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3,390,559

PIEZOMECHANICAL LOCKING MECHANISM

Filed Aug. 30, 1967

2 Sheets-Sheet 1

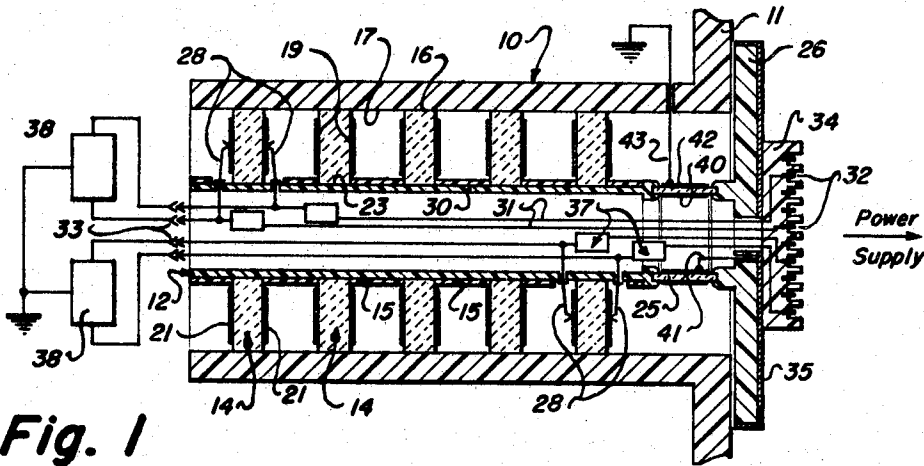


Fig. 1

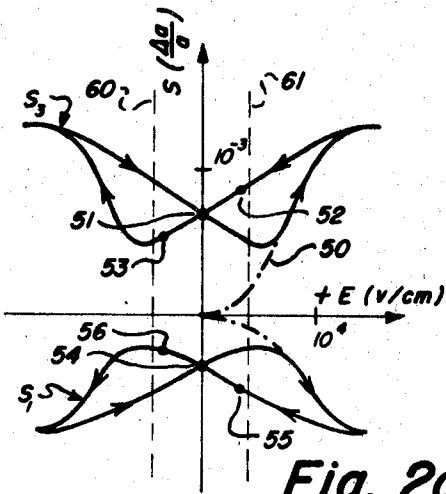


Fig. 2a

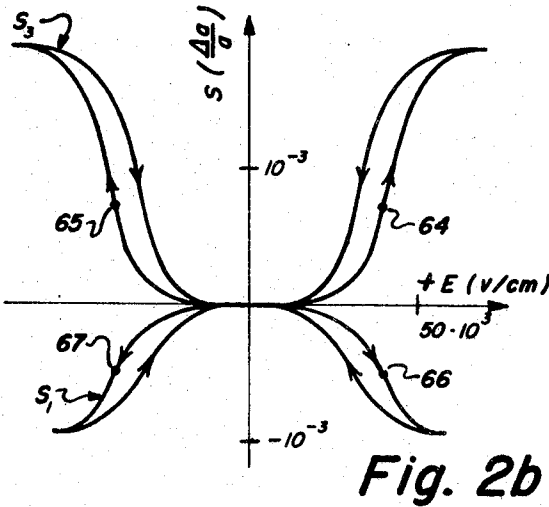


Fig. 2b

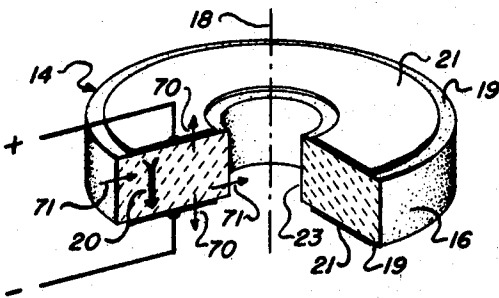


Fig. 3a

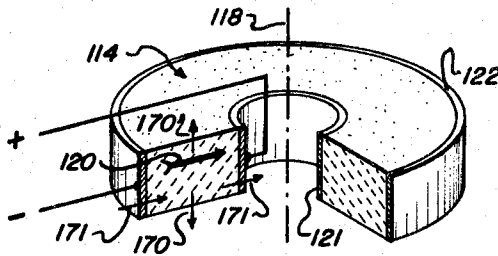


Fig. 3b

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2 Sheets-Sheet 2

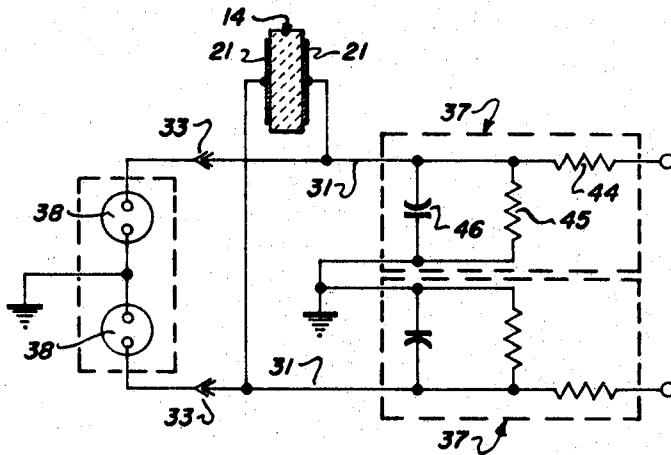


Fig. 4

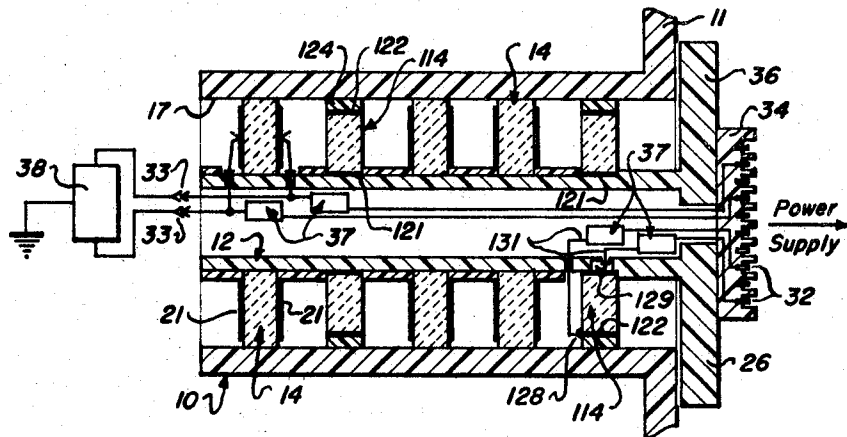


Fig. 5

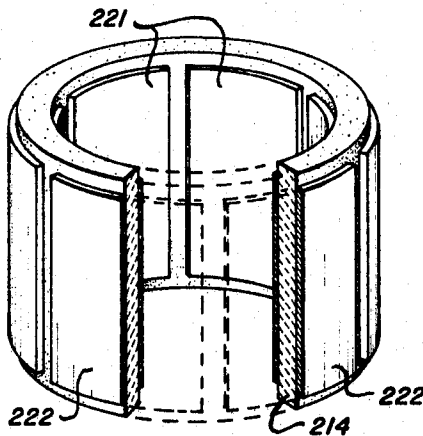


Fig. 6

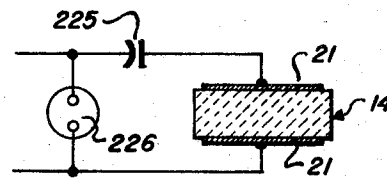


Fig. 7

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**PIEZOMECHANICAL LOCKING MECHANISM**  
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14 Claims. (Cl. 70—275)

## ABSTRACT OF THE DISCLOSURE

An electrically coded piezomechanical locking mechanism consisting of an outer housing having an internal cylindrical bore adapted to receive a lock actuating rod on which are mounted a number of similar circular piezoelectric discs spaced apart along the rod, each having a diameter slightly greater than that of the bore. Means are provided for applying an electric field of predetermined magnitude and direction across each disc such that they undergo sufficient lateral shrinkage to enable insertion of the rod within the bore. In the inserted position each of the discs in a de-energized state seeks to expand whereby sufficient outward radial pressure is exerted against the bore to prevent relative longitudinal movement of the bore and the actuating rod.

## Background of invention

The invention to be described is generally concerned with the field of mechanical fastening or locking mechanisms having means to prevent removal or relative motion between parts, and is more particularly concerned with devices of this character which are responsive to electrically coded signals for accomplishing mechanical locking and unlocking actions.

The invention takes advantage of the known electromechanical properties of ferroelectric and antiferroelectric materials, particularly the ceramics, in order to effect the alternate blocking and release of a tightly fitted piece of material. Heretofore the piezoelectric properties of such materials, i.e., the interrelation therein of strain and dimensional change with an applied electric field have not been, to the applicant's knowledge, employed for such purposes, especially in the construction of locking devices which are operable in response to electrically coded signals. Of particular importance is the fact that a ferroelectric material, if poled and used at remanence, possesses in effect an electrical memory, i.e., its strain behavior in response to the application of a given electrical field is dependent upon its direction of polarization.

There are a number of existing lock mechanisms which are operable in response to electrical codes of varying degrees of complexity. Most such codes, however, particularly those involving electronic memory, result in the completion of circuit connections or the application of suitable voltages in response to interrogation of the memory. Consequently they are capable of being circumvented if one is able to apply a voltage or close a circuit at the proper point. Furthermore, electrical memory circuits are generally sensitive to high magnetic fields which tend to destroy the memory.

Also, with sufficiently sophisticated techniques, these electrical codes may be deciphered or, if not, damage may result to the circuitry through application of undesirable electrical impulses.

Another limitation of prior art devices of the character described is that random trial and error operation which results in incorrect application of improper codes does not make the lock any more difficult to open.

## Summary of invention

It is therefore an object of this invention to provide electrically coded piezomechanical lock mechanisms in which the codes cannot be circumvented.

It is a further object of this invention to provide electrically coded piezomechanical lock mechanisms in which the electric power for opening and resetting the lock is furnished by the external code signal.

It is another object of this invention to provide electrically coded piezomechanical locking mechanisms with great simplicity of construction, ruggedness, and few moving parts.

It is another object of this invention to provide electrically coded piezomechanical lock mechanisms which are readily resettable.

It is a further object of this invention to provide piezomechanical locking mechanisms which are highly resistant to lock picking.

It is still another object of this invention to provide coded locking mechanisms wherein unsuccessful trial and error attempts to determine the code make successful operation progressively more difficult.

It is a further object of this invention to provide electrically coded locking mechanisms which are relatively unaffected by the presence of high magnetic fields.

It is another object of this invention to provide electrically coded locking mechanisms which will operate simultaneously in response to a given number of alternate electrical codes.

The invention consists of an electrically coded piezomechanical locking mechanism comprising an outer housing having an internal bore adapted to receive an elongated actuating member fixedly supporting in spaced alignment a plurality of piezoelectric elements of predetermined dimensions whereby insertion of said actuating member within said bore is initially prevented, together with means for applying an electric field of predetermined magnitude and direction across each of said piezoelectric elements whereby said elements undergo sufficient shrinkage to enable longitudinal insertion of the actuating member within the bore, each of the piezoelectric elements being thereafter adapted in a de-energized state to make outwardly-directed stress-producing contact with said bore.

## Description of drawings

The present invention is described in the accompanying drawings wherein:

FIG. 1 is a cross-sectional view of a piezomechanical locking device in accordance with this invention;

FIG. 2a is a graph of representative strain versus field characteristics of a ferroelectric ceramic;

FIG. 2b is a graph of representative strain versus field characteristics of an antiferroelectric ceramic;

FIG. 3a is a perspective view of a piezoelectric element under an axial electric field;

FIG. 3b is a perspective view of a piezoelectric element under a radial electric field;

FIG. 4 is a schematic diagram of a circuit with typical voltage limitation and protection circuit in accordance with this invention;

FIG. 5 is a cross-sectional view of another embodiment of the locking mechanism employing antiferroelectric elements and confusion elements;

FIG. 6 is a perspective view of a multi-electroded ferroelectric locking element in accordance with this invention; and

FIG. 7 is a schematic diagram showing connections to a polarization state controlled adaptive ferroelectric element.

Attention is now directed to FIG. 1 of the drawings which illustrates an embodiment of the invention in cross section. The lock mechanism is generally confined within a hollow outer housing 10 preferably of aluminum oxide or some other nonconductor. The housing 10 is terminated at one end by a shoulder 11 which may furnish support for external lock features. The main body of the housing 10 is adapted to extend within any desired structure wherein locking actions are required.

A movable elongated actuating member 12, for example, a hollow rod of plastic or fiber glass or other non-conductor, is adapted under proper conditions to be positioned coaxially within the longitudinal bore of the housing 10 as shown. A plurality of similar piezoelectric elements 14 may be slidably assembled over the member 12 and fixed in position by a plurality of similar ring spacers 15. The exact number of such elements 14 employed in the lock mechanism of this invention depends upon the complexity of operation and electrical coding desired. A total of 5 such elements 14 are shown in FIG. 1 for illustrative purposes only. The unstressed dimensions of the elements 14 in relation to the dimensions of the bore of the housing 10 in the absence of applied electric fields are important in the construction of this locking mechanism. As will be explained in more detail, the elements 14 may be constructed of either ferroelectric or antiferroelectric material and shall preferably be of a ceramic composition. They may, for example, be in the shape of circular discs and if so, the bore of the housing 10 should be cylindrical.

As shown, the entire outer periphery 16 of each of the elements 14 is in stress-producing contact with the inner bore surface 17 of the housing 10. Each of the opposing lateral flat surfaces 19 of each of the elements 14 is provided respectively with an electrode 21, for example, of thin electroplated silver approximately 1 to 2 mils thick. Electrodes 21 and all other similar electrodes are shown with exaggerated thickness for purposes of convenience and clarity. The electrodes 21 have an outer diameter less than that of the outer periphery 16 of any of the elements 14 and an inner diameter which is greater than the diameter of the inner periphery 23 of any of the elements 14. The diameter of the electrodes 21 is chosen so as to avoid voltage breakdown through the air at the potentials to be applied across elements 14 in lock operation. (Under normal conditions the air breaks down at 30 kv./cm.) Ring spacers 15 should also be wide enough to prevent voltage breakdown between facing electrodes 21 on successive elements 14.

The end of actuating member 12 adjacent the shoulder 11 may be provided with a peripheral piezoelectric element 25 also consisting of a ferroelectric or antiferroelectric material appropriately fastened to the outer surface 30 of the actuating member 12, through which the member 12 may be joined to a nonconductive plate 26 by means of which the member 12 is normally actuated. Under certain circumstances to be described, manipulation of the plate 26 is adapted to exert longitudinal or torsional forces upon the element 26 and thereby generate a piezoelectric voltage. The element 25 is an optional feature and if eliminated, the surface 30 of the actuating member 12 may become integral with the plate 26.

Associated with each of the elements 14 is a pair of conductive spring contacts 28 which are adapted individually to make good electrical contact with its two electrodes 21. For simplicity the connections are shown for only two of the elements 14. Each pair of spring contacts 28 may conveniently be brought through cylindrical wall 30 of the actuating member 12 and connected individually to a matching pair of internal leads 31. The leads 31 may be disposed longitudinally within the interior of the actuating member 12 and may be passed through an opening in the plate 26 to an insulated junction board 34 which may in turn be suitably fastened to an exposed conductive

covering 35 on the plate 26. Any desired electrical connections may be made from the opposite side of the junction board 34 to any of the leads 31 through pin contacts 32 from an external power supply (not shown).

Any pin contact 32 may be connected to any lead 31 without regard to any order or pattern. Since each of the elements 14 is provided with an identical pair of electrodes 21 and a pair of leads 31, in the illustrated embodiment there will be a total of 5 pairs of leads 31 connected internally to the junction board 34 to which connection may then be made from the external power supply.

A protective circuit 37, to be described later in more detail in connection with FIG. 4, may optionally be inserted in series with each of the leads 31 between the junction board 34 and the spring contacts 28. This circuit 37 is designed to thwart "lock picking," to make trial and error operation more time consuming, and to increase the potential complexity of electrical coding. Each of the leads 31 is also connected through a suitable circuit disconnect device 33 to a spark gap 38 or other suitable voltage limiting device which is in turn connected to ground, as described in more detail in connection with FIG. 4.

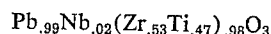
The piezoelectric element 25 may be provided with an internal peripheral electrode 40 to which may be affixed a lead 41, which in turn may be connected internally through the actuating member 12 and the plate 26 to the conductive covering 35. The outer periphery of the element 25 may be provided with an electrode 42 which may conveniently be connected by means of lead 43 through the surface of the housing 10 to any desired ground. The two electrodes 40 and 42 may be thin silver electro-deposited coatings and should be dimensioned suitably to avoid undesired voltage breakdown at the piezoelectric voltages which may be generated between them.

In a practical device the internal wiring within the actuating member 12 which consists of a plurality of leads 31 with associated protective circuits 37 may all be incorporated on a cylindrical printed circuit board (not shown) which may be inserted and removed at either end from the interior of the actuating member 12. In that event the spring contacts 28 would optionally terminate within the actuating member 12 in suitable pressure contacts adapted to be urged conductively against appropriate contact points on the surface of such a printed circuit board.

In order to fully understand the operation of the locking mechanism described in FIG. 1 and in other modifications thereof considered elsewhere in this application, it is important to consider certain details concerning the properties of ferroelectric and antiferroelectric materials.

#### Ferroelectric materials

FIG. 2a shows a representative strain-versus-electric field characteristic of a ferroelectric ceramic such as lead zirconate titanate, for example,



Electric field,  $E$ , expressed in volts per centimeter, is plotted along the abscissa, and strain  $S$ , expressed as the ratio of change of dimension to original dimension,  $\Delta a/a$ , is plotted along the ordinate. Application of an electric field,  $E$ , to an electroded element of ferroelectric material produces the well-known strain behavior shown in the "butterfly" loops of FIG. 2a.  $S_3$ , always positive, is the strain parallel to the field while  $S_1$ , the strain in the perpendicular or lateral direction, is always negative.

Once the ferroelectric material has progressed along the so-called "virgin curve" 50, shown in dotted outline, and has been initially polarized by a "saturating" electric field, the material has acquired, in effect, an electrical memory. This memory is retained as long as the device is operated within its linear region, identified in FIG. 2a as the area of the loop confined between the ordinates 60 and 61.

If, for example, a representative ferroelectric material has been subjected to a positive electric field in the sense of FIG. 2a and has been returned to a condition of remanence at point 51 by removal of the field, application of an electric field thereafter in the same direction, i.e., the direction of the initial polarization, will cause strain in a positive direction along the axis of polarization 57 as indicated, for example, by movement to some point 52 along the strain loop. However, application of a negative field in the sense of FIG. 2a, i.e., opposite to the direction of initial polarization, will cause strain in a negative direction along the same axis of polarization indicated, for example, by movement to some point 53 along the strain loop.

Consider also the strain simultaneously occurring perpendicular to the axis of polarization 57, as shown below the abscissa in FIG. 2a, from a corresponding initial point 54 of remanence. A positive field in the sense of FIG. 2a produces a strain in a negative direction indicated, for example, by movement to some point 55 along the strain loop. A field applied in the reverse direction produces a strain in a positive direction indicated, for example, by movement to some point 56 along the strain loop.

The above analysis will become more clear with reference to a representative piezoelectric element, as shown in FIG. 3a, which is similar in configuration to any of piezoelements 14 as described in connection with the embodiment of FIG. 1. Assume that the element 14 has been initially polarized along axis 18 and in the direction of arrow 20. If now an electric field is applied with the polarity shown between the electrodes 21, i.e., in the direction of polarization, the element 14 will experience axial expansion as shown by the arrows 70 and will experience contraction or shrinkage in the radial mode as shown by arrows 71. If either the direction of initial polarization 20 or the polarity of the applied electric field, as shown, were to be reversed, the disc 14 would contract axially and expand in a radial direction.

In FIG. 3b, a representative piezoelectric element is shown under the influence of initial radial polarization perpendicular to axis 118 and a subsequent radial electric field. Here a piezoelectric element 114 has been initially radially polarized, as indicated by the arrow 120. An electric field is now applied with the polarity indicated between inner and outer peripheral electrodes 121 and 122, i.e., in the direction of polarization. The resultant radial contraction is shown by arrows 171 and the corresponding axial expansion is shown by arrows 170. If again either the polarity of the applied electric field or the direction of polarization is reversed, the directions of axial and radial strain will also reverse, i.e., the element 114 will shrink radially and expand axially.

#### *Antiferroelectric materials*

Contrasted with the above is the strain-versus-electric field behavior of field-enforceable phase transition antiferroelectric materials as seen in FIG. 2b which illustrates representative strain characteristics for an antiferroelectric ceramic such as lead zirconate titanate stannate, for example,  $\text{Pb}_{.94}\text{La}_{.04}(\text{Zr}_{.43}\text{Ti}_{.17}\text{Sn}_{.40})\text{O}_3$ . For the type of material shown, the axial strain,  $S_3$ , in the direction of polarization is always positive and the lateral strain,  $S_1$ , is always negative. Materials of this sort acquire no remanent polarization. They expand parallel to the direction of the applied electric field and contract laterally regardless of the polarity of the electric field. For instance, application of a positive field in the sense of FIG. 2b produces a positive axial strain indicated by movement along the strain curve to a point 63 and application of a negative field of equal magnitude along the same axis again produces a positive axial strain as indicated by movement along the strain curve to a point 65.

In the lateral direction, application of a positive or negative field in the sense of FIG. 2b will produce a nega-

tive strain as indicated by movement along the strain curve to points 66 and 67, respectively. There are, in addition, some antiferroelectrics which can be used in the mechanisms of this invention which always exhibit positive lateral strain as well as positive axial strain. Components constructed of this material expand sizably in all directions when an electric field is applied.

With reference again to FIGS. 3a and 3b, it will now be appreciated that if elements 14 and 114 are composed of antiferroelectric rather than ferroelectric material, a reversal of the polarity of the applied electric field has no effect on the resultant dimensional changes. If the antiferroelectric material has a positive axial strain and negative lateral strain characteristics, then an electric field applied along axis 18 in FIG. 3a will always cause axial expansion, as shown by arrows 70 and radial contraction, as shown by arrows 71, regardless of the polarity of the field between electrodes 21. Similarly, if a radial electric field is applied between concentric electrodes 121 and 122 in FIG. 3b, there will be a resultant radial contraction of element 114, as shown by arrows 171, and an axial expansion, as shown by arrows 170, regardless of the polarity of the field.

If the antiferroelectric has both positive axial and positive lateral strain characteristics, elements 14 and 114 will both expand in all directions with the application of an axial or radial electric field of any polarity, for example,  $\text{Pb}_{.99}\text{Nb}_{.02}[(\text{Zr}_{.6}\text{Sn}_{.4})_{.95}\text{Ti}_{.05}]_{.98}\text{O}_3$ .

The operation of a locking mechanism in accordance with this invention as illustrated in FIG. 1 may now be considered. Prior to insertion within outer housing 10 and in a de-energized state, i.e., with no connection to the external power source, elements 14 should possess dimensions such that they just prevent insertion of the actuating member 12 within the outer housing 10.

An electric field of proper magnitude and direction is now applied simultaneously across each element 14 through the correct pair of pin contacts 32 on the junction board 34 and thence through the associated pair of leads 31, whereby each element 14 shrinks laterally enough to permit easy insertion of the actuating member 12 within the outer housing 10. As shown in FIG. 1, since elements 14 are side electroded, we can assume, for illustration, initial axial polarization and thus the field should be applied in the direction of polarization as explained in FIG. 3a. Once insertion is accomplished, the power supply is disconnected, whereupon elements 14 seek to expand toward their original diameters and depending upon the type and dimensions of material and the initial clearance between the outer periphery 16 of elements 14 and the inner bore surface 17 of outer housing 10, elements 14 will exert outward radial stress against the outer housing 10, thus producing a positive locking action between the actuating member 12 and the outer housing 10. Once the element 14 touches the surface 17 of the outer housing 10, the element 14 experiences a stress (since it can no longer fully expand) expressed as the product  $eE$ , where  $e$  is the piezoelectric pressure-field constant of the material. Hundreds of atmospheres are easy to obtain even with lubricated surfaces.

If it is now desired to operate the lock by removing actuating member 12, each element 14 must be energized from the external power supply in precisely the same manner as was required for initial insertion of the actuating member 12. Extraction of the actuating member 12 from the outer housing 10 may be adapted to effect any desired mechanical or electrical function.

In practice, it is advantageous to select for elements 14 a ferroelectric ceramic having a very high piezoelectric strain constant  $d$ . Ceramics of the lead zirconate titanate family are a preferred material. Once such a material is polarized with a "saturating" field, an electric field of about half the coercive field value will produce strain changes of about  $10^{-4}$ . For example, with a sample dimension of 1 cm., a dimension change within the linear region

is obtainable on the order of .0001 in. Since these changes are relatively small, it is important to insure that the peripheral surfaces 16 of the elements 14 and the inner bore surface 17 of the housing 10 are ground to optical tolerances.

For ease of insertion of the actuating member 12 within the outer housing 10, several modifications may be introduced within the general construction described in FIG. 1. For example, the first of the elements 14 to enter the bore of the outer housing 10 in insertion of the actuating member 12 may have its leading edge chamfered to make alignment more positive. Another possible variation is to provide the outer housing 10 with a bore of slightly tapered or conical proportions and to machine the outer peripheral surfaces 16 of the elements 14 so that each element 14 is also provided with a taper of matching degree with that of the bore of the housing 10 and so that the mean diameters of successive elements 14 vary along the actuating member 12.

In an actual device, elements 14 consisted of normally sintered ferroelectric discs of lead zirconate titanate, specifically  $\text{Pb}_{.99}\text{Nb}_{.02}(\text{Zr}_{.53}\text{Ti}_{.47})_{.98}\text{O}_3$ , approximately 12.5 mm. thick with an outer diameter of approximately 38 mm. After assembly on the actuating member 12, the elements 14 (discs) were machined to optically precise dimensions ( $\pm .000025$  in. tolerance) and the inner bore diameter of the housing 10 was drilled to provide a total interference of about .0002 in. A 10 kilovolt power supply was used.

The optimum thickness for the elements 14 is dependent on several considerations. Clearly the thicker the element 14 becomes, the stronger it is and the less susceptible to breaking under longitudinal or torsional forces. However, a thinner element 14 requires a lower voltage to accomplish axial polarization and thereby to produce the desired radial strain. A compromise may be adopted depending upon the intended usage and the voltages which are available for lock operation.

A lower practical limit must be observed in selecting the diameter of the elements 14 and consequently that of the bore of the housing 10. The smaller the diameter of the element 14, the less will be the absolute dimension change in the elements for the application of a given electric field. Consequently, the smaller the locking mechanism, the greater the precision which must be employed in machining the various mating surfaces.

In view of the explanation of FIGS. 2a, 2b, 3a, 3b, it will now be appreciated that within the framework of the above-described operation, a number of electrical coding variables may be introduced. Any given pair of leads 31 at junction board 34 may be connected across any given pair of electrodes 21. If we assume that elements 14 are axially prepolarized ferroelectric materials, then such elements may be assembled upon actuating member 12 in either of two axial orientations with respect to their initial polarization. The poling sequence of successive elements 14 constitutes the basic code of the lock. The operator must know, therefore, in which polarity to apply power from an external source to each of the elements 14 in order that such elements experience radial shrinkage. For example, with N identical locking elements 14, 2N leads 31 must be connected to the external power supply, N of these to a positive voltage. The number of possible combinations of connections to the power supply is

$$C = \frac{(2N)!}{(N!)^2}$$

only one of which will operate the lock. For 10 active elements 14, the number C is almost a million.

A modification of the embodiment of the locking mechanism shown in FIG. 1 may easily be devised in which elements 14 are replaced by a plurality of elements 114, each having an inner electrode 121 and an outer electrode 122 polarized, for example, as shown in FIG. 3b. With such construction the direction of axial assembly of the

elements 114 on the actuating member 12 would become immaterial. It would be necessary for the operator to apply power between electrodes 121 and 122 opposite to the direction of radial polarization 120 in order that there be a resultant radial contraction of element 114.

If we assume that the elements 14 are antiferroelectric, then the orientation of such elements on the actuating member 12 and the polarity of the power supply becomes immaterial and thus the available coding complexity decreases to that extent. Antiferroelectric materials, however, have an advantage, namely, that the strains obtainable are much higher than for corresponding ferroelectrics, that is, values of  $2 \times 10^{-3}$  are often found requiring electric fields of about  $5 \times 10^6$  volts per meter. A corresponding decrease in the closeness of machining tolerances of the active surfaces is also thereby permitted. For antiferroelectrics exhibiting positive lateral strain, volume increases of 0.4% under fields of  $5 \times 10^6$  volts per meter are not uncommon.

In order to increase the available complexity of the electrical coding variables of the locking mechanism described thus far, the elements 14 may be given different initial unstressed radial dimensions in the disassembled state. This will require that the operator apply voltages of differing values to individual elements 14 in order that each of such elements experience sufficient shrinkage to enable assembly within the outer housing 10. Conversely, on actuation of the lock after insertion is made, these differing voltages must be applied in the same manner to effect lock operation.

When ferroelectric ceramics are employed as elements 14, it is important to insure that the positive or negative strain applied to these elements be confined to their linear region as defined in FIG. 2a. FIG. 4 shows a schematic diagram of the electrical connections to any of the elements 14 in FIG. 1. The breakdown voltage of spark gaps 38 are set such that if an electric field, positive or negative, is applied to the element 14 sufficiently large to exceed its linear region as defined in FIG. 2a, a breakdown occurs and no field is applied across the element 14 thereafter. In an actual device the breakdown voltage for each spark gap 38 should be set, therefore, such that in combination they are slightly above the desired operating potential from the external power supply.

In addition, FIG. 4 shows the components of the optional protective circuit 37 associated with each of the elements 14 in FIG. 1. In series with each lead 31 is a resistor 44 which, in conjunction with a capacitor 46, forms a time constant circuit which imposes a lower limit on the time required to attempt a given code combination. For example, if the resistor 44 is on the order of  $10^8$  ohms and the capacitor 46 is on the order of  $10^{-8}$  farads, the time constant value is on the order of seconds. The resistors 45 may be of a magnitude to furnish a convenient discharge path for the capacitors 46. In addition, the protective circuit 37 insures that one may not compare the capacitance between various pairs of leads 31 and thereby determine externally which pair of leads 31 is connected across which of the elements 14. The addition of blind circuits, i.e., not connected to any piezoelectric element 14 but which are provided with protective circuits 37, compounds the difficulty involved in determining the correct combination.

Resistors 44 and 45 of each protective circuit 37 constitute in addition a voltage divider network. The selection of varying values for these resistors requires differing operating voltages for each element 14 and hence increases the possible complexity of the electrical code.

If it is desired to reset the electrical code of the device shown in FIG. 1 without mechanical disassembly (limited to ferroelectric elements), removal of the actuating member 12 from within the outer housing 10 disconnects the elements 14 from the spark gaps 38 through disconnect elements 33. It is then possible to apply positive or negative fields to each of the elements 14 of a magnitude

sufficient to exceed the linear range of such elements and cause repoling. This technique may be employed to reverse the polarity of electric field thereafter required for proper operation. Further code resetting flexibility is available within the scope of this invention by removing the elements 14 from the actuating member 12 and changing the order of their assembly and the direction of their polarization.

A modification of the locking mechanism described herein is shown in FIG. 5 in cross section. In this configuration a plurality of elements 14 with side electrodes 21 may be interspersed with a plurality of similar elements 114 with concentric inner and outer electrodes 121 and 122, as shown in more detail in FIG. 3b. In this modification the elements 14 may be either ferroelectric or antiferroelectric while the elements 114 should be only antiferroelectric. The outer peripheral electrode 122 of each of the elements 114 may be provided with a protective nonconductive layer 124 which in turn is adapted to make contact with the inner bore surface 17 of the outer housing 10. This will insure that the outer electrode 122 does not experience scoring or deformation in operation of the locking mechanism. The outer electrode 122 may be connected through a suitable spring contact 128 through the wall 30 of the actuating member 12 to one of a pair of internal leads 131. Similarly, inner peripheral electrode 121 may be connected through a spring contact 129 to the other lead 131. A pair of leads 131 associated with any of the elements 114 may then be channeled through the plate 26 to the junction board 34 and receive external power through appropriate pin contacts 32. A protective circuit 37, as described above in connection with FIG. 4, may again be inserted in series with each lead 131 associated with the element 114 to perform the functions described above in connection with FIG. 4.

In the modification of FIG. 5, the operation of the active elements 14 is the same in all respects as described in connection with FIG. 1. The elements 114 may be conveniently designed to additionally confuse and frustrate unauthorized attempts at lock operation. Since they have been identified as antiferroelectrics, the elements 114 are designed to expand radially against the bore of the housing 10 upon the application of an electric field between the electrodes 121 and 122 regardless of the polarity of the applied field. They are machined to fit into the outer housing 10 in the absence of an applied electric field. If lock operation is now attempted, application of power between the electrodes of any of the elements 114 will therefore prevent disassembly or removal of the actuating member 12.

If there are a total of N elements in the configuration of FIG. 5, M of which are antiferroelectric confusion elements 114 and the remainder are active antiferroelectric elements 14, and we assume either of the peripheral electrodes 121 or 122 is grounded, it can be shown that the total number of possible combinations C of connections to the external power source can be expressed as

$$C = \frac{(2N - M)!}{[(N - M)!]^2 M!}$$

Of this total only two are proper lock combinations. If  $N=10$  and  $M=5$ , the value for C is in excess of  $7.5 \times 10^5$ . If the operator does not know the value of M and if neither peripheral electrode 121 nor 122 is grounded, then the number of possible combinations is even higher.

In the locking mechanism described herein, temperature compensation does not constitute a serious problem. Ferroelectrics and antiferroelectrics have nonlinear temperature coefficients of the order of  $3 \times 10^{-6} \text{ }^\circ \text{C}$ . Several metals and alloys have similar coefficients of expansion. Fortunately, temperature compensation does not have to be very accurate since, as noted above, piezoelectric strains are of the order of  $10^{-4}$ . However, the better the temperature compensation is, the smaller the clearances between lock parts can be made and the

smaller the overall lock sizes can become. A solution to the problem of temperature compensation in the present device is to provide the inner bore surface 17 of the outer housing 10 with rings of piezoelectric material (not shown) against which the active elements 14 may radially expand in the inserted condition of the actuating member 12. If expansion or contraction of these two matching piezoelectric elements occurs with temperature, the radial clearance between them will tend to remain constant.

Within the scope of this invention, a number of additional modifications are possible to further increase the flexibility of the available coding arrangements. For example, in FIG. 6, there is shown in perspective a piezoelectric element 214 which may be a locking element, provided with a plurality of separated outer peripheral electrodes 222, each having an associated inner peripheral electrode 221. Such an element 214 may be designed to shrink or expand radially by the application of suitable electric fields across individual pairs of electrodes 221 and 222 bounded by the same circular radii. The element 214 may be designed such that proper energizing of any given number of electrode pairs out of the total will accomplish a desired degree of radial expansion or contraction of the element 214. This permits a large number of possible electrical codes, any one of which will successfully actuate a device relying upon a plurality of multi-electroded elements.

To further penalize lock picking attempts at operation of a lock of the character described, one may conveniently insert a capacitor 225 in series with the electrodes 21 associated with any one of the elements 14 whose capacitance is smaller than that of the element 14. Upon the application of a high enough voltage limited by a suitable spark gap 226, this will cause a certain amount of charge to flow into the element 14. Every application of an electric field to the element 14 in the wrong direction will depole such element to a certain degree, changing its piezoelectric properties. For every such wrong attempt the lock operator must apply the change once in the proper direction to such element 14 in addition to the regular code operation which normally opens the lock.

If an attempt is made to force the lock by pulling, pushing, or twisting the plate 26, or by applying external heat thereto without application of the proper electrical code, a piezoelectric or pyroelectric voltage will be generated by the electrodes 40 and 42 of the element 25 in FIG. 1. This may, for example, give a shock on the order of several kilovolts to any person completing the circuit between the cover 35 and ground. The voltage so generated can, of course, be conveniently applied to any desired signal device or other load circuit (not shown).

Consistent with the scope of the invention as described in this application, a variety of alternate configurations may be employed, for example, the bore of the housing 10 may have a generally rectangular cross section and the piezoelectric elements 14 may have a similar shape. Again the bore of the housing 10 and the configuration of the elements 14 may be provided with irregularities such that insertion of the actuating member 12 can be made readily in one plane but rotation of the actuating member 12 greatly reduces the available clearance and the consequent degree of expansion required for locking action. Still another modification may include a reversal of parts, i.e., the piezoelectric elements 14 may become portions of the inner bore of the outer housing 10 and may be adapted to expand inwardly to grip the actuating member 12 with radial force. Clearly also the point at which the connection of the locking mechanism to an external power supply is made may be suitably remote from the mechanism itself.

Those skilled in the arts with which this invention is concerned will have no difficulty in devising many

other modifications within the scope thereof as set forth in the description and the claims appended hereto.

What is claimed is:

1. An electrically coded piezomechanical locking mechanism comprising:

an outer housing provided with an internal longitudinal bore,

a plurality of similar piezoelectric elements fixedly supported in spaced alignment along an elongated actuating member adapted to be inserted longitudinally within said bore, said piezoelectric elements having predetermined dimensions whereby insertion of said actuating member within said bore is initially prevented, and

means for applying an electric field of predetermined magnitude and direction across each of said elements whereby said elements are adapted to undergo sufficient shrinkage to enable insertion of said actuating member within said bore, each of the piezoelectric elements being thereafter adapted in a de-energized state to make outwardly directed stress-producing contact with said bore.

2. An electrically coded piezomechanical lock as in claim 1 wherein each of said piezoelectric elements is composed of a ferroelectric material having a predetermined direction of axial polarization and wherein the polarity of the applied electric field is in the direction of polarization of each of said elements.

3. An electrically coded piezomechanical lock as in claim 1 wherein each of said elements is composed of an antiferroelectric material having a negative lateral strain characteristic and wherein said electric field is applied across each of said elements in an axial direction.

4. An electrically coded piezomechanical lock as in claim 1 including a piezoelectric element forming an integral part of the periphery of said actuating member and adapted to supply a piezoelectric voltage across a load circuit responsive to the application of predetermined forces on said piezoelectric element.

5. An electrically coded piezomechanical lock as in claim 1 wherein a plurality of capacitors of preselected magnitudes are connected individually in series with a predetermined number of said elements respectively.

6. An electrically coded piezomechanical lock as in claim 1 wherein each of said elements consists of a circular disc in axial alignment with said actuating member wherein said bore has a generally cylindrical configuration.

7. An electrically coded piezomechanical lock as in claim 6 wherein each of said piezoelectric discs is provided with a pair of electrodes substantially coextensive with the two opposite plane surfaces thereof and wherein said electric field is applied between said electrodes.

8. An electrically coded piezomechanical lock as in claim 6 wherein each of said discs is provided with a pair of electrodes substantially coextensive with its concentric inner and outer surfaces respectively and wherein said electric field is applied between said electrodes.

9. An electrically coded piezomechanical lock as in claim 6 wherein said internal bore is tapered and wherein

said piezoelectric elements consists of discs of successively increasing diameter.

10. An electrically coded piezomechanical lock as in claim 6 wherein each of said discs is provided with a plurality of pairs of spaced apart inner and outer peripheral electrodes, each of said pairs being composed of an inner and an outer electrode bounded by the same circular radii, and means for applying an electric field of predetermined magnitude and direction across each of said electrode pairs, said disc being adapted to undergo predetermined radial contraction in response to the application of said electric field across a predetermined number of said electrode pairs.

11. An electrically coded piezomechanical lock as in claim 6 wherein means are provided for limiting the magnitude of the voltage applied across each of said elements to a predetermined value.

12. An electrically coded piezomechanical lock as in claim 6 wherein an individual capacitor charging circuit of predetermined time constant is connected in parallel with each of said elements, each of said charging circuits also including a resistive discharge path.

13. An electrically coded piezomechanical lock as in claim 12 wherein said capacitor charging circuit includes voltage divider means for limiting the magnitude of said electric field to a predetermined value.

14. An electrically coded piezomechanical lock comprising:

a fixed outer housing provided with a cylindrical bore, a first plurality of axially polarized antiferroelectric discs supported in axial alignment at predetermined intervals along a movable rod adapted to be inserted longitudinally within said bore, each of said discs being dimensioned such that insertion thereof within said bore is initially prevented,

a second plurality of radially polarized antiferroelectric discs supported in axial alignment at predetermined intervals along said movable rod in preselected longitudinal relation to said first plurality of discs, each of said discs being dimensioned to enable insertion thereof within said bore,

means for applying an axial electric field of predetermined magnitude to each of said first plurality of discs whereby said discs undergo sufficient inwardly directed radial strain to enable slidable movement thereof with respect to said bore, and

means for applying a radial electric field of predetermined magnitude to each of said second plurality of discs whereby said discs undergo sufficient outwardly directed radial strain to prevent slidable movement thereof with respect to said bore.

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UNITED STATES PATENT OFFICE  
CERTIFICATE OF CORRECTION

Patent No. 3,390,559

July 2, 1968

Otmar M. Stuetzer

It is certified that error appears in the above identified patent and that said Letters Patent are hereby corrected as shown below:

In the heading to the drawings, Sheets 1 and 2, line 1, and in the heading to the printed specification, line 3, "Steutzer", each occurrence, should read -- Stuetzer --.

Signed and sealed this 23rd day of December 1969.

(SEAL)

Attest:

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Commissioner of Patents