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(72) Inventor DALE ROLAND KOEHLER

(19) THE PATENT OFFICE LONDON

(54) IMPROVEMENTS RELATING TO ELECTROMAGNETIC TRANSDUCER AND ELECTRONIC WATCH

(71) We, BULOVA WATCH COMPANY, INC., a corporation organized under the laws of the State of New York, one of the United States of America, of 630 Fifth Avenue, City and State of New York, United States of America, 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 generally to electronically-controlled timepieces which incorporate electromagnetic transducers for sustaining a tuning fork in vibratory motion, and more particularly to an improved trans.. ducer structure that makes possible a substantial reduction in the size of the timepiece.

In the United States Patents to Hetzel 2,900,786 and 2,971,323, there are disclosed electronic timepieces including a timekeeping standard constituted by a tuning fork whose vibrations are sustained by two electromagnetic transducers operating in conjunction with a battery-energized transistor circuit. The vibratory action of the fork is converted into rotary motion to turn the time-indicating hands of the timepiece. In timepieces of the type disclosed in the Hetzel patents, each electromagnetic transducer is associated with a respective tine of the fork, the transducer including a magnetic element attached to the end of the tine and vibrating therewith. The magnetic element on one tine reciprocates with respect to a stationary main dtive coil section, and that on the other tine moves back and forth with respect to a stationary minor drive coil section and a sensing coil. The two drive coil sections are connected in series to the output circuit of the transistor, while the sensing coil is connected to the input thereof, whereby alternating voltage induced in the sensing coil renders the transistor conductive to produce current pulses in the drive coil sections for magnetically actuating the tines. When a battery-operated timepiece is to be confined within a small watch casing or in a miniature housing of similar dimensions where space is at a premium, it is essential that the electrical and mechanical efficiency of the system be of exceptionally high order. Otherwise any loss of energy, which in a large- scale device may be negligible, can give rise to serious drawbacks in a more compact structure. It is vital, therefore, that the transducer or transducers which actuate the fork, operate at optimum efficiency, for in this way, even with a battery of small power capacity, it is possible to sustain the vibratory action of the fork for a prolonged period.

Because the sole source of energy for the timepiece is a single-cell miniature battery, any factor which dissipates energy or reduces efficiency not only cuts down the useful battery life, but also creates operating difficulties. In order, therefore, to create a highly compact timepiece, it is important that maximum use be made of all available space and that the transducers which actuate the fork be as small as possible without, however, requiring an undue amount of power.

In the above-identified Hetzel U.S. Patents, the transducer includes a magnet element formed by a cylindrical cup having a circular cross-section, a permanent magnet rod or core of uniform cross-section being coaxially mounted within the cylinder to define an annular air gap therein. The stationary drive or sensing coils associated with the magnet element are received within the annular air gap, whereby in operation, the magnetic element reciprocates with respect to the coil. These transducers will hereinafter he referred to as being of the cylindrical magnet rod type.

In the prior U.S. Patent to Bennett et al 3,221,190, there is disclosed an improved transducer arrangement for a timepiece generally of the type disclosed in said Hetzel patents. In this Bennett et al U.S. patent, the permanent magnet is not of uniform cross- section throughout its length, but is linearly tapered to assume a frustoconical form, the coil received in the annular air gap being similarly tapered in order to realize the greatest number of turns within the air gap at the position therein of maximum flux density. These transducers will hereinafter be referred to as being of the frustoconical magnetic rod type. While transducers of the frustoconical magnetic rod type are distinctly superior to those of the cylindrical magnetic rod type, they are not sufficiently efficient to make possible a reduction in the dimensions of a watch to the point where a truly miniature or a ladies’ size tuning-fork watch movement becomes feasible. The reason for this is that should one reduce the existing size of a transducer of a cylindrical or frustoconical magnetic rod type, a higher input power would be required to drive the same tuning fork to compensate for the reduction in magnitude of the electro mechanical coupling (e.m.c.) factor. The e.m.c. factor is a direct measure of the amount of electrical energy converted to mechanical energy at the transducer interface and there fore the smaller the e.m.c. factor, the larger the electrical power required for a given amount of mechanical power. Hence, with a single-cell battery of the type and size presently used in conjunction with electronic timepiece movements, the cell would be exhausted in a relatively short period. On the other hand, if a larger battery cell is employed, this would be self-defeating, for the very purpose of reducing the transducer size is to make a smaller watch; hence, if the reduction in transducer size dictates the use of a larger cell, then nothing has been gained. It must be home in mind that battery size is an important parameter in the over-all size of the timepiece, and that the existing dimensions of electronic timepiece battery cells are a limiting factor in producing a smaller watch movement.

In practice, a power requirement for a urn ing-fork watch which is in excess of about fifteen microwats cannot be satisfied within the limits of a commercially acceptable watch volume. With transducer designs of the type heretofore known, should the transducer be made smaller to conserve space, the resultant increase in power requirement would go beyond the tolerable limit due to an increase in the fork amplitude. The improvement resulting from the transducer design of this invention is manifested in both size and power whereby the battery volume may be reduced markedly and therefore the size of the watch movement In view of the foregoing, it is the main object of this invention to provide electro magnetic transducers of exceptional efficiency for actuating a tuning fork in an electronic watch, or for any other appropriate purpose. More specific4lly, it is an object of the invention to provide a transducer whose magnetic element includes a permanent magnet rod coaxially mounted in a cylindrical cup, the cross-section of the rod diminishing from the cup end to the free end in a nonlinear manner causing the rod to assume a bullet-like shape which gives rise to a substantially uniform magnetic flux density within the rod.

Among the significant advantages of the transducer including a bullet-shaped magnetic rod are the following:

(A) Because of its exceptional efficiency, one may reduce the size of the transducer and thereby reduce the size of the associated timepiece movement, and yet operate the timepiece with a material decrease in the power requirement of the movement, thereby affecting a decrease in battery size.

(B) Because the transducer is markedly more efficient than known transducers, one may scale down the size of the battery and effect a further reduction in volume of the timepiece.

(C) Because the improved transducer makes it feasible to reduce the size of the movement, it opens up many new design possibilities, not only for ladies-model watches, but for other miniaturized timing mechanisms.

(D) Though the transducer permits a marked reduction in the scale of the movement, it does so without impairing the timing accuracy thereof.

According to the present invention, there is provided an electromagnetic transducer comprising a magnetic element constituted by a cylindrical cup of magnetic material having a permanent-magnet rod fixedly supported coaxially therein to define an annular air gap, the rod having a cross-section which diminishes from the cup end of the rod to the free end thereof in a non-linear manner to yield substantially the same flux density at all points in the rod, whereby all of the flux is substantially restricted to the air gap, and a multi-turn coil received within said annular air gap, said magnetic element being movable relative to the coil, the cross-section of the coil substantially complementing the radially outer surface of the rod and the radially inner surface of the cup, thereby making possible the full use of the available space within the gap.

For a better understanding of the invention as well as further features thereof, reference is made to the following detailed description to be read in conjunction with the accompanying drawings, wherein like components in the several Figures are identified by like reference numerals. In the drawings:

Fig. 1 is a schematic representation, in perspective, of the basic components of an electronic timepiece including a transducer in accordance with the invention;

Fig. 2 is a separate view of the tuning fork structure showing the transducer partly in section;

Fig. 3 is a side view of the transducer;

Fig. 4 is an enlarged sectional view of the transducer;

Fig. 5 is a diagram of an idealized magnet assembly;

Fig. 6 is a diagram of a prior-art magnetic transducer element of the cylindrical rod type; and

Fig. 7 is a diagram of a prior-art magnetic transducer of the frustoconical rod type.

Referring now to the drawings, and more particularly to Fig. 1, the major components of a timepiece including a transducer in accordance with the invention are a timekeeping standard constituted by a tuning fork 10 and an electronic drive circuit 11 there- for, a rotary movement of conventional design including a gear train 12 for turning the hands of the time piece, and a motion transformer including an index wheel 13 operatively coupling the fork 10 and the rotary movement, and acting to convert the vibratory action of the fork into rotary motion. The tuning fork has no pivots or bearings and its timekeeping action is therefore independent of the effects of friction.

All of the electrical components of the drive circuit are mounted on sub-assembly units or modules F1 and F, attached to a disc-shaped metallic pillar plate 14 which may be supported within a watch casing of standard design, or within any other type of housing, depending on the use to which the timepiece is put. Electronic circuit 11 is constituted by a transistor TR having a base, a collector and an emitter, a resistance-capacitance biasing network R-C, and a by-pass capacitor C_b to prevent parasitic oscillations of the circuit The electronic circuit 11 is energized by a voltage source in the form of a battery V.

Tuning fork 10 is provided with a pair of flexible tines 15 and 16 interconnected by a relatively inflexible base 17, the base being provided with an upwardly-extending stem 18 secured to the pillar plate by suitable screws 19 and 20. The central area of the pillar plate is cut out to permit unobstructed vibration of the tines.

The tuning fork is actuated by means of transducers T_1 and T_2, Transducer T_1 is constituted by a magnetic element 21 secured to the free end of tine 15, the element coating with a stationary drive coil 22 and phase- sensing coil 23. These coils are wound on an open-ended tubular carrier 24 affixed to the sub-assembly F_1 which is secured to the pillar plate 14. Coils 22 and 23 may be wound in juxtaposed relation on carrier 24, or the phase- sensing coil 23 may be wound over drive coil 22.

The second transducer T_2 is constituted by a magnetic element 25 secured to the free end of tine 16, and coacting with a drive coil 26 wound on a tubular carrier 27.

The two transducers T_1 and T_2 are of like design, except that an additional coil is provided in transducer T_1. The construction and behavior of the transducers are similar to that of a dynamic speaker of the permanent-magnet type, save that the moving element is the magnet, and not the coil.

Figs. 2 and 3 show transducer T_1 in greater detail, and it will be seen that magnetic element 21 is constituted by a cylindrical cup 21a of high permeability magnetic material, such as iron, and a permanent-magnet rod 21b coaxially mounted therein. Magnet 21b, 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 21c defined by the inner magnet and the surrounding cylinder. Rod magnet 21b is of diminishing cross-section from the cup end to the free end thereof, to produce a longitudinal profile which is continuously curved, for reasons which will be later explained.

As best seen in Fig. 3, cylindrical cup 2hz is cut longitudinally along diametrically- opposed planes to form slots 21d and 21e. This effects a substantial reduction in the transducer dimension with relatively little flux leakage. The cut-outs act to reduce the space occupied by the cups in depth within the casing, and make possible a more compact construction of the timepiece. The slots also prevent so-called “dash-pot’ effects resulting from air compression by the magnet-and-cup assembly. Such damping is avoided by the slot openings and also by the openings in the tubular carrier.

It will be seen that fixed carrier 24 for supporting the drive coils 22 and 23 is horn- shaped and is dimensioned to complement the tapered magnet 21b. Carrier 24 and the drive coils supported thereon are received within annular gap 2lc and are spaced both from the magnet and the surrounding cylinder, whereby the magnetic element is free to reciprocate axially relative to the fixed coil.

In operation, an energizing pulse applied to the drive coils of transducers T_1 and T_2 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 each 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 transducer T1, in the phase-sensing coil as well. Since the magnetic element reciprocates in accordance with the vibratory action of the tuning fork, the back E.M.F. will take the form of an alternating voltage whose frequency corresponds to that of the tuning fork. Three functions are served by the transducers. They drive the tuning fork by converting pulses of current delivered to the coils to mechanical pulses. They control the amplitude of the tuning fork by sensing the alternating voltage induced during each cycle; and they control the instant during the cycle when the drive pulse is to be delivered to the coils.

Referring now to Fig. 4, the transducer in accordance with the invention is shown in enlarged form to clarify the relationship of the components thereof and the factors which come into play in optimizing the design. It will be seen that the permanent magnet rod 21b is coaxially mounted within the cylindrical cup 21a, which acts as a high-permeability return member; an annular gap being defined by the interior space between the rod and cup. In order to utilize the magnet to best advantage, there must be a uniform flux density within the magnet, and there must be no leakage flux escaping from the magnetic element. In this connection, reference is made to the article of S. Evershed—”l’ermanent Magnets in Theory and Practice”—J. Institute of Electrical Engineers, 13 May 1920 (Volume 58, page 797). Since as one progresses from the base or cup end of the magnet rod to the free end or tip thereof, flux leaks out of the magnet at a rate determined by the reluctance of the magnetic circuit, one must decrease the cross-section of the magnet so that the decreased amount of flux in the magnet divided by the decreased cross-sectional area, yields the same flux density at all points in the magnet to attain optimum magnetic performance. Furthermore, the cross-section of the rod should diminish to zero at the tip, whereby all of the flux will have been restricted to, or will have emanated in the annular air gap within the cylindrical cup. Thus the configuration of magnet rod 21b in Fig. 3 is such as to provide a cross-section which diminishes from the cup end to the free end in a non-linear manner such that the longitudinal profile is continuously curved to produce a rod having a bullet-like shape. The cross-section at the free end or tip is zero, thereby minimizing flux leakage, and the curvature of the profile is such as to yield the same flux density at all points in the magnet. The shape of coils 22, 23 which occupy the air gap between the rod and the cup complements that of the magnetic element, so that the outer boundary of the coils is cylindrical to conform to the inner surface of the cup, whereas the inner boundary is curved to con- form to the curvature of the rod. In this way, full use is made of the available space within the annular gap, the greatest number of coil turns being at the mouth of the gap.

Theoretical and Design Considerations

In designing an electromagnetic transducer of the type in question, with a view to optimizing its power performance, one must consider not only the magnetic flux generated by the permanent magnet, but also the volume of available space for the current conductors which are subjected to this magnetic flux.

In the electromagnetic transducer, we therefore encounter an interaction between the field created by the permanent magnet and the field developed by the current-carrying conductors. Hence the factors to be taken into account in seeking to attain optimum performance are the field strength of the permanent magnet, the field strength of the coil operating therewith (other factors remaining the same) and the mass of the magnet elements.

The characteristics of magnetic circuits and magnetic materials of which they are made, are expressed in terms of certain magnetic quantities and units which may be described as follows:

Magnetomotive Force.

In an electromagnet, magnetization is accomplished by means of electric current in windings linked with a magnetic circuit In an electromagnet of the type in question, the windings are those of the coil placed in the annular gap of a magnetic circuit defined by a permanent rod coaxially supported within a cylindrical cup of high permeability. The total measure of the magnetizing effect of such a coil is called the "magnetomotive force F", the units of the force (mmf) being called the "gilbert".

Magnetic Flux.

The total measure of the magnetized conditions of a magnetic circuit, when acted upon by a magnetomotive force, is called the "magnetic flux Φ". It is characterized by the fact that a variation in its magnitude gives rise to an E.M.F. in an electric circuit linked with it. The E.M.F. thus induced is at any instant, directly proportional to the time rate of variation of the flux.

Magnetic Reluctance.

That property of a magnetic circuit which determines the relationship between the magnetic flux and the corresponding mmf, is called the "magnetic reluctance R" of the circuit It is defined by the following equation:

$$\phi=\frac{F}{R},$$

where Φ =magnetic flux, maxwells; F=mmf, gilberts; and R=magnetic reluctance in cgs units.

Magnetizing Force.

The mmf acting on a magnetic circuit is distributed along its length in a manner determined by the distribution of the windings and the reluctance of the magnetic circuit. The mmf per unit length along the circuit is called the "magnetizing force H", and is defined by the following equation:

$$H=\frac{dF}{dl},$$

where H=rnagnetizing force, oersteds; F=mmf, gilberts; and 1=length, cm.

Magnetic Flux Density.

This is the magnetic flux per unit area of a section normal to the flux direction. The cgs unit is called the "gauss", and is defined by the following equation:

$$B=\frac{d\phi}{dA},$$

where B=magnetic flux density, gausses; Φ = magnetic flux, maxwells; and A=area, sq. cm.

In order to utilize the permanent magnet in the magnetic circuit to best advantage, it is essential that the magnetic flux density B be uniform within magnet. It will be shown that in the present magnetic circuit, which involves a cylindrical cup configuration, a diminishing cross-section of the magnet from the cup end to the free end is necessary to attain a uniform flux density. Since as one progresses from the cup end to the free end of the magnet, flux emanates from the magnet at a rate determined by the reluctance of the magnetic circuit, one must so decrease the cross-section of the magnet whereby the resultant decreased amount of flux divided by the decreased cross-sectional area, yields the same flux density B at all points in the magnet, thereby optimizing the performance of the magnet. Moreover, the cross-section must decrease to zero at the tip of the magnet so that all of the flux will have been restricted to or will have emanated in the annular air gap.

We shall begin by considering a transducer having an ideal magnet which produces magnetic flux and thereby generates a magnetic field in a working gap. This is done

under ideal circumstances; that is, without any leakage and hence with no loss of flux. In Fig. 5, there are shown two permanent magnets M1 and M, which are spaced apart to define an air gap in a magnetic circuit completed by a high-permeability, yoke-shaped return member. The transducer is to occupy a total volume V_0, which is part magnet, V_m, and part gap, V_g; hence

$$V_0=V_m+V_g.$$

The flux return volume and the wasted air volume is neglected, a truly ideal situation. The flux conservation statement is as follows:

$$(1)\quad B_mA_m=B_gA_g,$$

and the conservation of energy statement is:

$$(2)\quad \Phi H\,.\,dl=0;\; H_mL_m=H_gL_g=B_gL_g,$$

realizing that the permeability of air is approximately unity. After multiplying equation (1) by equation (2), we obtain:

$$B_mA_m\cdot H_mL_m=B_gA_g\cdot B_gL_g$$

or

$$(3)\quad B_mH_mV_m=B_g^2V_g$$

If we multiply this equation on the right by V_g, and on the left by its equivalent V_0—V_m, we obtain:

$$(4)\quad B_mH_mV_m(V_o-V_m)=B_g^2V_g^2$$

Assuming in our ideal system the absence of flux leakage and that we are able to utilize all of the air gap with ideally placed conductors, then V5, the volume of the gap, is a measure of the magnetic field generated by the conductors as a result of a fixed current flowing therein. On the further assumption that the size of the conductors and therefore the number of turns per unit area is fixed, the quantity, or $(B_gV_g)^2$, is therefore the interaction term that one seeks to maximize. Let us make the definition:

$$(5)\qquad q=(B_gV_g)^2=B_mH_mV_m(V_o-V_m).$$

We can maximize this quantity with respect to magnet volume by differentiating and setting the result equal to zero. That is:

$$\frac{dq}{dV_m}=B_mH_m(-V_m+V_o-V_m)=0,$$

Or

$$V_m=V_{o/2}.$$

With this result substituted in equation (5), we 95 obtain:

$$(6)\qquad q_{max}=B_mH_m\cdot\frac{Vo^2}{4}.$$

This quantity may be further maximized with respect to the operating conditions of the magnet by designing for peak energy-product point operation. Of course, it is to be realized that there is no guaranty that the two optimization requirements could be simultaneously satisfied. In practice, therefore, the actual design would probably not occur at either $V_mV_{o/2}$, or B_mH_m=maximum, for the magnetic material used. With given transducer volume dimensions as a working constraint, however, one would select a magnetic material to yield the maximum q, therefore achieving the best system possible. The analysis thus far has been concerned with an ideal system and the results are intended to serve as theoretical guidelines. We shall now proceed to apply these teachings to an electromagnetic transducer system for a mechanical vibrator such as a tuning fork or a reed. Practical considerations dictate a circular cross-section for the magnet and conductor coil, but this need not be the case. The prior-art transducer in Fig. 6, as applied to a tuning fork, is of the cylindrical magnet rod type, as shown in the above-identified Hetzel patents, and serves as a good approximation to the ideal system discussed in connection with Fig. 5, in that the annular air gap G between the central magnetic rod R0 and the cylindrical cup C_0, can be considered the working gap. Disposed in the gap is a cylindrical coil S_c. This also applies to the transducer shown in Fig. 7, which is of the prior-art frustoconical or linear tapered type shown in the Bennett et al patent, for most of the magnetic flux spans the volume occupied by the conductors, i.e., relatively little leakage flux is generated. In the tapered rod construction, rod R_t coaxially disposed within cup C_c operates in conjunction with a similarly tapered coil S_t. In discussing the ideal magnet in connection with Fig. 5, no mention was made of the shape of the magnet However, if there is to be no leakage and if a single Bm applies to the entire magnet, then a constant cross- section is implied. But in a magnetic element having a cup configuration operating in conjunction with a coaxially-mounted magnet rod, a decreasing cross-section is desired in the rod so that no flux extends out the end of the cylindrical volume. To this extent, the tapered rod in Fig. 7 is an improvement over the cylindrical rod in Fig. 6. Of greater importance is that there be a uniform flux density B within the magnet to utilize the magnet material to best advantage. This not only requires a decreasing cross- sectional area, but a rate of decrease which is proportional to the rate at which flux flows out of the magnet rod to the wall from the neutral or cup end of the rod to the free end. Reverting now to Fig. 4, which discloses the present invention, and considering a cylindrical hollow shell in the magnet, we can write the equivalent or Ohm's Law for the magnetic circuit. The flux in the circuit is:

$$(7)\qquad d\phi=2y\pi dyB=\text{mmf}\cdot\text{conductance}=(Hz)\frac{2\pi dz}{\log_e(R/y)}$$

We view this result as the differential equation prescribing the magnet profile, This formulation satisfies the criteria of (1), no flux out the end of the cylindrical volume, and (2), constant flux density B (and H) in the magnetic material.

Solving this differential equation for y, with the boundary conditions that y=o at z=L, and y=r0 at z=0, leads to the algebraic profile equation:

$$(8)\qquad y^2(1+2\log_e R/y)=a^2(1-\frac{Z^2}{L^2}),$$

Where

$$a^2=r_o^2(1+2\log_o R/r_o).$$

Having developed the qualitative shape of the magnet, it remains to determine the quantitative dimensions necessary to maximize the transducer efficiency. We can re-phrase the original optimization problem for our particular application by writing the differential form of the induced voltage:

$$dE=dn\cdot\frac{d\phi}{dt}=dn\frac{d\phi}{dz}\ \frac{dz}{dt},$$

where

$$dn=(R-\Delta-y)\lambda^2dz,$$

where Δ is a mechanical clearance between magnet and conductors and where λ^2 is the wire density (turns per unit area). Now

$$\frac{dz}{dt}=v$$

(velocity of the coil relative to magnet), and

$$\frac{d\phi}{dz}=\frac{2\pi Hz}{\log_e(R/y)},$$

whence we have:

$$(9)\qquad E=v\int_{\epsilon}^{L}2\pi\lambda^2\frac{(R-\Delta-y)}{\log_e(R/y)}Hz\times dz=kv$$

The quantity € is again a mechanical clearance at the bottom of the cylindrical cup. The maximization problem then reduces to determining the value for r0, the radius of the magnet at its base, which will yield a maximum in B.

For the case of a transducer as part of a mechanical vibrator, however, there is a further minor refinement necessary. If one examines the equation expressing the power consumed by the vibrator with transducer,

$$P=\frac{1}{\eta}\,\frac{E^2}{2R}=\frac{E^2}{2\eta}\,\frac{m}{Qk^2}$$

where

R=equivalent resistance of vibrator,
E=induced voltage in transducer coil,
$\omega=2\pi\cdot$frequency of vibrator,
η=efficiency of system,
Q=quality factor of vibrator,
m=mass of transducer and vibrator,
k=electromechanical coupling factor; and
p=power,

one sees that one should really maximize

$$\frac{k^2}{m}$$

as opposed to k^2. The quantity k has typically been a measure of the quality of the transducer, but one sees that if consumption of power is the foremost consideration, as it is in timepiece applications, then the quantity k^2/m is the more important measure.

A step-by-step variation of r_0, from a zero value up to a maximum value dictated by the cylindrical cup dimensions, accompanied by a numerical integration of equation (9) and a calculation of m, will yield a curve for k^2/m whose maximum determines the choice of r_0 for the optimized transducer for the particular magnetic material chosen.

It is understood that these teachings result in both the quantitative and qualitative shape of the magnet and conductor coil to optimize the transducer efficiency, and further, it is appreciated that approximations to the curve of equation (8) such as multi-taper configurations in which the cross-section of the rod diminishes in a series of tapered steps, whereby the flux density B is approximately uniform, can yield almost optimum results. These teachings therefore make possible the fabrication of very small transducers which can operate on a minimum of power.

Comparative Improvement

It has been determined, for a particular small transducer size applicable to a ladies' tuning-fork watch movement, that a transducer in accordance with the invention is strikingly superior in its performance characteristics to known types of transducers of the cylindrical magnet rod and the frustoconical magnet-rod type. The following table shows the approximate comparison for these three types of transducers, having the same magnetic-element cup sizes but different magnet rod shapes for a particular transducer size applicable to a ladies' watch movement of the type envisaged.

Transducer Magnet Shape	Power to Drive Fork $\frac{m}{k^2}$ in arbitrary units
Cylindrical	7.0
Frustoconical	2.5
Bullet-shaped (Present Invention)	1.0

This table shows clearly the significance of the present invention. It indicates a 7: 1 reduction in power input required to operate a tuning fork as a result of employing the optimum transducer design of this invention, in comparison with the more conventional cylindrical magnet shape. This, obviously, permits one to design a tuning-fork transducer drive system with substantially smaller size (which would otherwise require much more power because of reduced efficiency), yet requiring less battery power and therefore a smaller battery, resulting in a much smaller watch movement complete with self-contained battery.

It should also be appreciated that there are many areas of application for electromagnetic transducers other than the tuning fork utilization described above, such as loud-speakers, hearing aids, etc., and that for each application the electromagnetic transducer of this invention more optimally meets the requirements of minimum electrical energy per unit volume of transducer than does each of the existing transducer types. An expression of this optimization on a comparative basis is shown in Table II where the electromagnetic coupling factor squared is given for the three types of magnet shapes discussed above. Again, the obvious improvement shows the superiority of the present invention.

TABLE II

Transducer Magnet Shape	Relative Effectivity k^2 in arbitrary units
Cylindrical	.2
Frustoconical	.6
Bullet-shaped (Present Invention)	1.0

WHAT WE CLAIM IS : —

1. An electromagnetic transducer comprising a magnetic element constituted by a cylindrical cup of magnetic material having a permanent-magnet rod fixedly supported coaxially therein to define an annular air gap, the rod having a cross-section which diminishes from the cup end of the rod to the free end thereof in a non-linear manner to yield substantially the same flux density at all points in the rod, whereby all of the flux is substantially restricted to the air gap, and a multi-turn coil received within said annular air gap, said magnetic element being movable relative to the coil, the cross-section of the coil substantially complementing the radially outer surface of the rod and the radially inner surface of the cup, thereby making possible the full use of the available space within the gap.

2. A transducer according to claim 1, wherein the rod has a longitudinal profile which is continuously curved, the free end of the rod having a substantially zero cross-section.

3. A transducer according to claim 1 or 2, wherein the rod diminishes in cross-section in a series of tapered steps.

4. A transducer according to any one of the preceding claims, wherein the coil is stationary and the magnetic element is mounted on a vibratory member to reciprocate the element relative to the coil.

5. A transducer according to any one of the preceding claims, wherein the cylindrical cup is longitudinally slotted on diametrically opposed sides.

6. A transducer according to any one of the preceding claims, wherein the rod is formed of a material having a high value of residual magnetic induction and coercive force, and the cup is formed of a material having high flux permeability.

7. An electromagnetic transducer substantially as hereinbefore described with reference to Figures 1 to 4 of the accompanying drawings.

8. An electronic watch provided with a toning fork, means to convert the vibratory action of the fork into rotary motion to drive the gearworks of the watch, and an electromagnetic transducer as claimed in any one of the preceding claims, wherein the magnetic element of the transducer is mounted on one tine of the fork to vibrate therewith and the coil is mounted at a stationary position in the watch, and means to apply electrical pulses to the coil to sustain the fork in vibration.

9. An electronic watch including the transducer of claim 7, substantially as hereinbefore described with reference to Figure 1 of the accompanying drawings.

HASELTINE, LAKE & Co.,
Chartered Patent Agents,
Hazlitt House,
28, Southampton Buildings,
Chancery Lane,
London WC2A 1AT.
and
9 Path Square,
Leeds, LS1 2LH,
Yorks.
Agents for the Applicants.

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1346359 COMPLETE SPECIFICATION

3 SHEETS *This drawing is a reproduction of the Original on a reduced scale*

Sheet 1

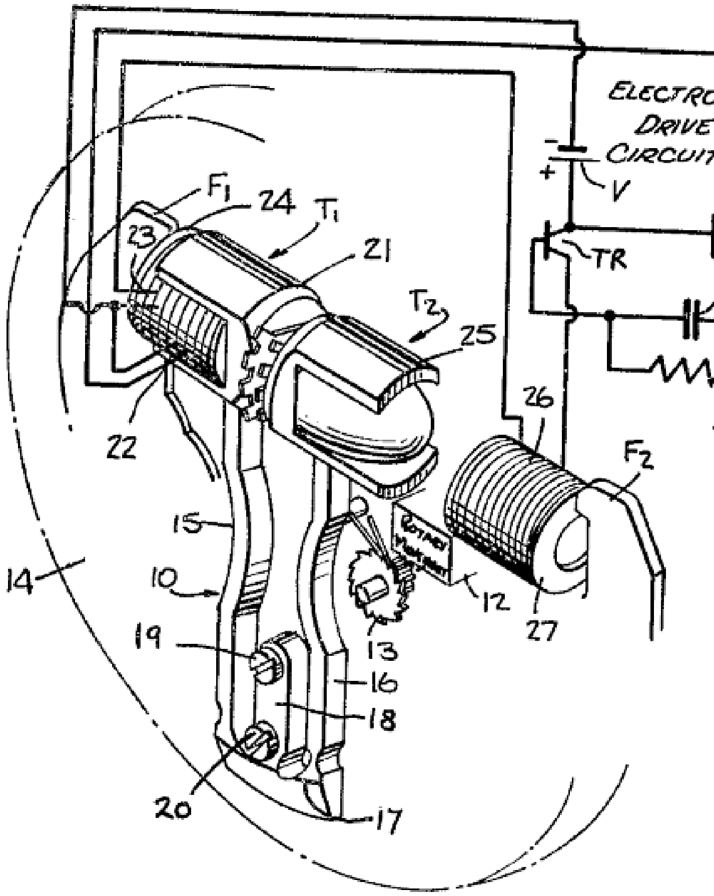

Fig.1.

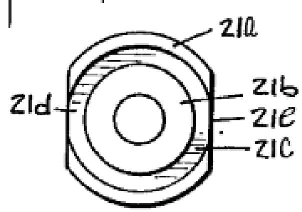

Fig.3.

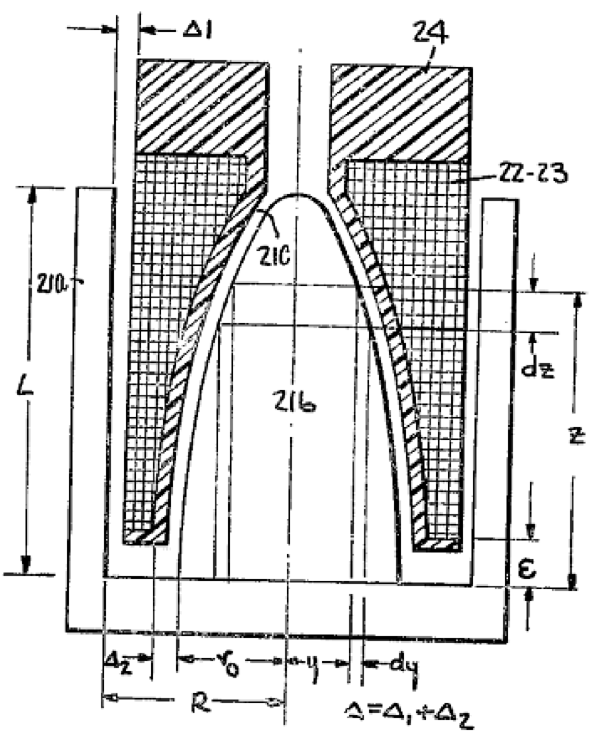

Fig.4.

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Fig.5.

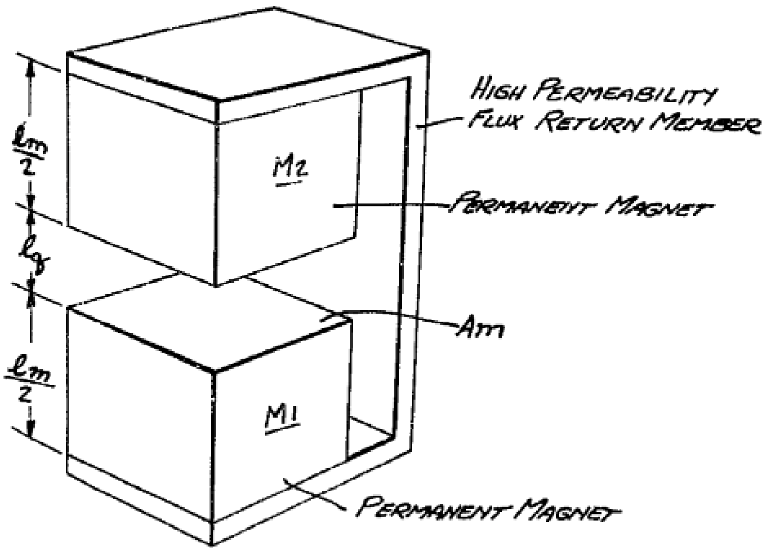

Fig.6.

PRIOR ART

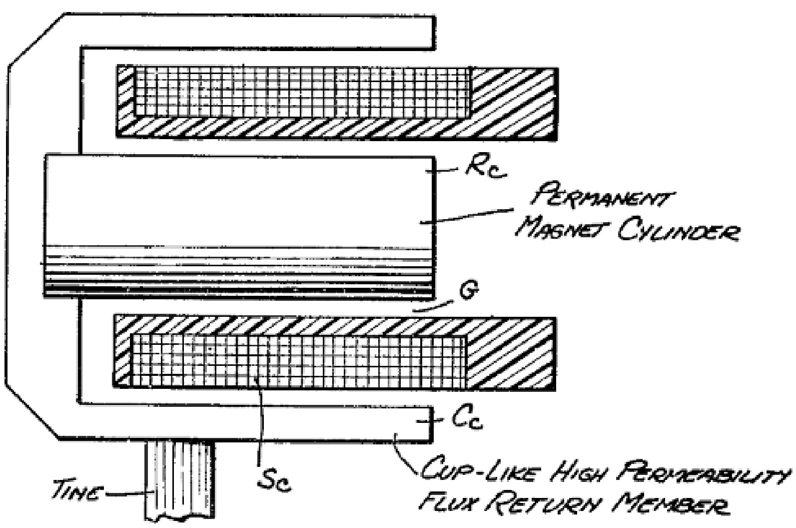

Fig.7.

PRIOR ART

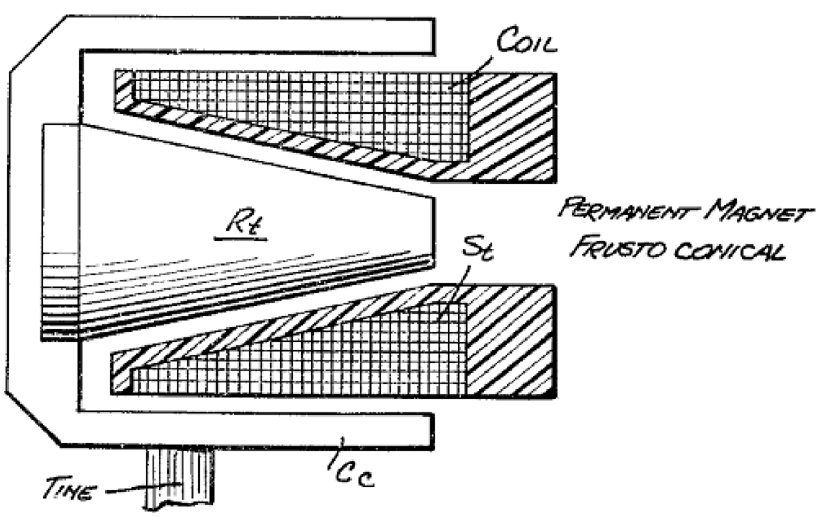

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Fig.2.