

July 18, 1939.

W. P. MASON

2,166,763

PIEZOELECTRIC APPARATUS AND CIRCUITS

Filed March 16, 1937

2 Sheets-Sheet 1

FIG. 1

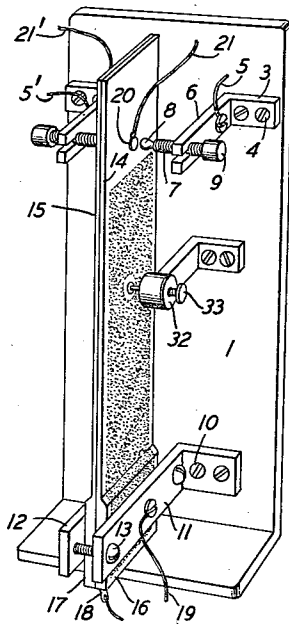


FIG. 2

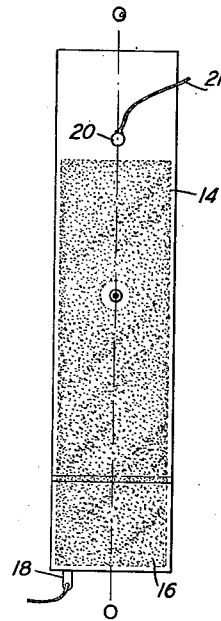


FIG. 3

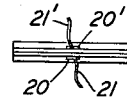


FIG. 4

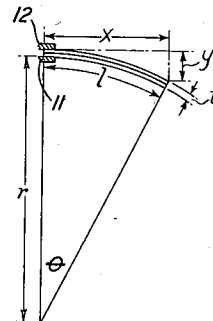


FIG. 5

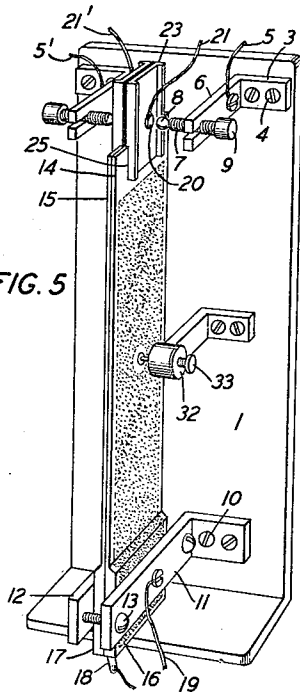


FIG. 6

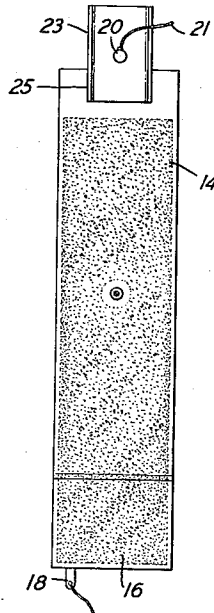
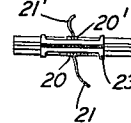


FIG. 7



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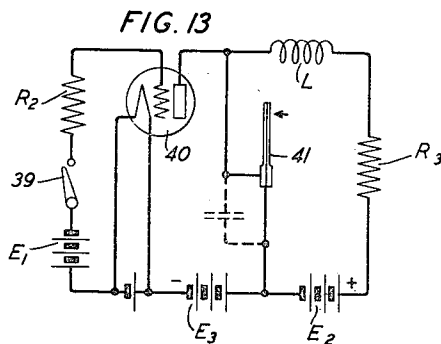
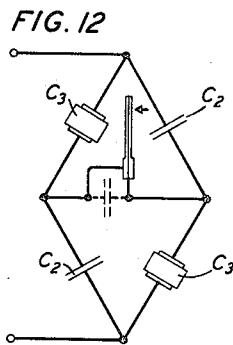
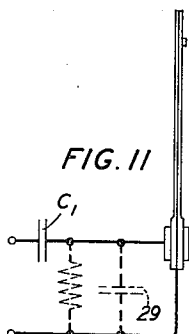
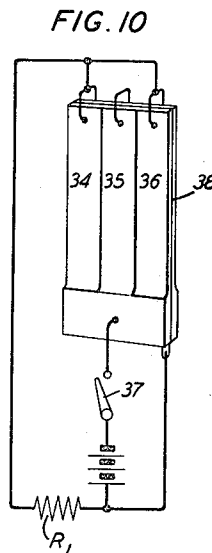
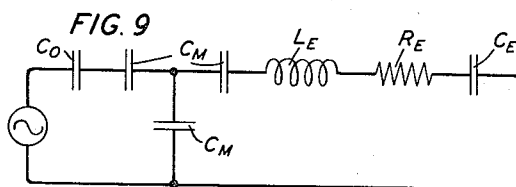
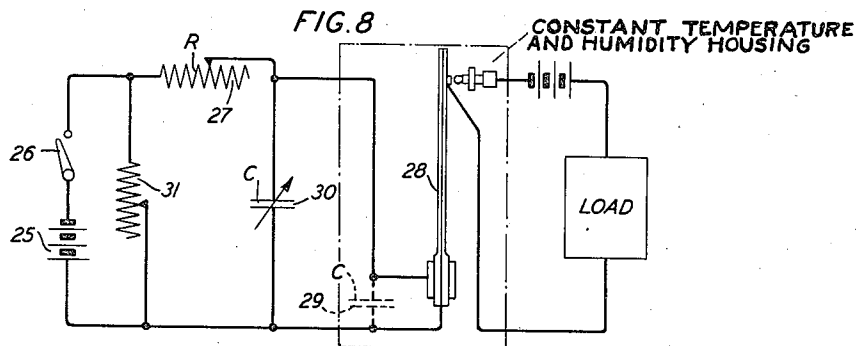
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PIEZOELECTRIC APPARATUS AND CIRCUITS

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2 Sheets-Sheet 2



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UNITED STATES PATENT OFFICE

2,166,763

PIEZOELECTRIC APPARATUS AND CIRCUITS

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Application March 16, 1937, Serial No. 131,160

19 Claims. (Cl. 175—320)

This invention relates to electrically operated relays and more particularly to piezoelectric apparatus and circuits.

Substantially all relays now in use having movable contacts are of the electromagnetic type. An electromagnetic relay operates by virtue of a magnetic field which arises when an electric current flows through the relay winding and which persists substantially for the duration of that current. It follows that the relay actuating force which the magnetic field produces is a function of the intensity of current in the relay winding. In the case of relays operated over long lines or in circuits of high resistance the operating force may be so small as to make electromagnetic relays impractical without amplifiers or other devices for increasing the actuating force. Moreover, the flow of current in the circuit of the relay winding is attended with an energy loss which in the case of long continued periods of operation, or large numbers of relays may be very costly.

As is well known, a piezoelectric body responds to a properly imposed electric field to alter its position or conformation in consequence of the mechanical stresses induced in it by the field. If such a body, as for example, a plate of Rochelle salt crystal be mounted by fixing one surface or margin on a support and be provided with a pair of electrodes coated or otherwise attached on its surfaces or position adjacent thereto, an electromotive force applied between the electrodes will set up such a stress as to cause a corresponding displacement of the free portions of the body. Accordingly, an electric contact element carried by such a displaced portion may be brought into engagement with a fixed position electric contact element upon application of an electromotive force to the electrodes of the piezoelectric body. If a local circuit including a source of current and a translating device as, for example, a lamp be connected to the two contact members, the piezoelectric body will operate as a relay to close the local circuit so that the lamp may be lighted by energy from the source of current.

Piezoelectric relays have several inherent advantages. Because they respond to potential upon their electrodes they may be operated by the very small quantity of electricity necessary to charge their electrodes to the required operating potential. Inasmuch as the charging currents are extremely small, the operating circuit losses are correspondingly small. Moreover, the operating circuit may suffice to transmit sufficient energy to operate the relay even if its resistances

are very high. It is quite possible to operate a piezoelectric relay over an operating circuit having a resistance of, for example, 1 megohm. Having once charged the electrodes and actuated the relay no further operating current is required except the infinitesimal amount necessary to compensate for leakage and maintain the charge and the relay remains operated until the charge on its electrodes is removed. The energy required is substantially only that necessary to initially actuate the relay and the usual holding current loss is almost entirely avoided. Moreover, these advantages are attained by a structure which is relatively simple and inexpensive to construct and which is rapid in operation.

An object of the invention is to provide a relay of the piezoelectric type which shall be quick-acting.

Another object of the invention is to prevent chattering at the contacts of a piezoelectric relay.

An additional object of the invention is to control the time of operation after application of the operating electromotive force and of release after withdrawal of the operating electromotive force to secure any desired time delay or duration of operation of a piezoelectric relay.

A further object of the invention is to produce a piezoelectric element that may be quick-acting and at the same time may impart a sufficient motion to its movable contact to operate circuits requiring considerable contact separation.

A still further object of the invention is to provide a piezoelectric relay element which may be rugged enough to withstand the stresses encountered in rapid operation for long periods.

Other objects of the invention are to improve the sensitivity of piezoelectric relays and to render the sensitivity more uniform throughout a wide range of operating temperatures.

A still further object of the invention is to render the piezoelectric element of a piezoelectric relay relatively immune to deteriorating atmospheric effects.

It is also an object of the invention to improve the force factor of a piezoelectric relay.

In accordance with the invention the operating element of a piezoelectric relay which carries the movable contact consists of thin blades of piezoelectric material clamped at one end at which they are made considerably thicker in the interest of ruggedness. A rigid beam structure of material of low density may be cemented to the piezoelectric blades near their free ends to carry the movable electric contact at the center of

percussion of the composite structure and to multiply the displacement available. Chattering of the contacts may be reduced by mechanical and electrical damping. Timing of the operation and release of the relay after application and withdrawal of an electromotive force from its circuit are predetermined by series resistance and shunt capacitance which cooperate with the inherent capacity of the electrodes associated with the piezoelectric blades.

The invention both as to its organization and mode of operation will best be understood from a consideration of the appended claims and the detailed specification in connection with the drawings in which:

Fig. 1 illustrates in perspective the mounting of the piezoelectric blades which form the operating part of a piezoelectric relay;

Fig. 2 a side view of the blades;

Fig. 3 an elevation of the structure shown in Fig. 2;

Fig. 4 a diagram to explain the calculations of the displacement available;

Fig. 5 a modification of the structure of Fig. 1;

Fig. 6 a side view of the piezoelectric blades of Fig. 5;

Fig. 7 an elevation of the structure shown in Fig. 6.

Fig. 8 is a circuit diagram of a system for determining the time of operation of a piezoelectric relay;

Fig. 9 shows the electrical equivalent circuit of a piezoelectric relay;

Fig. 10 shows a system for damping a piezoelectric relay;

Fig. 11 illustrates an expedient for rendering the sensitivity of a piezoelectric relay more nearly uniform under varying temperature conditions;

Fig. 12 shows a modification of the device of Fig. 11 in which the piezoelectric relay is incorporated as one element of a Wheatstone bridge; and

Fig. 13 shows the electrical diagram of a circuit for rendering a piezoelectric relay quick-acting and more sensitive to a small applied voltage.

Referring to Fig. 1 there is shown a supporting frame 1 of insulating material having a base member to mount the relay members in vertical position. On the frame 1 are two brackets 3 attached thereto by screws 4 which may support the terminals for the respective leads 5 and 5'. An angle portion 6 of the bracket is provided with a split screw-threaded opening through which works a contact carrying screw 7 having a contact member 8 and an adjusting head 9. Also, mounted on frame 1 by means of screws 10 is a bracket 11 with which a plate 12 connected to bracket 11 by screws 13 cooperates to clamp the piezoelectric members 14 and 15.

Piezoelectric elements 14 and 15 are preferably formed of Rochelle salt and their principal faces, indicated in Fig. 2, are parallel to the B and C axes and perpendicular to the A axis of the virgin Rochelle salt crystal. The rectangular plates 14 and 15 are so cut that their central longitudinal axis O—O indicated in Fig. 2 is in a direction inclined 45 degrees to the B or C axes of the virgin crystal. The lower end portions of the elements 14 and 15 indicated at 16 and 17 are made thicker than the principal portions so that they are less fragile and hence less likely to be fractured by the clamping action of plate 12 and bracket 11. The inner flat faces of elements 14 and 15 which are in contact with each other and the outer or opposite flat faces as well are preferably coated

with a conducting material. For this purpose, aquadag, a colloidal fine suspension of carbon, has been used. After drying the contiguous surfaces of elements 14 and 15 are each provided with a thin copper foil terminal strip 18. The surfaces of the elements 14 and 15 are then given a coat of shellac which serves the double purpose of protecting the Rochelle salt against atmospheric moisture and of causing the surfaces of elements 14 and 15 to adhere throughout their length.

One of the piezoelectric elements, e. g., element 14, is provided with a contact member 20 insulated from the coating on element 14 and having a very flexible lead or conductor 21 connected thereto. Elements 14 and 15 are so designed that upon application of an electromotive force between input terminals 18 and 19 one element lengthens and the other shortens. If the electromotive force is of the proper polarity it will cause the assemblage of adhering elements 14 and 15 to bend in the manner of a bimetallic thermostat to carry contact element 20 into engagement with contact element 8 thus completing an electrical path from lead 5 to lead 21. If an electromotive force of opposite polarity is applied elements 14 and 15 will bend in the opposite direction to cause the similar contacts on the opposite side to engage.

The displacement of the piezoelectric relay contact 20 may be calculated as follows by reference to Fig. 4. Assuming an effective length l from the bending fulcrum of the piezoelectric elements adjacent clamp 11 up to the contact 21, a thickness t of the two elements 14 and 15 and a radius r of bending with the final arc subtending an angle θ

$$(1) \quad \frac{l+dl}{r+\frac{t}{2}} = \frac{l}{r} = \theta$$

$$(2) \quad \frac{t}{2r} = \frac{dl}{l}$$

But from piezoelectric theory

$$(3) \quad \frac{dl}{l} = \frac{d_{12}V}{300t}$$

Where d_{12} is the piezoelectric constant of extension in the direction of axis O—O for a Rochelle salt plate cut as described in connection with elements 14 and 15 and subjected to an electric field in the direction of the A axis, V is the applied electromotive force and t the thickness of one of the crystals. For Rochelle salt d_{12} has a magnitude of about 2×10^{-5} at 24.5°C . and decreases on each side of that temperature. Solving for the radius of curvature

$$(4) \quad \frac{1}{r} = \frac{2d_{12}V}{300t^2}$$

But from elastic theory

$$(5) \quad \frac{1}{r} = \frac{d^2y}{dx^2}$$

Where y is the displacement of the center line of the crystal from its equilibrium position and x the distance from one end of the crystal, hence

$$(6) \quad \frac{d^2y}{dx^2} = \frac{d_{12}V}{150t^2}$$

$$(7) \quad \frac{dy}{dx} = \frac{d_{12}Vx}{150t^2} + C$$

For the relay considered here with the crystal plate clamped at one end

$$\frac{dy}{dx} = 0 \text{ when } x = 0$$

Accordingly

$$(8) \quad y = \frac{d_{12} V x^2}{300 t^2}$$

and the displacement at the end of the crystal of length l is

$$(9) \quad y = \frac{d_{12} V l^2}{300 t^2} = \frac{6.66 \times 10^{-8} V l^2}{t^2} \text{ cm.}$$

For example, for a crystal 3 inches (7.5 cm.) long and having a thickness of 25 mils (.0636 cm.) the displacement for an applied voltage of 45 volts will be .0418 cm. (16.5 mils). This calculated result checks quite closely with the measured displacement of such a crystal plate at 24.5° C.

Figs. 5, 6 and 7 illustrate a modification of the piezoelectric element of Figs. 1, 2 and 3 in which the displacement of the moving contact element is increased by positioning it on a rigid beam extension of the piezoelectric element. As indicated, the moving contact element 20 is mounted on one side of an I beam 23 preferably consisting of two channel shaped members placed back to back to constitute a rigid or substantially unbending beam. A similar contact 20' is mounted on the opposite side. To minimize the mass of the beam it is constructed of some low density material as, for example, aluminum. The piezoelectric elements 14 and 15 are slotted at their ends as indicated at 25 to accommodate the I beam which is attached to the piezoelectric elements by some adhesive material such as shellac. The conductive coatings forming the driving electrodes are interrupted short of the margins adjacent the beam so as not to be electrically connected thereby. Assuming a length of piezoelectric plate l_1 and an additional length l_2 of aluminum bar measured up to a contact point carried thereby we may calculate the displacement of the contact point for small displacements from Equation 7 since the aluminum bar will not bend but will have approximately the slope of the end of the piezoelectric plate to which it is cemented. Assuming the piezoelectric element to its junction with the end of the rigid bar to have a length l_1 and the rigid bar a length l_2 it may be readily shown since the slope of the rigid bar is from Equation 7

$$(10) \quad \frac{dy}{dx} = \frac{d_{12} V l_1}{150 t^2}$$

that the total displacement of the movable contact is

$$(11) \quad y = \frac{d_{12} V}{300 t^2} (l_1^2 + 2 l_1 l_2)$$

or designating by L the total length $l_1 + l_2$ from the clamped end of the piezoelectric element to the movable contact

$$(12) \quad y = \frac{d_{12} V}{300 t^2} (L^2 - l_2^2)$$

The force which the relay will exert on its contact points is also of interest. This can be calculated closely by using the formula for the deflection of a beam clamped at one end. This is

$$(13) \quad \delta = \frac{F l^3}{2 E w t^3}$$

where l is the length w is the width, t the thickness of one piezoelectric element, that is, half the

thickness of the relay tongue, d is the deflection, E is Young's modulus of the piezoelectric material and F the applied force in dynes. E for Rochelle salt is about 1.5×10^{11} dynes per square cm. for a plated crystal. Hence solving for the force required to displace the crystal by an amount d we find

$$(14) \quad F, \text{ in dynes, } = \frac{3 \times 10^{11} w t^3 d}{l^3}$$

To find the force applied by the relay to its contact Equation 11 can be used if d represents the displacement beyond the fixed relay contact surface that the contacting surface of the movable relay contact would experience if the fixed relay contact offered no obstruction. For example, with the relay element of Fig. 1, suppose the contact separation is normally 5 mils. Then the value d for 45 volts will be $16.5 - 5 = 11.5$ mils. We assume that the width of the relay is 1" or 2.54 cm.

$$(15) \quad F = \frac{3 \times 10^{11} \times 2.54 \times (.0636)^3 \times .0292}{(7.5)^3} = 13.6 \times 10^3 \text{ dynes} = 14 \text{ grams approx.}$$

Measured values appear to be of this order of magnitude.

The speed of operation of the relay or the time at which it closes its contacts after application of an electromotive force to its circuit is another important element. Since the piezoelectric element possesses an electrostatic capacity it takes a certain time to build up therein an electromotive force sufficient to actuate the piezoelectric elements. Moreover, once the capacity device is charged to the proper operating potential there is an additional time required for the operation of displacing the movable contact to take place.

Assuming the requisite charge or potential on its electrodes, a piezoelectric element will respond in an interval which is a function of its resonance frequency. The longitudinal or extensional mode of vibration of a Rochelle salt element has a natural frequency expressed by

$$(16) \quad f = \frac{96000 t}{l^2}$$

where as before t is the thickness of the Rochelle salt blade and l its effective length. Since the fixed contact stop arrests the motion of the movable contact, the duration of that motion is determined by Equation 16 and also by the ratio of the relay travel to total travel if the motion were not arrested. If this ratio is designated by m the time interval T_1 occurring during the motion will be approximately

$$T_1 = \frac{2m}{\pi f}$$

To the time T_1 required for the relay to operate after it has been subjected to the operating potential there must be added the time T_2 required for bringing the potential difference between the relay electrodes up to the operating magnitude. Consider, for example, the circuit of Fig. 8 in which a source 25 of actuating electromotive force is connected in a circuit with a piezoelectric relay of the type illustrated in Figs. 1 to 7, inclusive. The circuit which is normally open at the contacts of a signaling of remote control key 26 contains a resistance 27 in series with the piezoelectric relay 28, the inherent capacity of the electrodes of which is indicated in dotted lines at 29. A variable capacity element 30 is connected in parallel with the capacity of the piezoelectric element and a resistance element 31 is shunted across the circuit between

the key and the series resistance 27. The time required for the capacity elements 29 and 30 to jointly charge up to the operating potential will be approximately $T_2 = RC$ in seconds where R is the resistance of the series element 27 and C is the joint capacitance of capacity elements 29 and 30. If, for example, R is a 10 megohm resistance and the capacitance of 29 and 30 together is made as large as 1 mf. it requires about 10 seconds for the relay to close. It is accordingly readily possible to increase or decrease the preoperating period by varying the capacity and resistance. The capacity of the electrodes of such a piezoelectric element as was disclosed in Fig. 1 is of the order of .01 mf. It is, therefore, apparent that with the capacity 30 decreased to such an extent as practically to eliminate it and with the series resistance reduced from 1 megohm to 1000 ohms the preoperating time or delay period may be reduced to approximately .00001 second.

After the key 26 is closed and the capacitance 29 becomes charged up to the operating potential as has been described the relay tongue will bend to cause its contacts to engage. Thereafter substantially no energy is taken by the piezoelectric relay which remains actuated as long as its electrodes are held at the requisite potential. Consequently, if the key 26 be permitted to open immediately after the contacts of the relay 28 close, the contacts will remain closed until the charge on capacitances 29 and 30 leaks off to such a degree that the actuating force of the residual potential difference between the electrodes will no longer sustain a displacement sufficient to hold the contacts closed. The time T_3 required for the charge to leak off is a function of the capacitance of the element to be discharged and of the series resistances 27 and 31 through which it must discharge. Consequently, the holding time of the relay may be varied as desired by variation of the magnitudes of resistances 27 and 31 and of shunt capacity 30. This characteristic of a determinable holding time for an electromechanical relay without supply of substantial additional energy to hold the relay operated after once it is actuated is believed to render this device unique.

Chattering of relays at their contacts is an important factor particularly in high speed operation. The equivalent circuit of the relay for its fundamental mode of motion is illustrated in Fig. 9 where R_e , L_e and C_e are respectively the mechanical resistance, inductance, and compliance of the crystal for its first mode of motion. See Fig. 3 of the article entitled "An electromechanical representation of a piezoelectric crystal" by W. P. Mason, published in Proceedings of the Institute of Radio Engineers, vol. 23, pp. 1252-1263, October 1935. If the mechanical resistance R_e is very small the crystal will oscillate around its final displacement for a considerable time. If, however, there be introduced a mechanical resistance of such magnitude as to critically damp the crystal the crystal will come to its equilibrium position without oscillation. Such a resistance may comprise an oil-damping element 32 as illustrated in Fig. 1 in which motion of the relay drives a piston which pushes out the oil between the piston and a flat plate behind it. This produces a mechanical resistance which can be adjusted to any desired value by adjustment of the flat plate by means of an external knob 33.

It is also feasible to use the piezoelectric property of the vibrating body to advantage in intro-

ducing damping. Since in its motion the body generates piezoelectric electromotive forces the vibration of chattering produces an alternating electromotive force. If an electrical resistance element be connected between points at which such an alternating electromotive force is generated the resulting energy dissipation may be employed to effectively damp the vibration of the piezoelectric body. A structure of this kind is illustrated in Fig. 10 in which the front face of the front piezoelectric blade and the back face of the back blade are each provided with three separate coatings 34, 35 and 36. Each of the three front coatings is directly connected electrically with the corresponding back coating. When key 37 is closed an actuating electromotive force is applied directly between the coating 35 and the single central coating 38 between the two piezoelectric blades. The relay thereupon responds. Any chattering or vibration sets up an alternating piezoelectric electromotive force between front and back coatings 34 and front and back coatings 36, all acting as a coating of one potential and the central coating 38 of the opposite potential. Consequently, resistance R_1 connected between these coatings furnishes an energy dissipation path which provides the desired damping effect.

This damping effect can also be obtained by inserting an electrical resistance R in series with the relay of Fig. 1. This follows from the fact that when the relay tongue strikes the contact it is bent and this produces an additional charge on the relay which is dissipated through the resistance R in a similar way to that employed in the relay of Fig. 10. It has been shown theoretically that the best value for this resistance R is a value such that it equals the impedance of the relay capacitance at the resonant frequency of the relay; for example, if the relay has a static capacitance of .01 mf. and a resonant frequency of 150 cycles, the best value of R is about 100,000 ohms. This will not appreciably slow up the action of the relay.

Rochelle salt has a maximum capacitance and piezoelectric response at about 24.5° C. In order to give a more nearly uniform response with varying temperatures a condenser C_1 of considerably less capacity than the piezoelectric capacitance 29 at 24.5° C. may be connected in series with the piezoelectric element as is indicated in Fig. 11. Hence at 24.5° C. most of the driving electromotive force will be expended across the series condenser and the sensitivity of the piezoelectric device will be reduced. As the temperature changes from 24.5° C. the capacity 29 falls away rapidly and soon becomes less than that of condenser C_1 so that the relative portion of the driving voltage effective on the piezoelectric element is increased in such manner as to tend to compensate for its reduced piezoelectric sensitivity. The applied charge may leak off through the inherent leakage resistance of the crystal structure as indicated in dotted lines or a suitable physical shunt resistance may be provided.

A circuit capable of more exact compensation for variation of sensitivity with temperature is that of Fig. 12 which involves a Wheatstone bridge, two fixed condensers C_2 of which each have larger capacity at temperatures somewhat removed from 24.5° C. than the piezoelectric relay capacity 29. Two other capacity elements C_3 consist of Rochelle salt. If these elements have a capacity each of about the same magnitude as that of the capacity 29 the bridge will be unbalanced and the piezoelectric element will be

subjected to a certain driving electromotive force. As the temperature approaches 24.5° the piezoelectric element becomes more sensitive. At the same time its capacity and that of elements C₃ increase to a magnitude approximating the capacity of elements C₂. The bridge thus becomes more nearly balanced so reducing the electromotive force applied to the piezoelectric element and compensating for the increased sensitivity of the piezoelectric element.

Since Rochelle salt crystal relays are, in general, most sensitive at temperatures of about 24.5° C., that is 76° F., it is advantageous in many instances to operate them in air conditioned rooms or enclosures in which the temperature is at about that point. There is the additional advantage in rooms where humidity is regulated that the crystal is protected against dehydration. It is, therefore, to be understood that piezoelectric relays in accordance with the present invention may be placed singly or with numbers of other relays in enclosures provided with temperature regulation or with both temperature and humidity regulation. The broken line rectangle of Fig. 8 illustrates diagrammatically such an enclosure for the piezoelectric relay element 28.

If it is desirable to make the piezoelectric relay very fast it is necessary to increase the resonance frequency of the piezoelectric element either by making it shorter or thicker. In either case, the sensitivity of the relay will be considerably decreased so that the displacements obtainable with the driving electromotive forces ordinarily available for signaling will be considerably reduced. To overcome this a circuit arrangement in accordance with that of Fig. 13 may be used in which the piezoelectric element is operated by a relatively large actuating electromotive force controlled by an electron discharge device to the input circuit of which a relatively small electromotive force is applied. Although a high voltage source is used to actuate the piezoelectric relay very little power is consumed and, accordingly, such a system is of relatively high efficiency.

As shown in Fig. 13, the signal input is represented diagrammatically by the source E₁ and the signaling key 39, in series with resistance R₂ which may represent the resistance of a long line or other circuit over which the signals are to be transmitted. An electron discharge device 40 of the usual type has its input electrodes connected to the signal path just described. The anode circuit of the device 40 includes in series an inductance coil L, a resistance R₃ and a two-part space current source E₂, E₃ the negative terminal of which is connected to the cathode of the discharge device. A piezoelectric relay 41 has its actuating terminals connected respectively to the anode and to the common junction point of source E₂, E₃. The circuit is so adjusted that the normal space current passing through the tube and through the inductance L and the resistance R₃ in series causes a drop of potential in the inductance L and the resistance R₃ which is just equal to the electromotive force of source E₂. Under those circumstances there is a substantially zero difference of potential across the actuating terminals of the relay 41.

Assume that E₂, E₃ have a total series-aiding electromotive force of 1000 volts, μ , the amplification factor, is 30, R_p, the internal plate circuit resistance of the discharge device, is 50,000 ohms and R₃ is 100,000 ohms. If the circuit be so ad-

justed that the normal potential drop across L and R₃ just equals the electromotive force of E₂ the normal potential difference across the actuating terminals of relay 41 is zero. It will be obvious that under these circumstances, the source E₂ in effect supplies the potential drop across R₃ and the source E₃ supplies that within the internal space current path, or, in other words, that the electromotive forces of the sources E₂ and E₃ will bear the same ratio as R₃ and R_p. In other words, E₂ with the magnitudes of R₃ and R_p, as assumed, will be approximately 666 volts and E₃ of 333 volts electromotive force.

The normal space current in the circuit of Fig. 13 in the absence of impressed signal electromotive forces is

$$I_0 = \frac{E_2 + E_3}{R_p + R_3} = \frac{1,000}{50,000 + 100,000} = 6.6 \text{ milliamperes}$$

The change in current which occurs in consequence of introduction of a signaling electromotive force V of 33.3 volts into the grid circuit is

$$I_v = \frac{\mu V}{R_p + R_3} = \frac{30 \times 33.3}{50,000 + 100,000} = 6.6 \text{ milliamperes}$$

Now, if the electromotive force V is so directed that the change in current is a reduction the final space current I₀—I_v will be substantially zero. Under these conditions the full electromotive force of E₂ will be applied across the piezoelectric element 41. It is, therefore, apparent that a signal voltage of 33.3 volts has changed the actuating electromotive force applied to element 41 from an initial zero value to 666 volts. This very great effective amplification will enable high speed operation to be attained with short or thick piezoelectric elements of relatively low sensitivity.

The inductance L of the circuit of Fig. 13 is preferably given such magnitude and so incorporated into the circuit that together with the inherent capacitance 29 of the relay 41 it constitutes a one-half section low-pass filter of characteristic impedance R₃. Since this one-half section is terminated in its characteristic impedance the combination will, up to the cut-off frequency, have a pure resistance impedance equal to that of R₃. The magnitude of the inductance of L necessary for this is $L = R_3^2 C_{29}$. For example, if the capacitance of the relay is 1000 mmf. which is a representative value for a fast relay and R₃ is 100,000 ohms, the value of L will be 10 henrys. This, together with the capacitance C₂₉ will give a cut-off frequency of 1600 cycles which is ample for a very fast relay.

What is claimed is:

1. Apparatus for repeating electrical impulses comprising a pair of input terminals between which an electromotive force may be impressed, an electrostatic capacity device electrically connected thereto to be charged electrostatically by the impressed electromotive force and responsive to an impressed electromotive force to cause a displacement of a portion of the device, a movable contact mechanically fixed with respect to the displaced portion so that its position is shifted by displacement of said portion, a second contact mounted adjacent said movable contact and adapted to be engaged by the movable contact, and means predesigned to control the rate of application of the effective electromotive force to the electrostatic device to predetermine the interval which elapses after impression of the electromotive force upon the input terminals before the engagement of the contacts.

2. A relay comprising a pair of piezoelectric plates having juxtaposed flat surfaces, means holding the plates together as a unit with their lengths so arranged that one plate tends to shorten when the other plate lengthens, supporting means engaging the plates at one margin, a contact carried by the plates at a point remote from the supported margin, means for applying an electric field to the plates to cause motion of said contact, a stationary contact adapted to be engaged by the movable contact, and means for damping the motion of the plates to prevent chattering of the contacts subsequent to their engagement.

3. A relay comprising a plate of piezoelectric material having two oppositely disposed surfaces, conducting means affixed to the oppositely disposed surface, input terminals connected thereto and between which an electromotive force may be applied to cause displacement of a portion of the plate, a first contact carried by the displaceable portion, a second contact engageable by the first contact, the piezoelectric plate comprising a thin long member having a much thicker portion adjacent a margin remote from the first contact, and supporting means clamping the thickened portion of the plate whereby the tendency of the clamping to shatter the plate is materially reduced.

4. An electrically operated device comprising two relatively thin long blades of piezoelectric material each having two principal surfaces coated with conductive material, means causing one principal face of one plate to adhere to a principal face of the other, an input terminal connected to the coatings on the exposed faces of both blades, a second input terminal connected to the coatings on the adhering faces, each blade having an integral thickened portion at one end, and supporting means clamping the blades at their thickened portion.

5. A relay comprising an elongated member of piezo-electric material, input electrodes associated with two opposite faces thereof, an individual input contact connected to each electrode, means for supporting the piezoelectric member at one end, a rigid bar of material having low specific gravity carried by the piezoelectric member at a point remote from the supported end and extending in the same direction as the elongated member, and a contact carried by the rigid bar whereby upon application of an electromotive force between the input electrodes the contact member moves a greater distance than does the movable portion of the piezoelectric member and the motion is more rapid than it would be for a piezoelectric member having a dimension equal to the over-all length of the piezoelectric member and the bar.

6. A relay comprising a plate of piezoelectric material, the piezoelectric constant of which varies with temperature, electrodes associated with the plate, means for mounting the plate to hold one portion thereof relatively fixed, a stationary electrical contact member on said mounting means, a second electrical contact member on the plate and in position to engage the stationary contact member upon application of an electromotive force to the electrodes, and means for maintaining the temperature of the piezoelectric plate within a limited range of temperatures including that at which the piezoelectric constant of the piezoelectric plate is a maximum.

7. An electrostatic relay comprising a member having two electrodes in position to subject the

member to an electric field so as to cause a displacement of the member upon application of an electromotive force to the electrodes, and means to discharge any residual charge upon the electrodes after withdrawal of the applied electromotive force.

8. The combination according to claim 7, characterized in this, that the means to discharge the residual charge comprises a resistance, the magnitude of which is so related to the capacity of the electrodes as to predetermine the time during which the relay remains actuated after the actuating electromotive force has been withdrawn.

9. A relay comprising a piezoelectric element, electrodes mounted adjacent thereto, terminals connected to the electrodes to permit an electrical electromotive force to be impressed thereon to cause flexure of the piezoelectric element, and a yieldable mechanical damping device connected to the element to tend to damp oscillations resulting from the displacement occurring when the condition of charge of the electrodes is suddenly varied.

10. In combination an electron discharge amplifier having a cathode, an anode and an impedance control element, input terminals connected to the cathode and impedance control element, an output circuit connected to the anode and cathode, said output circuit including in series two sources of space current and a resistive impedance, the source of current adjacent the resistive impedance having an electromotive force just sufficient to compensate for the drop of potential in the resistive impedance, and a piezoelectric relay connected in shunt to the resistive impedance and its adjacent source whereby a normal zero potential difference exists across the piezoelectric relay and a large potential difference is impressed on the relay when an electromotive force is applied between the input terminals.

11. In combination an electron discharge amplifier having a cathode, an anode and an impedance control element, input terminals connected to the cathode and impedance control element, a space current source and a filter section connected in series between the cathode and anode, the filter section having a shunt arm comprising the capacitance of a piezoelectric relay element and a series arm comprising an inductance, and a resistance having one terminal connected to the inductance and the other to the piezoelectric element to terminate the filter section in its characteristic impedance whereby the filter section will present a pure resistance impedance in the output circuit of the electron discharge device.

12. In a delay action piezoelectric relay, in combination, a pair of input terminals, a resistance connected therebetween, a second resistance and a piezoelectric relay element in series therewith connected in shunt to the first resistance, and a capacity element connected in shunt to the piezoelectric relay element.

13. A relay comprising a long element of Rochelle salt having its two principal flat faces in planes parallel to each other and parallel to the B axis and perpendicular to the A axis of the mother crystal, the longitudinal axis of the piece lying at an angle of 45 degrees with the B axis, a second similar shaped element of Rochelle salt similarly cut, electrodes for each of the pieces of Rochelle salt associated therewith, means connecting the electrodes of one piece respectively to the electrodes of the other, means holding the two pieces in fixed back to back relation such

that an electromotive force applied between the electrodes tends to cause one piece to shorten and the other piece to simultaneously lengthen, a movable contactor carried by the Rochelle salt elements and a fixed position contact with which the movable contactor engages when the electromotive force is applied to the electrodes and a resistance capacity network connected to the electrodes and including a capacity element of such a predetermined magnitude that in conjunction with the resistance of the network and the capacitance of the Rochelle salt elements it fixes the desired time required for charging the electrodes to the operating voltage of the relay.

14. An electric relay comprising a pair of piezoelectric plates clamped together, electrodes associated with the plates to subject the plates to an electric field when the electrodes are electrically charged, a pair of input terminals connected to the electrodes in such manner that an electromotive force applied to the input terminals tends to cause one plate to increase in dimension along one direction and to simultaneously cause the other plate to decrease in dimension along the same direction whereby the assemblage of plates warps from its normal position, a stationary contact element mounted adjacent the plates, a movable contact element carried by the assemblage of plates for motion into engagement with the stationary contact element, means in series with the input terminals to determine the initiation of the response of the relay after an electromotive force is applied to the terminals, means for suppressing chattering of the contacts upon engagement to insure the precision of the contact interval, and means in shunt to the terminals and having such resistance relative to the magnitude of the capacity of the electrodes as to predetermine the time of release of the relay after the actuating electromotive force is withdrawn from the input terminals.

15. A relay comprising a pair of piezoelectric plates having juxtaposed flat surfaces, electrostatic capacity elements associated with the plates in fixed relation whereby in response to an electromotive force impressed upon the elements the plates are each subjected to an electric field, means holding the plates together as a unit with their dimensions so arranged that in response to an application of a given electromotive force to the elements one plate increases in dimension in a given direction and the other simultaneously shortens, a contact carried by the plates at a point remote from the holding means so as to be moved upon change in dimensions of the plates, a stationary contact adapted to be engaged by the movable contact, a resistor in series with the electrostatic capacity elements and having such magnitude of resistance with respect to the electrostatic capacity of the elements and the electric field required to initiate operation of the piezoelectric plates as to determine the initiation of the operating period of the relay, and a resistance path in shunt to the capacity elements whereby upon effective disconnection of an actuating source of electromotive force the charge accumulated upon the elements and the electric field may be dissipated, the resistance of the path

bearing such relation to the capacitance of the elements as to determine the time of dissipation of the charge and release of the relay after effective withdrawal of the source of actuating electromotive forces whereby the placing of the period of operation of the relay as well as its duration may be predetermined.

16. The combination presented in claim 15 together with means tending to eliminate chattering at the contacts upon initiation of the operation of the relay whereby the effective operation period is not disturbed by chattering.

17. A relay system comprising an electrostatic relay which includes two input terminals, two output terminals, a pair of electrostatic capacity elements respectively connected to the input terminals and the electrostatic capacity of which is of the order of .01 microfarad, a pair of contactor elements respectively connected to the output terminals, means physically connected to one of the contactor elements and responsive to relative motion of the capacity elements upon the application of a charging electromotive force to the input terminals to cause engagement of the contactor elements, and an electrical network connected to the input terminals of the relay which includes a conductive resistive path shunted across the capacity elements to determine the period required for the capacity elements to discharge to a release potential after withdrawal of the applied electromotive force from the input terminals.

18. A relay system comprising an electrostatic relay which includes two input terminals, two output terminals, a pair of electrostatic capacity elements respectively connected to the input terminals and the electrostatic capacity of which is of the order of .01 microfarad, a pair of contactor elements respectively connected to the output terminals, means physically connected to one of the contactor elements and responsive to relative motion of the capacity elements upon the application of a charging electromotive force to the input terminals to cause engagement of the contactor elements, and an electrical network connected to the input terminals and including a resistance in series between one of the input terminals and the respectively connected capacity element to determine the time required for the electrostatic capacity to charge up to a desired operating potential after application of the charging electromotive force to the input terminals.

19. A relay comprising a plate of piezoelectric material, the piezoelectric constant of which is a function of the condition of the surrounding atmospheric medium, electrodes associated with the plate, means for mounting the plate to hold one portion thereof relatively fixed, a stationary electrical contact member on said mounting means, and in position to engage the stationary contact member upon application of an electromotive force to the electrodes, and means for preventing change of the magnitude of the piezoelectric constant in consequence of change in the condition of the atmospheric medium surrounding the relay.

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