THE CLOCK AND STRIKING MECHANISMS FOR THE GREAT BELL OF THE UNIVERSITY OF BRISTOL.

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7th December, 1926.

The Bell.

Among the many munificent gifts of the Wills family to the University of Bristol, not the least is the magnificent block of buildings erected by Sir George and the late Mr. H. H. Wills in memory of their father, Henry Overton Wills, the founder of the University. This fine pile was designed by Sir George Oatley, LL.D., R.W.A., F.R.I.B.A., and was opened by His Majesty the King in July, 1925.

Its outstanding feature is a handsome tower, 54 feet wide by 200 feet high, dominating, from the top of Park Street, most of the ancient city and a considerable portion of the modern one. In the belfry of this tower is placed "Great George," the fourth largest bell in this country. Like "Great Paul" of St. Paul's Cathedral, which is the largest of all the British bells, its note is E flat, the deepest note given by any of them. Its tone is a great sonorous boom, and is supposed to be exceptionally fine.

As a matter of interest, the leading particulars of the other large bells of Britain are given in Table I, compiled from information kindly supplied by the bellfounders, Messrs. John Taylor & Co., of Loughborough.

The belfry floor is 132 feet above the level of the street, which is itself near the top of a hill, facing S.W. The ceiling of the belfry is 61 feet, and the sills of the belfry windows

17 feet above this floor level. By thus placing the bell entirely below the level of the windows, the tone is supposed to be heard at its best, but there is little doubt that the volume of sound emitted is thereby reduced, and some authorities object to the low position for this reason.*

TABLE I.

THE GREAT BELLS OF BRITAIN.

		Date.	Diameter. Ft.	Ins.	Weight. Tons.	Cwts.
1.	Great Paul, St. Paul's	1882	9	6½	16	14
2.	Big Ben, Westminster	1858	9	0	13	11
3.	Great Peter, York	1845	8	4	10	15
4.	Great George, Bristol	1925	8	4	9	11½
5.	Manchester Town Hall	1882	7	7½	8	3
6.	Beverley Minster	1901	7	3	7	1
7.	Birmingham University	1909	7	0	6	2
8.	Newcastle	1891	6	11½	5	18
9.	Great Tom, Oxford	1680	7	0	5	15 ?
10.	Great Tom, Lincoln	1835	6	10	5	8
11.	Downside Abbey	1903	6	10	5	7
12.	St. Paul's (Old)	1716	6	9½	5	2
	Glasgow University	1888	5	8	2	17¾

As the note is considerably below the pitch for which the ear is most sensitive, the range of audibility is much less than that of a shriller note of the same energy. Reports have been received of its being heard, under favourable circumstances, at places 10 or 12 miles distant, such as the hills over Bath. On the other hand, at my house, only 1,000 yards away, it cannot be heard on the ground floor with even a slight breeze from anywhere between N. and E., although on the top floor. from which a clear view of the tower can be had, it can still be heard.

The low note blends with the street noises, and is easily masked by them. For instance, I have frequently missed the

* See reply to Discussion.

middle strokes of 5 o'clock when listening for them at a point in Park Street not more than two or three hundred yards away, owing to a motor-car passing at the time.

(*Photo. John Taylor & Co.*)

Fig. 1.—Great Bell of the University of Bristol, Mounted at the Makers' Works.

Fig. 1 shows a photograph of the bell, with its mountings, taken at the makers' works, and Plate I a scale drawing specially prepared by them for this paper. The alloy is approximately 13 parts of copper to 4 of tin, and further particulars are given in Table II, taken partly from data supplied

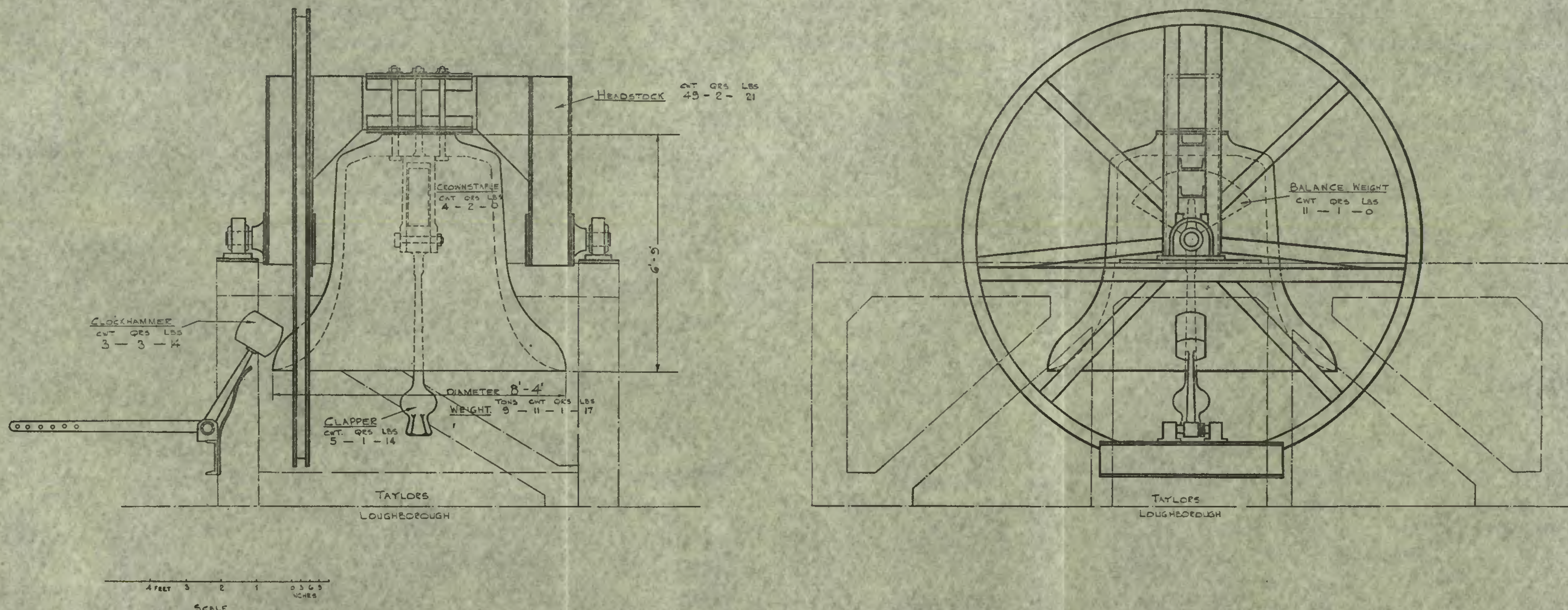


Plate I.—The Great Bell of the University of Bristol.

by the makers, and partly from tests made by my students after the bell was erected in Bristol.

Table II.

Particulars of the Great Bell of the University of Bristol.

Cast by John Taylor & Co., of Loughborough, in 1924. Arrived in Bristol, 4th April, 1925, and erection completed in June. First official tolling for opening ceremony, 9th July, 1925. Began to strike the hours in May, 1926.

Diameter, 8 feet 4 inches. Height, 6 feet 9 inches. Note, E flat.

Weights.	Bell alone - - - -	9 tons	11½ cwts.
	Headstock - - - -	2 ,,	9½ ,,
	Crown Staple - - -		4½ ,,
	Internal Clapper - - -		5½ ,,
	Balance for same - -		11 ,,
	Total weight on Trunnions -	13 tons	2 cwts.
	External Clock Hammer -		4 cwts.

Length of Hammer Rod to Centre of Hammer, 3 feet.
Travel, from 15 down to 30 degrees from vertical.
Vertical lift of Hammer, 4 inches.

Angle of swing, 90 degrees on each side.
Time of double swing, 6 seconds.
Centre of gravity, 3·53 inches below the centre line of trunnions.
Frictional moment cannot hold bell 0·05 degree out of plumb.

The hours are struck by the external hammer, but the bell is also provided with an internal clapper, and is mounted on trunnions so that it can be swung out 90 degrees on either side. These trunnions have roller bearings whose friction is remarkably small, so small, in fact, that it cannot hold the bell out of the vertical by as much as 0·05 degree. Starting with an amplitude of only 12 degrees, which is too little to strike the bell, over 30 double swings are made before the bell comes to rest.

The bell can be, and indeed has been, swung by one man, but as about 20 feet of rope have to be drawn in, or paid out, during the three seconds taken for a single swing, the job is not exactly "light work."

General Outline of the Mechanisms.

When I was asked, early in 1924, whether I could design an electrical machine for striking the hours on this bell, I thought that I had obtained a job after my own heart. I am considerably wiser now with respect to the time required and the difficulties to be overcome, but I had an entirely free hand, both as to methods and cost, and found the task a most agreeable and interesting one.

Since no clock face is provided on the tower, and the belfry is kept locked up and is exposed to the weather through the open windows, I decided to place in the belfry only the machine required to raise and drop the hammer, and to place the timing and counting mechanisms in the main corridor of the ground floor of the tower. Here they are always open to inspection by anyone sufficiently interested to watch them.

The hammer is normally set and held by a latch, which is released at the correct instant by an electro-magnet by means of an electrical impulse sent from the master clock. As the hammer falls, it switches on power for the motor, which drives a crank disc through worm gearing.

The crank pin then makes one revolution and resets the hammer, moving clear before the motor stops. The return of the hammer to the set position switches off the power and puts on the brake, This whole process takes about three seconds.

If the supply of power be interrupted, the hammer will not be reset. Consequently, only the first stroke of the hour will be struck unless the power is restored within the 55 seconds taken by the RA3 contacts to complete the series of 12 contacts.

The bell was used as a time signal on Armistice Day. Power was switched off after ten o'clock, and not put on again until some time after 11, in order that only one stroke should be given exactly at 11 o'clock.

The timing of the impulses is done by a time machine, consisting of two clockwork units which close the contacts at the required instants. One of these units keeps Greenwich mean time; it makes the final contacts for the bell circuit, and controls several other circuits in connection with the automatic control of the pendulum.

The other unit keeps civil time. It carries the stroke counter which determines the number of strokes to be struck at each hour, and controls the hours at which they are to be struck, as well as several circuits for small bells used for indicating the time for beginning and closing class lectures.

The time units are themselves driven electrically from the pendulum, which is the real timekeeper, and lastly, there is the time control apparatus by which the pendulum is regulated in accordance with the Greenwich time signals received daily over the Post Office wires.

An interval of about seven seconds between the strokes was discussed, but at my suggestion a five-seconds interval was adopted as the most convenient for timing purposes.

Every stroke is separately timed directly from the clock, and consequently, the intervals are exact. Thus the first stroke gives the time, but the succeeding ones can be employed for a closer estimate of the fraction of a second, and it is quite easy to compare the time given by the bell with another clock within one-fifth of a second, using a watch with a central seconds hand as an intermediary.

There is probably no other bell whose strokes, after the first, have any pretence to accuracy. The arrangement universally adopted is to have a separate striking train, which, after being released by the clock, takes entire charge of the striking, counting the strokes, and timing them. The striking train is driven by weights against a fan brake, and does not, as a rule, get up full speed before the first stroke is struck, with the result that the interval between them gets shorter as the strokes proceed. This variation of speed throughout the cycle can, to some extent, be compensated by having unequal distances between the teeth of the cam which releases the hammer, but the frictional resistance must always be variable, causing variations in the rate at which the striking train goes after release. These variations will not only affect the intervals between the strokes, but, as they will vary the lag between release and the first stroke, they will also cause irregularities in the time given by the first stroke.

For instance, "Big Ben" gives a five-seconds interval between the first and second strokes, but the interval gradually shortens down to about 4½ seconds between the last strokes of the big hours. In a series of tests I made last September, the actual time between the first and last strokes of 11 a.m. varied from 46½ to 48 seconds, instead of the 50 seconds it should be with an exact interval. It is probable that these times would be different during colder or hotter weather, but this has not yet been checked. Incidentally, during this autumn I have found "Big Ben" habitually 1½ to 2 seconds fast; as the clock is supposed to be kept much closer to time than this, the inference is that the bell is fast by about this amount when compared with its own clock.*

The Striking Machine.

As no precedents could be found for an electrical striking machine on anything like the scale of this one, the design had to be made without any guidance from the experience of others. The first idea was to provide weights which would make it to some extent independent of interruptions in the supply of power, but when particulars of the hammer were obtained this idea was at once abandoned.

To strike 12 o'clock alone would require a nett work of about 1,800 foot-lbs.; allowing for the losses in the machine, about 2 foot-tons would be necessary. The driving weight would thus be of the order of one ton, and if the rope should break and permit this weight to fall several feet, the risk of its crashing right through the floors is too great to be run.

A purely electrical machine was, therefore, adopted, and in the end proved quite simple to design.

The general arrangement is shown in Plate II, and a diagram

* See reply to Discussion.

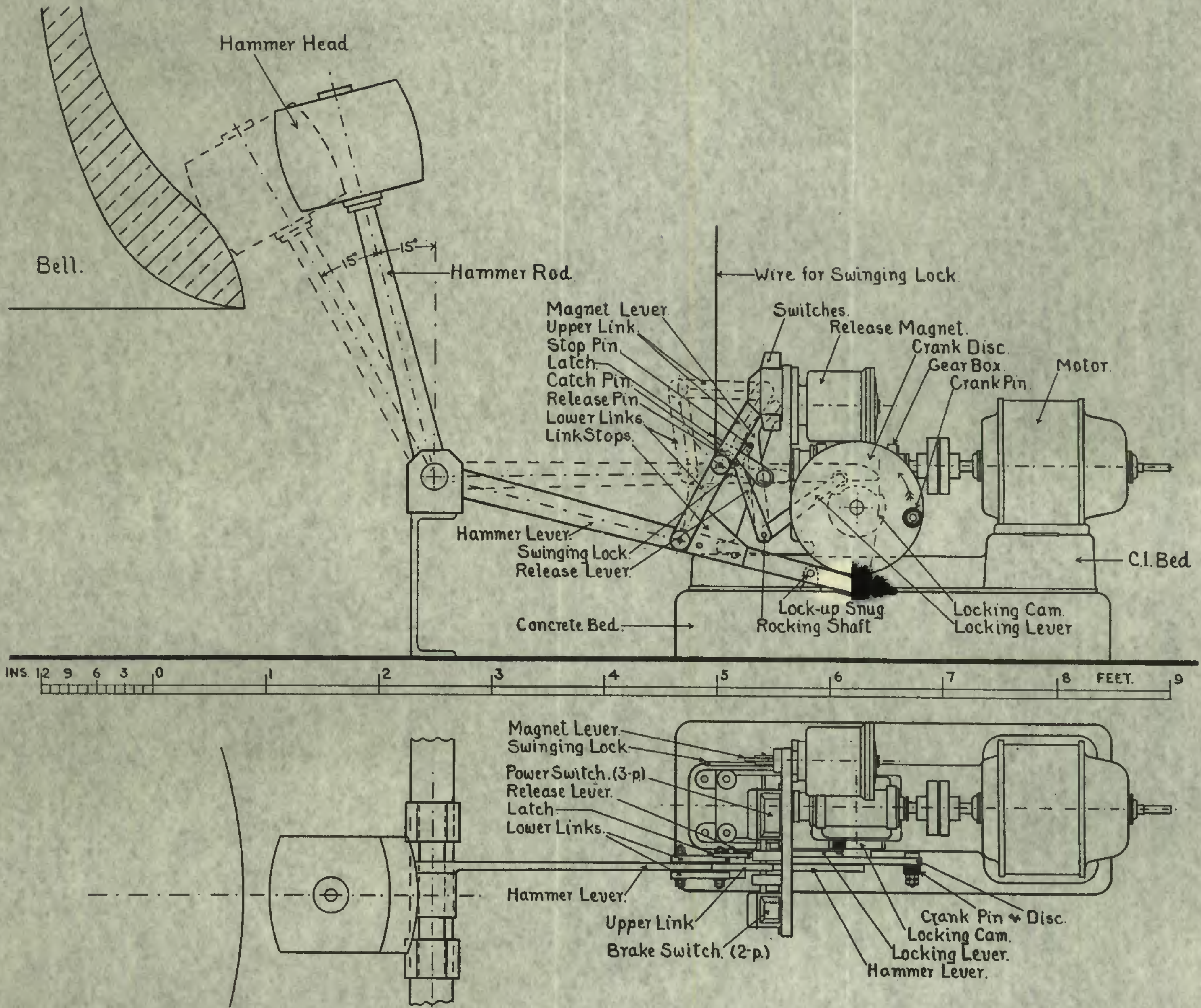


Plate II.—Striking Machine for the Great Bell of the University of Bristol.

of the link mechanisms, etc., in Fig. 2. The relative positions of the motor, worm gear, crank disc, links, switches, and release magnet can be quite easily followed from the former.

The tail lever of the hammer is held down by two links forming a toggle. Stop-plates attached to the hammer lever engage with the bottom link, which is double, and prevent the toggle from quite reaching the dead centre. Consequently,

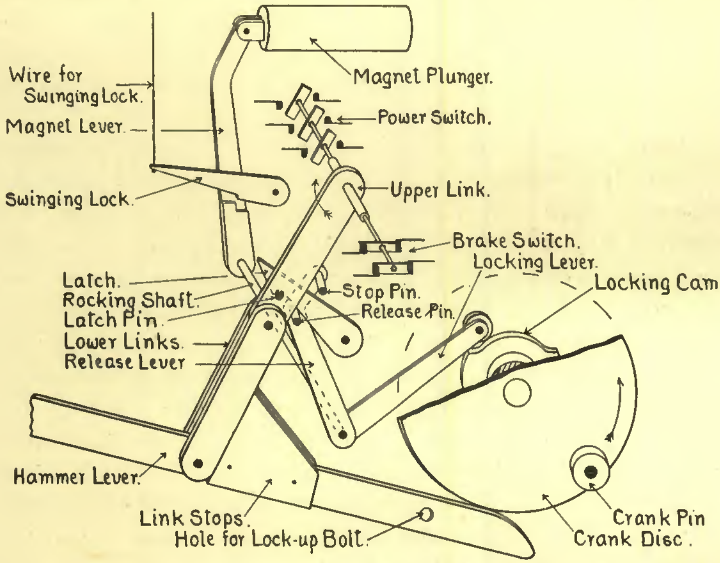


Fig. 2.—Mechanism of the Striking Machine.

the weight of the hammer will throw the toggle out when it is free (see Fig. 2). But a latch holds a pin on the upper link, and locks the toggle in. Through the intermediary of the magnet- and release-levers, and of the rocking shaft connecting them, the magnet plunger pulls the latch clear when the magnet is energised. The hammer then falls, and forces the links out to the position dotted in the elevation given in the plate.

The switch spindles are coupled to the upper link spindle; consequently, the rotation of the upper link throws the three-pole power switch to the "on" position, and the two-pole brake switch to "off."

The motor now starts to drive the crank disc through a $20\frac{1}{2}$ to 1 reduction. The crank pin engages with the end of the hammer lever, and depresses it to the set position; the links meanwhile move inwards until they are stopped at the correct position by the stop-plate already mentioned. This inward motion of the links resets the switches to their former position, cutting off the power and applying the brake. The inertia of the motor carries the crank pin round far enough before the motor stops for it to be quite clear of the path of the tail of the lever when released.

During the rotation of the crank disc, a cam cut behind it resets the rocking shaft, with its attached levers and the magnet plunger. In addition to restoring the plunger, this cam has another function. It acts as a safety lock to prevent the release lever being lifted unless the crank pin is in a clear position. This lock has frequently been called into play.

The links have ball bearings throughout, and, in spite of the great weight of the hammer (4 cwts.), the force needed to release the latch is very small, being no more than $1\frac{1}{4}$ lb. applied to the latch itself, or $3\frac{3}{4}$ lbs. at the magnet plunger. A much smaller magnet would have been sufficient to release the latch, but as that would have been a special design instead of a standard article, it would probably have cost more. Besides this, a smaller magnet would take considerably more power to do the job, and would probably require to be run from the 500-volt mains through relays, instead of being operated directly by the small 24-volt storage battery installed in the building for the private automatic telephone exchange.

For the crank pin and the cam follower, standard ball bearings are employed, with the outer race acting as the rubbing surface.

Since the bell can be swung out as well as struck externally, it is necessary to provide a lock to prevent release by the magnet when the bell is not there to receive the blow, for otherwise the hammer would fall about 4 feet, and then strike the floor. This would certainly wreck the machine, and would probably also do considerable damage to the building. This contingency is met by the swinging lock which is shown at the top left-hand corner of Fig. 2, and which is controlled by the mechanism shown in Fig. 3.

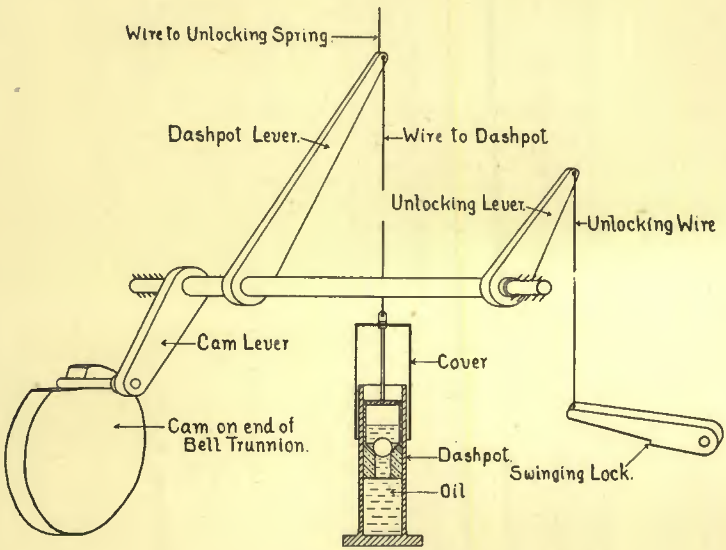


Fig. 3.—Mechanism for Swinging Lock.

Provided the hollow in the cam attached to the bell trunnion is in the vertical position, a spring (not shown) pulls up the dashpot-lever and lifts the swinging lock out of engagement. But as soon as the bell moves away from the vertical, the cam lifts the cam-lever and permits the swinging lock to fall down to the locked position. To guard against the possibility of the toggle being released by an impulse arriving when the bell is passing the zero position whilst swinging (each impulse lasts one second), in which event the bell would move right away before the hammer could reach it, a dashpot is provided to make the unlocking take place very slowly. Thus, to free the swinging lock, the bell must not only be at zero but must have been there for at least half-a-minute. As a further safeguard, a stop (not shown on the drawings) has been added to the hammer, and catches on a steel structure if the bell should fall below its normal position. This has been tried and found effective.

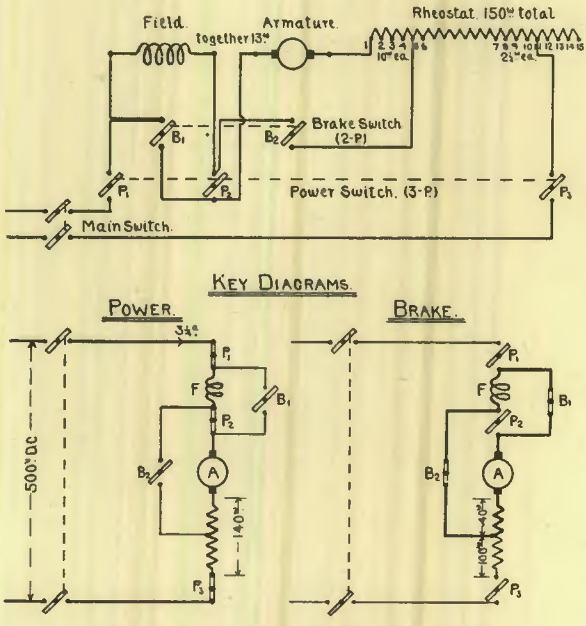
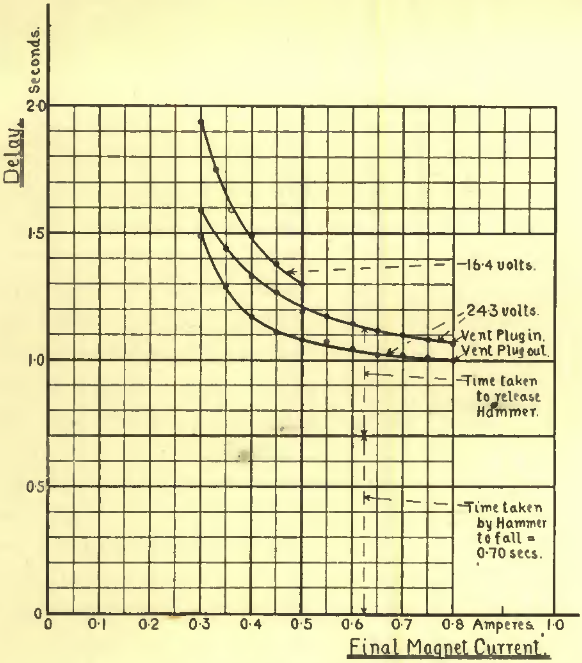


Fig. 4.—Power Circuit for Striking Machine.

Fig. 4 gives the connections of the power circuit, and the key diagrams show the circuits for the two positions of the switches. From these, it will be seen that the braking is accomplished by short-circuiting the motor through a portion of the starting rheostat. The resistance between the two tappings is sufficiently high to prevent any damage occurring if one switch should go on before the other goes off.

Quite a number of trial calculations had to be made before the right reduction ratio was found, and that arrangement was adopted in which the kinetic energy was about the same as the mechanical work done. With too high a reduction, an excessive amount of energy would have to be dissipated on braking, leading to difficulties in stopping, whereas with a low reduction the kinetic energy would be so low that variations in friction would cause too great variations in the time taken to perform the cycle.



(From tests by G. Bishop and A. E. O'Neill.)

Fig. 5.—Release Characteristics of Striking Machine.

The motor reaches a maximum speed of about 900 r.p.m., and must be stopped in about four revolutions. With a mechanical brake held off by a magnet, it would have already made these revolutions before the magnet could release the brake.

The release characteristics are given in Fig. 5. The hammer takes a constant time of 0·70 second to fall on the bell, but the time taken by the magnet to release it varies according to the current and voltage employed.

In the tests shown in this diagram, the current was set to a definite steady value by means of rheostats, using the specified battery voltage. The same switch which closed the release circuit started an electrical chronometer, which was stopped by the hammer opening another contact when it reached the bottom of its stroke.

The chronometer was made many years ago by adapting a meter of the shunted commutator type, known as the Westinghouse, type O. The shunt was removed, and a series resistor added sufficient to make the speed of the disc one revolution per second. A scale of 100 divisions round the disc gives hundredths of a second, and another on the next spindle gives the whole seconds. The starting and stopping errors of the instrument itself mutually cancel, and the instrument has proved of great service in a number of investigations.

This meter is now obsolete, which is unfortunate from my point of view, as I want more. If any reader should know where one or two can be obtained, I should be very glad indeed to hear from him.

The time taken by the hammer to fall was measured in a similar way, but in this case the chronometer circuit was closed by the release of a contact held off by the hammer when in its set position. The minimum release current is a little under 0·3 ampere. With the rheostats set for a larger current, the plunger begins to move before the current has reached its full value, and its acceleration at each point is greater; consequently, the release is quicker.

With different battery voltages, different amounts of resistance are needed to give the same current. Consequently, the time constant of the circuit (inductance divided by resistance) is smaller, and the current grows more quickly with the higher voltage, although the final value of the current may be the same for both. Thus the release with a given final current is quicker the higher the voltage employed.

Fig. 6 illustrates the machine whilst it was being tested in the laboratory last February, when the bell was represented by a large block of oak, which stood up well to the blows.

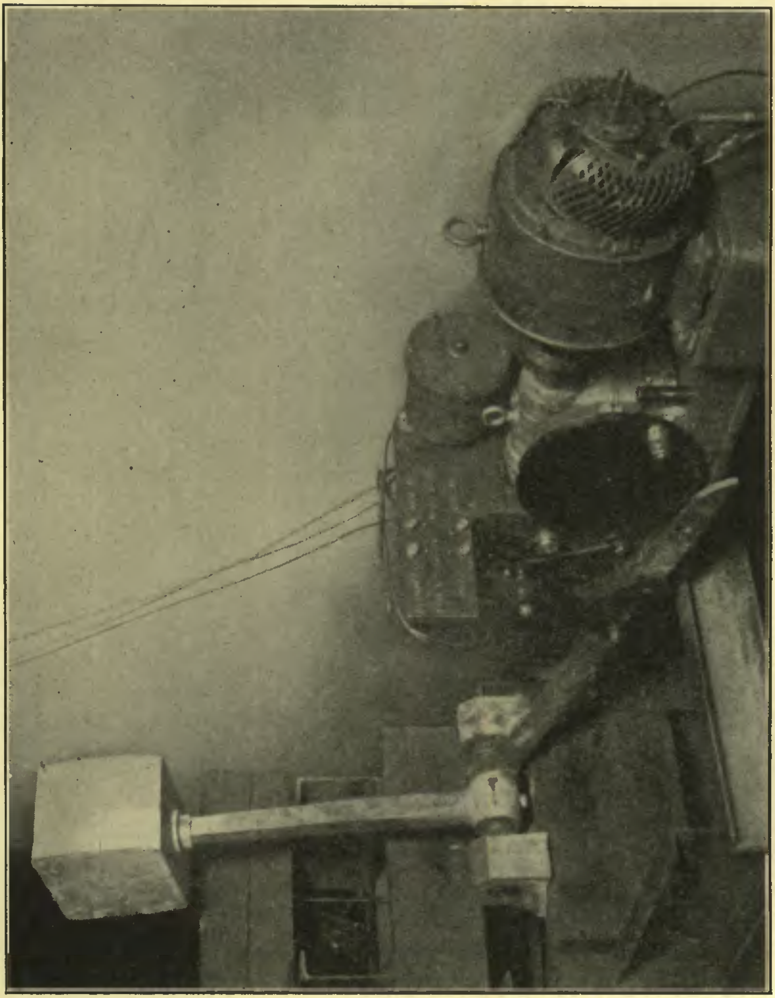


Fig. 6.—Striking Machine Under Test in the Laboratory.

(Photo. Bristol Times and Mirror.)

The floor at this part of the laboratory is on solid ground. It has not been possible to get a useful photograph of the machine

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in its permanent position, owing to the obstruction of the housing for it and the other building structures.

The cost of the energy taken to drive the machine is entirely negligible. It takes about 1,600 watts for 2½ seconds each stroke, or about 50 kw.-hr. per year, costing, say, 1½d. per week.

This machine has given very little trouble. The preliminary tests showed the desirability of adding a stop to limit the outward travel of the plunger, as otherwise it was possible to get the latch so low that the latch pin came down above it instead of below. Steel stops were, therefore, added outside the magnet, but they had to be changed for brass, as the leakage flux was sufficient to make the plunger hold to the stop against the pull of the magnet. It was also decided to increase the diameter of the rocking shaft because of the heavy duty on it when the cam happens to be made to pull the plunger out whilst the magnet is excited.

A few trial strokes were struck on the bell on 1st May, and regular use started a few days later. After running for some time, saddle keys which had been put on the rocking shaft by mistake, had to be changed for sunk keys, as originally intended.

About the end of June the bell started occasionally to strike double, the hammer falling again as soon as it was reset instead of waiting for the impulse. This was caused by the stop-plates for the links having moved by the amount of the clearance in the bolt holes, which had not been fitted to the bolts. The links then had some play between the stops and the latch, and both links and latch rebounded, the rebound of the link sometimes missing the latch owing to the rebound of the latter. Fortunately this only happened occasionally, or the bell would have kept on striking until the power was switched off. Dowels fitted into the link stops cured the trouble.

The flipper springs on the three-pole switch broke consecutively in July, August, and September, and had to be replaced. This did not put the switch out of action, but it made the instant of opening uncertain, with the result that the motor would now and again stop too soon, or run too far, according to the particular blade affected. The result was that the machine was tied up by the safety cam, and would not strike again until the crank had been set by hand to the correct position. When the first spring broke, it was some time before the cause of the stoppage was diagnosed, for by a curious coincidence it seemed to occur mostly at 8 a.m., just when the factories are starting up their machinery, and when the supply voltage might be expected to be a little irregular.

The new springs in this switch, and also the original springs in the other switch, have so far stood up to their work, and given no further trouble,* but it may be necessary to replace the switches by a special drum switch which does not depend on springs, for the duty upon them is much more severe than that for which they are intended. The switches are operated 118 times per day, or 43,000 times per year, which is rather trying for the springs.

During the summer the glands on the gear had been tightened. When the cold weather came the friction increased, until it got big enough recently to stop the motor too soon.

A snug is provided on the bedplate, to which the hammer lever can be bolted by a locking bolt kept handy for the purpose. The hammer can thus be locked up, and the machine made safe to handle when any cleaning or other work has to be done on it. The whole machine is enclosed in a lock-up room built round it in the belfry, large windows being provided so that it can be watched by visitors without their having access to it. It is thus protected from the weather and from interference.

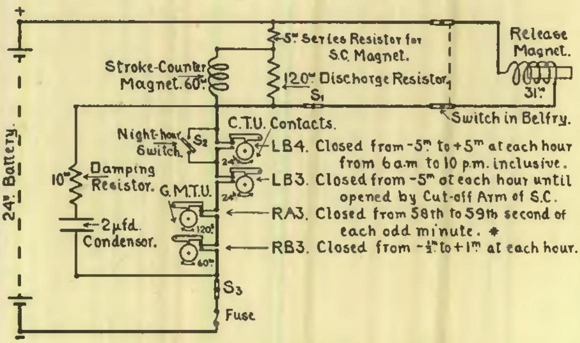
So far as it was possible to do so, standard apparatus has been employed in the construction of the striking machine; the makers of these parts, which were all obtained before the machine had been drawn out, are as follows:—Motor, Electrical Construction Co., Ltd., Wolverhampton; reduction gear, Henry Wallwork & Co., Ltd., Birmingham; switches,

* See reply to Discussion.

J. Crabtree & Co., Ltd., Walsall; release magnet, George Russell & Co., Ltd., Motherwell. The special parts were made by Messrs. Olver & Fry, Bristol, who assembled everything together and erected them at the Merchant Venturers' Technical College for testing, and again in their final position in the tower.

The Release Circuit.

From Fig. 7 it may be seen that there are four timed contacts in the release circuit of the striking machine. These



(* *And at 5 seconds intervals up to 12 times.*)

Fig. 7.—Release Circuit for Striking Machine.

contacts form parts of two clockwork mechanisms, of which one keeps Greenwich mean time and the other civil time.

During the winter months these two units indicate the same time, but only the civil time unit is advanced or retarded with the advent or end of summer time. This arrangement is necessary because the time at which the daily time signal from Greenwich, which is used for controlling the clock, is received remains at 10.00 Greenwich mean time throughout the year. The use of two separate units independent of one another has also proved convenient in other ways, as each forms a check on the other when any changes are being made, and either may be put temporarily out of commission without losing the time.

Each unit has three main drums for controlling the contacts, and two intermediate spindles for gearing them together. The first drum of the Greenwich mean time unit is driven by the seconds contact of the pendulum magnet, and makes one revolution in two minutes. This provides for the 55 seconds required to strike 12 o'clock, with a sufficient margin on each side to permit the slower contacts to come into play with certainty during the dead part of the revolution. The other drums on this unit revolve once in one hour and once in 24 hours.

The civil time unit is driven by the half-minute impulses from the pendulum; its drums make one revolution in one hour, 24 hours, and seven days. The last-mentioned drum is not required for the bell, but is employed to cut off certain other circuits at the week-ends.

Referring again to Fig. 7, the bottom two contacts are on the Greenwich mean time unit, and the other pair on the civil time unit. During each two minutes, and beginning at the 58th second of the odd minute, contact RA3 is made 12 times, corresponding to the 12 strokes of noon, at intervals of five seconds. The contacts are advanced two seconds on the instant at which the stroke is due, in order to allow for the various delays which occur before the hammer strikes the bell. There is the time taken for the magnet to release the latch, and the further time for the hammer to fall as already explained, but in addition to these there is a delay on the clock itself. The contact levers on the time machine do not begin to drop until the armature of the driving magnet returns after the pendulum contact is broken, whereas the time compared with the time signal is that given by the make of that contact, a difference of about one-third of a second.*

In addition, there is, of course, the time taken by the sound to travel from the bell to the point of observation, amounting to one second for each 370 yards, or 4·8 seconds per mile. With the two seconds advance of the contact, the bell is heard at the bottom of the tower about 0·4 second

* See reply to Discussion.

ahead of the clock.* A growl, which is caused by the blow given to the building when the hammer falls and is transmitted through the masonry, can be perceived just before the sound of the bell arrives.

Contact RB3 picks out the particular two minutes of each hour during which striking is to take place, being made about half-a-minute before the hour, and opened before RA3 begins a fresh series of contacts.

LB3 is the contact used with the stroke counter; it is closed a few minutes before the hour, and cuts off, as will be explained later, when the number of strokes struck corresponds to the hour indicated by the civil time unit.

The remaining contact, LB4, separates the hours which are to be struck (6 a.m. to 10 p.m. inclusive) from those which are to remain silent. It can be short-circuited by closing a small tumbler switch if at any time it is desired to strike throughout the night.

The arrangement of the spark-suppressing resistors and condensers should be noted. The non-inductive discharge resistor has approximately four times the resistance of the magnet coils, and thus limits the rise of voltage across these coils, when current is switched off, to four times the working voltage. The condenser has to be charged before the voltage across the contacts can rise when they open; consequently, some current is diverted away from the spark, whose intensity is thereby reduced. The energy stored in the magnetic field is thus partly dissipated in the discharge resistor, and partly stored in the condenser, only a small part being left to damage the contacts.

The damping resistor in series with the condenser prevents sparking when the contact is closed. So long as the contact is open, the condenser is kept charged to the full battery voltage, and it is discharged through the contacts when they come together. Without the resistor, the resistance of the discharge circuit is low, the current is momentarily very large, and the energy stored in the condenser is mainly spent in

* See reply to Discussion.

heating the contacts and in the spark which is formed just before they quite touch. The resistor restricts the current and absorbs most of the stored energy, thus protecting the contacts.

The magnet of the stroke counter is connected in parallel with the release magnet, so that both receive current together. The stroke counter thus counts the number of times the bell has been told to strike, not the number of strokes it actually does make. The particular way in which the stroke counter magnet is connected to an intermediate point on the discharge resistor of the release magnet has no special significance; it was adopted simply because the former magnet did not need such a large current as it would receive if connected straight to the battery like the latter one.

Tumbler switches in the circuit enable it to be broken entirely, or the bell to be cut off while the stroke counter is left running. There is also an ironclad switch in the belfry, by which the circuit can be entirely disconnected from the release magnet if it is desired to prevent impulses arriving whilst work is being done on the striking machine.

THE TIME MACHINE.

The time machine, and also the pendulum, were made in Bristol by Messrs. Brecknell, Munro & Rogers, Ltd., their mechanic, Mr. E. C. Hillier, being responsible for the fine work and the assembly. The final adjustments were made by trial in my laboratory and after the machine was in service. Wherever admissible the parts were made of gunmetal, and wherever possible they were polished and finished in Florentine bronze. The result is a very handsome piece of machinery.

Except that the civil time unit carries the stroke counter, the two units of the time machine are generally similar, but reversed left for right in order to bring the terminal boards next the outside of the case for both of them. Small side doors in the case give easy access to the terminals, with out any danger of disturbing the pendulum.

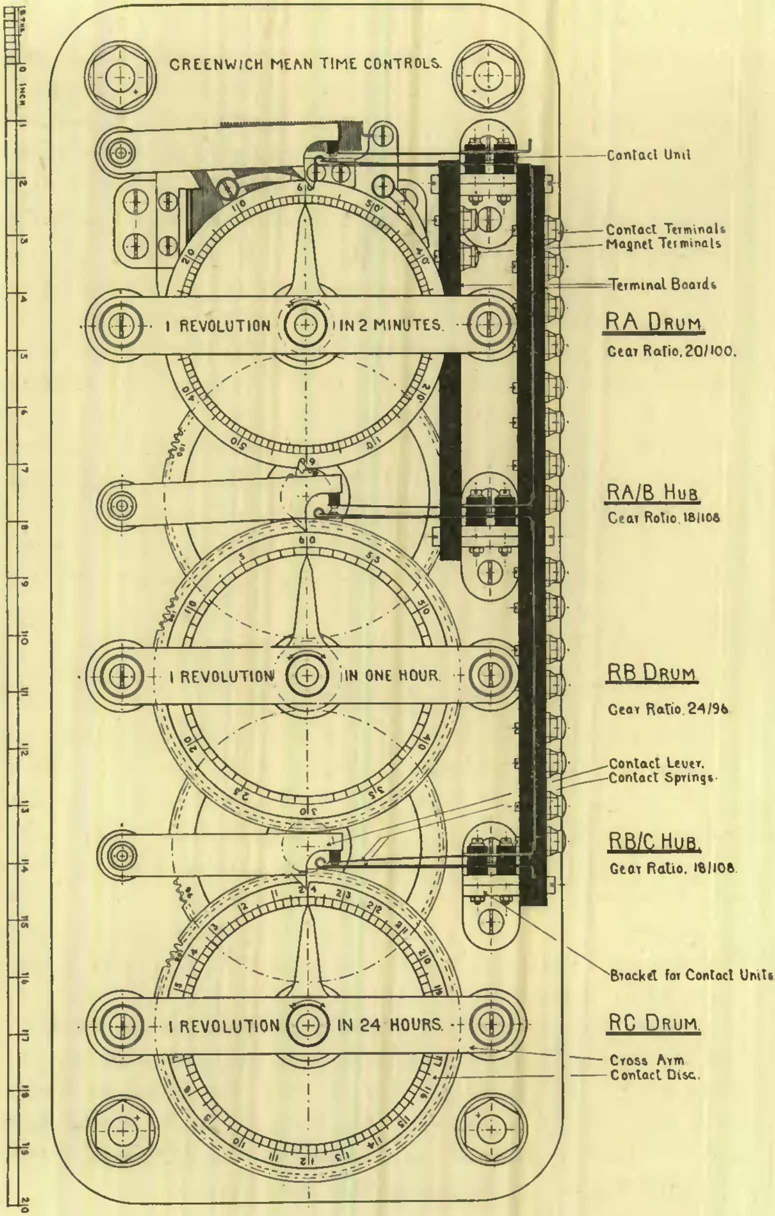


Plate III.—Greenwich Mean Time Unit. Front Elevation.

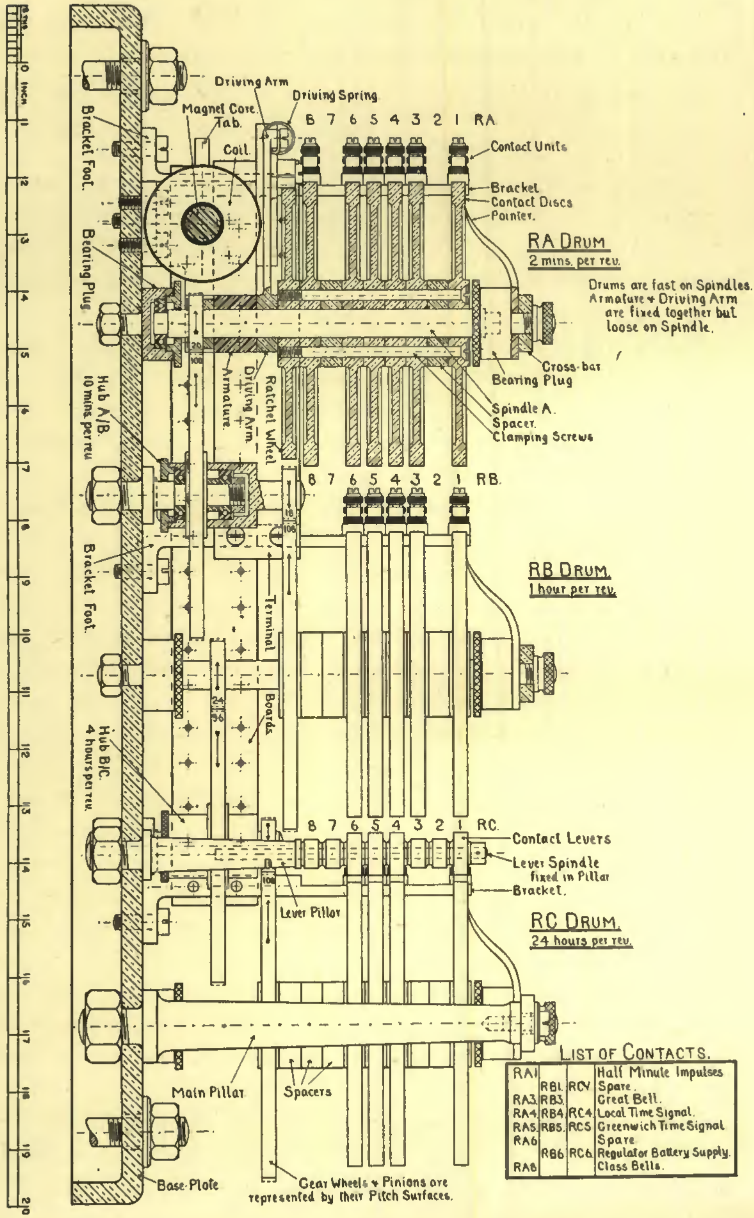


Plate IV.—Greenwich Mean Time Unit. Sectional Side Elevation.

The ratchet wheel has 120 teeth in both units, and the numbers in the reduction gears are as follows:—

Greenwich mean time unit - 20:100, 18:108, 24:96, 18:108.
Civil time unit - - - 24:96, 18:108, 40:80, 28:98.

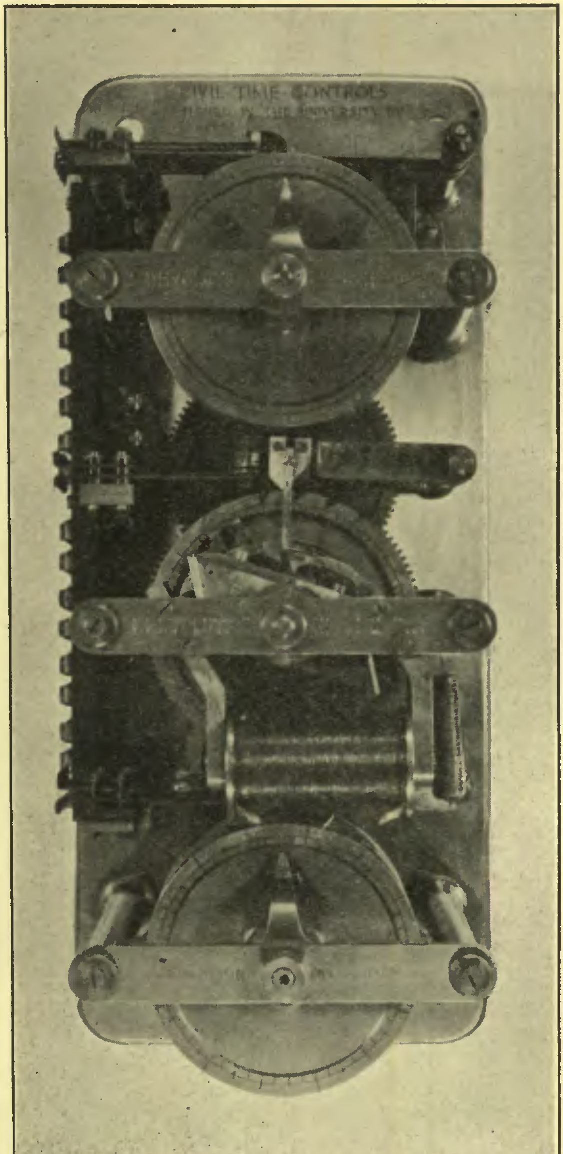
Both units have thus the same distances between the wheel centres, and only two such distances are employed, namely, 3 inches from drum to intermediate spindle, and 3·15 inches from the intermediate spindle to the drum, going downwards from the top.

Plates III and IV give elevations of the Greenwich mean time unit, and from the former the way in which the contacts are made can be seen quite readily. The drums comprise a number of contact discs, each notched at the place or places where its contact has to be made.

Contact levers, carried on side pillars, have pallets near their ends which ride on the periphery of the discs and drop into the notches as these arrive at the vertical position; they are afterwards lifted by the sloping sides of the notch. Ivory pegs on the lever ends hold the platinum pieces on the ends of the contact springs against one another whilst the lever is down. The bottom lever in Plate III is shown in the down position with the contact closed, and the others in the up position with the contact open.

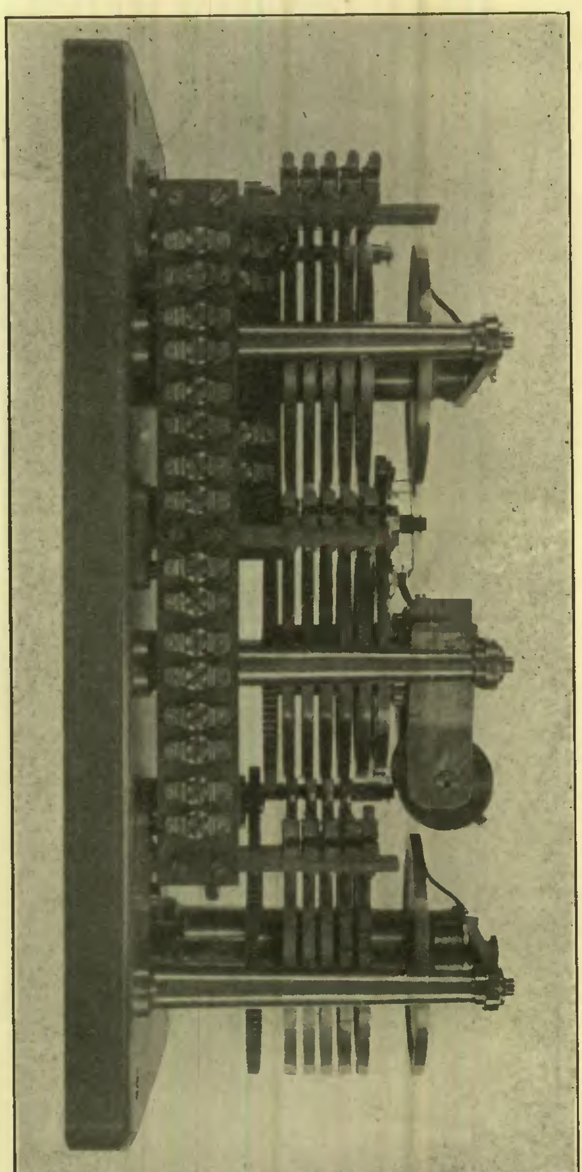
Each pair of contact springs, together with its ebonite insulating washers, is mounted on a small metal plate as a complete unit, which can be detached from the supporting bracket by removing the two little nuts below. Each set of three, or as many of them as the particular circuit may require, are connected in series (except those for the Post Office wires, which are in parallel) to the corresponding pair of terminals on the terminal board at the right. A front view of these terminals can be seen in the illustration of the civil time unit given in Fig. 9.

The principle of keeping the electrical circuits completely insulated from the frame has been strictly adhered to, both in these units and in the pendulum mechanisms. Electric



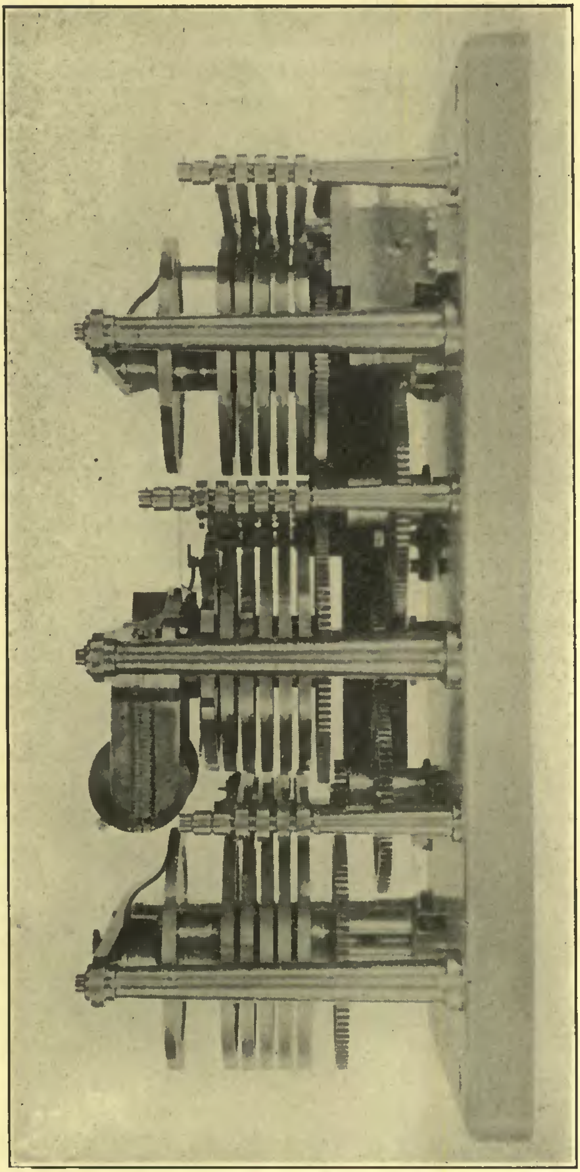
(Photo. Brecknell, Munro & Rogers, Ltd.)

Fig. 8.—Civil Time Unit. Front View,



(*Photo. Brecknell, Munro & Rogers, Ltd.*)

Fig. 9.—Civil Time Unit. Left Side.



(Photo. Brecknell, Munro & Rogers, Ltd.)

Fig. 10.—Civil Time Unit. Right Side.

clockmakers are rather fond of employing the frame itself as one pole of the circuit, which is rather apt to lead to unexpected fireworks and consequent damage when anything is moved, and may lead to other troubles by earthing the circuit, for ordinary masonry, and especially reinforced concrete constructions, are far from being insulators. In fact, although the wall upon which these machines are fixed has been perfectly dry for years, it is quite a fair conductor.

Details of the driving magnet are given in Plate V. The chief advantages of the diamond form of armature there shown are, that it gives a neat concentric arrangement, and that it is possible to make an approximate calculation of the torque it will give with a specified excitation of the magnet. The large end plates of the magnet have the disadvantage of causing considerable magnetic leakage, which is rather difficult to allow for in the calculation. The total gap in the iron circuit when the armature is down must not be less than 5 to 10 mils per inch length of iron, or the residual magnetism may hold the armature down against the restoring spring. The setting of the back stop provides for this gap.

In the driving magnets of these units, but not in the later magnets of similar pattern used for the stroke counter and pendulum, there are also thin pieces of brass attached to the faces of the poles. When the Greenwich mean time unit was first run for the preliminary tests, one of these brass sheets was struck by the heel of the armature at a place where the motion is nearly tangential, and caused a very curious sort of wear. The iron and brass were marked as if they had been corroded by acid, and there was formed a quantity of very fine black dust, which found its way into all the places where it could be most objectionable. There was a lot of trouble with the drive of this unit, owing to the first reduction being too tight. It seemed quite free at first, but developed a tendency to stick at one part of the revolution, which gradually got worse. The dust mentioned above had caked into the teeth, but even after cleaning them out, and easing one tooth in the pinion, which seemed to have got sprung a bit by the insertion of the set screw which fixes it to the spindle, the same trouble developed again several times, and in the end the distance between the centres had to be increased a few mils.

Shortly after this was done it began to miss again, but only once in a few tens of thousands of impulses. When tested, the gears seemed quite free, and everything appeared to work quite correctly with a reasonable margin. At last we were lucky enough to see it actually happen when both Mr. Roberts and I were watching it, and found that the pawl failed to drop in. On taking out the drum, we found that the tooth at the place where it had missed had got slightly burred, probably when inserting the drum on the previous occasion, and that this burr sometimes held up the pawl.*

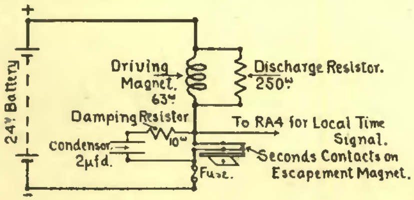


Fig. 11.—Driving Circuit for Greenwich Mean Time Unit.

Figs. 8, 9, and 10 illustrate the civil time unit, for which no separate assembled drawings have been made. The extra magnet, etc., in front are for the stroke counter, which is described in the next section. The photographs were taken in the makers' works when the machine was first assembled in the rough, and differ in some details of the stroke counter from the final design.

The driving circuit for the Greenwich mean time unit is shown in Fig. 11. The contact is part of the escapement magnet of the pendulum to be described later, and the spark suppressors are similar to those already discussed.

The civil time unit is driven by a similar circuit, which also contains the master dial in the clock case, but here the contact, operated by the same magnet as the other, is made once every half-minute only.

* See reply to Discussion.

THE STROKE COUNTER.

Much thought was given to the method of counting the strokes. The rack and locking-plate methods employed with mechanical clocks did not seem to fit in neatly with the electrical scheme, and I had a feeling that some sort of concentric arrangement must be possible. In the end I succeeded in finding it.

The principle of the new stroke counter can be described with the aid of Fig. 12. The front disc on the 24-hour drum

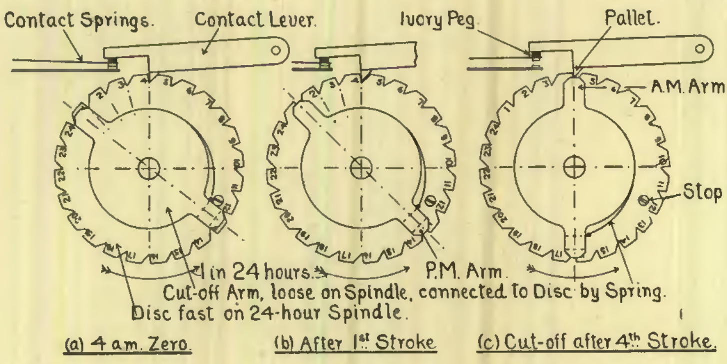


Fig. 12.—Action of Stroke Counter.

of the civil time unit is notched at the hours to be struck, with deeper notches than usual. In front of it a cut-off arm is mounted loose on the same spindle, but attached to the drum by a long spiral spring which holds it against a stop on the drum, so that normally they both revolve as one piece. The pallet of the contact lever for this disc projects in front so as to overlap the cut-off arm, and falls into the notch, making the contact in the usual way at a few minutes before the hour, as the notch comes round to the top position.

As we have already seen, the magnet of the stroke counter is excited when the release circuit for the striking machine is closed. This magnet operates a ratchet, which drives the cut-off arm backwards, one tooth at each stroke, by means of a ratchet wheel fixed to the cut-off arm, but not shown in Fig. 12. As the wheel has 24 teeth, one for each hour of the 24 taken by the drum to revolve, the number of strokes required to bring the cut-off arm to the vertical, where it opens the release circuit and prevents further impulses being sent, will be the same as the number of hour spaces between the initial position of the cut-off arm and the vertical, and this will agree with the hour indicated by the scale on the drum if the stop is properly set. The arm is made double, so that one end comes into play during the a.m. hours and the other during the p.m. hours; in this way the series of strokes begins again at 1 at 13 o'clock instead of proceeding right up to 24 at midnight, as it would do with a single radial arm.

Actually the zero position of the arm must be at 24½, not at 24, in order to leave the notches clear for both 12 and 1 o'clock. But this is allowed for by setting the driving pawl so that the first stroke only drives the wheel through one-half the tooth pitch, which brings the cut-off arm directly opposite the notch for 1 o'clock. Subsequent strokes drive a whole place at a time.

A detent on the ratchet wheel holds the cut-off arm in the vertical position while the drum revolves to mark the flight of time. After a little the sloping side of the notch lifts the pallet, and the cut-off arm is no longer needed to do so. A further rotation raises the pallet higher, and lifts the pawl and detent by means of a slotted link from the contact lever to the detent, until they clear the teeth. The cut-off arm then flies back to its zero position under the action of the spring, and it is ready for the next hour. This takes place just before the quarter-past.

The left-hand diagram of Fig. 12 shows the condition just before 4 o'clock begins to strike. The middle diagram shows the change of one half-place brought about by the first impulse, and the right-hand diagram how the cut-off arm opens the circuit when it gets to the vertical position after the fourth impulse.

Full details of the stroke counter are given in Plate VI; the details of the pawls and lifter can be easily followed in the elevation given in Fig. A of this plate with the aid of the detail drawings C, D, and E.

The stroke counter gave more trouble than any other part of the mechanism. First of all, several trials had to be made to get the right spring for restoring the cut-off arm to zero. This spring has to permit over half-a-turn of movement to the cut-off arm without being so slack at the beginning that it fails to return the arm against friction, or so tight at the end that the armature spring cannot drive against it. We cannot avoid the latter by making the armature spring too strong, or difficulties are encountered with the arm overshooting at the early impulses. The first spring was of round wire, but the turns wedged together and jammed the arm. The final spring was of strip, and worked better, but still jammed a bit when tight. A retaining disc fixed to the drum in front of the spring improved matters considerably, and when it was coned out slightly to give more room for the outer turns than for the inner ones, that difficulty was solved, but only to leave us free to attend to others.

The mechanism then seemed to work quite well when the armature was depressed and released by hand. But when operated by current the release was sharper, and the blow on the pallet at the cut-off position caused the lever to bounce far enough to lift the pawls and allow the wheel to slip back a tooth or two. The lever was then altered to the arrangement shown in detail in Fig. C, Plate VI. The pallet was divided into two parts, of which the one which engaged with the cut-off arm was rigidly fixed to the lever, and the other, which rides on the disc, was merely located relatively to the lever by a very light spring. The pawl lifter is attached to the latter portion of the pallet, and now the lever can bounce as much as it likes without lifting the pawls.

The armature is returned by a spring against a dead stop, but I have not been able to devise any such stop for the cut-off arm which would not interfere with the release of the pawls afterwards. The inertia of the cut-off arm must, therefore, be kept so low that the arm will not overrun far enough for

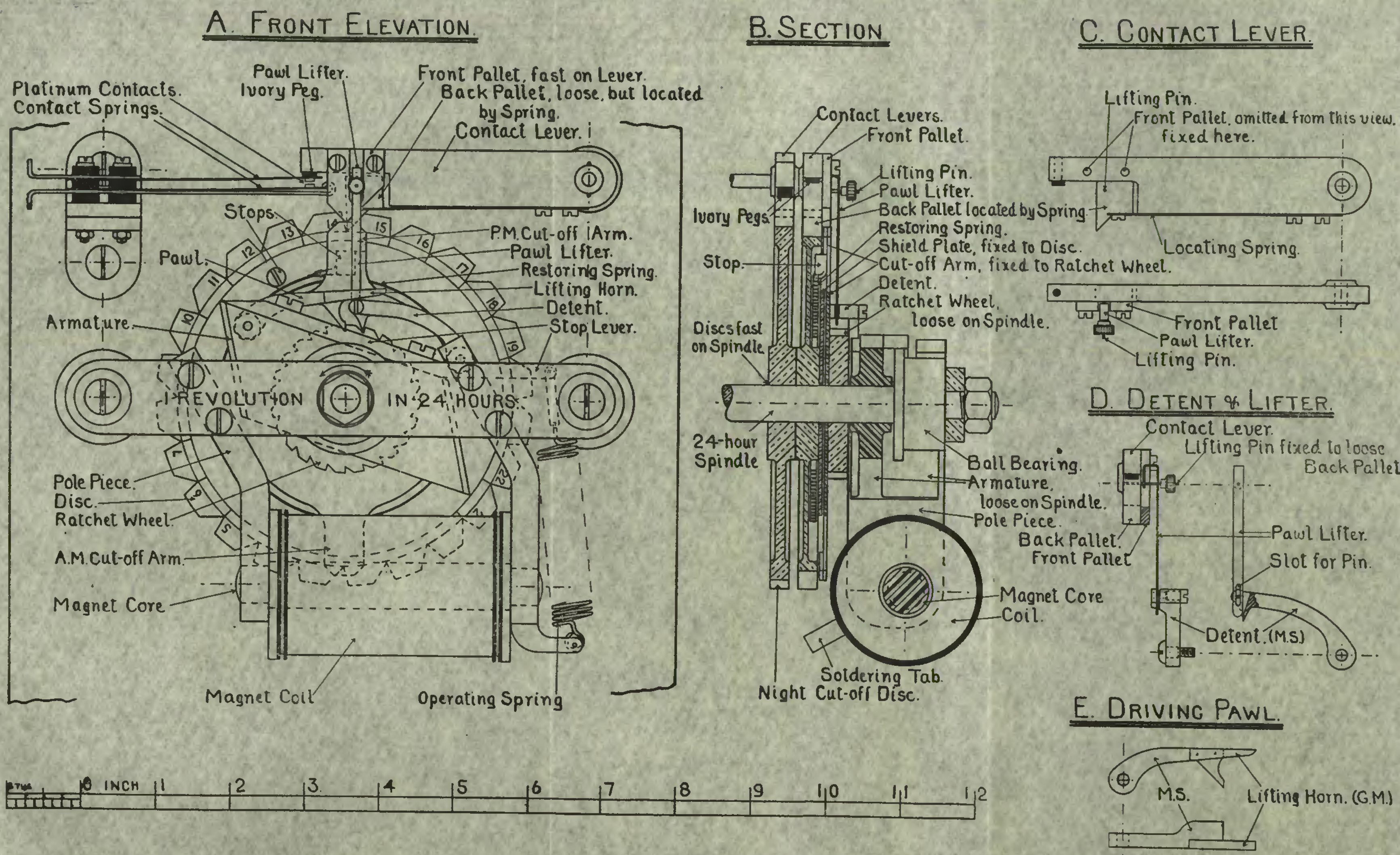


Plate VI.—Stroke Counter.

the detent to gather one more tooth than it ought. This is particularly liable to occur at the first stroke, because then the restoring spring is at its slackest, and the amount of movement of the arm before engaging an extra tooth is at a minimum, and the armature has a free movement of half-a-place before engaging with the arm, and consequently gives the latter a blow.

The first cut-off arm was, therefore, made with a boss reaching out only to the bottoms of the teeth of the ratchet wheel, and with the arms themselves perforated by large holes. This one is shown in place in Fig. 8. But the side play of the pawls allowed them to get mixed up with the arm; this did not happen during the preliminary trials, which were rather short, but caused the bell to strike anyhow, up to 12 strokes at each hour, during the first week-end it was put into service.

A new arm was, therefore, made with the circular boss carried out beyond the tips of the pawls, so that the actual arms are quite short. This got over the one trouble, only to land us in a new one. The inertia was too great, and overshooting, leading to counting the first stroke as two, frequently took place. Worse still, if the armature spring was rather tight, the overshooting at 1 o'clock would carry the arm right past the pallet, allowing it to drop again, when 12 would be struck and the machine get a bit mixed up.

However, by grooving out the ratchet wheel, which is fairly thick, and cutting some unnecessary material off the arms, it was found possible to adjust the armature spring so that the operation became perfectly certain. But the adjustment was like steering between Scylla and Charybdis; to go too far in one direction meant failure through overrunning, whereas to get beyond the line on the other side meant failure to drive the cut-off arm home at the big hours.

A very curious and unexpected thing was discovered whilst making these adjustments. The bell was cut off, but the stroke counter left on. By depressing the other contacts by hand, the final contact RA3 would operate the stroke counter 12 times every two minutes, so that many trials could be made between the hours. It would then work perfectly, and we would switch on the bell just before the hour. But when the bell was working, the stroke counter would start overrunning again. This was repeated over and over again with the same result.

It seemed rather difficult to see how a mechanical trouble in one machine at the bottom of the tower could be affected by electrical connection to another at the top, but the explanation is really quite simple. The release magnet is much bigger than the stroke counter magnet in parallel with it, and is able to reverse the current in the latter momentarily, with the result that the residual magnetism is wiped out more effectually than it otherwise would be. Consequently, that part of the energy given to the armature by the spring which is otherwise spent in overcoming the pull of the residual magnetism is, partly at least, spent in giving a greater velocity to the armature and cut-off arm, thus increasing the tendency to overshoot.

A second stop screw was added to the disc so as to restrict the movement of the arm to about 13 places, in order to prevent the spring being broken by overwinding if the arm should get past the pallets for any reason, such as the lifter failing to release the pawls. Such failure did actually take place once or twice owing to fouling between the stop-plate at the back of the cut-off arm and the second stop. This carried the arm round with the drum after striking 12 o'clock, putting so much pressure on the detent that the friction was too much for the slender pin carrying the lifter.

The reduction ratio (24:1) from the driving magnet of the civil time unit to the 24-hour spindle was sufficient to enable the main driving spring to break off the end of the pallet and to break the cut-off arm (the original one with slotted arms) at one side.

The first pawls (of which the breakage of the driving one has just been recorded) were of brass, with steel pallets soldered in. New ones of improved shape and entirely of steel were then substituted, but it was found that the attraction between the pawl and detent was sufficient to prevent the armature going down. The lifting horn was then made of brass, but even then the face of the pawl had to be hollowed out very considerably before we could with certainty eliminate the tendency to jump up to the detent and stick there as soon as the magnet was excited.

Figs. D and E of Plate VI give details of the final design of pawls and lifter. The latter is attached to the detent through a slotted hole, which gives the freedom necessary for the detent to ride over the teeth as the wheel is moved. The horn on the pawl rides on the top of the detent, so that both rise together when the lifter comes into action.

Originally the stroke counter disc was slotted for the hours from 6 a.m. to 10 p.m. only, but before it was put into service the notches were cut for the remaining hours. At a later date the next disc on the same spindle, which was a spare, was cut for the former hours, and was utilised to give the option of either ringing at night or not, without altering the machine, as already explained.

The stroke counter is fixed on the middle bar of the civil time unit, as may be seen from the photographic illustrations, two discs being omitted to give room for the cut-off arm and the armature, which is hollowed out to utilise the space surrounding the bearing plug.

The Pendulum.

We now come to the actual time-keeper, the pendulum, whose construction is shown in Plate VII. With the possible exception of the method of attaching the rods to the bob and headstock, it is probable that none of the features of the pendulum itself is new, although it is likely that they have never been all combined together before. The use of two rods is certainly unusual, and was adopted to enable the driving forces to be applied centrally without the use of a crutch, but it also has some advantages with regard to the method of fixing the bob to it, and in exposing the whole length of the rod to the air.

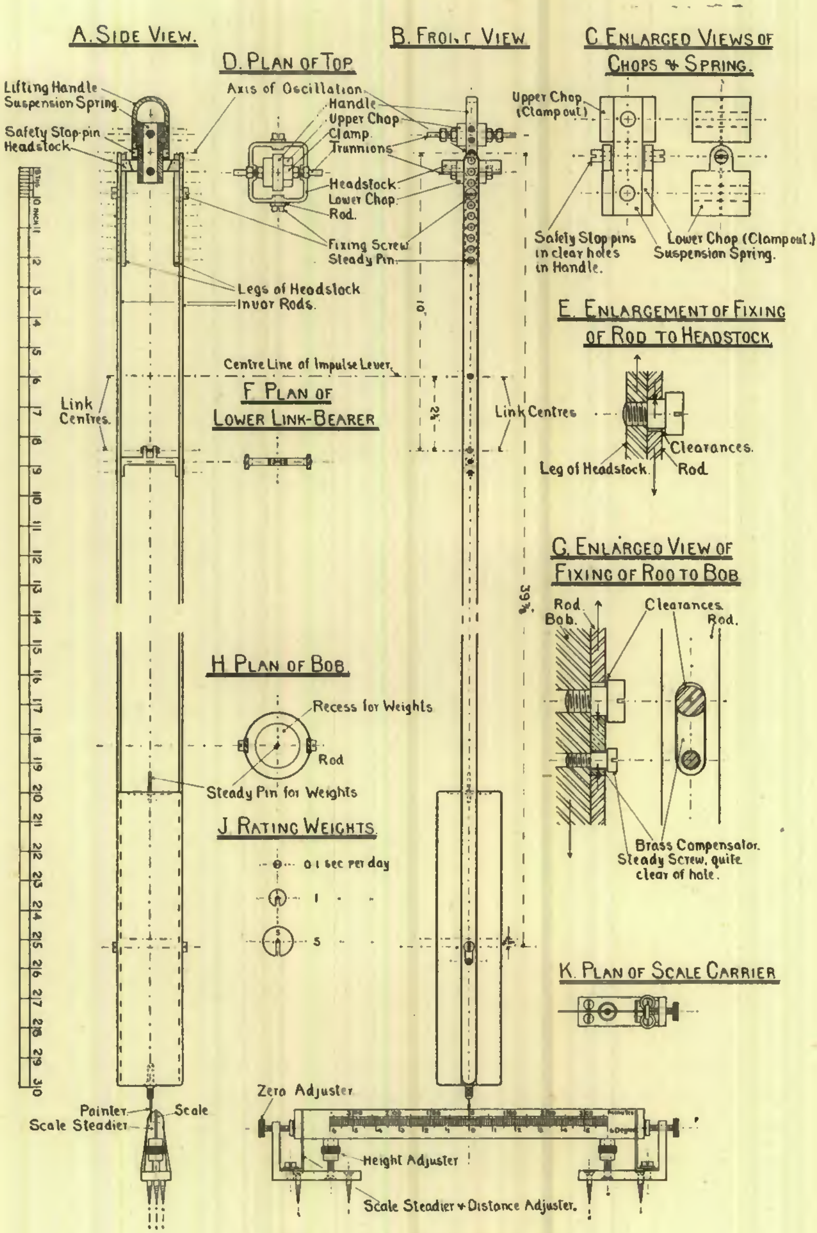


Plate VII.—Pendulum.

The rods are of nickel steel having a coefficient of expansion of the order of one part in a million per degree C. They are not bound to the other parts at either end, but simply rest on the round surfaces of the necks of the screws, as may be seen from Figs. E and G of this plate. The screws are of the same material as the pieces into which they are screwed, so that the effective length of each material may be known.

The length of steel which affects the equivalent length of the pendulum is measured from the centre of the free portion of the suspension spring to the highest point on the neck of the screw, upon which the rods rest, and that of the nickel steel is to be taken from the latter point down to the bottom of the slot which carries the bob.

A series of holes for the upper screw is provided, in order that the temperature compensation may be adjusted by the method proposed by King. The rods are always kept at the same level with respect to the mild-steel headstock, but by varying the position of the screws, keeping the two on the same level, we can, without altering the length of the pendulum, adjust the division of this length between the two metals, and thus regulate the amount of temperature compensation given. Each step corresponds to a change in the temperature compensation of about 0·005 second per day per degree C. The second screw through each rod is merely required to keep the rod and headstock in line when the pendulum is handled; normally it is just clear of the holes.

The sidewise expansion of the bob increases its moment of inertia. This is compensated by suspending the bob a little below its centre of gravity, the amount being calculated so that the effect on the rate of the upward expansion of this little piece exactly balances that of the increased moment of inertia, provided the whole bob is at one temperature. The bob is thus self-compensating, which is much better than using the expansion of the heavy bob, whose temperature will only change slowly, to balance that of the rods, which could be done by suspending the bob from a still lower point.

The expansion of the rods, headstock, and spring make the pendulum go slower, as the temperature rises, by an amount varying with the position of the headstock screws, as explained above. Changes in the elasticity of the spring produce a similar effect.

On the other hand, however, the expansion of the air reduces the buoyancy, thereby increasing the effective weight of the pendulum, and at the same time reduces the small addition to the effective mass caused by the movement of the air to and fro with the bob. The expansion of the air thus accelerates the pendulum with a rise of temperature, and compensates, in part, for the expansion of the rod.

Owing to the uncertainty as to the exact values of the coefficients of expansion of the particular rods, etc., which go to make up the pendulum, and to the doubt as to the magnitude of the inertia effect of the air, it is not possible to calculate accurately what the effect of temperature change will be. Such calculations as could be made indicate that the pendulum is probably slightly overcompensated with the screws in the top position, but this can only be verified, or disproved, by a long series of observations.

Should experiment prove that it is really undercompensated, the two slots at the bottom of the rods will be lengthened, and a brass piece, expanding upwards, inserted in each, as shown in Fig. G of Plate VII. When once the actual temperature coefficient is known by experiment, it will be quite easy to calculate the length of brass needed to annul it. By the way, the temperature coefficient varies slightly with the amplitude and with the barometric pressure.

Change of barometric pressure also affects the rate of a pendulum. When the air pressure falls, the density of the air falls with it, and so reduces the buoyancy, increasing the effective weight of the pendulum, and it also reduces the mass of the air which moves to and fro with the bob. Both effects raise the rate of the pendulum. The amount of this change is about one-third of a second per day for each one-inch change of barometric height, but it varies with the design of the pendulum. The scanty data so far obtained seem to indicate that with this particular pendulum the effect is greater than this amount.* An increase in humidity produces a similar, but somewhat smaller, change in the rate to that produced by a fall of barometer.

The suspension spring is carried between the two mild-steel chops with a free length of 0·5 inch. Its section is 0·5 inch by 8 mils. The first spring tried was thinner, but it gave a period of oscillation about a vertical axis almost identical with that of the applied forces, the resonant condition, and was liable to set up quite big oscillations about that axis, due to small errors in the symmetry of the driving forces. This was a mere coincidence; many trials would probably have been needed before resonance could be obtained if it was wanted.

Each chop has a trunnion parallel to the plane of vibration. The upper one rests on the cocks, and the lower one carries the headstock. The idea of this arrangement, which is not uncommon, is to permit the spring to take up its own line without danger of the weight of the bob tending to bend it edgewise, and so crumple it. This claim is a somewhat dubious one, for the friction at the trunnions can hold it out of line by an amount which is probably not less than what might be expected with careful workmanship and rigid connections.

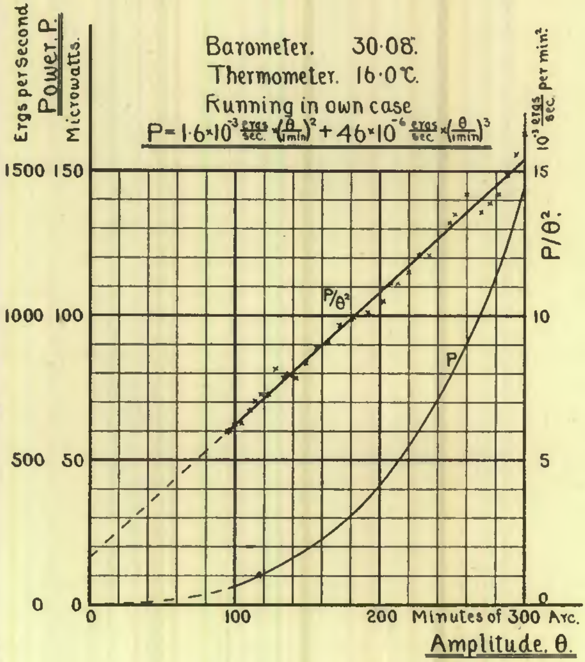
A handle is attached to the upper chop for convenience in dealing with the pendulum when it has to be taken down. Its lower end embraces two pins fixed to the lower chop in line with the virtual axis of oscillation, which passes through the centre of the spring. The pins do not actually touch the sides of the hole, but they prevent the spring being twisted when the pendulum is handled, and act as safety catches in the event of the spring breaking.

Fig. 13 shows the power consumed by the pendulum when running free in its own case before the two units of the time machine, or the thermometer and barometer, were put into it. Both in this test and in several others made in the laboratory, the power was measured by the running-down method by two students, Messrs. G. Bishop and A. E. O'Neill. The

* See reply to Discussion.

power taken in its own case was practically identical with that required when fixed on a wall without any case, care being taken to avoid draughts. A smaller cardboard case made the power very much greater.

The second graph shows the ratio of the power to the square of the amplitude; it follows a linear law with the amplitude,



(*Test by G. Bishop and A. E. O'Neill.*)

Fig. 13.—Power Absorbed by Robertson Master Pendulum No. 1.

showing that the power has a term proportional to the square of the amplitude and another proportional to its cube. The latter is by far the more important, except at quite small amplitudes. To avoid confusion, the experimental points have been marked only on the linear graph. The equation to the power is marked on the diagram, and need not be repeated here.

It was expected that the second rod would increase the air friction, which I believe to be no disadvantage. But a comparison with another pendulum having an almost identical bob with a single rod of the same size, but with the addition of a regulating nut of large diameter and a screw below the rod, showed very little difference between them. The extra friction of the nut and screw more or less made up for that of the second rod. At small amplitudes the single rod pendulum took least power, but at larger amplitudes the position was reversed, showing a difference in the relative values of the quadratic and cubic terms in the expression for the power.

The Escapement.

The escapement is entirely novel, and is shown diagrammatically in Fig. 14. A counterpoised impulse lever is pivoted at one side of the pendulum, and connected to the latter by a short link. When the pendulum is vertical, the centre line of the link should coincide with that of the pendulum. As the pendulum swings to and fro, the impulse lever will move up and down with double frequency, the highest point being reached when the pendulum is at zero. The end of the impulse lever carries one element of a contact whose other element is attached to a cradle carrying the driving weight. Both contacts are insulated, and connected to outside terminals by flexible wires.

The cradle rests in a hook attached to the end of a lever fixed to the armature of an electro-magnet, which is counterpoised so as to hold the lever up to a micrometer stop against the pull of the weights. A second micrometer stop limits the downward movement of the hook, and the upper stop is set so that contact is made at a level slightly below the highest point reached. The ratio of the levers is chosen so that the movement measured at the micrometers is the same as the corresponding travel at the top of the link.

As the pendulum swings inwards, and just before it reaches the central position, the lever lifts the cradle off the hook, and takes the weight of the cradle and weight, which together form the driving weight. As soon as the contact is made, the magnet is energised and pulls the armature down, leaving the weights on the contact.

During the outward swing to the other side, the lever and cradle fall together until the latter is again caught on the hook. This takes place at a lower level, depending on the

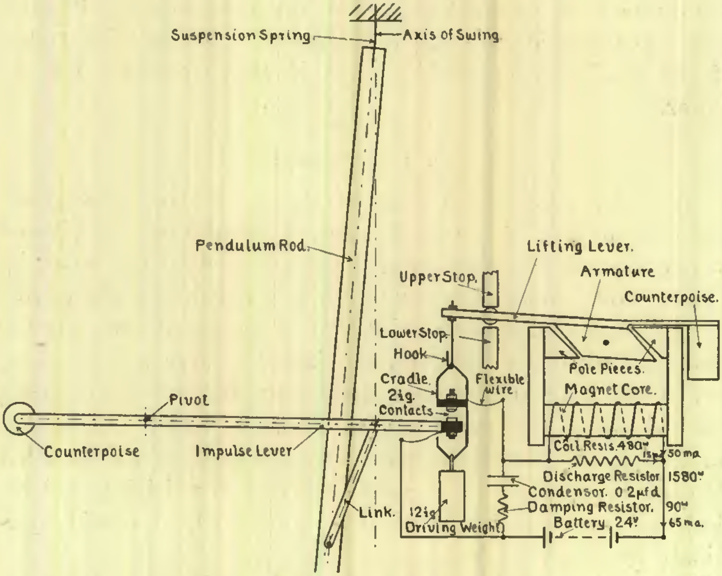


Fig. 14.—Robertson Link Escapement.

play between the stops, than that at which the cradle was picked up, and the difference of level multiplied by the driving weight gives the amount of energy supplied at each impulse. When the cradle is replaced on the hook, the contact is broken and the armature is released; the counterpoise then restores the weights to their original position ready for the next swing.*

The driving force used in this case is 15 grams weight, or about half-an-ounce, and the micrometers are set for a nett drop of 0·2 mm., the lift being 0·2 mm. and the total drop

* See reply to Discussion.

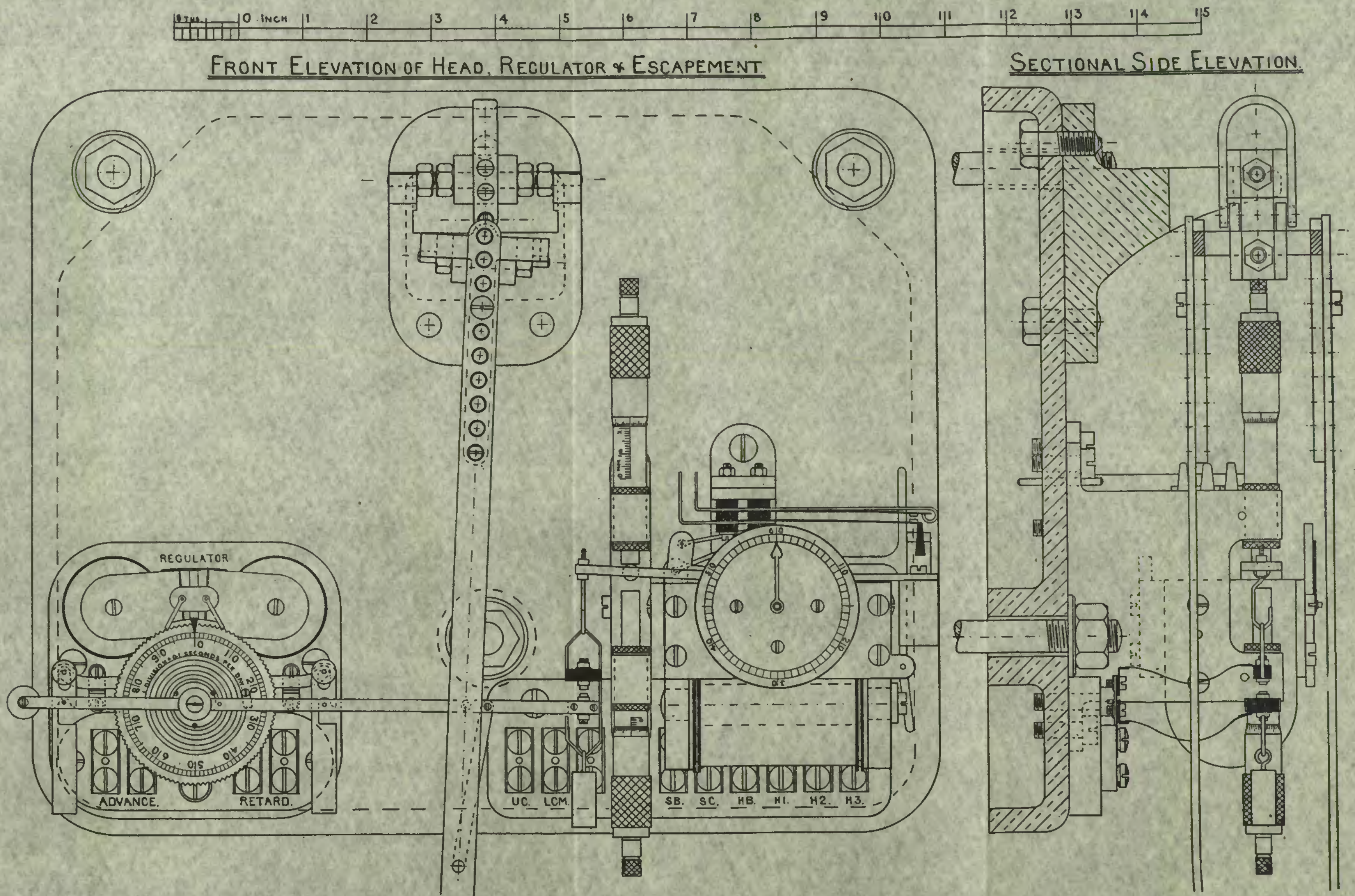


Plate VIII.—Pendulum Head with Escapement and Automatic Regulator.

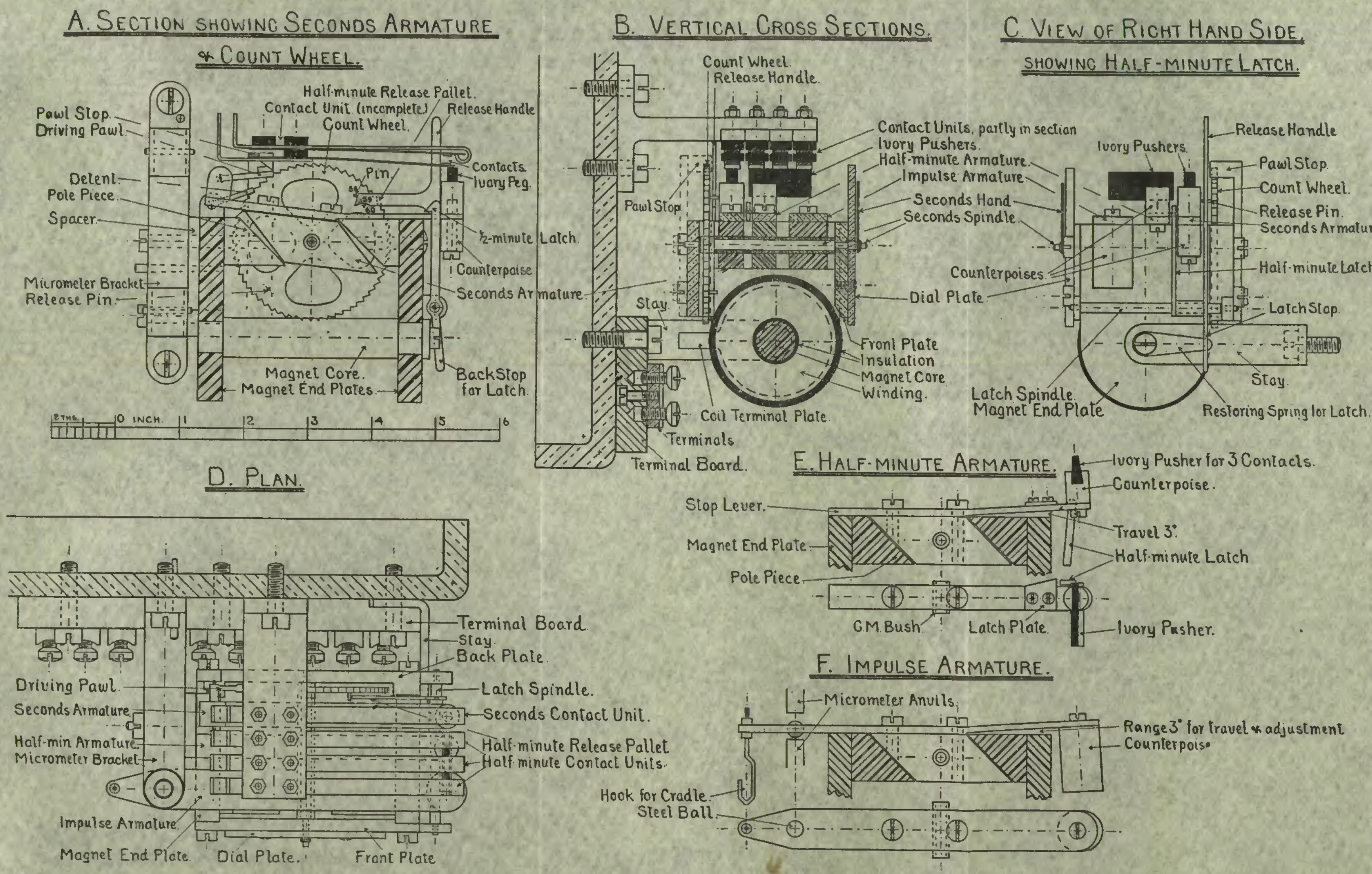


Plate IX.—Escapement Magnet, Armatures, etc.

0·4 mm., measured at the micrometers. The energy given at each impulse is thus almost 400 ergs.

This escapement has a low solid friction, with a consequent low variation of amplitude, but its chief advantage for the present purpose is the way in which it permits of automatic regulation by accurately calculated amounts, as will be explained later.

Tests show that the friction is considerably greater than was expected, but the cause of this is suspected, and it is hoped that it will be possible to improve it considerably in this respect.

Plate VIII shows the pendulum head with the escapement mechanisms and micrometers, as well as the automatic regulator, to be described later, while details of the escapement magnet and its accessories are given in Plate IX.

There are three separate armatures for the escapement magnet, running loose on a common spindle, which is itself mounted in bearings, and connects the count wheel at the back with the seconds hand in front.

The front armature, shown in Fig. F of Plate IX, is the one for lifting the driving weight as just described. The back one, which is shown in the section given in Fig. A, drives the 60-tooth ratchet wheel on the seconds spindle, and also relays the seconds contacts, so as to relieve the pendulum contacts of the comparatively large current required for the Greenwich time unit.

The middle armature, shown at E, operates three separate contacts once each half-minute in the following manner. Normally this armature is held down by a latch fixed to a side spindle at the right, but the same spindle carries a release pallet, which engages with two pins fixed diametrically opposite to one another on the ratchet wheel. The position of the wheel shown in Fig. A is that for the 58th (or 28th) second. At the end of the 59th impulse, the pin will push the release pallet to the right and hold the latch clear. Consequently, the 60th impulse will find the armature free, and will operate it along with the other two, making the half-minute contacts, On the return of the armature after the conclusion of the 60th impulse, the pin moves clear of the pallet, and the latter drops back to its normal position, relocking the armature.

The lever carrying the release pallet is extended upwards to form a handle by which the latch may be freed by hand when it is desired to advance the dials at the advent of summer time, or for any other reason. Impulses are then sent to the dials every second instead of every half-minute, so that they can be advanced one hour in about two minutes.

A considerable amount of difficulty was experienced in adjusting this mechanism so that it would operate with certainty. The restoring forces on the release pallet must not be so great that the counterpoise of the seconds armature cannot drive against it when the pin is in engagement. On the other hand, it must be sufficient to restore the latch with certainty. These difficulties are increased by the residual magnetism acting on the seconds armature. The restoring force on the seconds armature can be altered by changing the set of its contact spring, for this spring assists the return. But if the force be increased too much in this way, the armature fails to go right home, and the pawl does not get into the next tooth.

After running quite well for some months, the armature suddenly started to stick down under the residual magnetism, and the gap had to be increased. But this reduced the working forces as well, and made the other adjustments more delicate.

Just before this the seconds hand took a fit of gaining a few seconds per day on the Greenwich mean time unit. Naturally the latter was blamed for dropping behind, as it had been previously convicted of that offence, and it seemed impossible that the count wheel could gain on the pendulum. But it was found that the wheel did actually gain a tooth now and again just as the pin was moving clear of the release pallet. The bottom corner of the pallet, which had been rather badly treated during the various trials, was slightly rounded, and one of the pins got just under this rounding at the 59th second. The pallet then pushed the wheel forward instead of backwards, and did move it forward a bit when the wheel was unlocked by the withdrawal of the pawl at the 60th impulse.

As a rule, the only consequence was that the motion of the seconds hand from 59 to 60 took place in two steps, one on the withdrawal of the pawl and the other on its return, but once in a while the first movement would be sufficiently great to enable the pawl to gather an extra tooth. When once the true cause was diagnosed, which was very difficult indeed with a fault which only happened once in a few thousand times, it was a simple enough matter to correct the shape of the end of the release pallet.

The back half-minute contact is used for the civil time unit in series with the master dial, and the other two for several circuits for ordinary impulse electric clocks. A bigger travel for this armature would have been better, for at present there is some difficulty in adjusting the contacts so that their action is perfectly certain.

Deviations of the Rate with Amplitude.

The motion of a pendulum is a vibration about an axis passing through the centre of the free portion of the spring. If the restoring couple be proportional to the angular displacement from the vertical, or zero, position, the vibration will be a simple harmonic one, and the rate will be the same for all amplitudes so long as the motion is not disturbed by frictional and driving forces. But in an actual pendulum the restoring torque is not proportional to the angle, but to its sine, with the result that a free pendulum goes slower the bigger the amplitude. The difference between its rate and that with an infinitely small amplitude is known as the "circular error," or "circular deviation," as I prefer to call it.

The amount of this deviation is shown in Graph A of Fig. 15, from which it will be seen that it increases more and more rapidly as the amplitude is increased. If this were the whole story, we ought to run with as small an amplitude as possible.

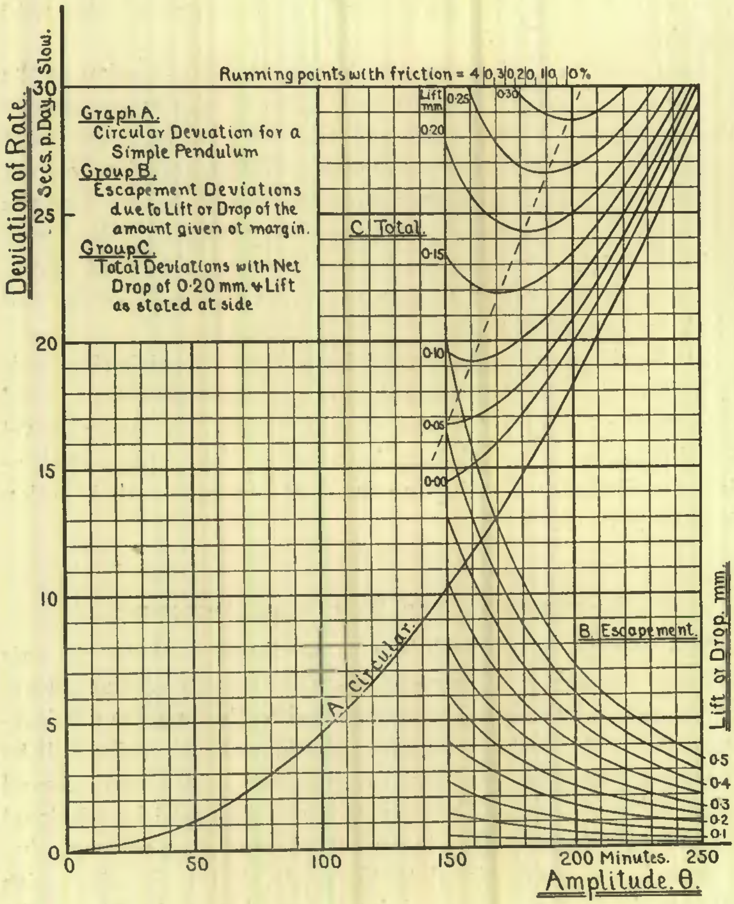


Fig. 15.—Amplitude Deviations of Rate of Pendulum with Driving Force ≡123 Seconds per Day.

As we shall see later in connection with the method of applying automatic regulation, a constant force on the link of the link escapement has practically the same effect on the motion as an increase or decrease of weight of the pendulum without change of inertia, and it will, therefore, produce a change of the rate which is nearly independent of the amplitude. It is thus convenient to specify the amount of the driving force in terms of the change of rate which it would produce if left on all the time instead of only for a portion of each cycle.

The driving force of the pendulum we are considering would slow it by 123 seconds per day if applied continuously. But it does not act continuously, but only during the lift and drop of the weights, and consequently the effect on the rate is only a fraction of this, the fraction depending on the durations of the lift and drop. We thus have another deviation of the rate due to the driving forces.

With a given force and given values of the lift and drop, the duration of both the last mentioned gets less as the amplitude increases. Consequently, the variation of the escapement deviation is opposite to that of the circular deviation, and at one particular amplitude for the given conditions the one variation will balance the other, and the rate will not change with a small change of amplitude. This is obviously the right point at which the pendulum should be run.

A feature of the link escapement which is believed to be unique is the accuracy with which the escapement deviations can be calculated without any assumptions as to the pallets having some exact shape, and the ease with which they can be varied in order to obtain the best conditions.

The group of curves marked B on Fig. 15 shows how the deviations, for different amounts of lift or drop, vary with the amplitude with the fixed driving force which will slow the pendulum by 123 seconds per day if allowed to act continuously.

The other family, C, gives the total amplitude deviation with a constant nett drop of 0·2 mm. (measured at the micrometers or at the link top), and with various amounts of lift. It is obtained by adding the ordinates of the curves for the circular deviation, for the selected amount of lift, and for the corresponding amount of total drop. The points at which the rate is constant are obvious from the curves.

As all the curves in the group C refer to the same impulse energy, they will correspond to the same running amplitude. This amplitude can be found by running the pendulum with that nett drop and any amount of lift. The lift should then be altered to that which has the running amplitude at the lowest point of the corresponding graph. This adjustment is quite easily made by turning both micrometers up or down to the same extent. With no other escapement known to me is anything like this possible.

The amount of the energy given at each impulse with the nett drop of 0·2 mm. is 392 ergs. A reference to Fig. 13 shows that this would give an amplitude of 198 minutes if it were all given to the pendulum and none lost by escapement friction. In the same way the amplitude for any assumed amount of friction can be found, and the scale obtained which is marked at the top of Fig. 15.

The pendulum actually runs at a little over 180 minutes of amplitude with this nett drop, showing that the friction is nearly 20 per cent. A comparison of the graphs shows that the one with a lift of 0·2 mm. is the right one for this amplitude, and so the micrometers have been set to give 0·2 mm. lift and 0·4 mm. total drop.

It must, however, be remembered that these curves assume that the variation of amplitude is caused by forces which do not themselves produce any direct change of rate. This condition is almost exactly fulfilled by variations of the air friction, and by variations in the link friction so long as that is the same at any point of the swing, whether the pendulum is moving inwards or outwards.

Wear of the contacts will cause a slow change of the rate, for it will alter the amount of the lift, and thereby change both components of the escapement deviation in the same direction. The wear caused by the electrical actions at the contacts will probably be more important than the purely mechanical wear. But the current through them is small, about 60 milliamperes, and the spark suppressors effectually prevent any visible sparking. After some months' running, a very slight pimple was visible on one contact and a faint marking on the other.

Such slow variations are of no importance whatever in a controlled clock, but they would have to be taken into account in one which has to go on its own rate. Nothing but lengthened experience can show the extent of the effect, which is inherent in all escapement actions.

As the baseplate expands with rise of temperature, it lowers the support for the impulse lever. The top of the link is lowered to a smaller extent by the expansion of the upper part of the rods, etc. Consequently, the lever contact is raised and the amount of lift increased, making the pendulum go slower. There is thus a temperature error caused by the escapement of the same sign as that due to the rods, which will, of course, be included in that to be found experimentally. From this point of view, the bronze base used with this pendulum for appearance sake is not so good as a cast-iron one would be. The lift must not be so small that the contraction of the baseplate down to the lowest temperature to which it will be subjected in use, will reduce the lift to zero; if it did, the contact would fail and the pendulum stop.

The Automatic Regulator.

The clock is arranged to be controlled by the Greenwich time signals received daily over the Post Office wires at 10.00 Greenwich mean time. Before the new escapement was invented, full consideration was given to the various means already employed for this purpose. The method most commonly adopted is to force the clock to time at each signal. The possibility of a signal arriving at the wrong time must be taken account of when reckoning up the merits of this system.

Another way is to keep the clock going slightly fast, and to stop when it reaches 10.00 until the signal arrives. Unfortunately the signal fails to come every now and again, and with this arrangement the clock would then be stopped altogether. Yet another method is to utilise the signal to increase, or decrease, the rate of the clock by a small fixed amount at each signal, according as the clock is found to be slow or fast. But Mr. F. Hope-Jones long ago* showed that this would not give the desired result, and that both the rate and the error must be adjusted. This last method has been adopted.

If the signal finds the clock slow, the time is advanced by 0·2 second and the rate increased by 0·1 second per day. If the clock be fast, it is retarded and slowed by similar amounts. The amount of the correction is always the same, no matter how much the clock may be found to be out. The effect of

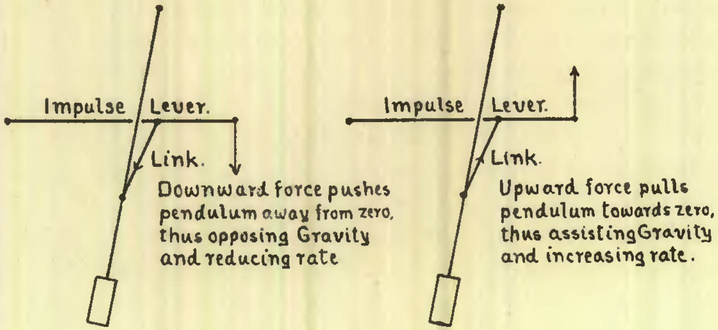


Fig. 16.—Effect of Link Forces on the Rate.

a false signal, if it does succeed in getting through to the regulator, is thus restricted to these small amounts.

Sufficient experience has not yet been obtained to admit of any definite statement being made as to the closeness with which the clock can be made to keep to time, for the regulator has not had a free run until recently, and that has been interfered with by a failure of the time signal for several days, and also by the extraordinary behaviour of the barometer. The indications are that, if the barometric phenomena of November, 1926, are to be a common occurrence, it will be necessary to increase the error correction to, say, 0·4 second. This change can be easily enough arranged for by altering the RB6 notch,

* Journ. Inst. of Electrical Engineers, vol. xlv, p. 112. 1910.

whose function is explained below, so that the battery is kept on the regulator for ten minutes instead of for five.

Fig. 16 shows how a thrust on the link acts against the weight of the pendulum, and consequently slows the rate, while a pull assists gravity and raises the rate. This property of the link escapement is applied to the regulation of the pendulum as follows:—

As will be seen from Fig. 17, a light spiral spring is attached at one end to the impulse-lever near the pivot, and at the other end to a rating disc carried in a friction bearing sufficiently tight to hold against the spring, but not a great deal tighter.

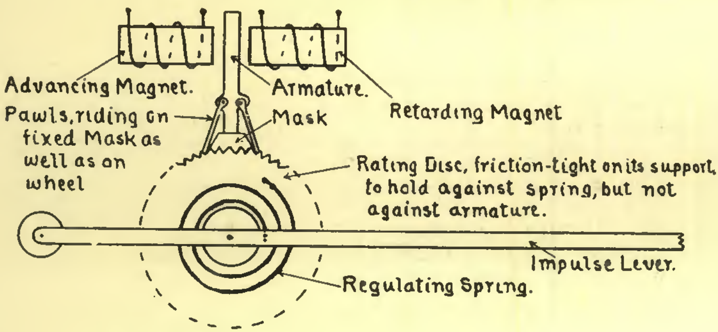


Fig. 17.—Principle of the Rate Adjuster.

An armature, placed behind the disc with its spindle con-eccentric with that of the impulse-lever and with the rating disc, carries two pawls which engage, in opposite directions, with teeth cut on the rating disc. A mask, fixed to the framework, lies between the pawls, and throws one of them out of action when the armature is deflected to either side. The armature is common to two separate magnets, one for advancing the clock and one for retarding it.

Suppose the right-hand magnet to be energised. The armature is pulled to the right, causing the right-hand pawl to push the rating disc round one tooth to the right. This applies a downward torque to the lever through the spring, and consequently slows the pendulum. When the armature is released, the mask prevents the other pawl from bringing the disc back again, and so it is left one place further to the right until the next time the regulator is operated, thus making the rate permanently slower until that time. The spring is designed to give a change of rate of about 0·1 second per day for each step. If the other magnet be excited, the same thing takes place in the opposite direction, and the rate is increased by the same amount.

The same armature advances, or retards, the clock a little bit each time the regulator is operated by means of the arrangement shown in Fig. 18. A rocking arm, attached to the arma-

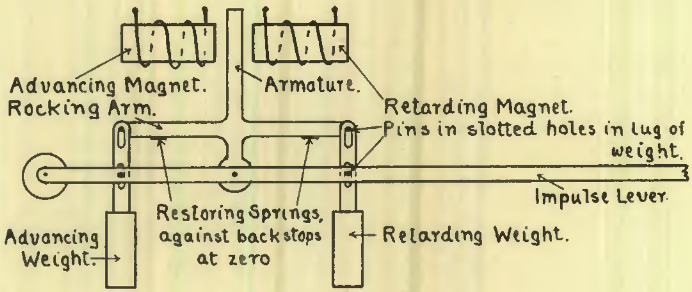


Fig. 18.—Principle of the Time Adjuster.

ture, carries two weights on pins passing through slotted holes in the lugs of the weights. Another hole in each lug surrounds a pin fixed to the impulse-lever, but normally these pins move up and down without touching the weights.

When the armature is pulled over to either magnet, one of these weights is deposited on the lever pin, and adds to the effect of the change of position of the spring, slowing, or accelerating, the pendulum by a considerable amount so long as the armature is held down. Each weight is calculated to alter the rate by one part in 1,500, which will give an advance, or retardation, of 0·2 second in five minutes, the interval for which the time machine at present keeps the current on to the magnets.

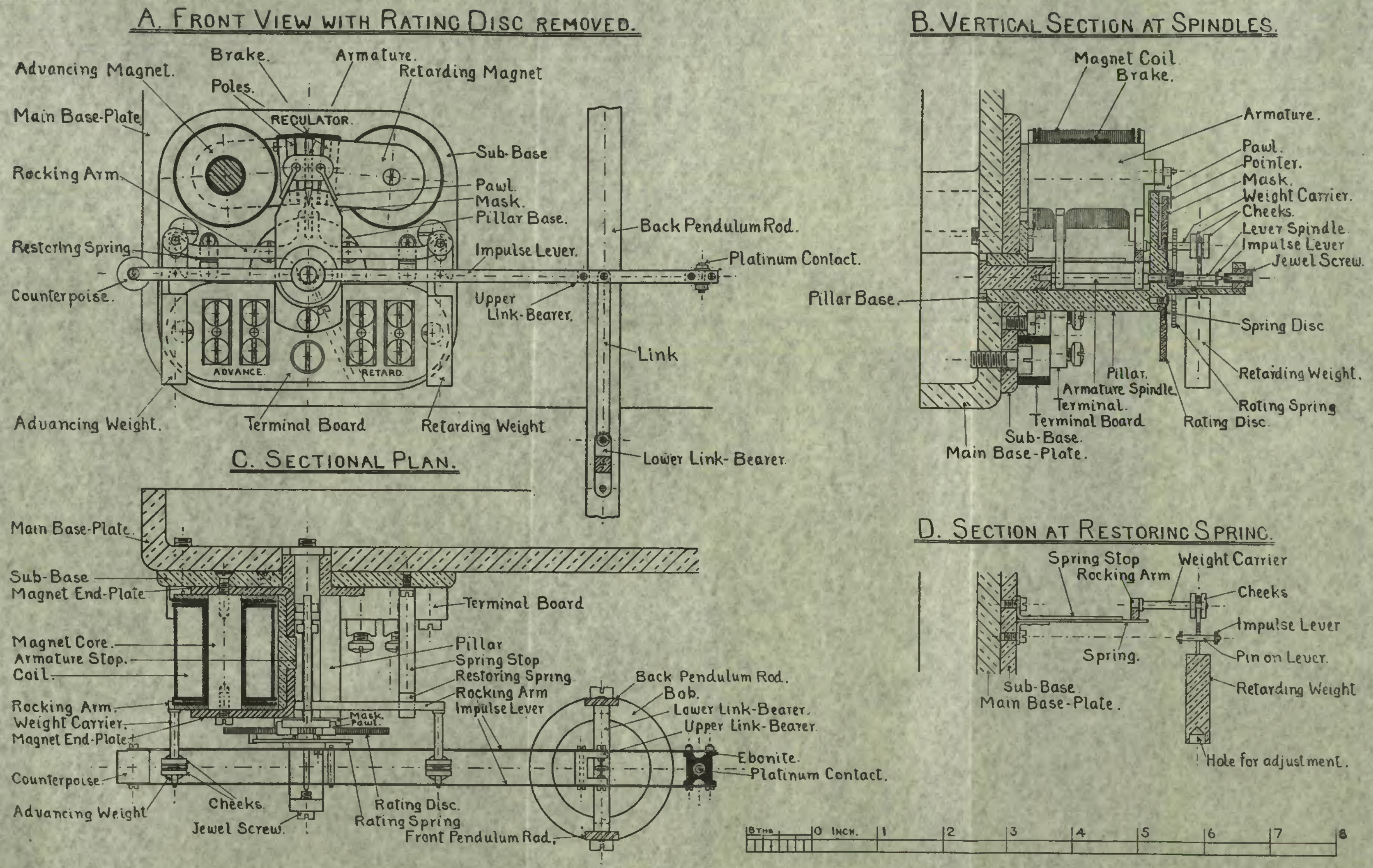


Plate X.—Automatic Regulator.

Plate X shows the construction of the regulator, and should be easily understood after the above explanation.

During the first trials it was found that the armature would oscillate when it was released, and that this would move the disc by several teeth instead of only one. A damping brake was added, consisting of a piece of thick cloth pressed on the top of the armature by a strip of copper foil fixed to both magnets, and this proved perfectly satisfactory. It was also found necessary to add cheeks to the pins on the rocking arm to prevent the weights being thrown off when the armature is suddenly brought to rest by striking the stop.

Fig. D of this plate gives the details of the restoring springs for the regulator armature. A flat spring under it presses the rocking arm up at each side, but in the normal position these springs bear against stops. Thus one spring has not to push against the other when returning the armature, and a considerable restoring force is available right up to the zero position.

Time Control Circuits.

The problem of controlling the regulating magnets by means of a momentary time signal was not altogether an easy one, but an earlier study of automatic telephone exchanges led to the solution illustrated in Fig. 19.

Three relays, of the standard pattern used by the Relay Automatic Telephone Co., Ltd., are employed, one each for the Greenwich and local time signal circuits, and the third for closing the final contacts which send current to one of the regulating magnets. Each of the former pair has four make contacts and two transfer contacts, all being shown in the diagram in the same vertical line as the relays themselves. The other relay has two make contacts and one break contact.

Contacts RB6 and RC6 on the Greenwich time unit connect the battery ready for these relays at 9.59 Greenwich mean time each morning, and switch it off again at 10.05.

Another set of contacts on the same unit, RA4, RB4, RC4, puts the local time signal circuit through to the seconds contact of the escapement magnet at the end of the impulse 9-59-59 by the clock. The beginning of the impulse 10.00 then completes the local circuit at the seconds contacts.

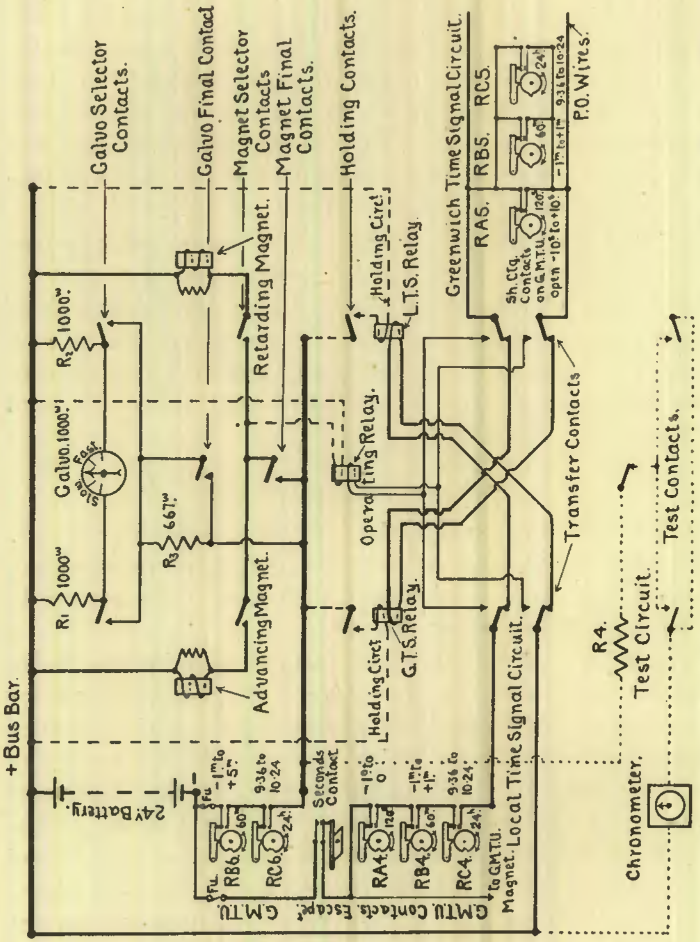


Fig. 19.—Time Control Circuits.

The Post Office wires are normally short-circuited by the R5 contacts, but this short-circuit is open for 10 seconds on each side of 10.00.

If the clock be fast, the local signal comes first, and passes to the L.T.S. relay, and energises it. The relay is locked in by one of its contacts closing the circuit of a separate holding coil. Another contact connects the retarding magnet to the main contact of the operating relay, but no current flows through the magnet until that contact is closed by the second signal. Yet another make contact on the L.T.S. relay connects the right-hand side of the central zero galvanometer to the battery through the resistor R_3, and permits sufficient current to flow from left to right to give a deflection half-way to the right. At the same time, the transfer contacts change over the Greenwich circuit from its own relay to the operating relay.

When the Greenwich signal arrives, it thus passes to the operating relay, energising it and closing the final contacts. The main contact of O.R. is put to the battery, which locks the relay in and admits current to the retarding magnet already selected by the first signal. The other make contact of O.R. short-circuits R_3, and sends the pointer to the end of the scale. Both the galvanometer and retarding magnet continue to receive current until the battery is cut off by the RB6 contact.

When the clock is slow, the Greenwich signal arrives first and excites its own relay, which transfers the local circuit to the operating relay, selects the advancing magnet ready to receive current at the second signal, and sends current from right to left through the galvanometer, giving half-deflection to the left. This time it is the local signal which operates O.R., and causes the final contacts to be closed.

Note that the first signal, whichever it may happen to be, selects the magnet which is to receive current, but that current is not supplied until the second signal has been received. Thus, the regulator is not operated unless both signals come within the limits set by the time machine contacts, but the galvanometer shows each signal separately, and is deflected in opposite directions according as the clock is fast or slow. Also that the time given by the local clock for comparison with the Greenwich signal is the instant at which the seconds contact of the escapement magnet is made at the beginning of the impulse.

During the five minutes for which the current is held on, the indication of the galvanometer shows whether the clock was found fast or slow, but by noting the positions of the regulator that information can be obtained at any time during the 24 hours between the signals.

In order to measure the error of the clock when desired, each relay has a test contact which is shown at the bottom of Fig. 19, and the electrical chronometer already described can be put into circuit with them as indicated. The first signal closes this circuit at either the L.T.S. or the G.T.S. relay, and the second signal opens it at the operating relay. The chronometer is thus started at the first signal and stopped at the second, and gives the interval between them to 0·01 second.

Should the two signals arrive simultaneously, both the L.T.S. and G.T.S. relays would operate and lock in. But no current would get to the operating relay, and the regulator would not be altered. The galvanometer would be short-circuited, and give no indication. The chances of this happening are rather remote, as the relays can discriminate between two signals whose time difference is of the order of 0·001 second.

Layout of Clock.

Fig. 20 illustrates the whole clock in its case. The master dial at the top is connected in series with the civil time unit, and driven by the half-minute impulses. This circuit is a local one, and does not include any of the dial circuits throughout the building. The pendulum head comes immediately underneath. The instrument at the right is the time signal galvanometer; the relays are in another case behind the wall, and consequently are not seen. The galvanometer is a Weston miniature instrument with the three resistors, R_1, R_2, R_3, wound in the base. The small switch above it is for cutting off the dials, including the civil time unit and the master dial, when they have to be put back.

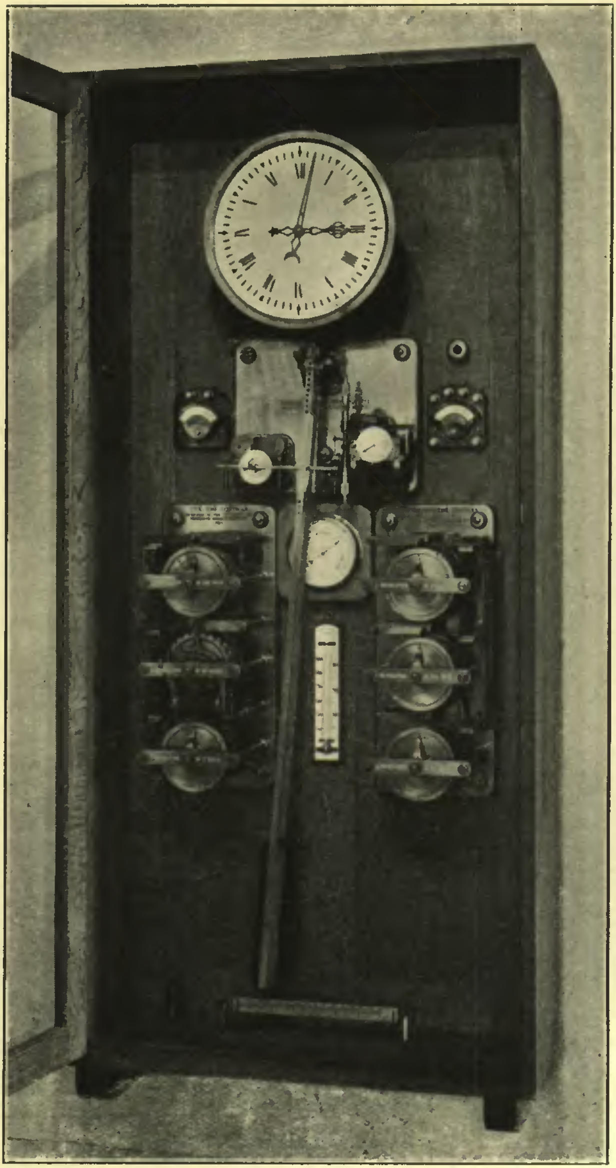


Fig. 20.—Master Clock in Case.

The other Weston instrument at the left is a milliammeter in circuit with the pendulum magnet, and is useful for checking the battery voltage and when finding the zero point for the top micrometer which adjusts the lift. It is a little doubtful how the pivots of this instrument will stand up to the wear of continually swinging to and fro about 30 million times a year.

The civil time unit is at the left of the pendulum, and the Greenwich mean time unit at the right. A Negretti & Zambra aneroid barometer and thermometer are placed between them, behind the pendulum. A scale at the bottom shows the amplitude, each division corresponding to five minutes.

The master dial was made by Messrs. W. Langford & Sons, of Bristol, to the architect's design, and uses a standard Gent impulse movement. The architect is also responsible for the oak case, which was made by the builders, Messrs. H. Willcock & Co.

The right-hand style of the door is a rather remarkable piece of wood. On the inside, just level with the top of the civil time unit, the grain of the wood forms a wonderfully good likeness of the face of a cat, which may be seen in the illustration. Naturally we attribute all our little troubles with the clock to the malign influence of "Satan," as this cat has been named.

The time signal relays, the resistors, condensers, fuses, and switches are all placed on a separate terminal board fixed on the other side of the wall, back to back with the clock case. All the wires from the various outside circuits end on separate terminals on this board, and the various interconnections are there made by suitable jumpers. This terminal board is itself quite an elaborate affair; in addition to the terminals on the battery bus-bars, it has 110 double terminals of the pattern shown on the drawings of the escapement and regulating magnets. These use Gent's patent spherical-headed screw, and proved most convenient in use.

The board, which was made by Messrs. Gent & Co., Ltd., of Leicester, is divided into two parts, one for clock circuits and one for bell circuits. Each portion has 11 vertical ebonite panels, and its own battery bus-bars. Each circuit is controlled by its own fuse, of the standard spring pattern used in telephone exchanges, and the circuits for bells have each a small Crabtree tumbler switch.

Almost 50 wires pass through the wall for connecting the terminal board to the apparatus in the clock case. The wiring was carried out by Mr. Roberts, using bare tinned copper wire, drawn into sistoflex insulating tubing. It was clipped on to the back of the clock case, and then bunched into groups for passing through the steel tubing in the wall.

Acknowledgments.

I wish to acknowledge my indebtedness to several of my engineering friends for much helpful criticism while the designs were in progress, notably to Messrs. G. A. Fry, A. H. Weddell, and J. Russell Taylor ; also to Prof. R. A. Sampson, Messrs. A. E. Ball, H. Whidburne, F. Hope-Jones, and John Taylor & Co. for information willingly supplied; to the "Bristol Times and Mirror," Messrs. Brecknell, Munro & Rogers, Ltd., and to Messrs. John Taylor & Co. for the use of their photographs and slides, and also to the last mentioned for so kindly preparing Plate I for this paper; to two of my students, Messrs. G. Bishop and A. E. O'Neill, for carrying out numerous tests on the apparatus; and above all to Mr. J. H. Roberts, the engineer to the University, for his most patient help in overcoming the difficulties incident to the installation of an entirely novel mechanism.

Further, I wish to thank Mr. Weddell for his kind acquiescence in the task of reading the paper, which was imposed upon him almost without his knowing it.

Discussion.

Mr. F. Hope-Jones: There is much to be said in favour of an engineer embarking upon a job involving a trade or profession to which he is a stranger. It ensures a fresh point of view, and prevents the virtue of a stereotyped form of

Mr. F. Hope-Jones.

procedure being taken for granted. Perhaps more valuable inventions have resulted from this ignorance of specialised trades than from the inventor who stands on the shoulders of those who have gone before. It has been said of my brother, the late Robert Hope-Jones, who has been called the Edison of the organ, that his inventions were due to his being an electrician and a musician, and not an organ builder. In the other pan of the scale there is, of course, the sense of responsibility appertaining to any well-established specialist firm, and in this case the profession concerned is that of the electric-clock maker. The reputation of a system may well be worth tens of thousands of pounds to its makers, and the success of their installation would be underwritten by that amount, whatever it might be.

Prof. Robertson has attacked this problem with the pluck and confidence which might be expected from such a skilled engineer with complete mastery of the electro-technics involved, and he has done everything in his own original way. Time alone will prove whether his installation is satisfactory, and since its maintenance will fall upon him and his assistants for many years, it may be long before its "fool-proofness" is put to the test. The inventions involved are not put forward as the basis of a new system of electric clocks, and frankly, I do not think they contain such a germ. He has been at immense pains to devise, and design anew, most of the necessary apparatus that already existed in a standardised and tried-out form. He is honest even to *naiveté* in relating his difficulties and failures, but it gives one a feeling almost of impatience that he should have set himself such difficult tasks as the design of a new striking machine, a new stroke counter, a new pendulum switch, a new electric impulse step-by-step dial movement, and a new synchronizer, when the ground has been all covered before and a reliable form of each standardised, emerging successfully from 30 years of commercial use and experience of that most cruel of nature's laws—the survival of the fittest.

He uses an electro-motor through worm gearing to depress the hammer tail, but instead of letting the cam space the blows, which it might just as well do, he has devised an independent release and a special electric circuit to take care of it. This seems to me to be altogether too high a price to pay—not, of course, in money but in complexity—for the advantage of precision in the timing of the strokes. It is only in wireless time signals, such as the six dots seconds, that such accuracy is required. The electrical equivalent of a mechanical hourly striking train is really quite a simple matter, and, however much we may admire the ingenuity of the time machine, with its separate Greenwich and civil time units and its stroke counter, I think we ought to assess the merit of a scheme as the moralist teaches us to assess a man's real wealth, mainly by the things he can do without. Prof. Robertson's escapement is Froment, 1855, with a link action introduced, presumably with a view to concentrating interference and impulse at or near zero, but surely the remedy is worse than the disease, inasmuch as the pendulum is now never free, but is permanently harnessed by a pivoted link to a pivoted lever. On the other hand, Prof. Charles Féry, of Paris, has shown how the desired improvement of Froment may be effected, so I contribute an illustration of it adapted to Prof. Robertson's form of construction, Fig. 21.*

Many will be grateful to Prof. Robertson for his mathematical analysis of the escapement. His graph in illustration of circular error and its compensation is a model for thoroughness and clarity, and I recommend it to teachers in horological technical schools. I suppose I have had more practical experience of time signals, both wired and wireless, than anyone else in this country; having used the former to correct forcibly both the indicated error and the rate of hundreds of electric master-clocks, and having never been without wireless signals since FL began to transmit in 1911. As a result of this experience, I am coming to the conclusion that signals by wire are not worth while. Prof. Robertson's Plate X and Fig.

* For Prof. Féry's own drawing see Horological Journal, June, 1923, p. 198.

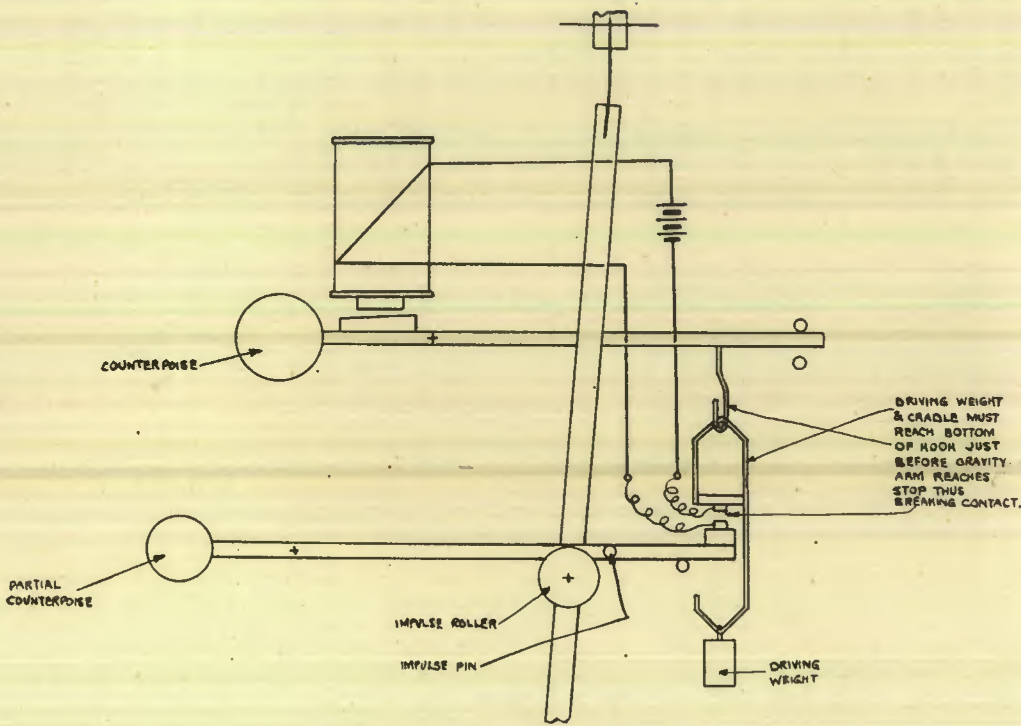


Fig. 21.—Adaptation of Féry's Escapement.

19, coupled with the unreliability and cost of the Post Office service, tend to conform this opinion. Again we can only compare it with existing forms, and wonder why the effort was made. I frankly prefer the Rudd arrangement of 1898, which is peculiarly suitable for application to Prof. Robertson's type of pendulum.

Mr. ALEX. STEUART: Prof. Robertson deserves great credit for his method of tackling the problem of electric striking, which is full of practical difficulties. For the clock itself, it might have been better had he adapted some existing type, and avoided link friction and the breaking of the contact by the pendulum. Sir David Gill had trouble with a similar idea about 50 years ago.

Several recent clocks get over the difficulties. The Steuart clock has the additional advantages of providing powerful continuous motion, and correction for missed or faulty contacts, while batteries may be replaced by mains. A clockmaker friend of experience suggests that the vertical fall of the hammer is insufficient to get the full tone of the Bristol bell.

Mr. GEORGE LANGFORD: It seems to me that, in the first place, the daily correction of the time of the pendulum destroys any means of ascertaining the reliability of its rate over a period of a week or month or longer; and in the second place, the manner of correction interferes with the regularity of the vibration of the pendulum, which is a cardinal point in all good horology. Then again, the escapement has the disadvantage of having three pivots constantly working on the pendulum. I have made exhaustive experiments to get isochronism of a pendulum, but so far without success, and I know of no one who has been successful as yet. In fact, when the vibration of the pendulum was reduced by 50 minutes from 190 minutes of arc on each side, it invariably produced a gaining rate from 6 to 7 seconds per day. The rates of the pendulum with a straight suspension spring and with a tapered spring were as follows:—

Mr. George Langford.

STRAIGHT SPRING, 0·5″ × 2 MILS THICK.

Driving weight, lbs. - - -	16	8	5	4
Amplitude (each side), minutes -	190	140	112	95
Rate, seconds per day - -	– 14·3	– 7·8	– 4·8	– 4·1
Gain of rate on 1st rate - -		+ 6·5	+ 9·5	+ 10·2

TAPERED SPRING, 0·5″ × 27 MILS TO 0·25″ × 3 MILS.

Amplitude, minutes - - -	190	140	95	75
Gain of rate, seconds per day -		6·3	7·0	7·4

These experiments were carried out for some months with a suspension spring ·5 inch wide, first parallel and then tapered to ·25 inch at the bottom, and in thickness from ·027 to ·003 inch, but it made no appreciable difference.

Mr. A. E. BALL: This subject is of particular interest to me, as my firm were among the earliest pioneers of striking and chiming mechanisms operated entirely electrically, and may be said to be the only one manufacturing motor-driven striking and tolling gear for large bells on a commercial scale. Patent records of 20 years ago illustrate some of our early designs, and examples are still giving good service. As my early training was that of a clockmaker—having been apprenticed to the trade—it is natural to expect that in designing motor-driven striking mechanism for large bells I should incorporate counting and hammer-lifting mechanism in accordance with clock-making practice. I employ, however, an electric motor in the place of heavy and dangerous weights which are also objectionable because of the space required for them.

There are two features which I specially admire in the striking gear designed by Prof. Robertson, and so clearly shown in the paper. The first is that the blows of the hammer are academically spaced throughout the striking of each hour, and this achievement marks a valuable addition to the science of clock-making and time distribution. The interval of five seconds chosen for the spacing of the blows is also a convenient one. I was able to appreciate fully this feature when in Bristol last summer. The hour of 11 a.m. boomed forth unexpectedly when I was in Park Street, and I was unable to check my watch from the first blow. As the last blow, however, must perforce occur at 11 hours 0 minutes 50 seconds, I used this time as a check. The second feature is that the first stroke of the hour occurs precisely as the hand of the master clock steps on to the 60 seconds mark on the dial. This is rendered possible by second-by-second contacts and the second-by-second progression of the contact wheel, which enables the release of the hammer to be accomplished in advance, as described in the paper.

With the more commercial clock systems employing half-minute contacts, the half-minute progression of any form of release must take place at the hour as shown by the master clock, with the result that the first stroke of the bell will be two seconds slow. This two-seconds interval is occupied in the releasing and falling of the hammer. This slight discrepancy is easily overcome, however, by keeping the master clock two seconds fast. When Westminster chimes precede the hour, however, the release of the same in advance is readily accomplished by employing the continuously-moving wheel train of the "waiting-train" movement, now used for driving the exposed hands of large turret clocks. This movement being under the constant control of a master clock, the necessary accuracy is assured. In some instances a "time train" known as a duration contact has been pressed into service for the purpose of obtaining the release of the striking in advance.

A review of the many electro-mechanical functions revealed in the paper, and a knowledge of the progress made in recent years by the science of electric clock-making, prompts me to remark that for the maintenance of such apparatus a new type of mechanic is being called into existence, namely, a man with the dual training of both electrician and clockmaker.

Mr. A. E. Ball.

On skilled attention being required for mechanism such as described by Prof. Robertson, the first impulse of the average person would be to call in a clockmaker. My definite experience is that no matter how clever a clockmaker a man may be, he finds himself hopelessly at sea with such work without a sound knowledge and a somewhat extended experience of electrics. I have met with some amusing blunders perpetrated by men who possessed the single knowledge only, but the possibilities can be readily imagined. Those intending to enter the clockmaking profession should be given a sound electrical training if they are to compete in the coming age.

Mr. W. E. PHILBROW (Member): From studies of human historical records, it would appear that time-indicating methods and mechanism were among the first intricate mechanical constructions attempted by man, and, presumably, we should now have reached some degree of finality with such mechanisms, but consideration of the many novel features described in Prof. Robertson's paper should certainly remove any doubt as to finality in human ability to conceive new ideas and mechanisms. I think the predominant feature is the elaborate care taken to secure an extreme degree of accuracy by the elimination of minor defects in design and construction, and it is unfortunate that the working results are subject to other less accurate influences, namely, daily time regulation from the National Observatory, and changing atmospheric conditions.

Possibly the national service of time regulation is as accurate as is necessary for our general requirements, and no change need be made for individual circumstances, but the difficulties arising from changing atmospheric conditions could be overcome by enclosing the mechanism, or at least the pendulum, in an air-tight case, maintained under vacuum pressures by means of a small electric pumping outfit. Alternatively, the barometer, etc., could be replaced with a temperature and humidity controller, thereby maintaining the air inside the case under predetermined conditions. Regarding the diffusion of sound, it is surely a benefit to the residents within a short distance of the University that the sound does not reach them, and the position of the bell is well judged.

Mr. C. R. H. Bonn (Associate Member): Prof. Robertson tells us that this clock was produced regardless of time or cost; it cannot, therefore, be considered as a commercial production. The complications introduced and the defects to which it appears to be liable put it out of court as a standard apparatus even for large tower clocks. This, however, in no way detracts from the interesting nature of the mechanism and the value of the experimental work carried out, which reflect great credit on Prof. Robertson and his assistants, and it is an advantage that the results of this long and laborious piece of work, with its excellent illustrations, are now available to those interested in the subject. The main problem in good time-keeping, ever since the first application of the principle of pendulum control, has been the escapement, and it cannot be said that an ideal escapement has yet been evolved. It has occurred to many that the difficulty might possibly be overcome by making use of the self-regulating possibilities of certain types of electric motor, but it has been reserved to Mr. Alexander Steuart, of Edinburgh, to find the perfect solution.

His invention is in essence an electric motor which drives the hands of a clock direct, whose speed is controlled by a pendulum which is strikingly small in respect to the power it controls. There are several unique and important features which differentiate this new clock from all previous attempts in the same direction. These will be made clear by reference to Fig. 22. The motor M, which drives the clock mechanism, is supplied from some source of power K. The motor circuit is completed by a resistance R and the gravity arm E, which acts as a switch, in parallel with it. The resistance R is so proportioned that the motor's speed is well above normal when the switch contacts G and H are closed, and well below normal when the contacts are open. The motor also drives a cam T, which, as it rotates, displaces a roller S carried by the lever P and maintained in contact with T by the action of the counterweight W. The displacement of S by T as it rotates causes the lever P alternatively to lift and release the gravity arm E, which in its descent presses against the pendulum A in the first part of its swing, and thus imparts to it the necessary impulse. Suppose the pendulum A is in the middle of its swing to the right, driven by the gravity arm E pressing it at F; then E will descend until G makes contact with H, and will maintain contact until E is lifted by the movement of P, which is stopped by J. In the meantime the pendulum A

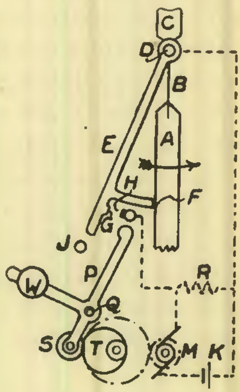


Fig. 22.—Steuart's Clock with Continuous Motion.

returns to the left, and P moves away again from E, allowing it again to descend and give another impulse to the pendulum. If the motor is slow, the contacts between G and H are longer, and hence the motor gets more current and speeds up. If the motor is fast, the contacts are of shorter duration, and the motor gets less current and slows down. In this way a ·25 horse-power shunt-wound motor driving a turret clock may be controlled by a pendulum weighing only eight ounces. Motors of greater power may be similarly controlled. There is, in fact, no limit to the power of the motor in this respect. It will be seen that the pendulum has no work to perform, and no contacts to make and break. Its only losses are air friction, the friction of the pendulum and the gravity-arm suspensions, and the impact of the pendulum and arm. These clocks frequently keep time to within one half-second per week, and have a power one hundred times or more that of an ordinary clock. The energy actually used is, of course, that required to overcome friction.

It should be noted that there is no stop and start of the mechanism each time the pendulum swings. On standing in front of one of these clocks, it will be observed that the second hand moves round with an absolutely uniform motion, in striking contrast to the jerky motion of the second hand of an escapement clock. This clock should be of particular interest to engineers, for it requires but little imagination to foresee extensions of this principle of control. Compared with Prof. Robertson's clock, its construction bears out a point I have been at pains to emphasise before, namely, that the correct application of first principles is always reflected in the simplicity of the ultimate design. I think it is a point peculiarly worthy of remark that two such extraordinarily ingenious mechanisms should owe their inception to Scotsmen, and can see no reason, other than the backwardness of our manufacturing methods, why Scotland should not be the home of a large and flourishing watch and clock industry.

Prof. Robertson: Since the paper was written, additional information has been obtained on several points. For instance, the architect tells me that when the belfry was designed there was no intention of striking the hours on the bell, and the position of the windows took account of the fact that when the bell is rung by swinging it, its mouth points upwards. The Astronomer Royal has also stated that for some years "Big Ben" has not been allowed to be slow because its chimes were at one time used as a warning for the Greenwich wireless time signal. The Observatory takes daily records of the time given by the first stroke, but is not responsible for the time kept by the clock.

Further breakages of the flipper springs on the switches on the striking machine have occurred, including one on the two-pole switch which had not previously given way. These flipper springs do not appear to be absolutely necessary for the action of the switch, and it has been arranged to try doing without them when the next breakage takes place. When the clock was first put into service, the release contact for the bell was advanced only one second on the clock, but this was altered to two seconds at the beginning of September. The bell was then heard at the bottom of the tower about 0·4 second before time on the clock. Now that the weather is colder, a longer time is taken to release the mechanism, probably due to a thickening of the oil round the magnet plunger, and the stroke of the bell is heard almost exactly to time. The bronze pivot-pin of the driving pawl of the Greenwich time unit has had to be replaced by a steel one, as it had worn nearly right through before the end of the year. This wear was quite unexpected, for during the drive the pressure on the pin is quite small, and the driving arm, pawl, and wheel go as one piece without relative movement. Probably the pawl is driven up slightly by the teeth after it strikes the stop, and the wear is caused by the inertia forces which act during this time. The under side of the head was also worn a bit, but remained flat without the slightest trace of a ridge, and the worn surfaces had quite a good polish without any scoring.

One little trouble with the escapement was not mentioned in the paper. The method of hanging the cradle on a hook constrains its direction to a particular azimuth, but it is free from that constraint when resting on the contact. Consequently there is a kick about a vertical axis unless things are adjusted so that the flexible wire holds the cradle in the same direction. This kick wastes energy in friction and reduces the amplitude. It is, therefore, proposed to locate the cradle by a light spring, which will also carry the current, and remove the constraint provided by the hook, but this will be tried on another pendulum before adopting it.

In conversation, questions have been asked by Mr. Langford and others regarding the effect of the regulator on the pendulum, with particular reference to its action when the time and rate happen to be correct. Fig. 23 has, therefore, been drawn

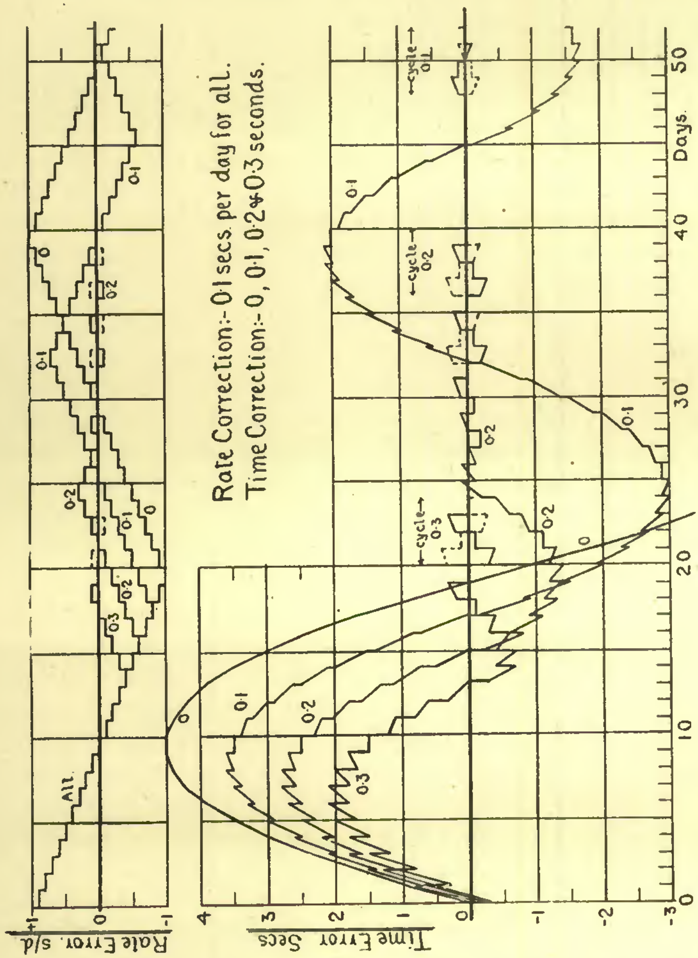


Fig. 23.—Effect of Regulator on Pendulum.

to illustrate these phenomena. In this diagram, the initial rate is supposed to be fast by one second per day and the time practically right, but just sufficiently ahead to make the regulator begin correcting the rate. Four cases are shown, all

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with the same daily rate correction of 0·1 second per day, but having different amounts of time correction, namely, 0, 0·1, 0·2, and 0·3 second. They all suppose the other conditions to remain constant during the time to which the graphs apply. With rate correction alone and no time correction, the rate error oscillates indefinitely between the limits ±1 second per day, and the time error between ±45 seconds. If the time and rate had been correct to begin with, there would be a repeated four-day cycle of amplitude ±0·1 second per day and ±0·1 second. With a time correction of 0·1 second at each daily signal, combined with the same rate correction as before, the original oscillation would gradually die away, and finally settle down to a four-day cycle of ±0·2 second for the time error, that for the rate error being unaltered. With greater time corrections, the decay is more rapid, but the amplitude of the final cycle of the time error is bigger. It is, therefore, desirable to apply the smallest time correction which will suffice to deal in a reasonable time with the changes of rate to be expected from changes of barometer, etc.

If the time error should come to exactly zero, the regulator would not be operated, but in practice there would always be a small residual error sufficient to give either a fast or a slow indication. It is, therefore, uncertain which way the regulator will move at the points where the graphs cross the zero line at the times when the signal is due; it has been assumed that the residual error is of the same sign as it had been before reaching zero. The alternative action is indicated by the dotted lines in the final cycles. The diagram also assumes that one position of the regulator will give exactly the correct rate. It is more probable that the correct rate would come between two positions of the regulator, in which case the amplitude of the final cycle would be less than that given, and it would be repeated every two days instead of every four. The course of events, when initially neither the rate nor the time is correct, can be studied from the same graphs by taking some other point as the starting point on the graph.

I agree with Mr. Langford that better time could be kept by hand regulation, using the wireless time signals, provided some really skilled person were available daily throughout the year to look after it; but as this clock is not in my laboratory, and as the University is in any case closed for most purposes during a large part of the year, I decided to eliminate the human element as far as possible by adopting automatic regulation. The choice of the corrections of 0·1 second per day and 0·2 second was made on the supposition that the barometric error would be somewhere about the one-third of a second per day for each inch of barometric change which is given in the paper. Observations indicate that the true figure for this pendulum is much higher. Another pendulum with the same size of bob gives more nearly one second per day, and this now seems to be near the figure for the University pendulum. The buoyancy part of the barometric effect is quite easily calculated from the relative densities of the air and the bob; for the steel bob it amounts to 0·22 second per day per inch of barometric change. But the inertia effect cannot be estimated with any certainty; it must be found by experiment on the particular pendulum concerned, run in its own case and at its usual amplitude. At 18 degrees C., a change of humidity from zero to saturation would produce about the same effect as a one-quarter inch change of barometer. When the amount of the barometric error has been more accurately ascertained, the time correction will be increased accordingly.

I thank Mr. Hope-Jones for his drawing of Prof. Féry's escapement. The resemblance between Figs. 14 and 21 is truly remarkable, the only essential difference being the substitution of the link for the roller. Mr. Hope-Jones has, however, considerably accentuated the resemblance when "adapting" the drawing by fitting in Féry's principle to my details. Although I must have seen the descriptions of the Féry and Froment escapements when I read Mr. Hope-Jones' paper in 1923, I had entirely forgotten about them. This device of pulling a stop out of the way when contact is made, in order to permit a weight or spring to fall further than it was lifted, is still older than 1855. Gill invented a similar arrangement, as mentioned by Mr. Steuart. Prof. Sampson has a Cottingham clock with the Gill escapement running at Edinburgh which has given most excellent results, and he describes the arrangement in his 1918 paper to the Royal Society of Edinburgh. More recently, Prince has adopted the same principle, with a spring instead of a weight, for driving the master pendulum of his system of electric clocks. A perusal of his paper to the British Horological Institute ("Horological Journal," December, 1924-January, 1925) shortly before I started the design of my pendulum is certain to have influenced me in adopting the device.

But I did not arrive at the link escapement from that starting point at all. Mr. Ball drew my attention to an escapement, patented by Mr. H. Whidbourne, which seemed to have some very attractive features, but which had not at that time been worked out in practical detail. In the Whidbourne escapement, a gravity lever is held up by a strut which is pivoted at the bottom and weighted so as to fall away when free; normally it is held in the upright position by the friction between its end and the gravity lever which it supports. A roller on the pendulum rod engages a pallet on the lever, much as in Fig. 21, and lifts the lever very slightly on passing through zero. The strut then falls clear, and the lever falls on the outward swing of the pendulum until it is caught by a stop, at a lower level than its original position. The fall of the strut makes an electrical contact, through which a magnet is excited, and resets both the strut and the lever. The special feature of this escapement is the exceedingly small amount of lift needed to release the lever, but in practice a much bigger lift would be necessary in order to ensure that expansion of the baseplate and rods would not put it out of action altogether, just as in my escapement. On working out the details, certain points were noted which seemed to me to be defects, and changes were made in the design to remove them. A second lever connected to the pendulum by a link was added below the gravity lever to do away with the pallet friction; the gravity lever then became a mere driving weight, and was modified accordingly. It was then obvious that the new lever could itself make the contact at the place where it lifted the weight, and so the original Whidbourne device vanished altogether. Although the Féry escapement provides the energy for the maintenance of the pendulum's motion in exactly the same way, it does not lend itself to regulation through the escapement as mine does.

For a clock continuously under my own observation, I also prefer to use the wireless signals and regulate by hand. But, as mentioned above, I wanted this clock to be regulated automatically, for which purpose the wireless signals are hardly applicable. Mr. Ball has patented a means of doing it, but its cost for capital charges and upkeep would be considerably more than that of the Post Office signal in cases such as this where the minimum rate applies. In any case, his apparatus would be at the mercy of the changes in the wireless code which take place now and again.

The Rudd synchronising arrangement which Mr. Hope-Jones mentions is described on page 113 of his 1910 I.E.E. paper. (See footnote on page 292.) It only adjusts the rate and not the time, but the amount of the adjustment is varied in accordance with the difference between clock time and true time. It seems from his description to be intended for use with the Post Office hourly signals, which depend on the Post Office clock, and not with the daily signals which come direct from Greenwich. I do not think the Rudd arrangement is inherently simpler than my own.

Mr. Hope-Jones complains that it was a waste of time to make new designs, and almost suggests that I could have bought everything needed over the counter, so to speak. This is rather an exaggeration. Without doubt either his company or Messrs. Gent could have produced the required mechanism based on their standard patterns for smaller bells, but so far as I can ascertain neither have had to deal with a bell of this size, and this is not to be wondered at, seeing that only ten

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bells of five tons and over, and only five of eight tons or more, have been erected in this country in 100 years, and not all of these are used for striking the hours. In fact, when Mr. Hope-Jones was definitely asked to offer a pendulum with seconds impulses he did not do so, but advanced arguments in favour of the usual half-minute impulses. He is quite right in stating that my escapement is not put forward as the basis of a new system of electric clocks. For ordinary purposes, the standard arrangement with half-minute impulses is certainly to be preferred.

Mr. Langford's account of his experiments on isochronism are of much interest. It may be taken for granted that it is quite impossible to obtain perfect isochronism with varying amplitude except under the very restricted conditions mentioned in the paper in connection with Fig. 15. His method of altering the amplitude by changing the driving weights must necessarily vary the escapement deviation at the same time, and would, therefore, give a different result from that obtained by varying the amplitude in some other way, such as a change in the friction of the pallets or the crutch (if there is one), or in the air friction.

Some time ago Mr. Ball showed me a graph for a Graham regulator obtained by varying the driving weights. It is of the same general nature as one of the top curves of Fig. 15, but when he set the weight to get the running point at the flat part of the curve he did not obtain the good time-keeping which he expected. I thank Mr. Ball for his appreciation of the exact timing of the strokes; in practice I find it of very great use in comparing the time given by the bell with that given by my own clock. I cannot do this anything like as easily, or as accurately, with "Big Ben," for it is difficult to time accurately a stroke whose exact time of arrival is not known. With "Great George" (except at one o'clock) we know exactly where to look for the strokes after the first; and so a number of observations are obtained for the odd fraction of a second.

Mr. Philbrow suggests enclosing the pendulum in an air-tight case. This is the usual practice with observatory clocks, which, in addition, are placed in an underground room kept at a constant temperature. But such an arrangement is not applicable in this case, because it was desired to make the clock a show piece of apparatus.

I do not think that Mr. Steuart's clock with continuous movement, either of the pattern described in his own paper or that referred to by Mr. Bonn, could with advantage be employed for my purpose. It is a mistake to suppose that continuous motion is of advantage in ordinary cases, although it is useful for subdividing the seconds. The beat of a step-by-step movement gives definite points of time which enable comparisons to be made to a much higher degree of accuracy than is possible with continuous motion without special devices. Has Mr. Bonn ever tried obtaining the error of a continuously-moving clock to say 0·2 second by means of the wireless signals? The statement that these clocks frequently keep time within 0·5 second per week means little, as even the poorest clock will do this now and again by accident. If the claim had been that it would not have gone wrong by more than that amount in any week for year after year, it would have indicated a very high order of time-keeping indeed. I have a pendulum which on several occasions, always during May, has done even better than half-a-second per week, but I know that the difference between a week of high barometer and one of low barometer, or between a week in summer and one in winter, amounts to a good many seconds per week.