time-intervals on the falling ball apparatus could be measured with the same degree of accuracy. That being the case it is clear that the "starting-stopping" error has been correctly compensated.

The second method of compensatiog this error involves less elaborate timing apparatus and is probably preferable in other respects. The principle of the method involves the timing of one complete revolution of the driving wheel itself. By means of a simple relay system, which we need not now describe, any two successive breaks of a contact by a revolving arm attached to the shaft of the driving wheel cause the dial mechanism to start and stop, thereby indicating the time of one revolution of the driving wheel. It required the same apparatus can be used to time any number of whole revolutions.

The following example is given as indicating the accuracy attained by the chronometer. Using the second method, just described, a hundred successive observations were made of the time-intervals indicated by the chronometer after adjustment.

Test of dial B. Chronometer N^o C 16398, *triple- dial type.* A hundred successive observations of the time of one revolution of driving wheel (nominally 0.4000 sec.). Smallest division of dial equivalent to 0.001 second, by estimation of 1/10 of a division readings could be taken to 0.0001 second — hence the probable error in estimating a time-interval may be ± .0002 second.

Out of a hundred successive observations, the errors were as follows:

	Negative $\times 10^4$ sec.										Correct	Positive $\times 10^4$ sec.										
Error	10	9	8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8	9	10	11
No. of observations	0	0	1	0	0	2	6	2	14	7	31	3	12	4	4	11	2	0	1	0	1	0

A simple analysis of these results by ordinary statistical methods indicates that 49 per cent. are correct, 25 per cent. have an error of .0002, 16.5 per cent. of .0004, 8 per cent. of .0006, 1 per cent. of .0008 and 0.5 per cent. of .001 second.

Similar observations could be quoted for other chronometers, and also by use of the falling ball apparatus. The above table is, however, sufficient to indicate the high order of accuracy of the chronometer after proper adjustment.

From such observations we can conclude that the starting and stopping lags and slips can be compensated with an accuracy of considerably less than .001 second.

Effect of variations in the voltage of the main supply. The rate at which the armature is attracted to the pole is of course dependent on the current exciting the electromagnet, *i. e.* on the voltage of the supply. With a correct operating current of 0.135 amp. one chronometer was found to have an error of ± .001 sec. for variations of ± .01 amp. It is important, therefore, to use a supply voltage of which the variations do not exceed 10 per cent. Chronometers should preferably be operated from a steady supply from accumulators.

(iii) *Error in gear-ratio and "slip" whilst running.* With careful workmanship the error in gear-ratio is not appreciably greater than 1 in 10,000 for friction wheels 80 mm. and 20 mm. in diameter. The extent of this error can be determined either directly by means of a vernier micrometer or by rotating the wheels in contact and noting the accumulated error in a large number of revolutions of the large driving wheel.

A more satisfactory method, however, measures the effective gear-ratio, and incidentally the slip, under actual running conditions. In this method an arm attached to the shaft of the driving wheel breaks a contact once per revolution. This contact actuates, through a spark coil, a neon tube which illuminates the dial once per revolution of the driving wheel. If the gear-ratio is an exact whole number and there is no slip, then the pointer attached to the dial wheel will appear quite stationary. If, however, the gear-ratio is not correct the pointer will appear to revolve slowly backwards or forwards according as the ratio is either too small or too great. If the rate of rotation is irregular, a variable "slip" is indicated, but if the rate is regular, the slip, if it occurs at all, must be uniform and can be allowed for by including it in the gear-ratio correction. Tests of chronometers by this method have shown in every case that the error is small and is quite uniform. That is, there is no variation in the slip, if it exists, whilst running.

Reference has been made earlier in the paper to a tuning-fork of adjustable frequency. This is used to correct for gear-ratio error in single-dial chronometers. Thus if the dial wheel is a little too small and the chronometer runs "fast", a slight outward adjustment of the weights loading the prongs of the fork will reduce the speed of the driving wheel and hence compensate for the error in gear-ratio. This adjustable fork is a very important feature of the phonic chronometer and in fact plays the part of the hair-spring and regulator in an ordinary watch mechanism.

(iv) *Eccentricity of wheels.* This point has been dealt with earlier in the paper. It is essential that the friction wheels should run free from wobble.

(*b*) *Electrical Errors.*

(i) *Electrical lag in the magnet circuits containing inductance.* This point has also been dealt with in Section III (vi).

(ii) *Residual magnetization of magnet core.* This is reduced as far as possible by using soft Swedish iron cores. The residual field is always a very small fraction of the total field when the magnet is energized. The extent of the effect of variation in residual field can only be judged by results such as those quoted above (Section IV (*a*) (ii). It would seem advantageous to reverse the current through the electromagnet between successive operations of the chronometer.

(c) *Tuning-Fork and Phonic Motor Errors*

It is impossible to summarize in a short statement even a part of the work that has been done on the design of tuning-forks to run at accurate speed over long periods of time. Reference has already been made to this point in Section III (iv). Experiments have shown, however, that a well-designed fork with contact pressures and vibration-amplitude kept constant will run with extremely little variation for considerable periods of time.

One of the methods employed by the writers to standardize the fork-phonic motor system is to observe the times of coincidence of the ticks of the phonic motor (one per rev. of driving wheel) and of a Greenwich chronometer. The latter ticks 150 times per minute, which happens to correspond to the R. P. M. of the phonic motor. Another method, which gives a mean rate of revolution of the phonic motor over a long period, employs a revolution counter which automatically counts the total number of revolutions in a known time-interval as indicated by the Greenwich chronometer.

In practice it has not been found difficult to maintain an accuracy of 1 part in 10,000 with a tuning-fork of 25 periods per sec. vibrating several hours daily for several weeks.

The extent of the "hunting" of the phonic motor can be seen to be negligible in view of such results as those quoted in the table in Section IV (*a*) (ii).

V. GENERAL REMARKS

In the foregoing we have dealt with the more important details of the design and the method of compensating or eliminating errors. A number of chronometers of the triple-dial and single-dial types have now been in use for several years and have been found to give very reliable results.

An examination of the photographs of such chronometers (Fig. 5 (*) and 6) at once indicates the robustness and compactness of these instruments. The dial units are easily accessible and permit of simple manipulation of all parts requiring adjustment.

Phonic chronometers are practically silent when running. This is an important feature when they are used in psychological research, where it is essential that a subject under test should not be disturbed by extraneous factors. In this respect the phonic chronometer is a considerable advance on the noisy Hipp chronoscope.

Fig. 6 shows the present arrangement (1927). The only addition to the Chronometer has been to make the pointers of the dials so that they can be re-set to zero by hand, after taking a reading, and in the case of the Tuning Fork, the contacts have been modified as the outcome of experience.

Fig. 7 shows the usual arrangement with the Tuning Fork complete, mounted upon one base.

The Chronoscope takes about 50 milliseconds to start to operate, so that if time intervals of less than 50 milliseconds have to be measured, the Chronoscope by itself cannot be used, as it would not have started to operate in this time.

If intervals of longer than 50 milliseconds are to be measured, the Chronoscope works quite well, as the time of stopping is adjusted to agree exactly with the time taken to start, so that there is a displacement of approximately 50 milliseconds in the operation.

An additional piece of apparatus is employed for these short intervals, which consists of a tuned reed, having a period of 400 milliseconds, the reed is held deflected and is released electromagnetically, by either the make or break of the circuit, according to which is more suitable, and the reed then swings across and makes and breaks simultaneously contacts on its centre point, or after it has traversed a quarter of its complete period. This gives a time delay of 100 milliseconds between the releasing of the reed and the operation of the centre

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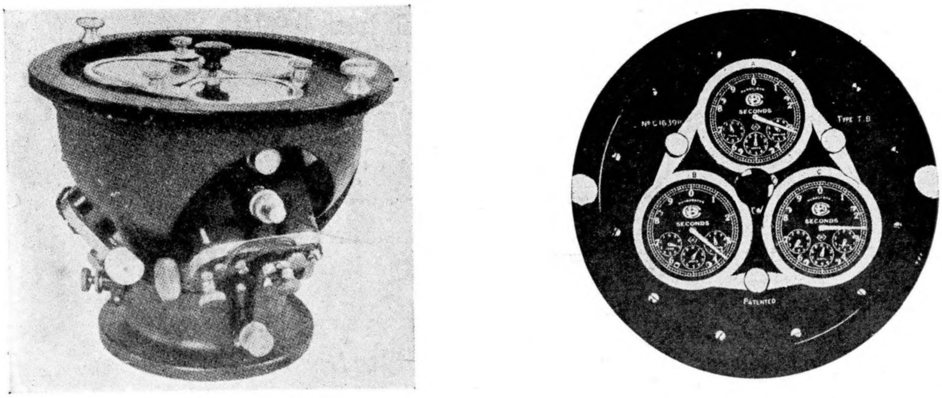
(*) *The triple-dial chronometer shown in Fig 5 is one of several constructed, to the author's design, by the CAMBRIDGE & PAUL Instrument C°., Ltd.*



a) Fig. 5 *b)*

TRIPLE DIAL CHRONOMETER — CHRONOMÈTRE A CADRAN TRIPLE

a) Complete instrument — Vue d'ensemble
b) View of dials — Vue des cadrans

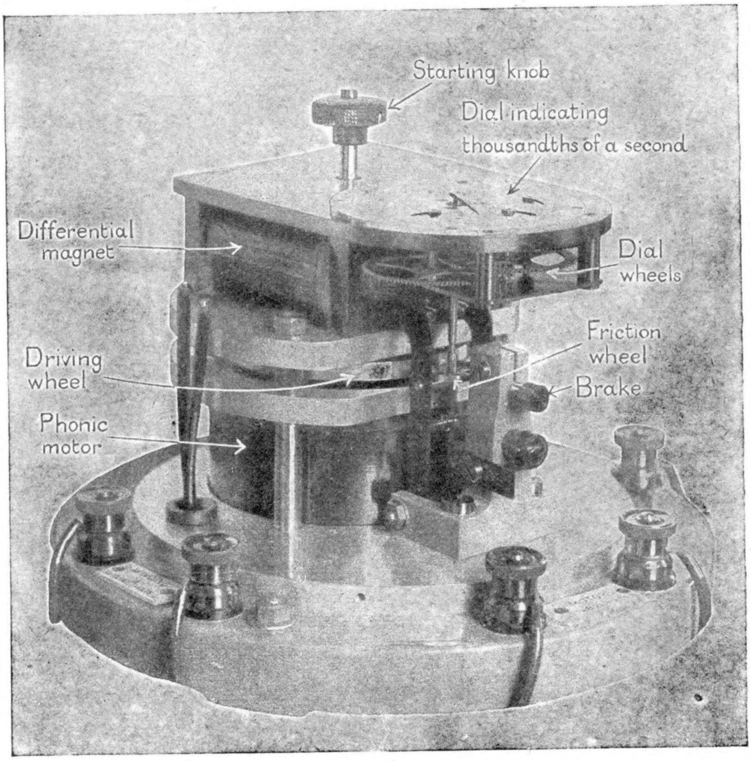


Fig. 6

SINGLE DIAL CHRONOMETER — CHRONOMÈTRE A CADRAN SIMPLE

Starting knob — Bouton de lancement
Dial indicating thousandths of a second — Cadran indiquant le millième de seconde
Dial wheels — Engrenages du cadran
Differential magnet — Electro-aimant différentiel
Driving wheel — Roue motrice
Phonic motor — Moteur phonique
Friction wheel — Roulette à friction
Brake — Frein


TIMING APPARATUS
MADE FOR LOW ENGINEERING Co Ld
82a HIGH St KENSINGTON
BY H TINSLEY & Co
12 VOLTS
PHONIC CHRONOSCOPE
PULL DOWN TO RESET
TRIP RELAY A
PULL DOWN TO RESET
TRIP RELAY B
TRACK CONTACT A
TRACK CONTACT A
TRACK CONTA
CONTACT B
WINDING
MOTOR
25
NING FORK

Fig. 7

position contacts. The final adjustment is made by small alterations, in the position of these contacts by means of the micrometer screw.

The procedure then is to start the Chronoscope on the releasing of the reed, and to start the phenomenon to be recorded when the reed reaches its mid-point, that is exactly 100 milliseconds later than the Chronoscope. In this way the readings of the Chronoscope are made to be just 100 milliseconds greater than the phenomenon under observation, so that this value has to be deducted from the values indicated upon the dials.

VI. APPLICATIONS

The triple-dial instrument was designed primarily for use in marine sound-ranging, but it was early realized that its applications were much wider than this. A single-dial phonic chronometer would be of great value in any experiment where it is desired to obtain an accurate measure of a time-interval of duration greater than, say, a tenth of a second. The *percentage* accuracy of the instrument increases with the length of the time-interval measured, consequently, it is best suited for measurement of comparatively long time-intervals (e. g. a minute), *i. e.* where ± .001 second is considered small.

Phonic chronometers have already been employed in the following measurements:

(1) *To determine the time of fall of a ball under the action of gravity.*

(2) *To determine the time of swing of a compound pendulum — and to find the relation between time of swing and amplitude.*

Results in good agreement with Lamb's theoretical values have been obtained. (See Lamb's *Dynamics*, p. 108.)

(3) *Determination of the velocity of sound in sea-water.* One of the earliest experimental phonic chronometers was used to determine the time of passage of an explosion wave between two receivers about one mile apart on the sea-bed. In a particular experiment the mean time indicated by the chronometer was 1.0945 sec. whilst the distance apart of the receivers was 5356 feet, whence the velocity obtained was 4894 ft. per sec. at a temperature of 11.7° C. — in good agreement with the value, 4897 ft. per sec., obtained more recently by more refined methods (See *Proc. Roy. Soc.* A 103 (1923) 284.)

(4) *Measurement of reaction times* — a psychological example.

(5) *Motor-car speed trials* — a set has been supplied to the Auto-Cycle Union for this purpose.

(6) *Sound-ranging, depth-sounding, and hydrographical survey* — the phonic chronometer replaces more elaborate photographic methods.

(7) *Electrical investigations* involving measurement of quantity (current × time) — a chronometer has been supplied to the N. P. L. for this purpose.

The above examples serve to show that the chronometer has valuable applications in many physical, psychological, and engineering problems involving the accurate measurement of time.

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