Aug. 31, 1943. W. P. MASON **2,328,478**

PIEZOELECTRIC TRANSDUCER

Filed March 30, 1940

FIG. 1

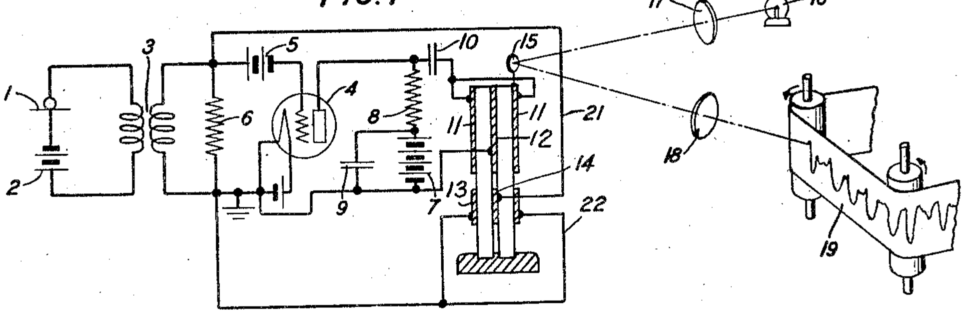


FIG. 2

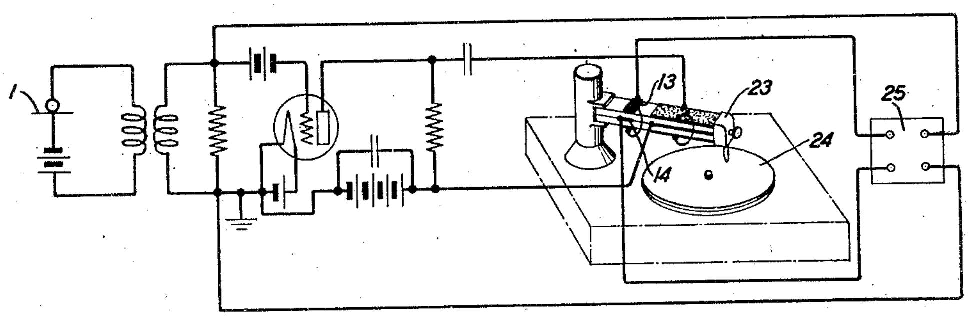


FIG. 3

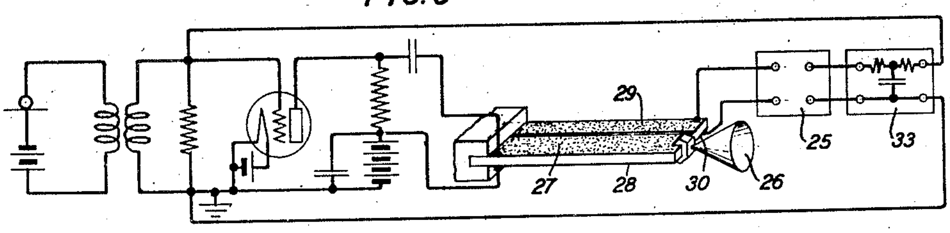
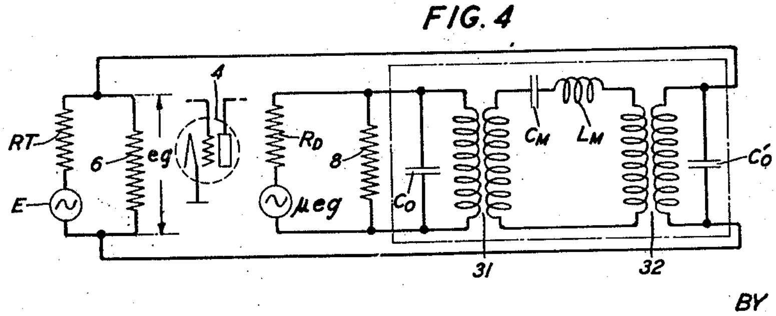


FIG. 4



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PIEZOELECTRIC TRANSDUCER

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5 Claims. (Cl. 179—100.4)

This invention relates to methods of and systems for improving the linearity of the response of piezoelectric transducers.

The use of electromechanical motors constructed from elements of Rochelle salt or other analogous piezoelectric materials for such purposes as light valves, telephone receivers, oscillographs, recorders and loud-speakers has been somewhat handicapped by the fact that such piezoelectric motors perform with an operating characteristic which is definitely non-linear. Among the reasons for the non-linear characteristic of such devices are hysteresis of piezoelectric material, the variation of dielectric constant, variation of the coefficient of piezoelectricity with change of temperature and the varying impedance which such devices present to currents of varying frequencies.

An object of the invention is to correct for the non-linearity of the response of piezoelectric motors to an impressed electromotive force.

Another object of the invention is to compensate for the hysteresis losses of piezoelectric devices.

A further object of the invention is to counteract the change in response of piezoelectric devices which occurs with change of temperature.

An additional object of the invention is to provide a Rochelle salt type piezoelectric motor for such apparatus as light valves, receivers, recorders, reproducers and loud-speakers, the characteristic response of which shall be substantially linearly proportional to an impressed electromotive force.

In accordance with the invention, a piezoelectric motor or transducer connected to the loud-speaker or other mechanical load device is energized by the output current from a thermionic amplifier upon the input terminals of which a control electromotive force is impressed. From a second pair of electrodes associated with the piezoelectric element an electromotive force which is directly proportional to the motion of the piezoelectric element is derived. This derived electromotive force is fed back to the input terminals of the thermionic amplifier in opposing relation to the control electromotive force originally impressed upon the input terminals of the amplifier and with such magnitude as to counteract any distortion introduced by the piezoelectric motor or lack of proportionality of response of the motion of the load device.

Other objects and aspects of the invention will be readily apparent from the following detailed description taken in connection with the accompanying drawing in which:

Fig. 1 shows a system for recording speech employing a piezoelectric oscillograph embodying the invention;

Fig. 2 illustrates a phonograph recorder involving a similar embodiment of the invention;

Fig. 3 portrays a public address system utilizing a piezoelectric loud-speaker embodying the invention, and

Fig. 4 is an equivalent electric circuit diagram of the apparatus of Figs. 2 and 3.

Referring to Fig. 1 a microphone or other source 1 of speech or signal currents is connected in series with the usual battery or current supply means 2 and primary winding of a transformer 3, the secondary winding of which is connected to the grid and cathode terminals of electron discharge amplifier 4. The grid circuit may be provided with the customary bias source 5 and impedance determining load resistance 6. The output circuit of the amplifier includes a space current source 7 in series with a resistance 8 and shunted by a by-pass capacity element 9. The external alternating current path is by way of the stopping condenser 10, external electrodes 11 and the internal electrode 12 back to the cathode. Electrodes 11 and 12 are associated with a piezoelectric relay motor unit which may be of the type disclosed in U. S. Patent 2,166,763 granted July 18, 1939. The piezoelectric motor of Fig. 1 has two sets of electrodes or coatings, however, a second smaller set 13, 14 being mounted on the same piezoelectric plates but insulated from the electrodes 11, 12 in order to function independently. The piezoelectric motor or moving element carries a mirror 15 which reflects a beam of light originating with source 16 and passing through concentrating lens 17, the reflected beam passing back through a suitable lens 18 and impinging upon a moving photosensitive strip 19 to record oscillations of the mirror 15 and, accordingly, the wave form of the sound waves applied to microphone 1.

As has already been stated the response of piezoelectric elements is subject to a number of distorting factors including non-linearity of response with changing electromotive forces and frequencies, change of response factor with change of temperature and hysteresis of the piezoelectric material. In order to compensate to a large extent for such distortions a negative feedback path 21, 22 is connected from the second set of electrodes 13, 14 to the input terminals of the amplifier.

The theory of operation of reverse feedback of the Black type to correct for distortion of amplifying systems need not be detailed in this specification. It is quite generally known as it has been presented in U. S. Patent to H. S. Black 2,102,671, December 21, 1937, and in an article entitled "Stabilized feedback amplifiers" by H. S. Black appearing at page 1 of the Bell System Technical Journal, January, 1934. Suffice it to say that the operation of the stabilized feedback amplifier circuit is such that under load conditions which would cause an amplifier without the feedback circuit to badly distort repeated waves the addition of the feedback circuit largely counteracts and eliminates the distortion at the expense of some reduction in gain. Practically, however, the reduction in gain is unimportant since the circuit permits operation with degrees of amplification at which the distortion, were the feedback circuit not used, would be quite intolerable. It will be sufficient for the purpose of this specification to bear in mind that the feedback circuit feeds back waves from the output circuit to the input circuit in reverse phase and in sufficient amount to reduce distortion in the desired degree depending upon the amount of feedback used.

The present invention takes advantage of the fact that a piezoelectric motor may be made to serve also as a piezoelectric generator. In other words, a piezoelectric motor connected to the output circuit of an amplifier to be driven by the output electromotive force in that circuit may be used to develop an entirely new electromotive force which reflects accurately the actual displacement obtained from the piezoelectric motor. It is, therefore, possible to secure for the distortion correcting feed-back circuit an electromotive force which inherently contains all the distortion introduced by the amplifier and besides that distortion, all additional distortions which occur in the translations involved in the operation of the piezoelectric motor. Consequently, the piezoelectric device considered as an element in the loop including the amplifier and the feedback circuit is effectively merely a part of the amplifier output circuit.

In operation, if the temperature increases and the piezoelectric efficiency of the material falls off as occurs with Rochelle salt after its Curie point is reached, there will be a smaller electromotive force generated between plates **13** and **14** for the reason that the displacement of the piezoelectric motor has decreased. Therefore, a lower reverse electromotive force will be placed on the grid and the amplification of the tube will correspondingly rise to tend to make the motor displacement constant. If, for example, the piezoelectric crystal does not exhibit a linear bending response to changing driving electromotive force the generated electromotive force at electrodes **13** and **14** will deviate from the desired electromotive force in exactly the same way that the bending deviates from the desired bending. The change in feedback will therefore be such as to counteract the distortion.

Hysteresis may manifest itself as a bending of the piezoelectric crystal plates which remains after the applied driving electromotive force has been withdrawn. Any such remanent bending sets up a strain in the crystal motor plates with a resultant charge on the surface of the feedback electrodes **13** and **14**. In this unique way the piezoelectric generator senses distortion of this type and generates its own correcting electromotive force to be applied to the feedback circuit. This action continues until the correcting driving electromotive force bends the crystal plates in the opposite direction when finally the plates become straightened out leaving no residual charge on their feedback electrodes **13** and **14**.

Fig. 2 illustrates schematically a phonograph recording system quite similar in its principal features to the system of Fig. 1. In the system of Fig. 2 the piezoelectric motor carries cutting or inscribing tool **23** which records the sound waves impressed on microphone **1** as sound tracks or grooves in the rotating record matrix **24**.

As is pointed out in the specification to Bode 2,123,178, July 12, 1938, for complete stability of feedback amplifiers against singing it is necessary that the magnitude of $\mu\beta$ become less than unity before its phase angle becomes zero. The Bode patent discloses the design details of the complete feedback loop so as to insure such stability. As shown in the Bode patent this design may involve use of a suitable network in the feedback path. It is preferred in accordance with the present invention to include such a network **25**, where necessary, connected in the path between the coatings or electrodes **13** and **14** and the amplifier input circuit. Inasmuch as the piezoelectric crystal has not only a natural resonance response frequency but also third and higher harmonic response frequencies, it is necessary to take these into account in the design of the network **25**.

Fig. 3 illustrates another embodiment of the invention in which the piezoelectric motor is mounted for longitudinal vibration to drive the loud-speaker **26**. It is provided with longitudinally divided pairs of electrodes insulated from each other of which the driving electrodes **27** and **28** are considerably wider than the feedback electrodes **29** and **30**.

The equivalent electric circuit diagram for Figs. 2 and 3 is illustrated by Fig. 4 in which E and RT represent respectively the effective alternating current source and the resistance introduced by elements **1**, **2** and **3** into the input circuit of the amplifier **4**. The input electromotive force developed across the terminals of resistance **6** is represented by e_g. Actually, of course, the equivalent resistance **6** will be somewhat modified in value by the shunt conductance of the input path of the device **4**. The internal space current path of the tube is represented in well-known manner by the source μe_g in series with the internal alternating plate current resistance R_p. The external circuit includes the large resistance **8** and the network in the broken line box which represents the piezoelectric motor together with its driving and feedback output terminals. The details of this network will be familiar upon review of the article "Electromechanical representation of a piezoelectric crystal" appearing in volume 23, page 1252 of the Proceedings of the Institute of Radio Engineers for October 1935. See particularly Fig. 5 of that article. C_o and C_o' are respectively the static capacitances of the pairs of input electrodes and output electrodes respectively. The electromechanical couplings between the electrical and mechanical systems are portrayed by ideal transformers **31** and **32** and the reactances of the mechanical system translated into their electrical equivalents are designated C_m and L_m, respectively.

The system lends itself readily to a number of modifications. The amount of feedback can be governed by the ratio of the area of the feedback electrodes to that of the driving electrodes. If, for example, as in Fig. 3 where the system is to be used for cutting records, a different frequency characteristic is desired in order to produce a record in which the reproduction may more faithfully follow the original sounds, this may be readily accomplished by proper design of the β or feedback network since it is possible to shape the amplitude-frequency characteristic of the system by inclusion of a shaping network of proper design in the feedback path. If it is desired to accentuate high frequencies in the record the β network may include an attenuator **33** of high frequencies, as for example, a T section with a shunt capacitance arm and series resistance arms as indicated in Fig. 3.

The resistance **8** in the plate circuit of the amplifier is made large. The internal plate circuit resistance R_p is made high compared to the magnitude of resistance **8**. This, to an extent, equalizes the response of the piezoelectric motor over a range of temperatures and of different frequency applied electromotive forces since the motor displacement is proportional to the current under all conditions and the current tends to remain more nearly constant if R_p is large. This type of equalization does not improve the situation with respect to distortion occasioned by hysteresis or non-linearity of the motor response characteristics. It does, however, reduce some of the distortions which would otherwise remain for correction by the feedback amplifier.

What is claimed is:

1. An amplifier having an input circuit and an output circuit, a piezoelectric element, means including a pair of electrically conducting electrode surfaces electrically connected to the output circuit of the amplifier mounted adjacent the piezoelectric element to impress an electric field thereon whereby the amplifier output circuit impresses an electric field upon the piezoelectric element and means including a second pair of electrically conducting electrode surfaces electrically connected to the amplifier input circuit and mounted adjacent the piezoelectric element to be subjected to the varying electric stress engendered by displacement of the piezoelectric element for feeding back to the input circuit an electromotive force derived from the piezoelectric element of such phase as to oppose the electromotive force originally impressed upon the input circuit in order to counteract non-linearities in the positional response of the piezoelectric element to its impressed electric field.

2. A transmission system comprising an input circuit, a thermionic amplifier having input terminals connected thereto and an output circuit, a piezoelectric device having electrodes connected to the output circuit to receive an electromotive force therefrom, a feedback path including an additional pair of electrodes physically connected to the piezoelectric device for deriving an electromotive force generated by the piezoelectric device in response to displacement thereof, the feedback path having a connection to the input terminals of the thermionic amplifier through a section which causes such phase shift at all frequencies for which the amplitude is large enough to result in oscillation that the total phase shift of the feedback path is less than 180 degrees.

3. In combination, an amplifier having an input circuit and an output circuit, a piezoelectric element having electrodes connected to the output circuit and a feedback path connecting an independent pair of electrodes on the piezoelectric element to the input circuit in opposing relation to the amplified energy impressed by the amplifier upon the element whereby distortions in consequence of non-linear temperature response and hysteresis of the element are compensated.

4. An electromechanical system comprising a piezoelectric motor having input electrodes, a load element mechanically connected to the motor to be driven thereby and presenting sufficient mechanical impedance to tend to cause the motor to work with a load at which its displacement does not faithfully follow the impressed driving electromotive force, an amplifier having an input circuit upon which a control electromotive force may be impressed and an output circuit connected to the piezoelectric motor to deliver driving energy thereto, and means connected to the piezoelectric motor to derive therefrom an electromotive force proportional to its displacement, said means comprising a second pair of electrodes physically connected to the piezoelectric electric motor and having a connection to the input circuit of the amplifier to feed back thereto an electromotive force opposing the original control electromotive force and of such phase and magnitude as to cause the positional response of the motor to bear substantially linear relationship with respect to the initial control electromotive force.

5. A piezoelectric element having input terminals and electrodes connected thereto, a mechanical device connected thereto and driven thereby, the element consisting of a material which exhibits piezoelectric hysteresis and means for automatically compensating for any hysteresis effect which would tend to cause a departure of the form of the wave motion of the mechanical device from the wave form of the driving electromotive force applied to the input terminals, said means comprising an additional pair of electrodes physically connected with the piezoelectric element to abstract therefrom piezoelectric electromotive forces generated in response to displacements of the element, a thermionic amplifier having input terminals and output terminals, a path connecting the pair of electrodes to the input terminals of the amplifier, a path connecting the output terminals of the amplifier to the input terminals of the piezoelectric device and an input circuit connected to the input terminals of the amplifier.

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