Feb. 14, 1961 M. HETZEL **2,971,323**

ELECTRONICALLY-CONTROLLED TIMEPIECE

Filed June 13, 1957 2 Sheets-Sheet 1

Fig. 1.

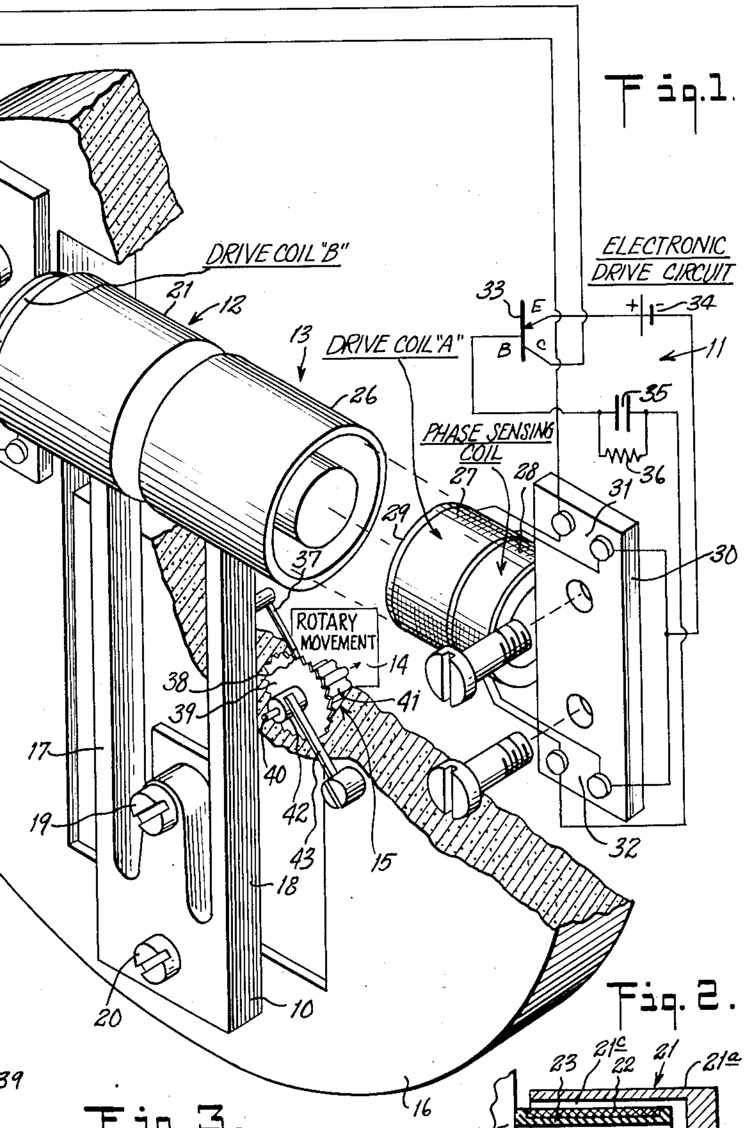

Fig. 4.

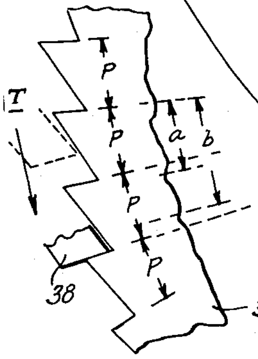

Fig. 2.

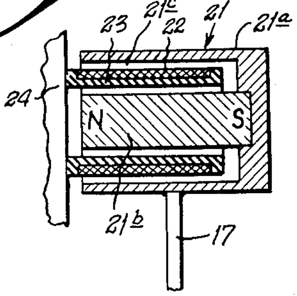

Fig. 3.

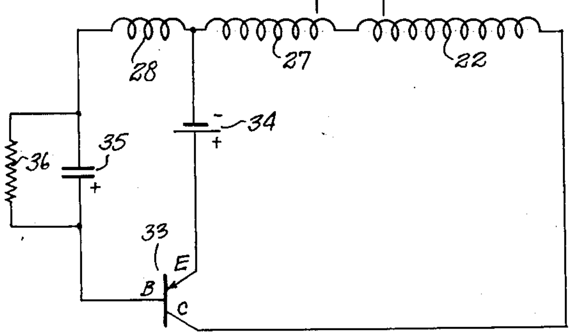

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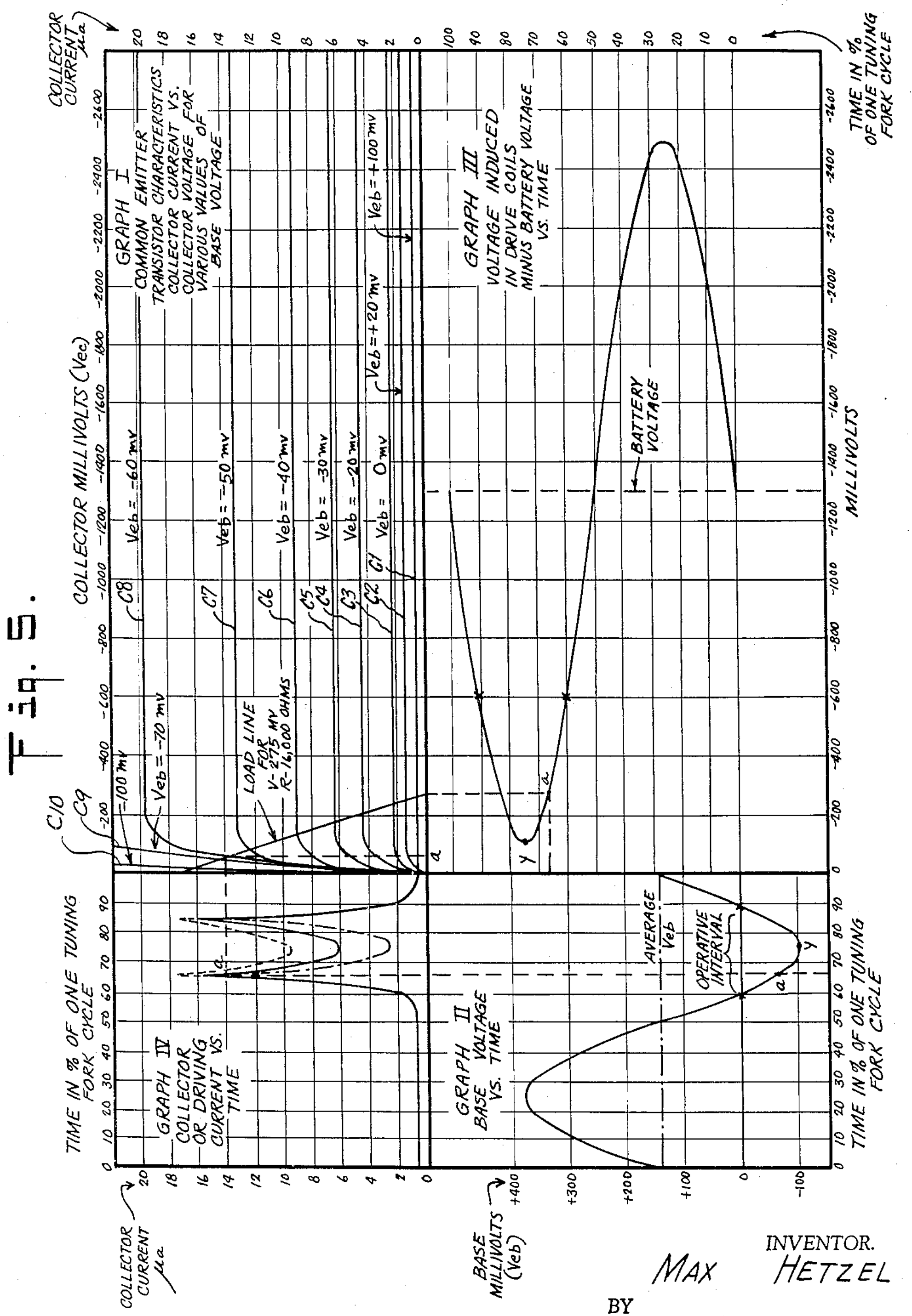
Fig. 5.



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2,971,323

ELECTRONICALLY-CONTROLLED TIMEPIECE

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Filed June 13, 1957, Ser. No. 665,480

Claims priority, application Switzerland June 19, 1953

13 Claims. (Cl. 58—23)

The present invention relates generally to electronically-controlled timepieces, and more particularly to a timepiece including a timekeeping standard constituted by a tuning fork excited by a transistorized drive circuit, the amplitude of vibration being regulated thereby.

The invention represents an improvement over electronically-controlled timepieces of the type disclosed in the co-pending applications Serial No. 436,949, filed June 15, 1954, now abandoned; Serial No. 565,451, filed February 14, 1956, now Patent No. 2,888,582; Serial No. 565,452, filed February 14, 1956, now Patent No. 2,949,727; Serial No. 570,958, filed March 12, 1956, now Patent No. 2,929,196; Serial No. 580,813, filed April 26, 1956, now Patent No. 2,908,174; Serial No. 584,709, filed May 14, 1956; Serial No. 588,409, filed May 31, 1956, now Patent No. 2,900,786; Serial No. 600,922, filed July 30, 1956; and Serial No. 615,329, filed October 11, 1956, as well as in applications Serial No. 463,462, filed October 20, 1954, now abandoned; Serial No. 485,781, filed February 2, 1955, now abandoned; and Serial No. 547,510, filed November 17, 1955, now abandoned. The instant application is a continuation-in-part of the above-noted copending application Serial No. 584,709.

Electrically-operated mechanisms are known in which a vibratory reed is actuated by an electromagnet energized by alternating-current drawn from a power line, the reed acting on a ratchet mechanism to drive a clock movement. Such mechanisms are not self-sufficient as timepieces, for their accuracy is determined by the frequency stability of the external alternating-current supply. Thus it is the alternating-current source which acts as the timekeeping standard, and not the vibrating reed. Moreover, since the operation of the ratchet mechanism depends on the amplitude of reed vibration fluctuations in the amplitude of the alternating-current source adversely affect the accuracy of the device.

Vibratory frequency standards are known in which a tuning fork is actuated by means of an electronic drive circuit including a vacuum tube oscillator. Such arrangements, however, have not been incorporated in timepieces nor is such use feasible, particularly within the confines of a watch case. The relatively heavy current drain and the voltage reguirements of a vacuum tube oscillator preclude energization by a miniature battery. Furthermore, while conventional electronic drive circuits are adapted to stabilize the frequency of vibration, they are incapable of accurately controlling the amplitude of fork movement under varying ambient conditions.

In the novel timepiece of the type disclosed in the above-identified copending applications, a tuning fork vibrator is 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.

In this way, 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.

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 on the vibrations of the tuning fork. The tuning fork is preferably operated at an amplitude at which the travel of the pawl impelling the ratchet wheel is 150% of the tooth-to-tooth distance or pitch for this wheel. In practice, this permits a variation of 33⅓% from the normal tuning fork amplitude before the ratchet wheel is caused to fall out of synchronism with the tuning fork and either is completely arrested or is impelled to advance two teeth for a single fork vibration.

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 tolerances indicated above.

In view of the foregoing, it is the principal object of this invention to provide a tuning fork timekeeping standard for a timepiece wherein the tines of the fork not only are excited into oscillation at their natural frequency but are maintained at a substantially constant amplitude.

A significant feature of the invention resides in the fact that the drive circuit will bring about a rapid restoration of amplitude to an assigned range in the event the fork is caused by disturbances to vibrate outside of said range.

Also an object of the invention is to provide an amplitude-stabilized electronic drive circuit for a tuning fork which may be energized by a miniature battery for a protracted period without requiring battery replacement.

An important advantage of the invention lies in the fact that the electronic drive circuit supplies current to an electromechanical transducer acting on the tuning fork only during a relatively small portion of its vibratory cycle, thereby minimizing battery drain.

More specifically it is an object of the invention to provide an electronic drive circuit including an electromechanical transducer which applies impulses to the tines of a tuning fork, the transducer being activated by pulses whose energy is controlled as a function of the amplitude of tine vibration to produce an amplitude-governing action.

Briefly stated, 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 is maintained in a substantially quiescent condition by a bias voltage and in the course of each full cycle of tuning fork oscillation it is 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 as well as further features and other objects thereof, reference is had to the following detailed description to be read in conjunction with the accompanying drawings wherein:

Fig. 1 illustrates, in perspective, an electronically-controlled timepiece in accordance with the invention, certain elements of the device being shown in exploded view, other elements being shown schematically.

Fig. 2 is a longitudinal section taken through one of the transducers.

Fig. 3 separately shows the schematic circuit diagram of the electronic control system.

Fig. 4 is an enlarged fragment of the ratchet wheel in the timepiece.

Fig. 5 is constituted by Graphs I to IV illustrative of the principles underlying the invention.

General description

Referring now to the drawings and more particularly to Figs. 1 and 2, the principal components of a timepiece in accordance with the invention are: (*a*) a timekeeping standard constituted by a tuning fork **10** and an electronic drive circuit **11** therefor, the circuit including electro-mechanical transducers **12** and **13** operatively coupled to the fork, (*b*) a rotary movement of conventional design including a gear train for turning the hands of the watch, the movement being represented by block **14**, and (*c*) a motion transformer **15** operatively intercoupling the fork **10** and the rotary movement **14** and acting to convert the vibratory action of the fork into rotary motion. All of the components are mounted at various positions on a disc-shaped base plate **16**. The plate may be contained within a watch casing of conventional design. A more detailed description of the physical arrangement of the components on the base plate may be found in the cited copending applications.

Tuning fork **10** is provided with a pair of tines **17** and **18**, the yoke portion of the fork being rigidly attached to the base plate **16** by means of screws **19** and **20**. The central area of the base plate is cut out to permit unobstructed vibration of the tines.

Transducer **12** is constituted by a magnetic element **21** secured to the free end of the tine **17**, the element coacting with a drive coil **22**. Drive coil **22** is wound on a tubular carrier **23** affixed to a mounting strip **24** which is secured to base plate **16** and is provided with a pair of connecting terminals **25**.

Transducer **13** is constituted by a magnetic element **26** secured to the free end of the tine **18** and coacting with a drive coil **27** and a phase-sensing coil **28**. The drive coil **27** and the phase-sensing coil **28** are wound in juxtaposed relation on a tubular carrier **29** affixed to a mounting strip **30**. In practice the phase-sensing coil may be wound over the drive coil rather than in juxtaposed relation thereto. Strip **30** is attached to base plate **16** and is provided with a first pair of connecting terminals **31** for the drive coil and a second pair **32** for the phase-sensing coil.

As best seen in Fig. 2, the magnetic element **21** is constituted by a cylindrical cup **21***a* of magnetic material such as iron, and a permanent magnet rod **21***b* coaxially mounted therein. The rod **21***b* which may be made, for example, of Alnico is supported on the end wall of the cup to provide a magnetic circuit in which the lines of magnetic flux extend across the annular air gap **21***c* defined by the inner rod and the surrounding cylinder.

The carrier **23** supporting the drive coil **22** is received within the anular gap **21***c*, the carrier being spaced both from the center rod and the surrounding cylinder whereby the magnetic element is free to reciprocate axially relative to the fixed coil. The construction of the transducer **12** is similar in design to a permanent magnet dynamic speaker, save for the fact that the moving element is the magnet and not the coil. Transducer **13** is of identical design except that an additional coil **28** is provided.

In operation, an energizing pulse applied to the drive coil of the transducer will cause an axial thrust on the associated magnetic element in a direction determined by the polarity of the pulse in relation to the polarization of the permanent magnet and to an extent depending on the energy of the pulse. Since the magnetic element is attached to a tine of the tuning fork, the thrust on the element acts mechanically to excite the fork into vibration.

The vibratory action of the fork and the concomitant movement of the magnetic element induces a back E.M.F. in the drive coil, and in the case of the transducer **13**, in the phase-sensing coil as well. Since the magnetic element reciprocates in accordance with the vibratory motion of the tuning fork, the back E.M.F. will take the form of an alternating voltage whose frequency corresponds to that of the fork.

A tuning fork is a high "Q" mechanical oscillator and will vibrate at a natural frequency determined by the dimensions of the tines and the loading thereon which, in this instance, is determined by the mass of magnetic elements attached to the free ends. As disclosed in the above-identified copending applications, various expedients are available to adjust the frequency of the fork to a desired value. The rate at which the timepiece movement is driven is directly proportional to the frequency of the vibrator, so that the accuracy of the timepiece may be regulated by pre-determining the operative frequency of the tuning fork.

The electronic drive circuit **11** of the tuning fork comprises a transistor **33**, a single cell battery **34** and an R–C biasing network constituted by a condenser **35** shunted by a resistor **36**. Transistor **33** is provided with base, emitter and collector electrodes represented by letters B, E and C, respectively.

The base electrode is coupled through the R–C bias network **35**, **36** to one end of the phase-sensing coil **28**, the other end of the coil being connected to one end of the drive coil **27**. Drive coil **27** is connected in series with drive coil **22** to the collector electrode C of the transistor.

The emitter electrode E is connected to the positive terminal of battery **34**, the negative terminal thereof being connected to the junction of drive coil **27** and phase-sensing coil **28**. Thus the battery is connected serially through both drive coils **22** and **27** between the emitter and collector electrodes of the transistor, the collector being negative relative to the emitter.

The transistor is of the germanium junction type, and the polarity of the battery connection is shown as it exists when the transistor is of the PNP type. Obviously for other types of junction and point contact transistors made of such materials as silicon or germanium, the battery connections are arranged in accordance with the particular requirements.

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. The motion transformer **15** by means of which this is accomplished is shown in Fig. 1, and it includes a pawl **37** in the form of a light leaf spring. Pawl **37** is secured at one end to the tine **18** and carries at its other end a tip **38** which may be a precious or semi-precious stone, such as a ruby or sapphire. The tip **38** engages the teeth of a ratchet **39** so that the oscillation of the tine **18** transmits turning impulses to the ratchet wheel. The ratchet wheel shaft **40** is provided with a pinion **41** which engages the first gear in the gear train of the rotary movement **14**.

Shaft **40** of the ratchet wheel is provided with a miniature brake drum **42**, lightly engaged by one end of a brake member **43** whose other end is fixedly mounted on the base plate **16**. The brake member **43** functions to prevent the ratchet wheel **39** from advancing beyond the point to which it is pushed by the pawl tip **38** during its forward stroke and also holds this wheel in position during the return stroke. Thus overrunning of the ratchet wheel under the influence of its own inertia is prevented, as is backward rotation due to friction between the pawl of the ratchet tooth during the back stroke of the pawl.

Behavior of motion transformer

The ratchet wheel **39** acts as the actuator for the rotary movement **14** 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 **39** 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, as shown in Fig. 4, the length of the stroke of reciprocation of the pawl and more particularly of the tip **38** 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 from Fig. 4 that if the pawl tip **38** 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 **38** 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 **39**.

It will be readily understood that the stroke length of the pawl tip in the tangential direction T is a function of the amplitude of oscillation of the tine **18**. Thus, in order for the tip **38** to reciprocate in the direction T with a stroke length equal to at least P, and, in practice, with a stroke length *a* 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 *b* which is somewhat smaller than 2P, the amplitude of oscillation of the tine **18** 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 **18** 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 work 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 behavior will be considered in the next section, operates to regulate the amplitude of oscillation so as to maintain the accuracy of the watch under the most rigorous working conditions.

Behavior of electronic drive circuit

Referring now to Fig. 5, 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 employed in the electronic drive circuit. 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 (μa), 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 —20 mv., C_5 is for —30 mv., C_6 is for —40 mv., C_7 is for —50 mv., C_8 is for —60 mv., C_9 is for —70 mv., and C_{10} is for —100 mv.

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 microampere 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 radio $\mu a/Vec$ 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 now to Fig. 3, it will be seen that the battery **34** is coupled through the emitter and collector electrodes of transistor **33** to the serially connected drive coils **22** and **27** of the transducers such that the drive coils are simultaneously energized only when collector current is permitted to flow through the transistor. The battery voltage is preferably obtained from a constant voltage source such as a mercury cell providing a 1.3 volt output.

Transistor **33** 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 E by means of R–C network **35**, **36** which is unidirectionally charged by the voltage induced in phase-sensing coil **28** 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 network **35**, **36** 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 **28** 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 **35** 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 **36** 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 Fig. 5 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 **35** 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 28 in the course of a cycle of tine oscillation. It will be seen that between about 60 and 90 percent 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 percent of the full cycle, the voltage Veb on the base changes from zero to —100 mv. 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 Fig. 3, the drive coils **22** and **27** are connected in the collector circuit of the transistor in series with the battery **34**. The collector voltage at any instant is the algebraic sum of the instantaneous voltage induced in the drive coils by the moving magnetic elements on the tines and the voltage of the battery, neglecting the IR drop in the drive coils when current flows therein.

In accordance with the invention, 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 coils (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 coils 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 the sum of the turns on the two drive coils, 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 coils 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 percent).

It will be noted that at zero time (tuning fork velocity is zero) the collector voltage is at battery level (−1300 millivolts), at 25 percent of a cycle later the collector voltage is about −2500 millivolts which is almost twice battery voltage, at 50 percent the voltage is again at battery level, at 75 percent (point *y* midway in the operative interval *x*—*x* of the transistor between 60 and 90 percent) the voltage is about −105 millivolts, and at 100 percent (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 coils, for the collector current is sensitive to small changes in collector voltage, below 200 millivolts. Though the current is relatively low, the drive coils contain many turns of very small diameter wire and hence present a high resistance which may not be neglected. The drive coils for the various graphs shown on Fig. 5 are 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 microamperes. 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 V*eb* −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 coils 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 portion 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 33⅓% 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 coils. 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 coils resulting in a rapid increase in amplitude. As the amplitude increases, the difference between the battery voltage and the peak induced voltage in the driving coils 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.

Practical embodiment of the invention

In one practical embodiment of the invention, the following values were employed for the various components in the timepiece.

Ratchet wheel:	
Outside diameter	.095″
Thickness	.0015″
Material	Steel
Number of teeth	300
Pitch of teeth	.0010″
Depth of teeth	.0003″
Tuning fork:	
Frequency of vibration	360 cycles per second.
Amplitude (on center line of magnet)	.0025″.
Magnetic element: Outside diameter of cylindrical cup	.235″
Coils:	
Wire size over insulation	.0006″
Material	Copper.
Number of turns on drive coils	6000 and 9000 respectively.
Number of turns on phase-sensing coil	3000.
Electronic circuit components:	
Transistor—	
Type	PNP, germanium junction.
Mfg	Raytheon QC156.
Capacitor	0.1 mfd. electrolytic.
Resistor	5.6 megohms.
Battery cell:	
Type	Mallory R-M400.
Voltage	1.3+ volts.
Average battery current	5 to 6 microamperes.

While there has been disclosed an arrangement involving two transducers acting on separate tines of a tuning fork, it is also possible to obtain similar results by means of a single transducer having a drive coil and a sensing coil cooperating with a single tine, the other tine carrying a balance weight of equivalent mass. Alternatively, two transducers may be provided for the two tines, one including a drive coil and the other a phase-sensing coil. The behavior of the system in either case is substantially the same as described herein.

It is also possible to have the coils carried by the tines and to maintain the magnetic elements stationary relative thereto. The shape of the tuning fork is by no means limited to that shown herein and may be in any of the various forms disclosed in said copending applications. The several forms of motion transformers and braking means shown in said copending applications may also be substituted for that shown herein.

Thus it is evident that many changes and modifications may be made without departing from the essential spirit of the invention. It is intended in the appended claims to cover all such changes and modifications as fall within the true spirit of the invention.

What is claimed 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 system for applying impulses to said fork for a relatively brief 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. In a timepiece, a timekeeping standard comprising a tuning fork, and an electronic drive circuit therefor including an electromechanical transducer operatively associated with said fork for applying impulses thereto and 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, 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 a relatively brief 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. In a timepiece, a timekeeping standard comprising a tuning fork and an electronic drive circuit therefor including an electromechanical transducer operatively associated with said fork for applying impulses thereto and having a drive coil and a phase-sensing coil, a direct voltage supply, a transistor having base, collector and emitter electrodes, 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 a relatively brief 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. In a timepiece, a timekeeping standard comprising a tuning fork having a predetermined natural frequency and an electronic drive circuit therefor including an electromechanical transducer operatively associated with said fork for applying impulses thereto and 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, a direct voltage supply having a predetermined constant potential, a transistor having base, collector and emitter electrodes, 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 biasing source between said base and said emitter electrodes, said bias normally maintaining said transistor in a quiescent condition and said induced phase-sensing voltage acting to overcome said bias to render said transistor operative for a relatively brief interval in the course of a vibratory cycle, the induced drive coil voltage being added algebraically to said voltage of said supply whereby current through said transistor during said operative

period is controlled in accordance with the amplitude of said fork.

5. In a timepiece, a timekeeping standard comprising a tuning fork having a predetermined natural frequency and an electronic drive circuit therefor including an electromechanical transducer operatively associated with said fork for applying impulses thereto and 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, a battery, a junction transistor having base, collector and emitter electrodes, means connecting said drive coil in series with said battery between said emitter and collector electrodes, 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 a relatively brief interval in the course of a vibratory cycle, the induced drive coil voltage being added algebraically to said voltage of said battery whereby the current through said transistor during said operative period is controlled in accordance with the amplitude of said fork.

6. In a timepiece, a timekeeping standard comprising a tuning fork having a predetermined natural frequency and an electronic drive circuit therefor to excite said fork and to maintain the vibration at desired amplitude including an electro-mechanical transducer operatively associated with said fork for applying impulses thereto and 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, a battery, a junction transistor having base, collector and emitter electrodes, means connecting said drive coil in series with said battery between said emitter and collector electrodes, 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 a relatively brief interval in the course of a vibratory cycle, the induced drive coil voltage being added algebraically to said voltage of said battery whereby the current through said transistor during said operative period is controlled in accordance with the amplitude of said fork, said transducer being 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.

7. In a timepiece, a timekeeping standard comprising a tuning fork having a predetermined natural frequency and an electronic drive circuit therefor including an electromechanical transducer operatively associated with said fork for applying impulses thereto and 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, a direct voltage supply having a predetermined constant magnitude, the instantaneous maximum value of the induced drive coil voltage being slightly less than the magnitude of said supply when said fork reaches a chosen amplitude, an electronic control device having a control electrode, means connecting said drive coil to said supply through said device, a biasing source, means connecting said phase-sensing coil in series with said source to said control electrode normally to maintain said device biased in a quiescent condition, said induced phase-sensing voltage acting to overcome said bias to render said device operative for a relatively brief interval in the course of a vibratory cycle, the induced drive coil voltage being added algebraically to said voltage of said supply whereby the current through said transistor during said operative period is controlled in accordance with the amplitude of said fork.

8. In a timepiece, a timekeeping standard comprising a tuning fork having a predetermined natural frequency and an electronic drive circuit therefor including an electromechanical transducer operatively associated with said fork for applying impulses thereto and 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, a constant voltage battery, a junction transistor having base, collector and emitter electrodes, means connecting said drive coil in series with said battery between said emitter and collector electrodes, 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 a relatively brief interval in the course of a vibratory cycle, the induced drive coil voltage being added algebraically to said voltage of said battery whereby the current through said transistor during said operative period is controlled in accordance with the amplitude of said fork, said transducer including a magnetic element secured to said fork and movable therewith relative to said coils, said transducer being proportioned to produce an instantaneous maximum induced voltage in said drive coil slightly less than the voltage of said battery when the amplitude of said fork attains a chosen maximum value.

9. An electronically controlled timepiece comprising a timekeeping standard comprising a tuning fork having a predetermined natural frequency and an electronic drive circuit therefor including an electromechanical transducer operatively associated with said fork for applying impulses thereto and 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, a direct voltage supply source having a predetermined constant potential, a junction transistor having base, collector and emitter electrodes, means connecting said drive coil in series with said supply source between said emitter and collector electrodes, 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 a relatively brief interval in the course of a vibratory cycle, the induced drive coil voltage being added algebraically to said voltage of said supply source whereby the current through said transistor during said operative period is controlled in accordance with the amplitude of said fork; transformer means to convert the vibratory movement of said fork into rotary motion; and a watch movement driven by said transformer.

10. A timekeeping standard comprising a tuning fork, a transducer for actuating said fork and including a drive coil in which a voltage is induced in accordance with the amplitude of fork vibration, a battery for energizing said drive coil, an electronic control device including a transistor for connecting said battery to said coil for a brief interval in the course of each fork cycle of vibration, and means to control current flow through said transistor during said interval in accordance with the difference between said induced voltage and the battery voltage.

11. An electronic watch comprising a casing subject to changes of position and containing a tuning fork having a natural frequency which is at least 300 cycles per second; a drive system for said fork including transducer means operatively associated with said fork for exciting same into vibratory movement at its natural

frequency, a direct-voltage source and transistor control means periodically coupling said voltage source to said transducer to apply energizing pulses thereto; and means mechanically coupled to said fork to convert the vibrations thereof into rotary motion and including rotary speed reduction means for effecting time indications under the control of said fork movement.

12. In a timepiece: a timekeeping standard including a vibratory tuning fork and an electronic drive system for applying impulses to said fork to sustain the vibratory motion thereof, said electronic drive system being provided with an electromechanical transducer operatively associated with said fork for exciting same into vibration, a direct-voltage source for energizing said transducer and a control circuit having a transistor connecting said source to said transducer and means responsive to the vibratory motion of said fork to render said transistor effectively conductive for a relatively brief interval in the course of a vibratory cycle thereby to produce said impulses; and motion transformer means mechanically coupled to said fork to convert the vibratory motion thereof into rotary motion indicating time.

13. In a timepiece: a timekeeping standard including a vibratory tuning fork and an electronic drive system for applying impulses to said fork serving both to sustain the vibratory motion and to govern the vibratory amplitude thereof, said electronic drive system being provided with an electromechanical transducer operatively associated with said fork for exciting same into vibration, a direct voltage source for energizing said transducer and an electronic control circuit having a transistor connecting said source to said transducer and means responsive to the vibratory motion of said fork and the amplitude thereof to render said transistor effectively conductive for a relatively brief interval in the course of a vibratory cycle and to govern the degree of conductivity thereby to produce said impulses; and motion transformer means mechanically coupled to said fork to convert the vibratory motion thereof into a rotary motion indicating time.

References Cited in the file of this patent

UNITED STATES PATENTS

405,471	Gleeson	June 18, 1889
1,560,056	Horton	Nov. 3, 1925
2,036,917	Favre-Bulle	Apr. 7, 1936
2,628,343	Murray	Feb. 10, 1953
2,644,920	Tierney	July 7, 1953
2,652,460	Wallace	Sept. 15, 1953
2,680,160	Yaeger	June 1, 1954

FOREIGN PATENTS

579,298	France	July 29, 1924
746,465	Great Britain	Mar. 14, 1956