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PATENT SPECIFICATION

DRAWINGS ATTACHED

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COMPLETE SPECIFICATION

Electrical Timepiece

We, BULOVA WATCH COMPANY INC., 75–20 Astoria Boulevard, Flushing 70, New York, United States of America, a Corporation organized under the laws of the State of New York, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to an electronically-controlled timepiece, including a timekeeping standard constituted by a tuning fork excited by an electronic drive circuit.

Such an electronically controlled timepiece is disclosed in Patent Specification No. 761,609 and comprises a tuning fork vibrator controlled by an electronic drive circuit. The entire mechanism including a battery is containable within a wrist watch casing. The major elements of the electronically-controlled timepiece are the following:—

(a) A self sufficient timekeeping standard including a tuning fork having a predetermined natural frequency and a battery-energized transistorized drive circuit to sustain the vibratory motion of the fork.

(b) A rotary timepiece movement including a gear train and the usual pointers.

(c) A motion transformer operatively intercoupling the tuning fork and the rotary timepiece movement to convert the vibratory action of the fork into a rotary motion for actuating the movement.

The vibratory motion of the tuning fork in the timekeeping standard is converted into rotary motion by driving a tiny ratchet wheel having a large number of teeth. This is accomplished by attaching a pawl to one tine of the tuning fork, the pawl engaging the teeth of the ratchet wheel and functioning to advance the wheel one tooth for each complete vibration of the fork. The ratchet wheel in turn acts to drive the gear train of the watch movement.

The pawl reciprocates with a stroke, the length of which is dependent upon the amplitude of tine oscillation. Hence the electronic drive circuit for the tuning fork must be capable of normally maintaining the amplitude of oscillation of the tine within a range wherein the stroke of reciprocation of the pawl, in a direction substantially tangent to the ratchet wheel at the point of engagement, is at least as great as the pitch of the ratchet teeth but is not greater than twice this pitch.

It is clear that with such a timepiece each vibration of the tine will cause the ratchet wheel to turn through an angular distance which corresponds to the pitch of the ratchet teeth. Thus, the rotational speed of the ratchet wheel will be exactly proportional to the frequency of oscillation of the tine, and since the latter may be maintained constant with an extremely high degree of accuracy, the rotational speed of the ratchet wheel and consequently that of the timepiece mechanism which is driven thereby may be similarly stabilized.

Furthermore if the travel of the pawl never exceeds twice the tooth-to-tooth distance, nor drops below the tooth-to-tooth distance, the ratchet wheel will neither gain nor lose the vibrations of the tuning fork.

However, with such a timepiece, inasmuch as the tuning fork mechanism is incorporated in a wrist watch which is subject to various mechanical disturbances affecting the amplitude of vibration under actual operating conditions, shocks will be imparted to the tuning fork causing the amplitude thereof to exceed the desired tolerances.

According to the present invention, an electronically-controlled timepiece comprising a timekeeping standard including a tuning fork having a predetermined natural frequency of vibration, and an electronic drive circuit for applying impulse to said fork for an interval in the course of each cycle of vibration to sustain the vibratory action thereof at said frequency, said system having means res-

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ponsive to the amplitude of said vibratory motion for varying the energy of said impulses as a function of said amplitude to effect amplitude regulation of said fork; a rotary timepiece movement; and a motion transformer intercoupling said fork and said rotary movement to convert said vibratory motion into rotary motion for actuating said movement accordingly.

Thus, in an electronic drive circuit in accordance with the invention, a constant potential source or battery is connected through an electronic control device, such as a transistor, to the drive coil of an electromagnetic transducer adapted to apply actuating impulses to a tuning fork. The control device may be maintained in a substantially quiescent condition by a bias voltage and in the course of each full cycle of tuning fork oscillation it may be rendered operative for a relatively brief interval. For example, the operative period may be 30% of each cycle, the circuit being quiescent for 70% of the cycle. This is accomplished by means of a phase-sensing coil incorporated in the transducer, the vibration of the fork inducing an alternating voltage in the coil which when the peak portion thereof exceeds a threshold value acts to overcome the cut-off bias.

The energy pulse applied to the drive coil of the transducer during the operative interval of the control device is determined by the comparative relation between the voltage induced in the drive coil by the vibratory action of the fork and the constant battery potential. The induced voltage is proportional to the amplitude of fork vibration. The more the relatively constant battery voltage exceeds the maximum instantaneous induced voltage in the drive coil, the greater is the energy pulse applied to the drive coil to actuate the fork. If the tuning fork amplitude should be increased by an abrupt mechanical shock to a level at which the maximum instantaneous induced voltage exceeds the battery potential, no energy pulse will be delivered.

Thus the transducer serves a threefold purpose. First, it converts pulses of electrical energy into corresponding mechanical impulses which drive the tuning fork; second, it acts to detect the amplitude of tuning fork oscillation; and, third, it controls the duration of the interval and the phase position thereof in the course of a tuning fork cycle during which driving pulses are delivered. In this manner a governing action is obtained acting to regulate the amplitude of tuning fork vibration within close limits.

For a better understanding of the invention and to show how the same may be carried into effect reference will now be made to the accompanying drawings in which:—

Figure 1 illustrates, in perspective, an electronically-controlled timepiece in accordance with the invention,.

Figure 2 shows the schematic circuit diagram of the electronic drive system.

Figure 3 is a graphical representation of certain voltages and currents as a function of time.

Referring to the drawings the timepiece as shown in Figure 1 comprises a timekeeping standard including a tuning-fork type vibrator 1102 having a pair of tines 1103 and 1104, and an electronic drive system for oscillating the same. Each of the tines 1103 and 1104 carries an electric component which is part of the drive system means.

The vibrator is operatively associated with a driving means which forms part of a motion transformer for converting oscillations of the vibrator to rotary movement of the hands of the timepiece. In the instant embodiment, the motion transformer is of the pawl and ratchet type, but it will be understood that the vibrator may be used in conjunction with any suitable type of motion transformer.

The pawl and ratchet mechanism includes a pawl 1120 carried by the tine 1104, a tip 1120*a* being provided at the free end of the pawl. The tip co-operates with the ratchet teeth 1121*a* of a rotatably mounted ratchet wheel 1121 in such a manner that the ratchet wheel is caused to rotate in the direction of the arrow 1140 during oscillation of the tine 1104. A friction wheel 1121*b* which is mounted for rotation together with the ratchet wheel 1121 is engaged by a leaf spring 1121*c* which is carried by the base 1101 of the timepiece. The friction wheel 1121*b* and leaf spring 1121*c* constitute a brake for preventing rotation of the ratchet wheel under the influence of anything other than the pawl 1120.

The ratchet teeth 1121*a* have a pitch P, so that stroke of reciprocation of the tip 1120*a*, in a direction tangential to the ratchet wheel at the point of engagement of the tooth and the ratchet wheel, should be not less than P and not greater than 2P.

The drive system for oscillating the tines comprise electro-mechanical driving means capable of converting electrical energy into mechanical energy for oscillating the vibrator, electro-mechanical sensing means capable of converting mechanical energy into electrical energy and responsive to the oscillation of the vibrator for producing an electrical signal which is a function of the amplitude thereof, and electrical energy supplying means connected in circuit with the driving means and the sensing means for supplying electrical energy to the former in a manner dependent upon or controlled by the electrical signal produced by the latter. Each of these electro-mechanical means includes a magnetic field producing component and a magnetic field responsive component which is in circuit with the electrical energy supplying means, one of which components is carried by the vibrator for movement therewith during oscillation thereof and the other of which components is carried by the base of the timepiece and co-operates with the one component in such a manner that oscillation of the vibrator is concomitant with the existence of a voltage across the magnetic field responsive component.

The magnetic field producing components are carried by the tines 1103 and 1104, respectively. Each of these magnetic field producing components is constituted by a substantially cup-shaped permanent magnet 1106 which is formed with a rim portion and a central boss portion, the former being shown as constituting an S pole and the latter as constituting an N pole. These portions define an annular space between themselves, as is clearly shown in the drawing. If desired, the central boss portion may be omitted and the magnetic characteristics may be imparted to the components 1106 by providing a permanent bar magnet in place of this boss portion.

One of the magnets 1106 carries an abutment element 1107*b* the free end of which is spaced a distance *s* from the other magnet 1106, thus establishing the absolute maximum amplitude at which the tines 1103 and 1104 can oscillate.

Each of the magnets 1106 co-operates with a magnet field responsive component which is constituted by coil. The coil associated with one of the magnets 1106 is a sensing coil indicated as S and the coil associated with the other magnet 1106 is a driving coil indicated as D which has approximately five to six times as many turns as the sensing coil S. Each coil is carried by a stationary tubular carrier 1110 which is fixed to a support 1113, each support in turn being mounted to the base plate of the timepiece (not shown). The arrangement of the parts is such that the coils extend into the annular spaces formed by the rim and boss portions of the respective magnets 1106, there being sufficient clearance between the outer surface of each coil and the inner surface of the rim portion of the corresponding magnet as well as between the inner surface of each tubular carrier 1110 and the outer surface of the boss portion of the corresponding magnet to permit reciprocation of the magnets relative to the coils during oscillation of the tines. It will be understood, therefore, that oscillation of the tines is concomitant with the existence of a voltage across the coils, the amplitude of oscillation and the amplitude of the voltage being inter-dependent upon each other. Thus, each coil together with its co-operating magnet forms an electro-mechanical transducer.

More particularly, the driving coil D together with its co-operating magnet 1106 forms an electro-mechanical driving means capable of converting electrical energy into mechanical energy, *i.e.*, a voltage placed across the driving coil D will cause movement of the co-operating magnet and an alternating voltage will cause reciprocation of the magnet and consequently oscillation of tine 1103 and, by force, of tine 1104 since it is one of the basic characteristics of a tuning-fork type vibrator that its tines oscillate together. The amplitude of oscillation of the tines will depend upon the amplitude of the voltage placed across the driving coil.

Similarly, the sensing coil S together with its co-operating magnet 1106 forms an electro-mechanical sensing means capable of converting mechanical energy into electrical energy, *i.e.*, oscillation of the tine 1104 and reciprocation of the associated magnet 1106 will induce an alternating voltage across the sensing coil C, the amplitude of this induced voltage being dependent upon the amplitude of oscillation of the tine 1104.

The coils S and D are connected in circuit with the electrical energy supplying means. The latter is responsive to the signal or control voltage induced in the sensing coil and produces a driving voltage across the driving coil which is a function of the amplitude of the signal, the arrangement being such that the control voltage which, by virtue of the fact that the sensing coil has fewer turns than the driving coil, is smaller than the driving voltage is amplified in such a manner as to maintain the driving voltage constant.

In the arrangement shown in the drawings, the electronic drive system includes a transistor TR having base, emitter and collector electrodes respectively indicated at B, E and C, a battery or other suitable source of substantially constant voltage B, a capacitor C and a resistor R constituting together an R.C. biassing network. The transistor is preferably a Germanium junction transistor and the battery is preferably one the terminal voltage of which, throughout substantially the entire useful life of the battery, remains substantially constant, with the voltage decreasing sharply only when the battery is almost completely discharged. For example, the battery may be of the mercury-cell type having a terminal voltage of approximately 1.3V.

The capacitor C having a capacitance of the order of 2 microfarads and the resistor R having a resistance of the order of 2 megohms are connected in parallel with each other, and the parallel circuit is in series with the sensing coil S so as to form a series circuit one terminal of which is connected to the transistor base and the other of which is connected to the positive terminal of the battery. The negative terminal of the battery is connected to one terminal of the driving coil D and forms another series circuit therewith, the terminals of which are constituted by the opposite terminal of the coil D and by the positive terminal of the battery, respectively. This last-mentioned terminal of the coil D is connected to the transistor collector, and the transistor emitter is connected to the positive terminal of the battery as so to complete the circuit.

The battery may equally well be interposed between the driving coil D and the collector, in which event one terminal of the driving coil D is connected to the positive terminal of the battery, the negative terminal thereof being connected to the collector. The emitter and the one terminal of the sensing coil-capacitor series circuit are connected to the free terminal of the driving coil. Alternatively the battery may be connected in the emitter branch of the transistor instead of in the collector branch.

The interaction of the electronic drive circuit and the tuning fork is self-regulating and functions not only to cause the tines to oscillate at their natural frequency, but also to maintain oscillation at a substantially constant amplitude. In practice, the amplitude of oscillation of the tines will be maintained at a substantially constant value or quickly returned to this value in the event of a mechanical disturbance.

The oscillations of the vibrator are converted into a rotary movement which is then utilized to drive the hands of the timepiece.

Now the ratchet wheel 1121 acts as the actuator for the rotary movement and it is therefore essential that the ratchet wheel be rotated at a constant rate. This result is achieved if the impulses transmitted to the ratchet wheel cause it to turn the same angular distance in each instance, in which case each oscillation of the vibrator will result in the same angular displacement of the ratchet wheel.

To this end, the length of the stroke of reciprocation of the pawl 1120 and more particularly of the tip thereof, in a direction tangential to the ratchet wheel at the point of engagement between the tooth and the ratchet wheel, should be greater than P but not greater than 2P, where P represents the pitch of the ratchet teeth.

It will be evident that if the pawl tip 1120*a* were to reciprocate with a stroke length smaller than P, then the tip would not, during successive reciprocations, engage successive ratchet teeth but would simply remain in engagement with the same ratchet tooth. Also, it will be seen that in the event the tip were to reciprocate with a stroke length greater than 2P, then the tip would engage non-consecutive or alternate teeth. If this were to occur, then each reciprocation during which the stroke length of the tip exceeded the distance 2P would bring about at least a double angular displacement of the ratchet wheel 1121.

It will be readily understood that the stroke length of the pawl tip in the tangential direction is a function of the amplitude of oscillation of the tine 1104. Thus, in order for the tip to reciprocate in the direction with a stroke length equal to at least P, and, in practice, with a stroke length which is somewhat greater than P, the tine will have to oscillate at a certain minimum amplitude.

Similarly, in order for the stroke length of the tip not to exceed 2P, and, in practice, not to exceed a length which is somewhat smaller than 2P, the amplitude of oscillation of the tine 1104 may not exceed a certain maximum amplitude. However, shocks or other extraneous forces to which a timepiece is very often exposed may be sufficient to cause the tine 1104 to oscillate momentarily at an excessive amplitude, *i.e.*, at an amplitude which exceeds the normal maximum value and which causes the tip to reciprocate with a stroke length greater than 2P.

It is not sufficient, therefore, for the electronic drive circuit to excite the fork into oscillation at its natural frequency. For accurate timekeeping it is essential that the amplitude of fork oscillation be stabilized and when the normal amplitude of oscillation is upset by external shock forces that the amplitude be quickly restored to its proper value.

The tuning fork is preferably operated at an amplitude at which the stroke length of the pawl tip in a direction tangential to the ratchet wheel is 150% of the tooth-to-tooth distance or pitch of the ratchet wheel. This permits a substantial departure in either direction from the set amplitude before the ratchet wheel loses synchronism with the tuning fork. The electronic drive circuit, whose behaviour will now be considered, operates to regulate the amplitude of oscillation so as to maintain the accuracy of the watch under the most rigorous working conditions.

Referring now to Figure 3, there is shown a composite graph combining separate plots of the transistor characteristics with the voltage in the base and collector circuits of the transistor.

Graph I shows collector voltage vs. collector current characteristics of the type of junction transistor TR employed in the electronic drive circuit. The characteristics illustrated are representative of transistors of standard design. The abscissa is calibrated linearly in terms of collector millivolts (Vec), the collector being negative relative to the emitter. The range is from 0 to −2800 millivolts. The ordinate is scaled in terms of collector microamperes (a), the range being between 0 and 22 microamperes.

The respective curves C_1 to C_{10} illustrate the collector current vs. collector voltage characteristics for different values of base voltage (Veb) expressed in millivolts (mv). Curve C_1 is for a base voltage Veb of +100 mv, C_2 is for +20 mv, C_3 is for zero mv, C_4 is for −20mv, C_5 is for −30mc, C_6 is for −40mv, C_7 is for −50mv, C_8 is for −60mv, C_9 is for −70mv, and C_{10} is for −100mv.

It will be noted that there is an appreciable current flow in the collector circuit only when the base voltage is negative. Actually transistors of standard design cannot be completely cut off by the application of a positive base voltage. However, for positive base voltages greater than 50 to 100 millivolts, the collector current remains at a minute value and in the example shown, this value is about 0.6 microamperes for all negative values of collector voltage.

For practical purposes, therefore, collector current in the transistor may be blocked by maintaining a positive base voltage. As will be explained later in greater detail, it is this transistor characteristic which enables the phase-sensing coil to determine the duration and phase position of the operative interval in the course of a full cycle of vibration during which the driving current pulse may be delivered.

Each of the curves C_3 to C_8 (zero or negative base voltage) in Graph I has a proportional zone wherein the collector current to collector voltage ratio is relatively high. That is to say, a small change in collector voltage produces a relatively large change in the collector current. The proportional zone runs between zero to at most minus 200 collector millivolts in the several curves. The proportional zone in the characteristic curves is followed by a saturation zone in which the ratio a/Vec is relatively low, i.e., a large change in collector voltage causes a relatively small change in collector current. For practical purposes, above approximately −200 millivolts, the collector current is independent of collector voltage and depends solely on base voltage.

Referring again to Figure 2, it will be seen that the battery B is coupled through the emitter and collector electrodes of transistor TR to the drive coil D of the transducer such that the drive coil is energized only when collector current is permitted to flow through the transistor. The battery voltage, as mentioned previously, is preferably obtained from a constant voltage source such as a mercury cell providing a 1.3 volt output.

Transistor TR is maintained in a substantially quiescent condition by a bias voltage applied to the base, and in the course of each full oscillatory cycle of the tuning fork it is rendered operative for a relatively brief interval. Base B of the transistor is biased positively relative to emitter R by means of the R-C network which is unidirectionally charged by the voltage induced in phase-sensing coil S and applied to the network through the emitter-base electrode circuit acting as a diode. Thus the drain on the battery is limited to the brief operative interval in each cycle.

The R-C values of the bias network are so chosen that the time constant of the combination is long compared to one tuning fork cycle. The diode action of the transistor permits the phase-sensing coil S to charge the capacitor to a value higher than battery voltage, a current flowing from emitter to base whenever the base is negative with respect to the emitter.

However, condenser C cannot discharge through the transistor during the portion of the cycle in which the voltage induced in the phase-sensing coil causes the base to go positive relative to the emitter. Resistor R therefore is provided to cause a portion of the charge on the condenser to leak off so that during a relatively short interval in each cycle the base will become negative with reference to the emitter. During this interval, the charge which leaked off the condenser is replaced.

Graph II of Figure 3 shows the base voltage (Veb) plotted as a function of time. The base voltage is expressed in the ordinate in terms of millivolts, the scale running from −200 through zero to +400 millivolts. Time is expressed on the abscissa in percentages of one tuning fork cycle, the scale extending from 0 to 100%.

The biasing action is illustrated diagrammatically in Graph II. The charge accumulated on condenser C in the biasing network is indicated by the broken horizontal line as the average base voltage Veb. The average Veb is at +140 millivolts which, as can be seen in Graph I, is more than sufficient to bias the transistor effectively to cut off. It will be recognized that this charge is not constant, hence the actual wave form for base voltage vs. time is a somewhat distorted sine wave. Nevertheless the base is at a positive potential for a large portion of each tuning fork cycle, thereby preventing the flow of current in the collector circuit during this time.

The curve in Graph II represents one full cycle of the alternating voltage wave induced in the phase-sensing coil S in the course of a cycle of tine oscillation. It will be seen that between about 60 and 90 per cent of the time in the course of one full cycle, the negative peak of the phase-sensing voltage overshoots the zero or threshold line on the base millivolts scale at x-x, whereby for an interval whose duration is 30 per cent of the full cycle, the voltage Veb on the base changes from zero to −100mv and back to zero. During this interval, as is evident from Graph I, collector current may flow in the transistor as long as the collector voltage is negative with respect to emitter E.

Thus the negative peak of the phase-sensing coil voltage wave overcomes the base bias and renders the transistor operative for a brief interval in the course of the vibratory cycle. Whether collector current is caused to flow during the operative interval and the amplitude of such current flow will depend on the magnitude of collector voltage, as can be seen in Graph I.

The effect of driving impulses upon the frequency of any mechanical vibrating system is zero for instantaneous impulses applied at the point of maximum velocity. This point falls midway in the oscillatory swing. Impulses of finite duration will have a negligible effect upon the frequency of the tuning fork if the impulses are symmetrical about the point of maximum velocity of the tines. Since the voltage induced in the phase-sensing coil of the transducer is proportional to the instantaneous velocity of the tuning fork tines, the base potential reaches its maximum negative value at the exact midpoint y of the oscillations of the tines (middle of swing in forward stroke). Driving pulses therefore occur at this time, thereby minimizing any disturbance to the natural frequency of the tuning fork.

The voltage and current conditions in the collector circuit will now be analyzed to determine the manner in which the driving current pulses vary with the amplitude of fork vibration. As explained previously in connection with Figure 2, drive coil D is connected in the collector circuit of the transistor in series with the battery B. The collector voltage at any instant is the algebraic sum of the instantaneous voltage induced in the drive coil by the moving magnetic elements on the tines and the voltage of the battery, neglecting the IR drop in the drive coil when current flows therein.

The transducers are designed so that at the chosen operating amplitude of the fork, the peak-to-peak induced voltage at no load in the drive coil (measured open circuit) is close to twice the given battery voltage. The algebraic sum of the battery voltage and the voltage induced in the drive coil will therefore vary sinusoidally from a small value approaching zero to nearly twice the battery voltage.

The coils and magnets of the transducers are so proportioned as to obtain the desired amplitude of pawl stroke at the point at which the instantaneous induced voltage is slightly less than the voltage of the battery. In practice this instantaneous value should come within 7 to 10% of the battery voltage. As indicated previously, the preferred amplitude is such as to cause a pawl travel equal to 150% of the tooth-to-tooth distance on the ratchet wheel. The desired dimensions may be calculated mathematically or determined empirically. The phase-sensing coil preferably contains about one-fifth as many turns of wire as on the drive coil D, whereby the voltage induced therein is about one-fifth of that in the drive coils.

The result of the transducer design is shown in Graph III in which the curve represents the algebraic sum of the voltage induced in the drive coil and the battery voltage. The battery level (1.3 volts) is represented by the broken vertical line at −1300 millivolts. The collector to emitter voltage varies sinusoidally in the course of a full tuning fork cycle (0 to 100 per cent).

It will be noted that at zero time (tuning fork velocity is zero) the collector voltage is at battery level (−1300 millivolts), at 25 per cent of a cycle later the collector voltage is about −2500 millivolts which is almost twice battery voltage, at 50 per cent the voltage is again at battery level, at 75 per cent (point y midway in the operative interval x-x of the transistor between 60 and 90 per cent) the voltage is about −105 millivolts, and at 100 per cent (the end of a full cycle) the voltage is again at battery level.

Quantitatively, the operation of the collector circuit may be observed by referring again to Graph I. Above about −200 millivolts, the collector current is independent of collector voltage and is responsive only to base voltage, this being the saturation zone. The base voltage vs. time curve (Graph II) shows that the base voltage is zero and going increasing negative at the 60% point in the cycle. At this same instant Graph III indicates that the collector potential is −600 millivolts. The collector current will therefore rise rapidly as the base voltage becomes more negative. However, as the cycle progresses, the collector voltage decreases (Graph III) to a point at which the collector current is strongly dependent upon this voltage, thereby causing a sharp drop in current and reaching a minimum at the exact mid-point of oscillation of the tines. It is this sharp drop in collector current with a decrease in collector voltage which results in tuning fork amplitude control.

At low amplitudes of vibration where the collector voltage (algebraic sum of battery voltage and induced drive coil voltage) remains at relatively large values, large pulses of current controlled only by the peak value of negative base voltage (saturation zone of curve) will be applied to the drive coils. This results in a rapid increase in amplitude into the range of amplitude control (proportioned zone of curve). Furthermore, if the amplitude should reach such a large value that the collector voltage is zero or positive when the base potential becomes negative in the operative interval, no pulses of current could occur. As a consequence, the tuning fork amplitude rapidly falls into the range of amplitude control.

Quantitative determination of the amplitude of the driving current requires correction for the IR drop in the drive coil, for the collector current is sensitive to small changes in collector voltage, below 200 millivolts. Though the current is relatively low, the drive coil contains many turns of very small diameter wire and hence presents a high resistance which may not be neglected. The drive coil for the various graphs shown on Figure 3 is assumed to have a total resistance of 16,000 ohms.

Graph IV shows the driving current plotted against time, for a complete cycle. This curve is derived from Graphs I, II and III, employing the conventional "load line" technique to correct for the drive coil resistance. The following example of the method for determining one point on this curve demonstrates the method used to obtain the remainder of the curve.

Referring to Graph II, point "a" indicates the instant in the cycle at which the base potential is −70 millivolts. This occurs at 66.5% point in the cycle. At this same instant, Graph III shows that the collector voltage would be −275 millivolts if no current were flowing in the drive coils. Calculation shows that a voltage drop of 275 millivolts will occur in a 16,000 ohm resistor when the current is 17.2 microamperes.

The load line is therefore drawn on Graph I intersecting the collector voltage axis at −275 millivolts, and intersecting the collector current axis at 17.2 micro-amperes. It is apparent that for any point on this line, its vertical projection indicates the collector voltage for that particular collector current, corrected for IR drop across the 16,000 ohm drive coils. This load line intersects the Veb −70 millivolts curve C_9 at a collector potential of −50 millivolts. For this collector voltage and base voltage the collector current is 14 microamperes. In other words, for a value of −275 millivolts, obtained by subtracting battery voltage from the voltage induced in the drive coil at a time of 66.5% of a cycle, at which time the base voltage is −70 millivolts, the collector voltage is −50 millivolts, giving a driving current of 14 microamperes at this instant. This may be plotted as point "a" on Graph IV for driving current vs. time. The remainder of this curve is obtained in a similar manner.

A careful study of the Graph IV of driving current vs. time, together with the various factors which contribute to the nature of this driving pulse, will reveal the effectiveness of this circuit in maintaining the tuning fork amplitude within the necessary limits. Graph IV shows typical current conditions at normal amplitude. The area under the curve for driving current vs. time is, of course, about proportional to the energy delivered to the tuning fork drive coils during a particular cycle.

If this energy is less than the total energy losses per cycle, the tuning fork amplitude will decrease. This decrease will have a relatively small effect upon the base voltage during the period when it is negative. The initial rise of the driving current pulse will therefore remain approximately the same as that shown on Graph IV. However, the central portion of the driving current vs. time curve will rise due to the larger value of collector voltage during the driving pulse, thus delivering more energy per pulse. This process will continue, the amplitude decreasing until the energy input per cycle exactly equals the total losses per cycle, after which the amplitude will remain constant. In Graph IV, changes in the central position of the curve resulting from amplitude variations are shown in dotted lines.

As pointed out previously, a fixed value for amplitude is not required by the tuning fork mechanism. It is only necessary that the normal amplitude remain within $33\frac{1}{3}\%$ of the value for which the mechanism has been designed, or that the amplitude be quickly brought back to this range if disturbed by a mechanical shock. We have found that the electronic drive circuit disclosed herein will return the amplitude within the required range in a small fraction of a second after a large disturbance in amplitude.

Experience has also shown that the "normal" amplitude remains nearly constant for a very wide range of conditions. For instance, a relatively large change in the friction of the gear train driving the hands gives rise to a negligible change in the "normal" amplitude. Furthermore, while the characteristics of a Germanium transistor are known to change widely with temperature, watches incorporating this circuit function without significant changes in amplitude from 0°C. to 40°C.

It has been stated that the tuning fork driving impulses vary as a function of the difference between the battery voltage and the peak voltage induced in the drive coil D. This voltage difference is normally small in comparison with the peak induced voltage, resulting in relatively large changes in difference voltage for small changes in amplitude. Assuming for example that the difference voltage is 5% of the peak value of the induced voltage at normal amplitudes, a drop in tuning fork amplitude of only 5% will result in a 100% increase in the difference between battery voltage and induced voltage, thus causing a large increase in driving current.

It should now be apparent that if the tuning fork were operating at a very low amplitude, perhaps a moment after starting to vibrate, large current pulses would be applied to the driving coil resulting a in rapid increase in amplitude. As the amplitude increases, the difference between the battery voltage and the peak induced voltage in the driving coil becomes smaller, thus reducing the driving pulses as explained above. When a certain amplitude level is reached, these driving pulses are reduced to the point at which they exactly match the energy dissipated during each tuning fork cycle by windage, hysteresis, train friction, etc., and the amplitude will remain at this value. In other words, the amplitude will be maintained at the value where the input energy per cycle exactly matches the loss in energy per cycle.

Obviously, the tuning fork amplitude is quite sensitive to battery voltage, for a given percentage change in battery voltage will cause a similar percentage change in amplitude.

However, mercury cells presently available have the property of maintaining a very constant voltage for about 99% of their useful life.

WHAT WE CLAIM IS:—

1. An electronically-controlled timepiece comprising a timekeeping standard including a tuning fork having a predetermined natural frequency of vibration, and an electronic drive circuit for applying impulses to said fork for an interval in the course of each cycle of vibration to sustain the vibratory motion thereof at said frequency, said system having means responsive to the amplitude of said vibratory motion for varying the energy of said impulses as a function of said amplitude to effect amplitude regulation of said fork; a rotary timepiece movement; and a motion transformer intercoupling said fork and said rotary movement to convert said vibratory motion into rotary motion for actuating said movement accordingly.

2. A timepiece according to claim 1 wherein said electronic drive circuit includes an electromechanical transducer operatively associated with said fork for applying impulses thereto said transducer having a drive coil and a phase-sensing coil, said coils having respective voltages induced therein in accordance with the vibratory motion of said fork, said drive circuit furthermore including a direct voltage source, an electronic control device coupling said source to said drive coil, biasing means to maintain said device in a quiescent condition, means to apply the induced voltage from said phase-sensing coil to said device to overcome said bias to render said device operative for an interval in the course of a vibratory cycle, whereby a current pulse is permitted to flow in said drive coil, and means algebraically to add the induced voltage from said drive coil to said voltage source to produce a control voltage regulating said current pulse as a function of the amplitude of fork vibration.

3. A timepiece according to claim 2 wherein said control device is constituted by a transistor having base, collector and emitter electrodes, there being furthermore provided means connecting said drive coil in series with said supply between said emitter and collector electrodes, a biasing source, means connecting said phase-sensing coil in series with said source between said base and said emitter electrodes normally to maintain said transistor in a quiescent condition, the voltage induced in said phase-sensing coil acting to overcome said bias to render said transistor operative for an interval in the course of a vibratory cycle, the voltage induced in said drive coil being added algebraically to the voltage of said supply whereby the current through said transistor during said operative period is controlled in accordance with the amplitude of said fork.

4. A timepiece according to claim 3 wherein there is provided a resistance-capacitance biasing network, means connecting said phase-sensing coil in series with said network between said base and said emitter electrodes whereby said network develops a bias normally maintaining said transistor in a quiescent condition and said induced phase-sensing voltage acts to overcome said bias to render said transistor operative for an interval in the course of a vibratory cycle.

5. A timepiece according to claim 4 wherein said transducer is dimensioned to produce the desired amplitude of fork vibration at a point at which the maximum instantaneous induced voltage in said drive coil is slightly less than the voltage of said battery.

6. An electronically-controlled timepiece substantially as hereinbefore described with reference to the accompanying drawings.

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840086 COMPLETE SPECIFICATION
2 SHEETS *This drawing is a reproduction of the Original on a reduced scale*
Sheet 1

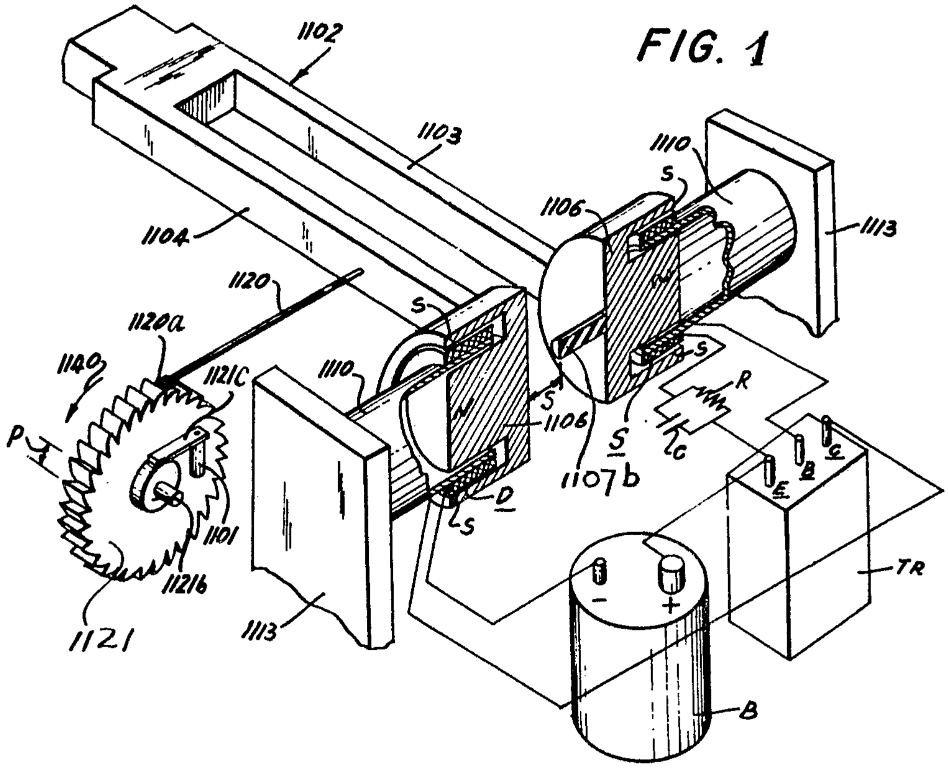


FIG. 1

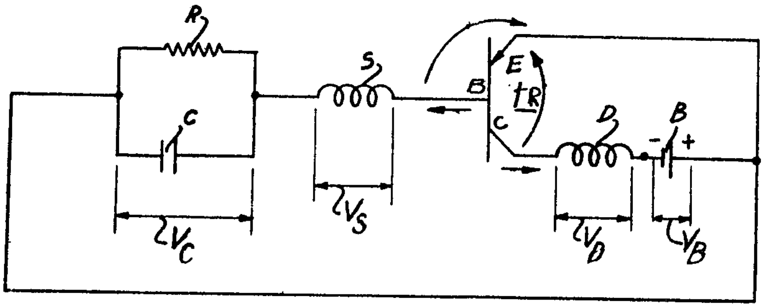


FIG. 2

FIG. 3

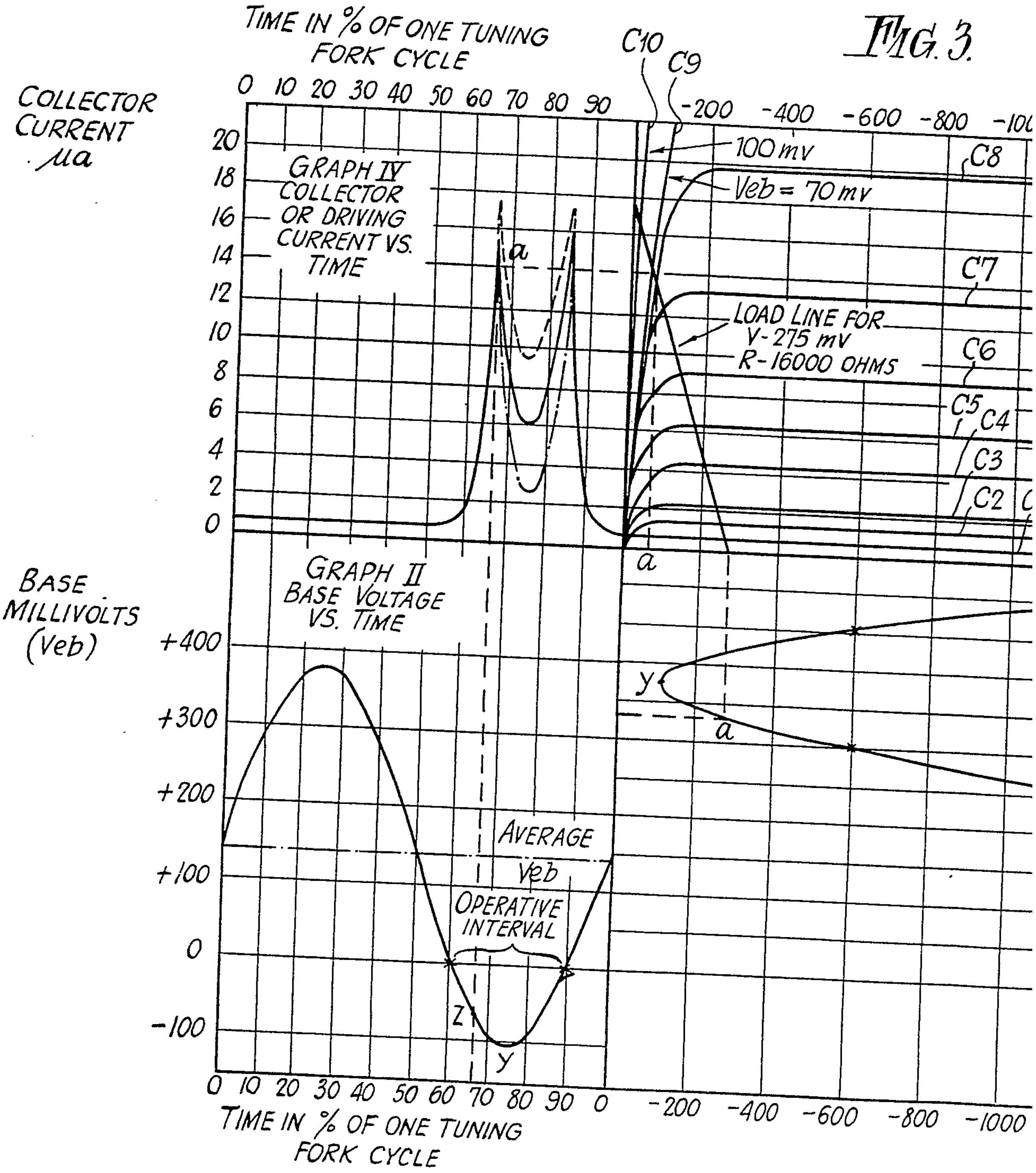
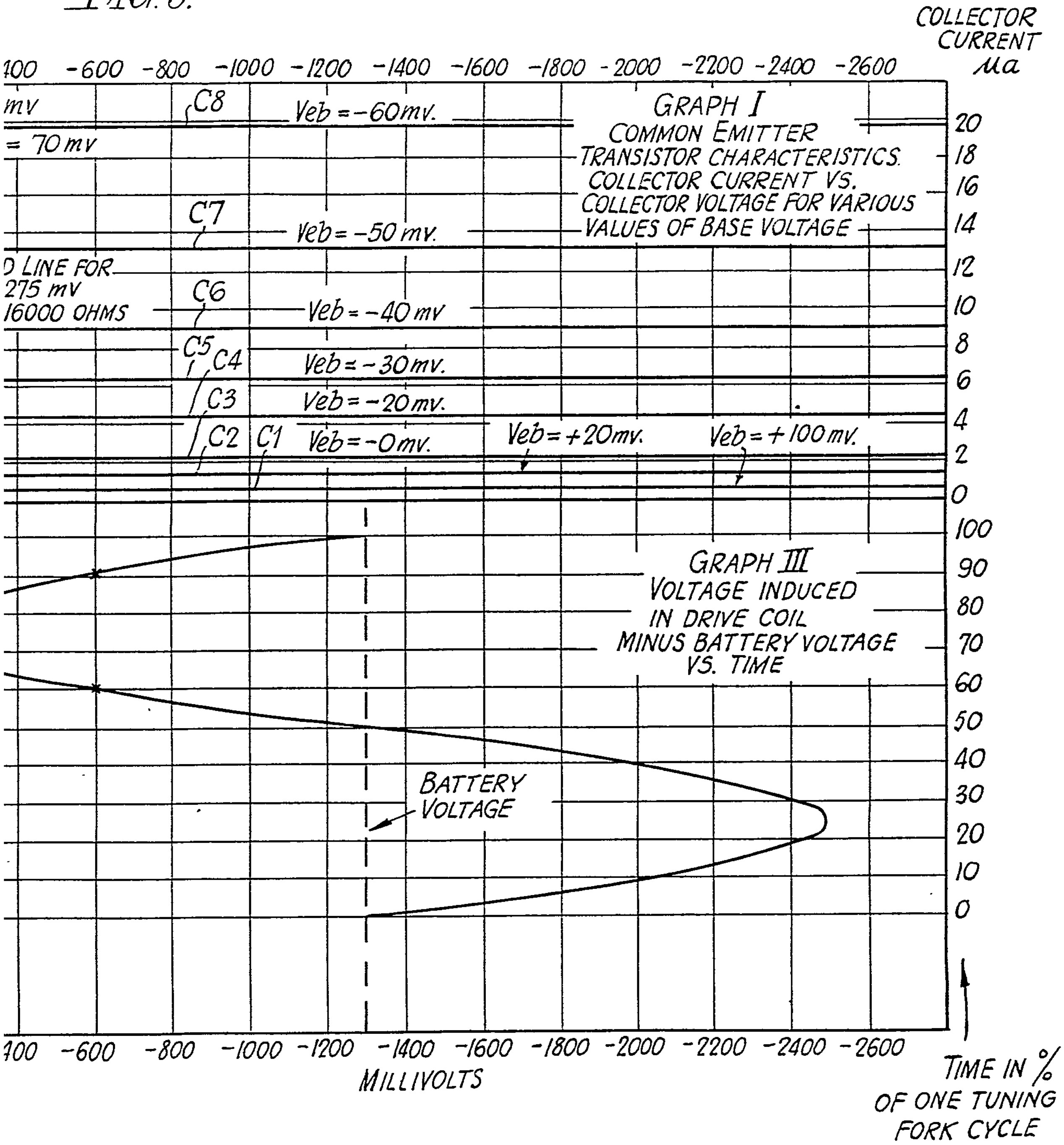

TIME IN % OF ONE TUNING FORK CYCLE
0 10 20 30 40 50 60 70 80 90
COLLECTOR CURRENT μa
20 18 16 14 12 10 8 6 4 2 0
GRAPH IV COLLECTOR OR DRIVING CURRENT VS. TIME
a
C10
C9
-200 -400 -600 -800 -100
100 mv
Veb = 70 mv
C8
C7
LOAD LINE FOR V-275 mV R-16000 OHMS
C6
C5
C4
C3
C2
C
a
BASE MILLIVOLTS (Veb)
+400 +300 +200 +100 0 -100
GRAPH II BASE VOLTAGE VS. TIME
y
a
AVERAGE Veb
OPERATIVE INTERVAL
Z
y
0 10 20 30 40 50 60 70 80 90 0
-200 -400 -600 -800 -1000
TIME IN % OF ONE TUNING FORK CYCLE

FIG. 3.


COLLECTOR CURRENT Ma
400 -600 -800 -1000 -1200 -1400 -1600 -1800 -2000 -2200 -2400 -2600
mv
= 70 mv
C8
Veb = -60 mv.
GRAPH I
COMMON EMITTER
TRANSISTOR CHARACTERISTICS.
COLLECTOR CURRENT VS.
COLLECTOR VOLTAGE FOR VARIOUS
VALUES OF BASE VOLTAGE
C7
Veb = -50 mv.
D LINE FOR
275 mv
16000 OHMS
C6
Veb = -40 mv
C5
C4
Veb = -30 mv.
C3
Veb = -20 mv.
C2
C1
Veb = -0 mv.
Veb = +20 mv.
Veb = +100 mv.
20 18 16 14 12 10 8 6 4 2 0
100 90 80 70 60 50 40 30 20 10 0
GRAPH III
VOLTAGE INDUCED
IN DRIVE COIL
MINUS BATTERY VOLTAGE
VS. TIME
BATTERY VOLTAGE
400 -600 -800 -1000 -1200 -1400 -1600 -1800 -2000 -2200 -2400 -2600
MILLIVOLTS
TIME IN %
OF ONE TUNING
FORK CYCLE

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Sheet 2

FIG. 3.