

Aug. 9, 1960

R. S. DITTO
TRANSDUCER

2,948,842

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3 Sheets-Sheet 1

Fig. 1

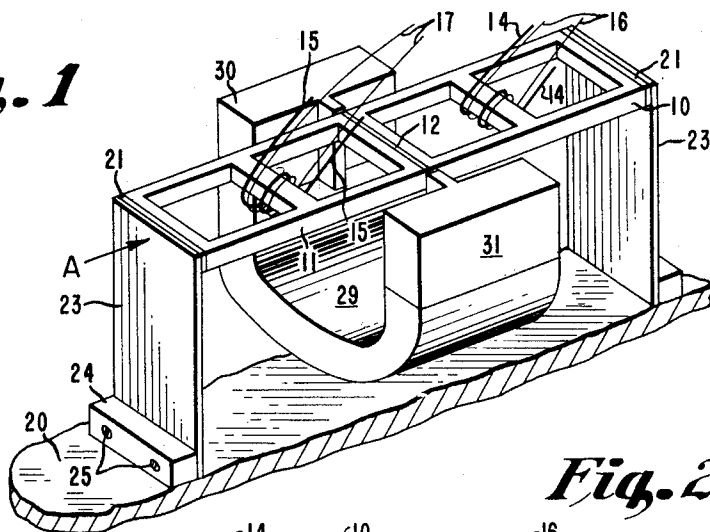


Fig. 2

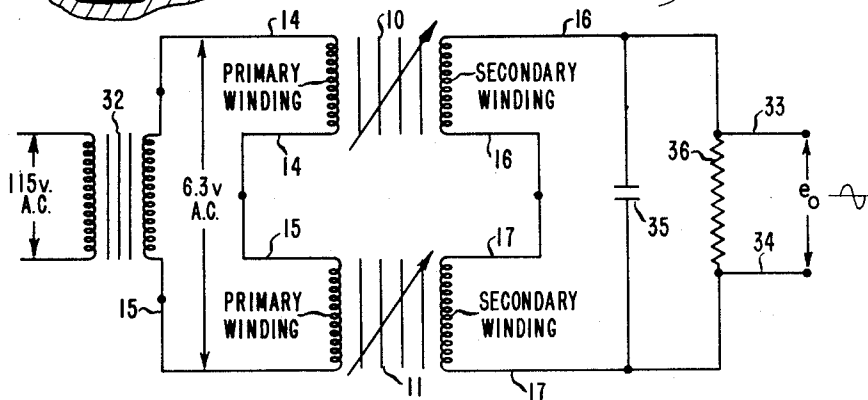
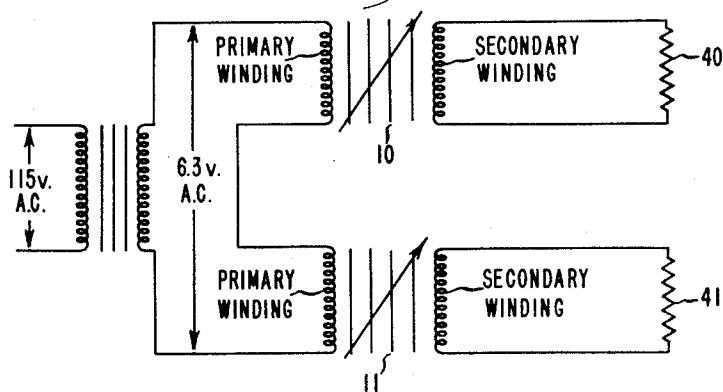


Fig. 3



INVENTOR

RICHARD S. DITTO

BY

Harry J. M^cCanby
ATTORNEY

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R. S. DITTO

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3 Sheets-Sheet 2

Fig. 4

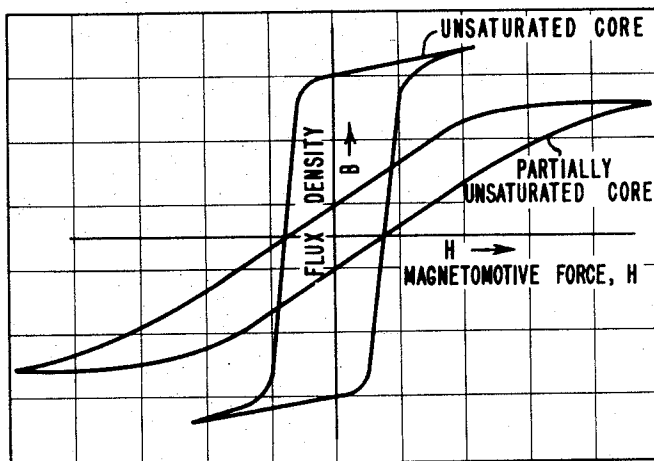
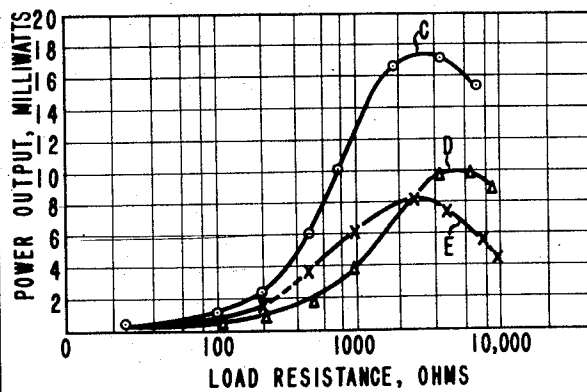
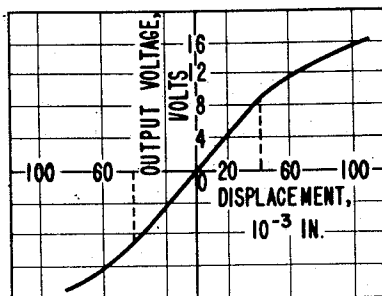


Fig. 6

Fig. 5



INVENTOR
RICHARD S. DITTO

BY

Harry J. McCauley

ATTORNEY

Aug. 9, 1960

R. S. DITTO
TRANSDUCER

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3 Sheets-Sheet 3

Fig. 7

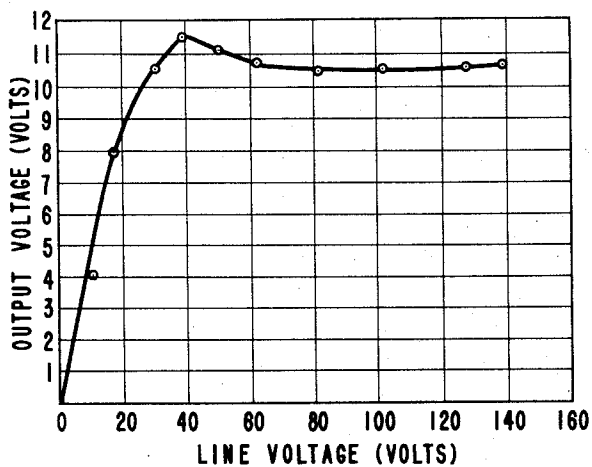


Fig. 8

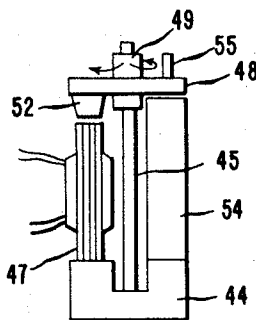


Fig. 9

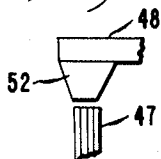


Fig. 10

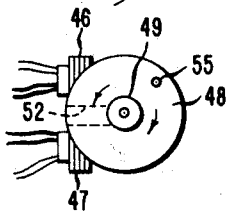
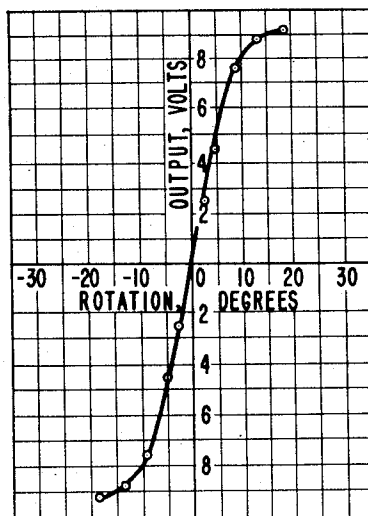


Fig. 11



INVENTOR

RICHARD S. DITTO

BY

Harry J. McCauley

ATTORNEY

1

2,948,842

TRANSDUCER

Richard S. Ditto, Newark, Del., assignor to E. I. du Pont de Nemours and Company, Wilmington, Del., a corporation of Delaware

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6 Claims. (Cl. 323—51)

This invention relates to improvements in electrical transducers, and particularly to an improved electrical transducer having a saturable core.

The emphasis on automatic controls and automation in technology has led to a great demand for transducers which are adapted to give an electrical output representative of a physical change in the environment upon which control is predicated, such as a change in force relationships, relative movement of elements, or the like.

In general, transducers should desirably have certain mechanical characteristics, including minimum static friction, reaction forces and inertia, high thermal stability and sturdy construction. For electrical designs, it is additionally desirable that the transducer develop sufficient power so that it can be used to drive power amplifiers of the magnetic or vacuum tube type directly without the use of preamplifiers, thereby reducing first cost as well as maintenance.

A primary object of this invention is to provide an electrical transducer which has an improved sensitivity and a power output sufficiently high to drive magnetic amplifiers or like low impedance amplification equipment directly. Other objects of this invention include the provision of an electrical transducer displaying insignificant reaction forces, of a design permitting either a linear or an angular motion input and of a construction which is extremely rugged and relatively economical to fabricate.

The manner in which these objects are attained will become apparent from the following detailed description hereinafter set forth, and the following drawings in which:

Fig. 1 is a perspective partially schematic view of a preferred embodiment of linear type transducer constructed according to this invention,

Fig. 2 is a diagrammatic sketch of a preferred electrical circuit for the apparatus of Fig. 1 where a high voltage signal output is desired,

Fig. 3 is an alternate circuit which can be substituted for the circuit of Fig. 2 if the primary requirement is enhanced power output, or if the external circuit powered is of the split load connection type,

Fig. 4 is a plot of hysteresis curves for an individual transformer core in both the saturated and unsaturated states,

Fig. 5 is a representation of the transfer characteristic of a saturable core transducer of the design of Fig. 1 in terms of a plot of displacement versus output voltage,

Fig. 6 is a graphical representation of transducer power output as a function of load resistance for the circuit of Fig. 3,

Fig. 7 is a graphical representation of transducer voltage output as a function of supply line voltage,

Fig. 8 is a side elevation view of a preferred embodiment of angular transducer constructed according to this invention,

Fig. 9 is a detailed side elevation view of a preferred

2

shape of foot of the bridging pole piece for the apparatus of Fig. 8,

Fig. 10 is a top plan view of the apparatus of Fig. 8, and

Fig. 11 is a graphical representation of the transfer characteristic of the angular design of transducer shown in Figs. 8-10 as a plot of rotation in degrees versus signal output voltage.

Generally, the transducer of this invention comprises as one element a pair of transformers fixedly attached one to another with their cores in a common plane and electrically connected with their primary windings in series and, as the other element, means maintaining a substantially constant total direct magnetic flux through the transformer cores for differentially saturating one of the cores over the other core in proportion to the extent of relative movement of the transformer cores from null position with respect to the saturating means, whereby a representative signal is generated in the secondary windings of the transformers.

A preferred embodiment of linear transducer according to this invention is shown, as regards mechanical details, in Fig. 1 and, as regards the electrical circuit, in Figs. 2 and 3. As shown in Fig. 1, the transducer comprises two closed core transformers 10 and 11 cemented or otherwise fixedly attached one to another at 12 with the cores in a common plane, the assembly being supported at each end by cantilever uprights 23 secured thereto by cemented joints 21. Transformers 10 and 11 may be of a commercially available design, such as transistor coupling transformers having iron-nickel cores, provided with primary and secondary leads connected to the individual primary and secondary windings, such as leads 14 and 16, respectively, for transformer 10 and leads 15 and 17, respectively, for transformer 11. The transformer assembly is centrally mounted between the soft iron pole pieces 30 and 31 which are secured to opposite poles of the permanent magnet 29, the latter being preferably fabricated from "Alnico V" or other strongly magnetizable material. Cantilever supports 23 and magnet 29 are attached at the lower ends to a support, indicated generally at 20, which is one point of reference with respect to which it is desired to measure transducer displacement. Supports 23 are attached to blocks 24, integral with support 20, by means of screws 25, while magnet 29 may be secured by clamps or other equivalent means not shown. As a result, the transformer assembly is free within limitation to move transversely of the air gap defined by pole pieces 30 and 31 by deflection of the upper ends of supports 23 under the influence of a force applied longitudinally of the assembly, such as that in the direction of the arrow A.

The details of the electrical circuit of the apparatus of Fig. 1 are shown for one embodiment of the device, wherein it is desired to obtain a relatively high voltage signal output e_o , in Fig. 2. Here, transformers 10 and 11 are indicated by the conventional symbol representative of a variable flux core, since such flux variation is brought about in the course of operation as hereinafter described. In the embodiment of Fig. 1, the two primary windings of the transformers are connected in series circuit, while the two secondary windings are connected in series opposition. The apparatus is powered from a conventional 115 v. A.-C. source through a step-down transformer 32 which delivers 6.3 v. A.-C. to the primaries of transformers 10 and 11. The output from the apparatus, e_o , is withdrawn from leads 33 and 34 across which are connected in parallel capacitor 35 and resistor 36, the purpose of which is to smooth the output to substantially sinusoidal form as indicated by the voltage trace drawn in adjacent the output leads.

3

An alternative construction, which is particularly preferred when the apparatus is used to power directly apparatus performing control operations, such as magnetic amplifiers or the like, is shown in Fig. 3. The circuits of Figs. 2 and 3 are identical in all respects except as regards the connections of the secondaries to the loads which, in Fig. 3, are made directly and individually from each secondary to a specific load, represented in each case by resistors 40 and 41.

The principle according to which my invention operates will be explained with particular reference to the hysteresis plots of Fig. 4, which constitute a representation of magnetic field intensity, H , as the abscissa versus magnetic flux density, B , as the ordinate for a single transformer core under the influence of an alternating current. If an A.-C. voltage is applied to the primary coil of an unsaturated core the current is a minimum while, if the core is partially saturated, the A.-C. voltage that can be supported or absorbed by the transformer primary is less and a greater current flows, as is indicated by the relative disposition of the second hysteresis curve with respect to the first, the impedance in circuit with each primary being equal. Consequently, a lower voltage exists across the impedance for the partially saturated core than for the unsaturated core. If two cores are utilized with primary windings connected in series, as shown in Figs. 2 and 3, a voltage decrease in one is accompanied by a corresponding voltage increase in the other when the cores are differentially saturated by displacement from null position, thus yielding a voltage signal in the secondary windings representative of the displacement of the transformer cores from null position with respect to the saturating means. A usable signal is obtained for even relatively low degrees of core saturation; however, higher saturations are preferred, for the reason that the output signal voltages developed are greater.

An important characteristic of the transducer of this invention is the substantial absence of reaction forces. Elimination of reaction forces is obtained by preserving the iron path dimensions such that there is substantially constant total direct magnetic flux through the transformer cores at all positions taken by the movable element of the transducer during operation, while still saturating one core differentially with respect to the other to obtain a signal representative of the displacement of the cores from null position with respect to the saturating means, which, for the apparatus of Fig. 1 is magnet 29. As an aid in maintaining constant total magnetic flux it is sometimes desirable to employ non-magnetic materials for the fabrication of supports 23, especially where the supports are in relatively close proximity to the saturating magnet 29; however, for a transducer having the general disposition of parts shown in Fig. 1, magnetic materials may be used without interference from this cause.

As hereinbefore explained, the transformer assembly 10-11 of the device of Figs. 1 and 2 is intended to occupy null position with both transformer cores symmetrically disposed with respect to pole pieces 30 and 31, whereupon both cores will be partially saturated to the same extent and the net output voltage of the secondary windings will be zero due to the series opposition connection of the secondaries. However, if the transformer assembly is moved transversely in either direction with respect to pole pieces 30 and 31, the transformer closest to the pole pieces will have a different saturation level than its neighbor, resulting in an increase in the supply voltage delivered to the primary of the more remote transformer, with an accompanying decrease in the voltage of the more saturated transformer. The voltages induced in the two secondary windings are correspondingly affected, and the difference between the secondary voltages constitutes the A.-C. output e_o . A typical plot of output voltage in volts against displacement of the trans-

4

former assembly for an apparatus constructed according to this invention and operating at essentially saturation level is shown in Fig. 5, the range of linearity being indicated by the broken line projections drawn to the abscissa, which corresponded to about 36 mils displacement away from null position in either direction. At the same time, the sensitivity expressed in volts output per mil was approximately 0.220, giving a maximum linear output of about 8 volts, the null voltage at zero displacement was 0.27 volt and the power output was approximately 4×10^{-3} watts. It should be mentioned that the ± 36 mil range given by way of example is not limiting, since the use of broader pole piece faces makes it possible to go to 50 to 200 mils, plus-or-minus, or beyond.

Operation of the embodiment of Fig. 3 is similar to that having the circuit of Fig. 2, except that the secondary windings are not connected in the same circuit and therefore there is a substantial current flow in each of the loads 40 and 41 at null position, but characteristically different current outputs for different displacements of the cores.

For maximum voltage output of the transducer, it is preferred to operate so that a high order of saturation exists in the transformer cores; however, it will be understood that the transducer of this invention will still be operable at considerably lower flux levels than saturation, since the only requirement is that sufficient differential saturation between cores results to yield a practicable signal level.

Fig. 6 is a plot of power output versus load resistance for maximum and minimum voltage output (open circuit) for a typical device having the circuit of Fig. 3. Curve C is the maximum power plot and curve E is the minimum power plot, the difference between the two being the differential, or usable, control power, which is plotted as curve D. The transducer should preferably be operated in conjunction with an effective load resistance corresponding to the maximum differential power output and, from the magnitudes of the plotted values of Fig. 6, it will be seen that the output of the device is of sufficient magnitude to be employed as the input for conventional power amplifiers.

Fig. 7 is a plot of output voltage of my transducer as the ordinate versus line voltage as the abscissa, from which it is apparent that the output voltage of the device remains substantially constant over relatively great deviations in line voltage of the order of 30 or 40 volts magnitude. Tests revealed that the output voltage variation was below $\pm 2.0\%$ for a supply voltage variation of the order of $\pm 20\%$, demonstrating the high stability of the design.

Performance tests on a typical apparatus constructed according to this invention showed that the reaction forces were of such a low value as to cause no difficulties whatsoever and no compensatory measures were required to nullify their effects. In addition, the apparatus was found to possess the following general characteristics:

- M, the electrical resolution ----- Maximum rated output voltage/output voltage at null=400.
- K, the gain or sensitivity (in mv./mil) ---- Change in output voltage/change in displacement=230.
- R, the mechanical resolution (in micro-inches) ----- Output voltage at null/K=87.

These characteristics are substantially better than those possessed by conventional transducers now known to the art. The relatively high K value of devices constructed according to this invention simplifies calibration and, at the same time, improves the accuracy of the calibration operation. It is preferred to match the transformers of

a pair utilized in a particular transducer to obtain substantially equal linear regions over both the upper and lower portions of the transfer curves, and this can be readily done by a composite comparison procedure taking into account both performance characteristics and core weights, so that an essentially symmetrical transfer characteristic is obtained for the combined transformer element.

While the foregoing description relates to a specific construction in which the transformers are moved relative to the direct magnetic saturating means, it will be understood that the reverse arrangement can be utilized equally well, i.e., a transducer in which the transformers are stationary and the saturating means moves, for the reason that relative movement of these members is all that is required for operation, although there is an obvious advantage in choosing the part of least mass as the moving element.

For many applications an angular transducer is preferred over a linear type such as that hereinbefore described. An angular transducer constructed according to this invention is shown in Figs. 8-10, wherein the transformer assembly is maintained stationary, while the magnetic field is effectively moved with respect to the transformer assembly, thus reversing the relative movement of elements over that of the linear transducer of Fig. 1.

The angular transducer can be constructed in a design wherein the transformer assembly is movable and the saturating means is stationary, if this is desired, thus affording the same flexibility in this regard as hereinbefore described for the linear transducer.

Referring to Figs. 8 and 10 particularly, the angular transducer embodies a magnet member 44, one of the upstanding legs of which is magnetized to one polarity, whereas the other upstanding leg is magnetized to the opposite polarity. The magnet 44 constitutes the base of the apparatus to which is centrally attached a stationary shaft 45, as by bolting, cementing or other means. The dual transformer assembly, corresponding to 10-11 of Figs. 1-3, is made up of two vertically disposed units 46 and 47, which are cemented together along their adjacent edge and are also cemented along their bottom edges to the adjacent pole piece of magnet 44. A rotatable ferromagnetic armature member 48 is journaled for free rotation at the top of shaft 45 through bearing 49 integral with the armature.

Armature 48 is provided on the bottom side with an integral pole element 52, the bottom surface of which is disposed at a very small clearance from the transformer assembly 46, 47. A segmental ferromagnetic bridge piece 54, which is cemented to the magnet 44 opposite the transformer assembly, provides a low reluctance flux return path to the armature of the apparatus.

It will be apparent from Fig. 10 that, when pole 52 is disposed equidistant from transformers 46 and 47, the saturation effect of armature 48 exerted through pole 52 on each transformer will be equal and, accordingly, the armature will be in null position. On the other hand, if armature 48 is rotated either clockwise or counterclockwise away from null position, within the limits of the range of the device, a proportional electrical unbalance will be set up in the transformer pair 46, 47 which can be utilized by circuits of the same type as hereinbefore described with reference to Figs. 2 and 3 for the linear transducer. Angular motion can be transmitted to armature 48 in a variety of ways, such as by providing a vertically disposed driving pin 55 adjacent the periphery of the armature, providing bearing housing 49 with a pulley, providing the periphery of armature 48 with gear teeth, or in other ways known to the art.

I have found that reactive forces in the angular type transducer can be deliberately reduced by shaping pole element 52 with receding front and rear edges as shown in Fig. 9, angular movement of pole element 52 with

respect to the vertical axis of the transformer assembly then maintaining essentially uniform magnetic flux across the air path over the useful range of movement of armature 48, thereby substantially eliminating reaction forces.

Fig. 11 is a plot of the transfer characteristic of a rotary transducer of the type shown in Figs. 8-10 in terms of output in volts plotted against rotation in degrees. Typical characteristics for a transducer of the same general power output (4×10^{-3} watts) as that hereinbefore reported for the linear transducer are as follows: range $\pm 8^\circ$, sensitivity one volt/degree of rotation and null voltage 0.050 volt. The operating range of the angular transducer can, of course, be expanded by suitable design of the cooperating field and transformer assembly elements, reaction forces being generally negligible so long as armature pole element 52 is not moved off of the transformer cores.

From the foregoing, it will be apparent that the transducer of this invention is applicable to either linear or angular displacement use and that the design is sufficiently rugged to withstand the severe conditions of industrial environments while, at the same time, developing a strong signal with high sensitivity. It will be understood that my transducer may be varied in numerous respects without departure from the essential spirit of the invention, wherefore it is intended to be limited only within the scope of the following claims.

What is claimed is:

1. An electrical transducer comprising in combination a stationary pair of transformers fixedly attached one to another along an adjacent side with the transformer cores in a common plane, the primary windings of said transformers being connected in series electrical circuit with an A.-C. power source, a stationary magnetic saturating means disposed in proximity to said transformer cores and maintaining a substantially constant direct magnetic flux through said cores, a rotatable armature in magnetic circuit with said magnetic saturating means provided with a pole piece adjacent to said transformer cores, said pole piece being adapted to differentially saturate one of said transformer cores over the other of said transformer cores in proportion to the extent of movement of said armature and said pole piece from null position with respect to said transformer cores, and output leads in electrical circuit with said secondary windings.

2. An electrical transducer comprising in combination two transformers fixedly attached one to another along an adjacent side with the transformer cores in a common plane constituting a unitary transformer assembly, the primary windings of said transformers being connected in series electrical circuit with an A.-C. power source, a magnetic saturating means disposed in proximity to said transformer cores and maintaining a substantially constant direct magnetic flux through said cores, one member of the pair consisting of said magnetic saturating means and said unitary transformer assembly being movable with respect to the other member and said magnetic saturating means being adapted to differentially saturate one of said transformer coils over the other of said transformer cores in proportion to the extent of relative movement of the movable member of said pair consisting of said magnetic saturating means and said unitary transformer assembly from null position with respect to the other member, and output leads in electrical circuit with the secondary windings of said transformers.

3. An electrical transducer according to claim 2 wherein said one member of the pair consisting of said magnetic saturating means and said unitary transformer assembly is movable linearly with respect to the other member and said magnetic saturating means is adapted to differentially saturate one of said transformer cores over the other of said transformer cores in proportion to the extent of relative linear movement of the movable member of said pair consisting of said magnetic saturating means and said uni-

7

tary transformer assembly from null position with respect to the other member.

4. An electrical transducer according to claim 2 wherein said one member of the pair consisting of said magnetic saturating means and said unitary transformer assembly is movable angularly with respect to the other member and said magnetic saturating means is adapted to differentially saturate one of said transformer cores over the other of said transformer cores in proportion to the extent of relative angular movement of the movable member of said pair consisting of said magnetic saturating means and said unitary transformer assembly from null position with respect to the other member.

5. An electrical transducer comprising in combination two transformers fixedly attached one to another along an adjacent side with the transformer cores in a common plane constituting a unitary transformer assembly, the primary windings of said transformers being connected in series electrical circuit with an A.-C. power source and the secondary windings being connected in series opposition electrical circuit, a magnetic saturating means disposed in proximity to said transformer cores and maintaining a substantially constant direct magnetic flux through said cores, one member of the pair consisting of said magnetic saturating means and said unitary transformer assembly being movable with respect to the other member and said magnetic saturating means being adapted to differentially saturate one of said transformer cores over the other of said transformer cores in proportion to the extent of relative movement of the movable member of said pair consisting of said magnetic saturating means and said unitary transformer assembly from null position with respect to the other member, and output leads in electrical circuit with said secondary windings.

8

6. An electrical transducer comprising in combination two transformers fixedly attached one to another along the adjacent side with the transformer cores in a common plane constituting a unitary transformer assembly, the primary windings of said transformers being connected in electrical circuit with an A.-C. power source and the secondary windings of said transformers being connected in series opposition, a magnetic saturating means disposed in proximity to said transformer cores and maintaining a substantially constant direct magnetic flux through said cores, one member of the pair consisting of said magnetic saturating means and said unitary transformer assembly being movable with respect to the other member and said magnetic saturating means being adapted to differentially saturate one of said transformer cores over the other of said transformer cores in proportion to the extent of relative movement of the movable member of said pair consisting of said magnetic saturating means and said unitary transformer assembly from null position with respect to the other member, output leads in electrical circuit with said secondary windings, and a capacitor and resistor connected in individual electrical shunt relationship across said output leads.

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