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(72) **Inventeurs/Inventors:**
WANG, PENGHUI, CN;
LIU, GUOXI, CN;
WANG, ZHIPENG, CN;
SHI, HUADUO, CN

(73) **Propriétaire/Owner:**
BEIJING SUPERSONIC TECHNOLOGY CO., LTD., CN

(74) **Agent:** ROBIC

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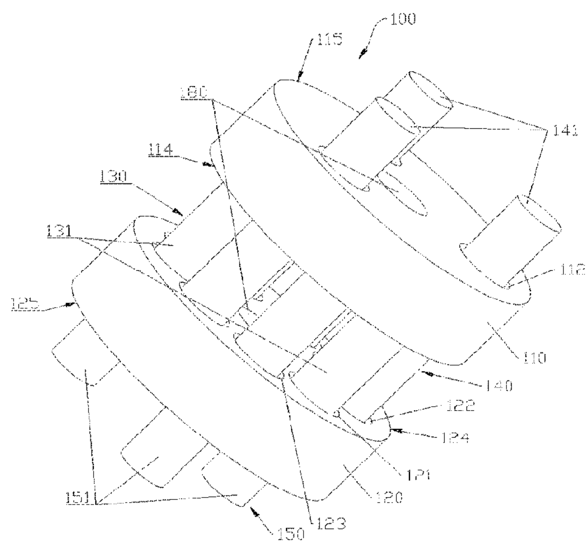
(54) **Title: PIEZOELECTRIC ACTUATOR AND LOW FREQUENCY UNDERWATER PROJECTOR**



(57) **Abrégé/Abstract:**
A compact piezoelectric actuator of large axial displacement is disclosed that includes opposed first and second level connectors of sufficient rigidity, and three sets of piezoelectric material columns (PMCs) each comprising three individual PMCs equally spaced along a circumferential line of the level connectors. In the construction, respective ends of each PMC in the first set are connected to facing surfaces of the level connectors. Each second (third) PMC has one end connected with the second (first) level connector and its free end passing through three equally spaced through-holes in the first (second) connector away from the second (first) connector. During operation, the first set of PMCs contract (extend) while the other two sets extend (contract), producing an overall axial displacement approximately the sum of the three sets of PMC. A low-frequency underwater projector using the disclosed piezoelectric actuator as its motor section is also described.

Abstract

A compact piezoelectric actuator of large axial displacement is disclosed that includes opposed first and second level connectors of sufficient rigidity, and three sets of piezoelectric material columns (PMCs) each comprising three individual PMCs equally spaced along a circumferential line of the level connectors. In the construction, respective ends of each PMC in the first set are connected to facing surfaces of the level connectors. Each second (third) PMC has one end connected with the second (first) level connector and its free end passing through three equally spaced through-holes in the first (second) connector away from the second (first) connector. During operation, the first set of PMCs contract (extend) while the other two sets extend (contract), producing an overall axial displacement approximately the sum of the three sets of PMC. A low-frequency underwater projector using the disclosed piezoelectric actuator as its motor section is also described.

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Piezoelectric Actuator and Low Frequency Underwater Projector

FIELD OF THE INVENTION

The present invention relates to the field of acoustic sensors, and in particular to a piezoelectric actuator and a low frequency underwater projector.

BACKGROUND OF THE INVENTION

Currently, the use of sound waves as an information carrier is relatively effective means of underwater communication, and an underwater projector is an indispensable key part for underwater communication. With the rapid development of modern sonar technology and the continuous increase of application requirements, the low frequency, light weight and miniaturization of the underwater projector has become an important trend of its development. The low frequency underwater projectors currently widely used include magneto-strictive low frequency underwater transducers, flextensional transducers and modified products thereof, flexural transducers, and so on.

However, although most of the existing low frequency underwater acoustic transducers can be miniaturized, a piezoelectric material in the low frequency underwater acoustic transducer often has a small axial displacement, leading to a limited sound power capacity of the transducer.

SUMMARY OF THE INVENTION

In view of this, embodiments of the present invention provide a piezoelectric actuator and a low frequency underwater projector to improve the problem of the limited sound power capacity of the existing low frequency underwater projectors.

To achieve the above object, an embodiment of the present invention provides a piezoelectric actuator, characterized by comprising a first level connector, a second level connector disposed opposite to the first level connector, a set of first piezoelectric material columns, a set of second piezoelectric material columns, and a set of third piezoelectric material columns,

wherein the first level connector and the second level connector are both of disc-shaped and of a certain thickness such that they are sufficiently rigid;

wherein the numbers of piezoelectric material columns in the first, second and third sets of piezoelectric material columns are the same; each set has three piezoelectric material columns;

wherein the three first piezoelectric material columns are spaced at equal angular separation along a circumferential line of the first and second level connectors and both ends of each of the first piezoelectric material columns are connected with the first level connector and the second level connector, respectively;

wherein the three second piezoelectric material columns are spaced at equal angular separation along a circumferential line of the first and second level connectors and each of the second piezoelectric material columns has one end connected with the second level connector and another end passing through three equally spaced through holes in the first level connector in a direction away from the second level connector so that the three second piezoelectric material columns and the second level connector are able to displace relative to the first level connector;

wherein the three third piezoelectric material columns are spaced at equal angular separation along a circumferential line of the first and second level connectors and each of the third piezoelectric material columns has one end connected with the first level connector and another end passing through three equally spaced holes in the second level connector in a direction away from the first level connector so

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that the three third piezoelectric material columns and the first level connector are able to displace relative to the second level connector;

wherein recesses are provided on opposite surfaces of the first level connector and the second level connector at locations where the first, second and third piezoelectric material columns are connected and the first, second and third piezoelectric material columns are bonded into the corresponding recesses; and

wherein during operation, the first piezoelectric material columns contract while the second and third piezoelectric material columns extend, or vice versa, so that axial displacements of the three sets of piezoelectric material columns add up to produce a larger overall displacement of the actuator.

Another embodiment of the present invention provides a low frequency underwater projector, characterized in that the low frequency underwater projector comprises a piezoelectric actuator as disclosed herein and further comprises a front radiation head and a tail mass, wherein the other ends of the second piezoelectric material columns are connected with the front radiation head, and the other ends of the third piezoelectric material columns are connected with the tail mass.

Another embodiment of the present invention provides a piezoelectric actuator comprising: a first level connector, a second level connector disposed opposite to the first level connector, a set first of piezoelectric material columns, a set of second piezoelectric material columns, and a set of third piezoelectric material columns. A surface of the first level connector that is opposite to the second level connector is provided with a set of first recesses, a surface of the second level connector that is opposite to the first level connector is provided with a set of second recesses corresponding to the first recesses, and the number of the first recesses and the number of the second recesses are each equal to the number of the first piezoelectric material columns; the set of first piezoelectric material columns and the first level connector are connected in a way that the first piezoelectric material columns are matched with the first recesses; and the set of first piezoelectric material columns and the second level connector are connected in a way that the first piezoelectric material columns are matched with the second recesses.

The surface of the first level connector that is opposite to the second level connector is provided with a set of first through holes running through the first level connector, the surface of the second level connector that is opposite to the first level connector is provided with a set of third recesses, and the number of the first through holes and the number of the third recesses are each equal to the number of the second piezoelectric material columns; the set of second piezoelectric material columns and the first level connector are connected in a way that the second piezoelectric material columns are inserted into the first through holes; and the set of second piezoelectric material columns and the second level

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connector are connected in a way that the second piezoelectric material columns are matched with the third recesses.

One end of each of the second piezoelectric material columns in the set of second piezoelectric material columns is inserted into one of the first through holes of the first level connector, and the other end of each of the second piezoelectric material column is matched with one of the third recesses of the second level connector, that is, the second piezoelectric material columns are connected with the second level connector, but the second piezoelectric material columns do not penetrate through the second level connector; and the second piezoelectric material columns are inserted into the first through holes located in the first level connector, and the second piezoelectric material columns penetrate through the first level connector.

The number of the second piezoelectric material columns may be three, then the number of the first through holes located in the first level connector is also three, and the number of the third recesses located in the second level connector is likewise three.

The surface of the first level connector that is opposite to the second level connector is provided with a set of fourth recesses, the surface of the second level connector that is opposite to the first level connector is provided with a set of second through holes running through the second level connector, and the number of the fourth recesses and the number of the second through holes are each equal to the number of the third piezoelectric material columns; the set of third piezoelectric material columns and the first level connector are connected in a way that the third piezoelectric material columns are matched with the fourth recesses; and the set of third piezoelectric material columns and the second level connector are connected in a way that the third piezoelectric material columns are inserted into the second through holes.

One end of each of the third piezoelectric material columns is matched with one of the fourth recesses of the first level connector, and the other end of each of the third piezoelectric material column is inserted into one of the second through holes of the second level connector, that is, the third piezoelectric material columns are connected with the first level connector, but the third piezoelectric material columns do not penetrate through the first level connector; and the third piezoelectric material columns are inserted into the second through hole of the second level connector, and the third piezoelectric material columns penetrate through the second level connector.

The number of the third piezoelectric material columns may be three, then the number of the fourth recesses of the first level connector is also three, and the number of the second through holes of the second level connector is likewise three.

Optionally, in the piezoelectric actuator described above, the first piezoelectric material columns, the second piezoelectric material columns, and the third piezoelectric material columns are all cylindrical piezoelectric material columns.

All the piezoelectric material columns described above may be cylindrical piezoelectric material columns, and it should be understood that the piezoelectric material columns may also be of other shapes such as rectangular shapes or square shapes, and the specific shape of the piezoelectric material column should not be construed as limiting the present invention.

Optionally, in the piezoelectric actuator described above, the piezoelectric material columns are each composed of a piezoelectric ceramic stack of a suitable cross-section.

The piezoelectric material columns may be each composed of a piezoelectric ceramic stack, and specifically, each piezoelectric material column may be formed by bonding an even number of piezoelectric ceramic sheets in series, and polarization directions of two adjacent piezoelectric ceramic sheets are opposite, wherein the piezoelectric ceramics include PZT piezoelectric ceramics and materials derived therefrom.

The piezoelectric material column may be formed in other ways, for example, composed of a radially polarized piezoelectric ceramic tube, and the specific way of forming the piezoelectric material column should not be construed as limiting the present invention.

Optionally, in the piezoelectric actuator described above, the set of first piezoelectric material columns, the set of second piezoelectric material columns, and the set of third piezoelectric material columns are all rectangular parallelepiped piezoelectric material columns.

The piezoelectric material columns described above may be all rectangular parallelepiped piezoelectric material columns, and it should be understood that the piezoelectric material columns may also be of other shapes such as prism, and the specific shape of the piezoelectric material column should not be construed as limiting the present invention.

Optionally, in the piezoelectric actuator described above, the rectangular parallelepiped piezoelectric material columns are all made of lead-based relaxor ferroelectric single crystal.

The lead-based relaxor ferroelectric single crystals may specifically comprise $Pb(Zn_{1/3}Nb_{2/3})O_3$-$PbTiO_3$, $Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$, $Pb(In_{1/2}Nb_{1/2})O_3$-$Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$, $Pb(Mg_{1/3}Nb_{2/3})O_3$-$Pb(Zr_{0.48}Ti_{0.52})O_3$, and materials derived therefrom.

It will be appreciated that the piezoelectric material column may also be made of other material, and the specific material from which the piezoelectric material column is made should not be construed as limiting the present invention.

Optionally, in the piezoelectric actuator described above, each of the rectangular parallelepiped piezoelectric material columns comprises a first single crystal active element and a second single crystal active element, the size of the first single crystal active element is the same as that of the second single crystal active element, and the first single crystal active element and the second single crystal active element are connected by bonding.

The single crystal slices of the first single crystal active element and the second single crystal active element have a polarization direction of [011] and have a higher transverse piezoelectric coefficient in the [100] direction, wherein, the [011] direction is the polarization direction of the single crystal, and the [100] direction is a driving direction.

Optionally, in the piezoelectric actuator described above, a central mechanical preloading mechanism is further comprised, the first level connector further comprises a central through hole located in the first level connector, and the second level connector further comprises a central through hole located in the second level connector, the central mechanical preloading mechanism is inserted into the central through hole of the first level connector, and the central mechanical preloading mechanism is inserted into the central through hole of the second level connector.

The first level connector comprises a central through hole running through the first level connector, the second level connector comprises a central through hole running through the second level connector, and the position of the central through hole of the first level connector corresponds to the position of the central through hole of the second level connector. The central mechanical preloading mechanism may be inserted into the central through hole of the first level connector, and the central mechanical preloading mechanism is inserted into the central through hole of the second level connector.

The embodiment of the present invention also provides a low frequency underwater projector comprising a piezoelectric actuator described above and further comprising a front radiation head and a tail mass, one end of the piezoelectric actuator is connected with the front radiation head, and the other end of the piezoelectric actuator is connected with the tail mass.

The embodiment of the present invention provides a piezoelectric actuator comprising a first level connector, a second level connector disposed opposite to the first level connector, a set of first piezoelectric material columns, a set of second piezoelectric material columns, and a set of third piezoelectric material columns,

wherein both ends of each of the first piezoelectric material columns are connected with the first level connector and the second level connector, respectively;

wherein each of the second piezoelectric material columns has one end connected with the second level connector and the other end running through the first level connector and extending in a direction away from the second level connector, and the second piezoelectric material columns are connected with the second level connector and movably connected with the first level connector; and

wherein each of the third piezoelectric material columns has one end connected with the first level connector and the other end running through the second level connector and extending in a direction away from the first level connector, and the third piezoelectric material columns are connected with the first level connector and movably connected to the second level connector.

Optionally, a surface of the first level connector that is opposite to the second level connector is provided with a set of first recesses at equal angular separation, a surface of the second level connector that is opposite to the first level connector is provided with a set of second recesses corresponding to the first recesses, and the number of the first recesses and the number of the second recesses are each equal to the number of the first piezoelectric material columns; and

the set of first piezoelectric material columns and the first level connector are connected in a way that the first piezoelectric material columns are matched with the first recesses; and the set of first piezoelectric material columns and the second level connector are connected in a way that the first piezoelectric material columns are matched with the second recesses.

Optionally, a surface of the first level connector that is opposite to the second level connector is provided with a set of first through holes at equal angular separation running through the first level connector, a surface of the second level connector that is opposite to the first level connector is provided with a set of corresponding third recesses, and the number of the first through holes and the number of the third recesses are each equal to the number of the second piezoelectric material columns; and

the set of second piezoelectric material columns and the first level connector are connected in a way that the second piezoelectric material columns are inserted into the first through holes; and the set of second piezoelectric material columns and the second level connector are connected in a way that the second piezoelectric material columns are matched with the third recesses.

Optionally, a surface of the first level connector that is opposite to the second level connector is provided with a set of fourth recesses at equal angular separation, a surface of the second level connector that is opposite to the first level connector is provided with a set of corresponding second through holes running through the second level connector, and the number of the fourth recesses and the number of the second through holes are each equal to the number of the third piezoelectric material columns;

the set of third piezoelectric material columns and the first level connector are connected in a way that the third piezoelectric material columns are matched with the fourth recesses; and the set of third piezoelectric material columns and the second level connector are connected in a way that the third piezoelectric material columns are inserted into the second through holes.

Optionally, the first recesses are disposed in an annular array manner, a connection line from the center of one of the first recesses to the center of the said annular array is a first connection line, and angles between any two adjacent first connection lines are the same.

For example, the number of the first recesses is three, and an angle between any adjacent first recesses is 60°, that is to say, the angle between any two adjacent first connection lines is 60°.

Optionally, the third recesses are disposed in an annular array manner, a connection line from the center of one of the third recesses to the center of the said annular array is a third connection line, and angles between any two adjacent third connection lines are the same.

The first through holes are disposed in an annular array manner, a connection line from the center of one of the first through holes to the center of the annular array is a second connection line, and angles between any two adjacent second connection lines are the same.

For example, the number of the third recesses is three, and an angle between any adjacent third recesses is 60°, that is to say, the angle between any two adjacent third connection lines is 60°.

For example, the number of the first through holes is three, and an angle between any adjacent first through holes is 60°, that is to say, the angle between any two adjacent second connection lines is 60°.

Optionally, the fourth recesses are disposed in an annular array manner, a connection line from the center of one of the fourth recesses to the center of the said annular array is a fourth connection line, and angles between any two adjacent fourth connection lines are the same; and

the second through holes are disposed in an annular array manner, a connection line from the center of one of the second through holes to the center of the said annular array is a fifth connection line, and angles between any two adjacent fifth connection lines are the same.

Similarly, when each of the number of the fourth recesses and the number of the second through holes is three, an angle between two adjacent fourth recesses is 60°, and an angle between two adjacent second through holes is 60°.

Optionally, the piezoelectric actuator further comprises a first pre-stress mechanism, wherein the first pre-stress mechanism is connected with the first level connector and the second level connector, the first pre-stress mechanism is configured to apply pre-stress to the first level connector and the second level connector so that the first piezoelectric material columns are under predetermined compressive stress during operation.

Optionally, the first level connector further comprises a central through hole located in the first level connector, and the second level connector further comprises a central through hole located in the second level connector.

Optionally, the first pre-stress mechanism comprises a first stress rod, at least one first resilient member and at least one first locking member. Both ends of the first stress rod pass through the central through holes corresponding to the first level connector and the second level connector, respectively. The at least one first resilient member, between the at least one locking member and the first level connector and/or the second level connector, are pressed by the at least one locking member and the first level connector and/or the second level connector.

The embodiment of the present invention provides a low frequency underwater projector comprising any of the piezoelectric actuators described above and further comprising a front radiation head and a tail mass, wherein the set of second piezoelectric material columns is connected with the front radiation head, and the set of third piezoelectric material columns is connected with the tail mass.

Optionally, a first pre-stress mechanism is further comprised, the first pre-stress mechanism is connected with the first level connector and the second level connector, and the first pre-stress mechanism is configured to apply pre-stress to the first level connector and the second level connector so that the first piezoelectric material columns are under predetermined compressive stress during operation.

Optionally, both the first level connector further comprises a central through hole located in the first level connector, and the second level connector further comprises a central through hole located in the second level connector; and

the first pre-stress mechanism comprises a first stress rod, at least one first resilient member and at least one first locking member, both ends of the first stress rod pass through the central through holes corresponding to the first level connector and the second level connector respectively, and the at least one first resilient members, between at least one locking member and the first level connector and/or the second level connector are pressed by the at least one locking member and the first level connector and/or the second level connector.

Optionally, a second pre-stress mechanism is further comprised, the second pre-stress mechanism is connected with the front radiation head and the tail mass, and the second pre-stress mechanism is configured to apply pre-stress to the front radiation head and the tail mass so that the second piezoelectric material columns and the third piezoelectric material columns are under predetermined compressive stress during operation.

Optionally, the second pre-stress mechanism comprises a second stress rod and at least one second resilient members; and

the first stress rod has a central through hole running along its own length direction, and the second stress rod is movably embedded in the central through hole of the first stress rod and has both ends extending beyond the central through hole; and at least one end of the second stress rod is connected with the front radiation head and/or the tail mass through the second resilient members, respectively, so as to apply the predetermined compressive stress to the second and third piezoelectric material columns in between the front radiation head and the tail mass.

Optionally, the compressive stress applied by the first pre-stress mechanism is at least 2 times the compressive stress applied by the second pre-stress mechanism.

Optionally, an anti-bending guide means is further comprised, and the guide means and the piezoelectric actuator are movably connected in a direction of extending and contraction of the piezoelectric actuator and connected in a direction perpendicular to the direction of extending and contraction.

The advantageous effects of the piezoelectric actuator and the low frequency underwater projector provided in the embodiments of the present invention are as follows:

the piezoelectric actuator and the low frequency underwater projector provided in the embodiments of the present invention comprise a first level connector, a second level connector, a set of first piezoelectric material columns, a set of second piezoelectric material columns, and a set of third piezoelectric material columns. When the set of first piezoelectric material columns is contracted, the first level connector and the second level connector can be brought close to each other so that the distal ends of the set of second piezoelectric material columns and the distal ends of the set of third piezoelectric material columns are further away from each other. In an allowable electric field or voltage condition, when the set of first piezoelectric material columns is contracted and the set of second piezoelectric material columns and the set of third piezoelectric material columns extend, the net extending or contraction displacement of the piezoelectric actuator as a whole is almost equal to the sum of the displacements of the set of first piezoelectric material columns, the set of second piezoelectric material columns, and the set of third piezoelectric material columns. The axial displacements of the piezoelectric materials can be superimposed and increased by excitation at an appropriate AC voltage, thus the sound power capacity of the low frequency underwater projector using the piezoelectric actuator as a driving mechanism is increased. The piezoelectric actuator and the low frequency underwater projector provided in the embodiments of the present invention improve the problem of the limited sound power capacity of the existing low frequency underwater projectors. The piezoelectric actuator provided in the embodiments of the present invention can also be referred to as a piezoelectric enhanced actuator because its axial displacement is enhanced.

BRIEF DESCRIPTION OF DRAWINGS

For illustrating technical solutions of embodiments of the present invention or of the prior art more clearly, drawings required for use in the description of the embodiments or the prior art will be introduced briefly below. It is apparent that the drawings in the following description are merely illustrative of some embodiments of the present invention, and it would be understood by those skilled in the art that other drawings could also be obtained from these drawings without using any inventive efforts.

Fig. 1 is a structural schematic view of a first level connector provided in a preferred embodiment of the present invention;

Fig. 2 is a structural schematic view. from another viewing angle. of the first level connector provided in the preferred embodiment of the present invention;

Fig. 3 is a structural schematic view of a second level connector provided in a preferred embodiment of the present invention;

Fig. 4 is a structural schematic view, from another viewing angle, of the second level connector provided in the preferred embodiment of the present invention;

Fig. 5 is a schematic view showing parital structure of a piezoelectric actuator provided in a preferred embodiment of the present invention;

Fig. 6 is a structural schematic view of the piezoelectric actuator provided in the preferred embodiment of the present invention, in a specific implementation;

Fig. 7 is a simplified schematic view of an operation state of the piezoelectric actuator provided in the preferred embodiment of the present invention.

Fig. 8 is a structural schematic view of a low frequency underwater projector provided in a preferred embodiment of the present invention;

Fig. 9 is a structural schematic view, from another viewing angle, fof the low frequency underwater projector provided in the preferred embodiment of the present invention;

Fig. 10 is a structural schematic view of a piezoelectric actuator provided in another preferred embodiment of the present invention; and

Fig. 11 is a structural schematic view of a low frequency underwater projector provided in another preferred embodiment of the present invention.

Reference numerals: 100- piezoelectric actuator; 110- first level connector; 111- first recess; 112- first through hole; 113- fourth recess; 114- first base; 115- second base; 120- second level connector; 121- second recess; 122- third recess; 123- second through hole; 124- third base; 125- fourth base; 130- combination of first piezoelectric material columns;,131- first piezoelectric material column; 140- combination of second piezoelectric material columns; 141- second piezoelectric material column; 150-

combination of third piezoelectric material columns; 151- third piezoelectric material column; 161- first single crystal active element; 162- second single crystal active element; 170- central mechanical preloading mechanism; 180- central through hole; 200- low frequency underwater projector; 210- front radiation head; 220- tail mass.

DETAILED DESCRIPTION OF THE INVENTION

The technical solutions of the embodiments of the present invention will be described below clearly and completely with reference to the drawings of the embodiments of the present invention. It is apparent that the embodiments to be described are some, but not all of the embodiments of the present invention. The following detailed description of the embodiments of the present invention, as represented in the figures, is not intended to limit the scope of the present invention as claimed, but is merely representative of selected embodiments of the present invention. All the other embodiments obtained by those skilled in the art based on the embodiments of the present invention without using inventive efforts would fall within the scope of the present invention as claimed.

Embodiments

Figs. 1 and 2 show a first level connector 110 provided in a preferred embodiment of the present invention, Figs. 3 and 4 show a second level connector 120 provided in a preferred embodiment of the present invention, and Fig. 5 shows partial structure of a piezoelectric actuator 100 in a preferred embodiment of the present invention. Referring to Figs. 1 to 5 for details, the piezoelectric actuator 100 provided in the embodiment of the present invention comprises a first level connector 110, a second level connector 120, and a set of first piezoelectric material columns (combination of first piezoelectric material columns 131) 130. The set of first piezoelectric material columns 130 is connected with the first level connector 110 and the second level connector 120, respectively.

The first level connector 110 comprises a set of first recesses 111, a set of first through holes 112, a set of fourth recesses 113, and a central through hole 180, referring to Fig. 1 for details, and the set of first recesses 111, the set of first through holes 112, the set of fourth recesses 113 and the central through hole 180 are all disposed at a first base 114 of the first level connector 110. The first level connector 110 may be specifically in a disc-like structure.

Each of the number of the first recesses 111, the number of the first through holes 112, and the number of the fourth recesses 113 may be three, and the first recesses 111, the first through holes 112, and the fourth recesses 113 are uniformly distributed at the first base 114 of the first level connector 110, referring to Fig. 1 for details.

The first through holes 112 run through the first level connector 110, referring to Fig. 2 for details, and the first through holes 112 running through the first level connector 110 are shown in a second base 115 of the first level connector 110 as shown in Fig. 2.

The central through hole 180 is disposed at the position of a circle center of the disc-like first level connector 110, and the central through hole 180 likewise runs through the first level connector 110, referring to Fig. 2 for details.

The second level connector 120 comprises a set of second recesses 121, a set of third recesses 122, a set of second through holes 123 and a central through hole 180, referring to Fig. 3 for details, and the set of second recesses 121, the set of third recesses 122, the set of second through holes 123 and the central through hole 180 are all disposed at a third base 124 of the second level connector 120. The second level connector 120 may be specifically in a disc-like structure.

Each of the number of the second recesses 121, the number of the third recesses 122, and the number of the second through holes 123 may also be three, and the second recesses 121, the third recesses 122, and the second through holes 123 are uniformly distributed at the third base 124 of the disc-like second level connector 120.

The second through holes 123 run through the second level connector 120, referring to Fig. 4 for details, and the second through holes 123 running through the second level connector 120 are shown in a fourth base 125 of the second level connector 120 as shown in Fig. 4.

The central through hole 180 is disposed at the position of a circle center of the disc-like second level connector 120, and the central through hole 180 likewise runs through the second level connector 120, referring to Fig. 4 for details. The set of first piezoelectric material columns 130 comprises three first piezoelectric material columns 131, referring to Fig. 5 for details.

In the partial structure of the piezoelectric actuator 100 as shown in Fig. 5, the first base 114 of the first level connector 110 is opposite to the third base 124 of the second level connector 120. The positions of the three first recesses 111 located in the first base 114 of the first level connector 110 are corresponding to the positions of the three second recesses 121 located in the third base 124 of the second level connector 120, respectively.

The positions of the three first through holes 112 located in the first level connector 110 are corresponding to the positions of the three third recesses 122 located in the third base 124 of the second level connector 120, respectively.

The positions of the three fourth recesses 113 located in the first base 114 of the first level connector 110 are corresponding to the positions of the three second through holes 123 located in the second level connector 120, respectively.

The three first piezoelectric material columns 131 are corresponding to the three first recesses 111 of the first level connector 110 respectively, that is, the set of first piezoelectric material columns 130 and the first level connector 110 are connected in a way that the first piezoelectric material columns 131 are matched with the first recesses 111. Specifically, the first piezoelectric material columns 131 may be correspondingly bonded into the first recesses 111 of the first level connector 110 by means of bonding, and one ends of the first piezoelectric material columns 131 are matched with the first recesses 111 located in the first base 114 of the first level connector 110.

The three first piezoelectric material columns 131 are corresponding to the three second recesses 121 of the second level connector 120 respectively, that is, the set of first piezoelectric material columns 130 and the second level connector 120 are connected in a way that the first piezoelectric material columns 131 are matched with the second recesses 121. Specifically, the first piezoelectric material columns 131 may be correspondingly bonded into the second recesses 121 of the second level connector 120 by means of bonding, the other ends of the first piezoelectric material columns 131 are matched with the second recesses 121 located in the third base 124 of the second level connector 120, and the first base 114 is opposite to the third base 124, referring to Fig. 5 for details.

The piezoelectric actuator 100 provided in the embodiment of the present invention further comprises a set of second piezoelectric material columns (combination of second piezoelectric material columns 141) 140 and a third set of piezoelectric material column (combination of third piezoelectric material columns 151) 150, referring to Fig. 6 for details.

In the piezoelectric actuator 100 shown in Fig. 6, the first base 114 of the first level connector 110 is opposite to the third base 124 of the second level connector 120. The positions of the three first recesses 111 located in the first base 114 of the first level connector 110 are corresponding to the positions of the three second recesses 121 located in the third base 124 of the second level connector 120, respectively.

The positions of the three first through holes 112 located in the first level connector 110 are corresponding to the positions of the three third recesses 122 located in the third base 124 of the second level connector 120, respectively.

The positions of the three fourth recesses 113 located in the first base 114 of the first level connector 110 are corresponding to the positions of the three second through holes 123 located in the second level connector 120, respectively.

The set of second piezoelectric material columns 140 comprises three second piezoelectric material columns 141, referring to Fig. 6 for details. The three second piezoelectric material columns 141 are corresponding to the three first through holes 112 of the first level connector 110, respectively, that is, the set of second piezoelectric material columns 140 and the first level connector 110 are connected in a way that the second piezoelectric material columns 141 are inserted into the first through holes 112. One ends of the second piezoelectric material columns 141 are inserted into the first through holes 112 located in the first level connector 110, and the second piezoelectric material columns 141 may penetrate through the first level connector 110 through the first through hole 112 and extend out of the second base 115 of the first level connector 110, referring to Fig. 6 for details. The second piezoelectric material columns 141 and the first level connector 110 are connected in an insertion manner so that the second piezoelectric material columns 141 are enabled to be moved or displaced relative to the first level connector 110.

The three second piezoelectric material columns 141 are corresponding to the three third recesses 122 of the second level connector 120, respectively, that is, the set of second piezoelectric material columns 140 and the second level connector 120 are connected in a way that the second piezoelectric material columns 141 are matched with the third recesses 122. Specifically, the second piezoelectric material columns 141 may be correspondingly bonded into the third recesses 122 of the second level connector 120 by means of bonding, and the other ends of the second piezoelectric material columns 141 are matched with the third recesses 122 located in the third base 124 of the second level connector 120.

The set of third piezoelectric material columns 150 comprises three third piezoelectric material columns 151, referring to Fig. 6 for details. The three third piezoelectric material columns 151 are corresponding to the three fourth recesses 113 of the first level connector 110, respectively, that is, the set of third piezoelectric material columns 150 and the first level connector 110 are connected in a way that the third piezoelectric material columns 151 are matched with the fourth recesses 113. Specifically, the third piezoelectric material columns 151 may be correspondingly bonded into the fourth recesses 113 of the first level connector 110 by means of bonding, and one ends of the third piezoelectric material columns 151 are matched with the fourth recesses 113 located in the first base 114 of the first level connector 110.

The three third piezoelectric material columns 151 are corresponding to the three second through holes 123 of the second level connector 120 respectively. That is, the set of third piezoelectric material columns 150 and the second level connector 120 are connected in a way that the third piezoelectric materials 151 are inserted into the second through holes 123. The other ends of the third piezoelectric material columns 151 are inserted into the second through holes 123 located in the second level connector 120, and the third piezoelectric material columns 151 may penetrate through the second level connector 120 through the second through holes 123 and extend out of the fourth base 125 of the second level connector 120, referring to Fig. 6 for details. The third piezoelectric material columns 151 and the second level connector 120 are connected in an insertion manner so that the third piezoelectric material columns 151 are enabled to be moved or displaced relative to the second level connector 120.

The first recesses 111 are disposed in an annular array manner, a connection line from the center of one of the first recesses 111 to the center of the said annular array is a first connection line, and angles between any two adjacent first connection lines are the same. For example, the number of the first recesses 111 is three, and an angle between any adjacent first recesses 111 is 60°, that is to say, the angle between any two adjacent first connection lines is 60°.

The third recesses 122 are disposed in an annular array manner, a connection line from the center of one of the third recesses 122 to the center of the said annular array is a third connection line, and angles between any two adjacent third connection lines are the same. For example, the number of the third recesses 122 is three, and an angle between any adjacent third recesses 122 is 60°, that is to say, the angle between any two adjacent third connection lines is 60°.

The first through holes 112 are disposed in an annular array manner, a connection line from the center of one of the first through holes 112 to the center of the annular array is a second connection line, and angles between any two adjacent second connection lines are the same. For example, the number of the first through holes 112 is three, and an angle between any adjacent first through holes 112 is 60°, that is to say, the angle between any two adjacent second connection lines is 60°.

Further, in Fig. 1, each of the first recesses 111, the first through holes 112, and the fourth recesses 113 arranged along a circumferential direction in the first level connector 110 are in an alternate deposition. Similarly, each of the second recesses 121, the third recesses 122 and the second through holes 123 in the second level connector 120 are in an alternate deposition.

The piezoelectric actuator 100 further comprises a central mechanical preloading mechanism 170, the central through hole 180 of the first level connector 110 is opposite to the central through hole 180 of the second level connector 120, and the central mechanical preloading mechanism 170 penetrates through both the central through hole 180 of the first level connector 110 and the central through hole 180 of the second level connector 120, referring to Fig. 9 for details.

The piezoelectric actuator 100 provided in the embodiment of the present invention comprises a first level connector 110, a second level connector 120, first piezoelectric material columns 131, second piezoelectric material columns 141, third piezoelectric material columns 151, and a central mechanical preloading mechanism 170, wherein the first piezoelectric material columns 131 are connected with both the first level connector 110 and the second level connector 120 by being matched with the recesses; the second piezoelectric material columns 141 penetrate through the first level connector 110 and are connected with the second level connector by being matched with the recesses; and the third piezoelectric material columns 151 are connected with the first level connector 110 by being matched with the recesses, and penetrate through the second level connector 120. The central mechanical preloading mechanism 170 penetrates through the first level connector 110 and the second level connector 120.

By excitation at an appropriate AC voltage, the second piezoelectric material columns 141 and the third piezoelectric material columns 151 extend (i.e., the set of second piezoelectric material columns 140 and the set of third piezoelectric material columns 150 extend), while the first piezoelectric material columns 131 are contracted (i.e., when the set of first piezoelectric material columns 130 is contracted); or the second piezoelectric material columns 141 and the third piezoelectric material columns 151 are contracted (i.e., the set of second piezoelectric material columns 140 and the set of third piezoelectric material columns 150 are contracted), while the first piezoelectric material columns 131 extend (i.e., when the set of first piezoelectric material columns 130 extends); and as a result, the axial displacements of the respective sets of material columns are superimposed on each other to achieve a greater axial displacement. And, since each of the number of the first piezoelectric material columns 131, the number of the second piezoelectric material columns 141, and the number of the third piezoelectric material columns 151 is three, the connection of the piezoelectric material columns with the first level connector 110 or the second level connector 120 will be more firm, and a failure of the piezoelectric actuator 100 caused by a vibration or shock load does not occur easily.

Referring to the schematic view shown in Fig. 7, as a schematic view, the displacement of each part is enlarged in Fig. 7, and in a practical case the displacement may not be so obvious, wherein the dashed lines at left and right sides serve as auxiliary lines to facilitate the observation of a change in displacement of each part.

The piezoelectric actuator 100 in an upper portion of Fig. 7 is in an unactivated state, and the piezoelectric actuator 100 in a lower portion of Fig. 7 is in an activated state. In both states, the position of the first level connector 110 is unchanged. The position of the first level connector 110 and the above-mentioned two auxiliary lines are used as a reference. When it is converted from the unactivated state to the activated state, the first piezoelectric material columns 131 are contracted and generate a displacement D1, the second piezoelectric material columns 141 extend and generate a displacement D2, and the third piezoelectric material columns 151 extend and generate a displacement D3. Compared to the piezoelectric actuator 100 in the unactivated state, the total displacement of the piezoelectric actuator 100 in the activated state is a sum of the displacements of the first piezoelectric material columns 131, the second piezoelectric material columns 141 and the third piezoelectric material columns 151, i.e., D1+D2+D3.

The first piezoelectric material columns 131, the second piezoelectric material columns 141, and the third piezoelectric material columns 151 may be all cylindrical piezoelectric material columns. Further, the respective cross sections of the piezoelectric material columns perpendicular to the axis line may be the same. The number of the first piezoelectric material columns 131, the number of the second piezoelectric material columns 141, and the number of the third piezoelectric material columns 151 may be adjusted according to different applications.

The cylindrical piezoelectric material columns may be each composed of a piezoelectric ceramic stack, wherein the piezoelectric ceramic includes lead zirconate titanate piezoelectric ceramic (piezoelectric ceramic transducer, PZT) and materials derived therefrom.

The first piezoelectric material columns 131, the second piezoelectric material columns 141, and the third piezoelectric material columns 151 each may also be constituted by a radially polarized piezoelectric ceramic tube, a single piezoelectric crystal or bonded piezoelectric single crystal active elements.

Further, the first level connector 110 and the second level connector 120 are made of a lightweight, high-strength metal or alloy, including, but not limited to, an aluminum alloy, a magnesium alloy, a titanium alloy, an aluminum beryllium alloy, and aluminum-based or magnesium-based composite. The simulation experiment showed that if the material of the first level connector 110 and the second level connector 120 is an aluminum alloy, and the first piezoelectric material columns 131, the second piezoelectric material columns 141, and the third piezoelectric material columns 151 are each made of a PZT piezoelectric ceramic stack, the bending displacement of the first level connector 110 and the second level connector 120 is about five percent of the total axial displacement of the piezoelectric actuator 100.

The first level connector 110 and the second level connector 120 may be disc-shaped, have a certain thickness, and may be specifically approximated to a short cylindrical level connector. The short cylindrical structure contributes to ensuring the reliable connection of the above-mentioned piezoelectric material columns with the recesses, so that the first level connector 110 and the second level connector 120 are not easily bent or deformed in operation.

The central mechanical preloading mechanism 170 of the piezoelectric actuator 100 provided in the embodiment of the present invention is configured to apply compressive stress to the first set of piezoelectric material column 130, the second set of piezoelectric material column 140 and the third set of piezoelectric material column 150 so that the above-mentioned piezoelectric actuator 100 is operated under the action of the compressive stress.

Referring to Fig. 8 for details, Fig. 8 shows a low frequency underwater projector 200 provided in an embodiment of the present invention. The low frequency underwater projector 200 is driven by the piezoelectric actuator 100 as described above. The low frequency underwater projector 200 further comprises a front radiation head 210 and a tail mass 220, the second piezoelectric material columns 141 of the piezoelectric actuator 100 are connected with the front radiation head 210, the third piezoelectric material columns 151 of the piezoelectric actuator 100 are connected with the tail mass 220, and preload force is provided to the piezoelectric actuator 100 by the central mechanical preloading mechanism 170.

The resonant frequency of the low frequency underwater projector 200 as shown in Fig. 8 is the lowest value of the coupled resonance of the respective parts, i.e., the front radiation head 210, the first level connector 110, the second level connector 120, the first set of piezoelectric material column 130, the second set of piezoelectric material column 140, the third set of piezoelectric material column 150, the tail mass 220, and the central mechanical preloading mechanism 170 as a whole. The low frequency underwater projector 200 can effectively utilize the multimode coupled resonance to expand the operating frequency band.

Referring to Fig. 10 for details, Fig. 10 shows a piezoelectric actuator 100 provided in another preferred embodiment of the present invention, and the piezoelectric actuator 100 shown in Fig. 10 is distinguished from the piezoelectric actuator 100 shown in Fig. 6 in that the first piezoelectric material columns 131, the second piezoelectric material columns 141, and the third piezoelectric material columns 151 of the piezoelectric actuator 100 shown in Fig. 10 are each of a rectangular parallelepiped structure, and the materials of the set of first piezoelectric material columns 130, the set of second piezoelectric material columns 140, and the set of third piezoelectric material columns 150 are lead-based relaxor ferroelectric single crystals.

Specifically, each of the rectangular parallelepiped material columns may comprise a first single crystal active element 161 and a second single crystal active element 162, the size of the first single crystal active element 161 is the same as that of the second single crystal active element 162, and the first crystal active element 161 and the second single crystal active element 162 are connected by bonding, referring to Fig. 10 for details.

The transverse piezoelectric properties of the lead-based relaxor ferroelectric single crystals are more excellent. The lead-based relaxor ferroelectric single crystals may specifically include $Pb(Zn_{1/3}Nb_{2/3})O_3\text{-}PbTiO_3$, $Pb(Mg_{1/3}Nb_{2/3})O_3\text{-}PbTiO_3$, $Pb(In_{1/2}Nb_{1/2})O_3\text{-}Pb(Mg_{1/3}Nb_{2/3})O_3\text{-}PbTiO_3$, $Pb(Mg_{1/3}Nb_{2/3})O_3\text{-}Pb(Zr_{0.48}Ti_{0.52})O_3$, and materials derived therefrom.

Referring to Fig. 11 for details, Fig. 11 shows a low frequency underwater projector 200 driven by the piezoelectric actuator 100 shown in Fig. 10. The low frequency underwater projector 200 shown in Fig. 11 is distinguished from the low frequency underwater projector 200 shown in Fig. 8 in that the piezoelectric actuator 100 of the low frequency underwater projector 200 shown in Fig. 11 is different from the piezoelectric actuator 100 of the low frequency underwater projector 200 shown in Fig. 8. The center frequency of the same-size underwater projector made from PZN-5.5% PT d_{32} transverse mode single crystal slices polarized in the [011] direction is 1/4 lower than that of one driven by PZT piezoelectric ceramic stacks.

It is possible to select conductive epoxy and nonconductive epoxy, as desired, to bond the first level connector 110 and the corresponding piezoelectric material columns, and bond the second level connector 120 and the corresponding piezoelectric material columns.

Further, the low frequency underwater projector 200 further comprises a first pre-stress mechanism. The first pre-stress mechanism is connected with the first level connector 110 and the second level connector 120, and the first pre-stress mechanism is configured to apply pre-stress to the first level connector 110 and the second level connector 120 so that the first piezoelectric material columns 131 are under predetermined compressive stress during operation.

Optionally, the first level connector 110 further comprises a central through hole located in the first level connector 110, and the second level connector 120 further comprises a central through hole located in the second level connector 120. The first pre-stress mechanism comprises a first stress rod, at least one first resilient member and at least one first locking member. Optionally, the resilient member is provided with at least one locking member. Both ends of the first stress rod pass through the central through holes corresponding to the first level connector 110 and the second level connector 120, respectively. When there is one first resilient member the first resilient member, between the first level connector 110 and the first locking member or between the second level connector 120 and the first locking member, are pressed by the first level connector 110 and the first locking member or by the second level connector 120 and the first locking member. when there are two first resilient members, one of the two first resilient members is located between and pressed by the first level connector 110 and one first locking member, and the other is located between and pressed by the second level connector and another first locking member. The first resilient member may be embodied as a spring washer or a disc spring. The first locking member may be embodied as a locking nut and be in threaded connection with the end of the first stress rod.

Further, the low frequency underwater projector 200 further comprises a second pre-stress mechanism, the second pre-stress mechanism is connected with the front radiation head 210 and the tail mass 220, and the second pre-stress mechanism is configured to apply pre-stress to the front radiation head 210 and the tail mass 220 so that the second piezoelectric material columns 141 and the third piezoelectric material columns 151 are under predetermined compressive stress during operation.

Optionally, the second pre-stress mechanism comprises a second stress rod and at least one second resilient member. The first stress rod has a central through hole running along its own length direction, and the second stress rod is movably embedded in the central through hole of the first stress rod and has both ends extending beyond the central through hole. At least one end of the second stress rod is connected with the front radiation head 210 and/or the tail mass 220 through the second resilient members, respectively, so as to apply predetermined compressive stress to the second piezoelectric material columns 141 and the third piezoelectric material columns 151 during operation. That is, when there is one second resilient member, one end of the second stress rod is connected with the front radiation head through the second resilient member, or one end of the second stress rod is connected with the tail mass through the second resilient member. When there are two second resilient members, two ends of the second stress rod are connected with the front radiation head and the tail mass through the two second resilient members.

The first pre-stress mechanism applies compressive stress F1 to the first piezoelectric material columns 131. The front radiation head 210 is connected with the second level connector 120 through the second piezoelectric material columns 141, and the tail mass 220 is connected with the first level connector 110 through the third piezoelectric material columns 151. Therefore, when the second pre-stress mechanism provides preset compressive stress F2 to the front radiation head 210 and the tail mass 220, the second pre-stress mechanism simultaneously applies tensile stress F2 (opposite to the direction of the compressive stress F1) to the first piezoelectric material columns 131 connected between the first level connector 110 and the second level connector 120.

Thus, optionally, the compressive stress applied by the first pre-stress mechanism is at least 2 times the compressive stress applied by the second pre-stress mechanism. This will ensure that the set of first piezoelectric material columns 130, the set of second piezoelectric material columns 140, the set of third piezoelectric material columns 150, and various related connections on the material columns of the embodiment of the present invention are always operated under predetermined compressive stress. The second resilient member may be a combination of a spring washer and a locking structure.

It should be noted that the first pre-stress mechanism and the second pre-stress mechanism may be of other structures. For example, a set of first stress rods (equipped with suitable spring washers and locking structures) are disposed, and the set of first stress rods are arranged uniformly along the circumferential directions of the first level connector 110 and the second level connector 120, so as to apply a pre-pressure to the first level connector 110, the second level connector 120, and the first piezoelectric material columns 131.

Optionally, an anti-bending guide means is further comprised, and the guide means and the piezoelectric actuator 100 are movably connected in the direction of extending and contraction of the piezoelectric actuator 100 and connected in a direction perpendicular to the extending and contraction direction.

Further, a housing may be added, which has an inner cavity, and the piezoelectric actuator 100 is disposed in the inner cavity of the housing so that the housing protects the various components of the piezoelectric actuator 100.

The piezoelectric actuator 100 and the low frequency underwater projector 200 provided in the embodiments of the present invention comprise a first level connector 110, a second level connector 120 and a set of first piezoelectric material columns 130. One ends of the first piezoelectric material columns 131 are matched with a set of first recesses 111 located in the first level connector 110, and the other ends of the first piezoelectric material columns 131 are matched with a set of second recesses 121 located in the second level connector 120. The first piezoelectric material columns 131 are contracted or extend to drive the displacement of the first level connector 110 and the second level connector 120. Moreover, the displacements of the second piezoelectric material columns 141 and the third piezoelectric material columns 151 may be superimposed with the displacements of the first level connector 110 and the second level connector 120.

The axial displacements of the piezoelectric materials can be superimposed and increased by excitation at an appropriate AC voltage, thus the sound power capacity of the low frequency underwater projector 200 using the piezoelectric actuator 100 as a driving mechanism is increased. The piezoelectric actuator 100 and the low frequency underwater projector 200 provided in the embodiments of the present invention improve the problem of the limited sound power capacity of the existing low frequency underwater projectors 200.

In order to make the objects, technical solutions and advantages of the embodiments of the present invention more clear, the technical solutions of the embodiments of the present invention have been described above clearly and completely with reference to the drawings of the embodiments of the present invention. It is apparent that the embodiments described are some, but not all of the embodiments of the present invention. Generally, the components of the embodiments of the present invention, as described and illustrated in the figures herein, may be arranged and designed in a wide variety of different configurations.

Thus, the above detailed description of the embodiments of the present invention, as represented in the figures, is not intended to limit the scope of the present invention as claimed, but is merely representative of selected embodiments of the present invention. All the other embodiments obtained by those skilled in the art based on the embodiments of the present invention without inventive efforts would fall within the scope of the present invention as claimed.

It should be noted that similar reference numerals and letters refer to similar items in the following figures, and thus once an item is defined in one figure, it may not be further defined or explained in the following figures.

In the description of the present invention, it should be indicated that the indicated orientation or positional relations are based on the orientation or positional relations as shown in the drawings, or the orientation or positional relations in which the inventive product is conventionally placed in use, and are intended only to facilitate the description of the present invention and simplify the description, but not intended to indicate or imply that the referred devices or elements must be in a particular orientation or constructed or operated in the particular orientation, and therefore should not be construed as limiting the present invention.

In the description of the present invention, it should also be indicated that unless otherwise expressly specified or defined, terms "coupled" and "connected" should be understood broadly. For example, connection may be fixed connection or detachable connection or integral connection, or may be direct coupling or indirect coupling via an intermediate medium or internal communication between two elements. The specific meanings of the above-mentioned terms in the present invention could be understood by those skilled in the art according to specific situations.

Industrial Applicability: in use of the piezoelectric actuator 100 and the low frequency underwater projector 200 of the present invention obtained by the above-mentioned design, the axial displacements of the piezoelectric materials can be superimposed and increased by excitation at an appropriate voltage, and thus the sound power capacity of the low frequency underwater projector 200 using the piezoelectric actuator 100 as a driving mechanism is increased. The piezoelectric actuator 100 and the low frequency underwater projector 200 of the present invention obtained by the above-mentioned design can improve the problem of the limited sound power capacity of the existing low frequency underwater projectors 200 and are suitable for widespread use in industries.

Claims:

1. A piezoelectric actuator, characterized by comprising a first level connector, a second level connector disposed opposite to the first level connector, a set of first piezoelectric material columns, a set of second piezoelectric material columns, and a set of third piezoelectric material columns,

   wherein the first level connector and the second level connector are both of disc-shaped and of a certain thickness such that they are sufficiently rigid;

   wherein the numbers of piezoelectric material columns in the first, second and third sets of piezoelectric material columns are the same; each set has three piezoelectric material columns;

   wherein the three first piezoelectric material columns are spaced at equal angular separation along a circumferential line of the first and second level connectors and both ends of each of the first piezoelectric material columns are connected with the first level connector and the second level connector, respectively;

   wherein the three second piezoelectric material columns are spaced at equal angular separation along a circumferential line of the first and second level connectors and each of the second piezoelectric material columns has one end connected with the second level connector and another end passing through three equally spaced through holes in the first level connector in a direction away from the second level connector so that the three second piezoelectric material columns and the second level connector are able to displace relative to the first level connector;

   wherein the three third piezoelectric material columns are spaced at equal angular separation along a circumferential line of the first and second level connectors and each of the third piezoelectric material columns has one end connected with the first level connector and another end passing through three equally spaced holes in the second level connector in a direction away from the first level connector so that the three third piezoelectric material columns and the first level connector are able to displace relative to the second level connector;

   wherein recesses are provided on opposite surfaces of the first level connector and the second level connector at locations where the first, second and third piezoelectric material columns are connected and the first, second and third piezoelectric material columns are bonded into the corresponding recesses; and

   wherein during operation, the first piezoelectric material columns contract while the second and third piezoelectric material columns extend, or vice versa, so that axial displacements of the three sets of piezoelectric material columns add up to produce a larger overall displacement of the actuator.

2. The piezoelectric actuator according to claim 1, wherein the first and second level connectors further comprise a central through hole respectively and both central through holes match one another in position.

3. The piezoelectric actuator according to claim 2, further comprising a first pre-stress mechanism which includes a first stress rod which passes through the central through holes in the first level connector and the second level connector, at least one first resilient member and at least one first locking member, such that the first pre-stress mechanism applies a compressive force to the first level connector and the second level connector to place the first piezoelectric material columns under predetermined compressive stress during operation.

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4. The piezoelectric actuator according to any one of claims 1 to 3, wherein the first, second and third piezoelectric material columns are each a piezoceramic stack of a suitable cross-section, a piezoceramic of rectangular or parallelepiped shape, or a radially polarized piezoceramic tube, wherein the piezoceramics include lead zirconate titanate [$Pb(Zr_xTi_{1-x})O_3$] piezoceramics and materials derived therefrom.

5. The piezoelectric actuator according to any one of claims 1 to 3, wherein the first, second and third piezoelectric material columns are each a rectangular shaped piezoelectric single crystal or bonded piezoelectric single crystals comprising $Pb(Zn_{1/3}Nb_{2/3})O_3$-$PbTiO_3$, $Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$, $Pb(In_{1/2}Nb_{1/2})O_3$-$Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$, $Pb(Mg_{1/3}Nb_{2/3})O_3$-$Pb(Zr_{0.48}Ti_{0.52})O_3$, and materials derived therefrom.

6. The piezoelectric actuator according to any one of claims 1 to 5, wherein the first level connector and the second level connector are made of a lightweight, high-strength metal or alloy, including but not limited to, an aluminum alloy, a magnesium alloy, a titanium alloy, an aluminum beryllium alloy, and aluminum-based or magnesium-based composite.

7. The piezoelectric actuator according to any one of claims 1 to 6, wherein the number of first piezoelectric material columns, the number of second piezoelectric material columns, and the number of third piezoelectric material columns are adjustable and the number of through holes and recesses in the first level connector and the second level connector are adjusted correspondingly.

8. The piezoelectric actuator according to any one of claims 1 to 7, further comprising a housing, wherein the housing has an inner cavity, and the piezoelectric actuator is disposed in the inner cavity of the housing so that the housing protects the various components of the piezoelectric actuator.

9. A low frequency underwater projector, characterized in that the low frequency underwater projector comprises a piezoelectric actuator as claimed in claim 1 or 2, and further comprises a front radiation head and a tail mass, wherein the other ends of the second piezoelectric material columns are connected with the front radiation head, and the other ends of the third piezoelectric material columns are connected with the tail mass.

10. The low frequency underwater projector according to claim 9, further comprising a first pre-stress mechanism and a second pre-stress mechanism,

    wherein said first pre-stress mechanism is configured to apply pre-determined compressive stress onto the first piezoelectric material columns,

    wherein said second pre-stress mechanism is configured to apply pre-determined compressive stress to the second and third piezoelectric material columns, and

    wherein the compressive stress exerted by the first pre-stress mechanism is larger than that exerted by the second pre-stress mechanism, such that the first, second and third piezoelectric material columns are all placed under compression during operation.

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11. The low frequency underwater projector according to claim 10,

wherein the first pre-stress mechanism comprises a set of stress rods, suitable spring washers and locking structures; wherein the set of the first stress rods are arranged uniformly along a circumferential length of the first level connector and the second level connector and apply a compressive force to the first level connector and the second level connector to place the first piezoelectric material columns under predetermined compressive stress;

wherein the second pre-stress mechanism comprises a second stress rod, at least one second resilient member and at least one second locking member, wherein one end of the second pre-stress rod is connected to the front radiation head and the other to the tail mass to enable the application of pre-determined compressive stress onto the second and third piezoelectric material columns under compression; and

wherein the compressive force exerted by the first pre-stress mechanism is larger than that exerted by the second pre-stress mechanism, such that the first, second and third piezoelectric material columns are all placed under compression during operation.

12. The low frequency underwater projector according to claim 9, further comprising a first pre-stress mechanism and a second pre-stress mechanism,

wherein the first pre-stress mechanism consists of a first stress rod with a central through hole, at least one first resilient member and at least one first locking member; wherein said first stress rod passes through the central through holes in the first level connector and the second level connector and applies a compressive force to the first level connector and the second level connector to place the first piezoelectric material columns under predetermined compressive stress;

wherein the second pre-stress mechanism comprises a second stress rod, at least one second resilient member and at least one second locking member; wherein the second stress rod passes through the central through hole in the first stress rod, one end of the second stress rod being connected to the front radiation head and the other end to the tail mass to enable the application of pre-determined compressive stress onto the second and the third piezoelectric material columns; and

wherein the compressive force exerted by the first pre-stress mechanism onto the first piezoelectric material columns is larger than that exerted by the second pre-stress mechanism onto the second and third piezoelectric material columns, such that the first, second and third piezoelectric material columns are all placed under compression during operation.

13. The low frequency underwater projector according to any one of claims 9 to 12, further comprising an anti-bending guide means which allows the piezoelectric actuator to move freely in its axial direction but with restricted side-way movement.

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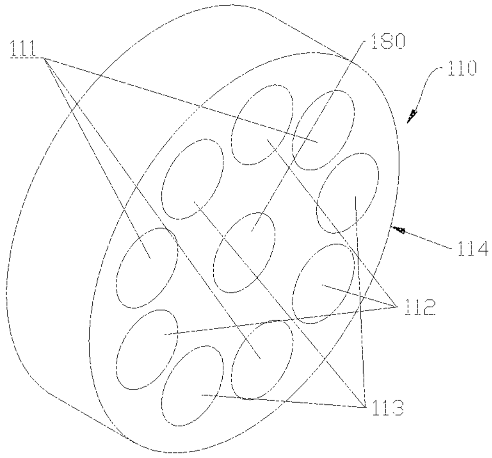


Fig. 1

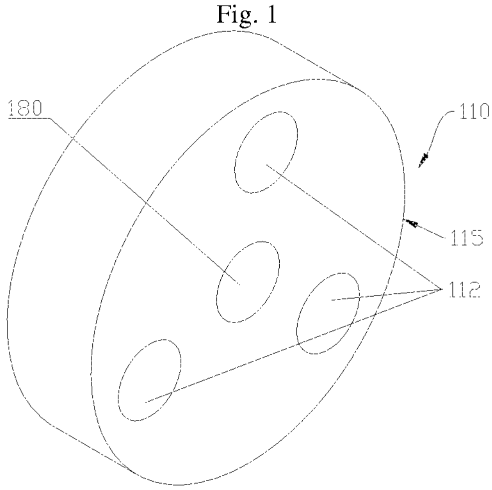


Fig. 2

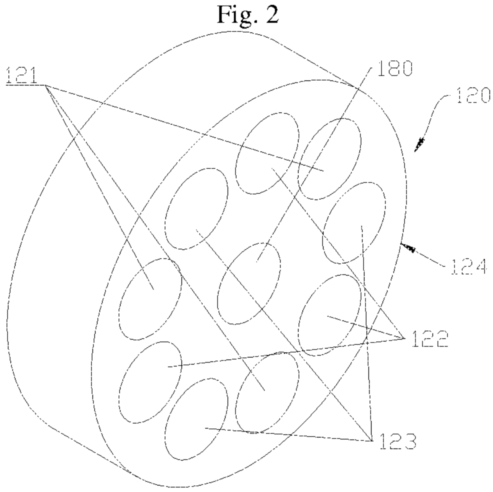


Fig. 3

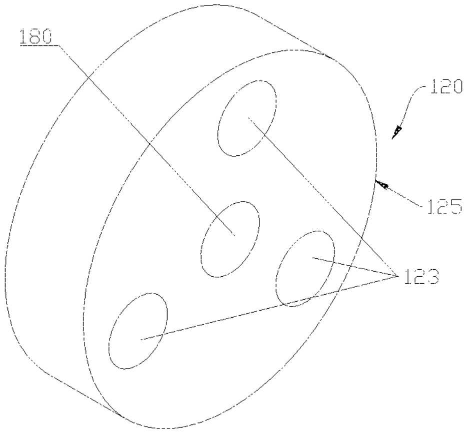


Fig. 4

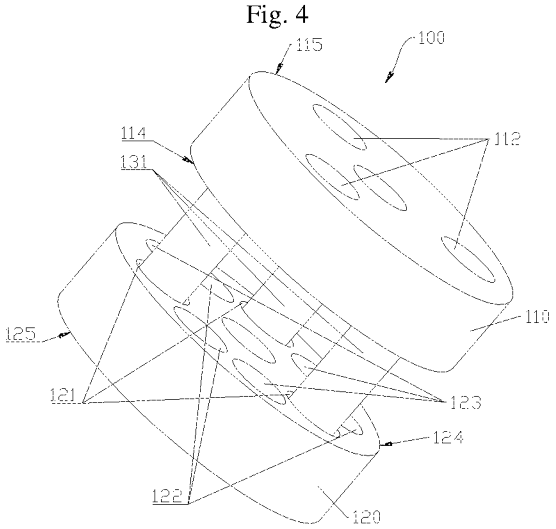


Fig. 5

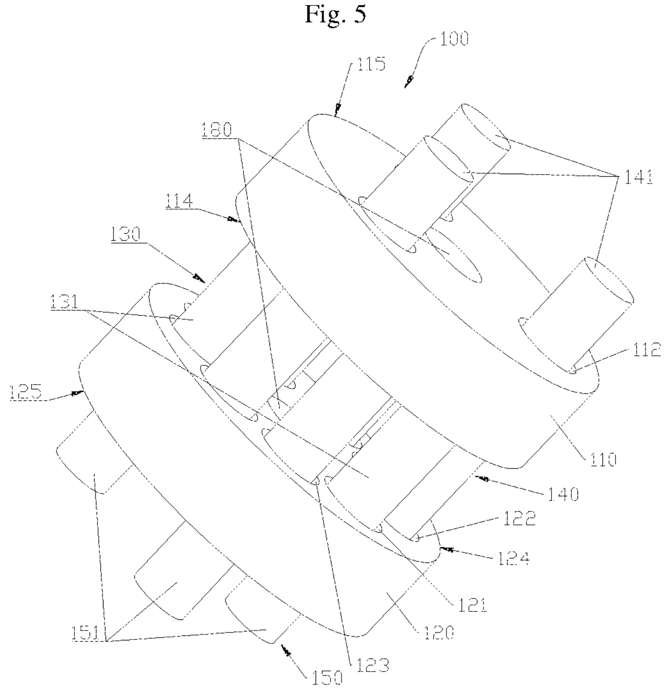


Fig. 6

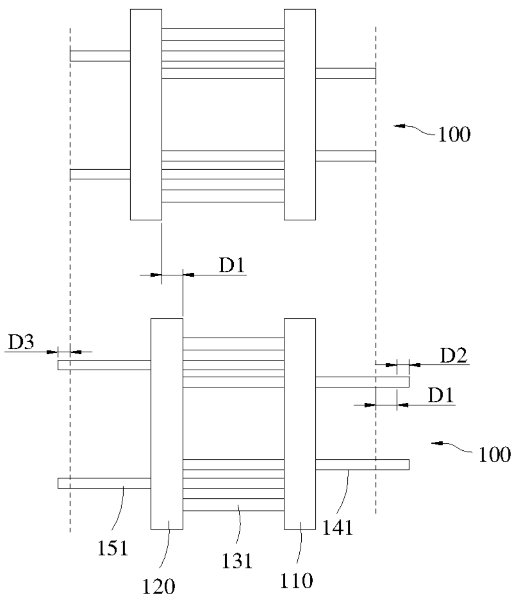


Fig. 7

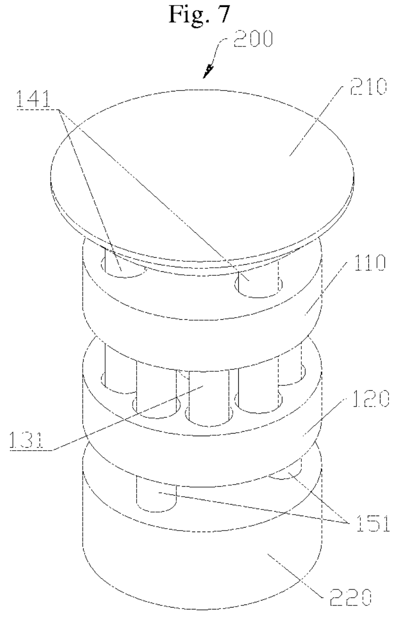


Fig. 8

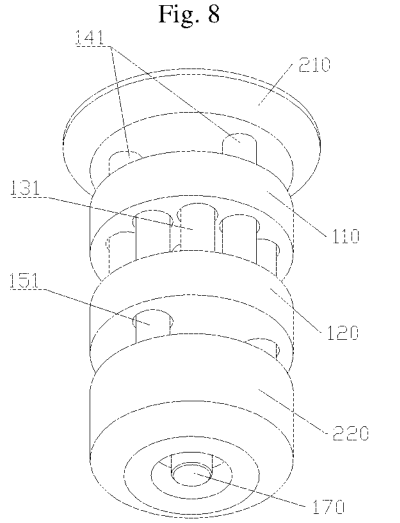


Fig. 9

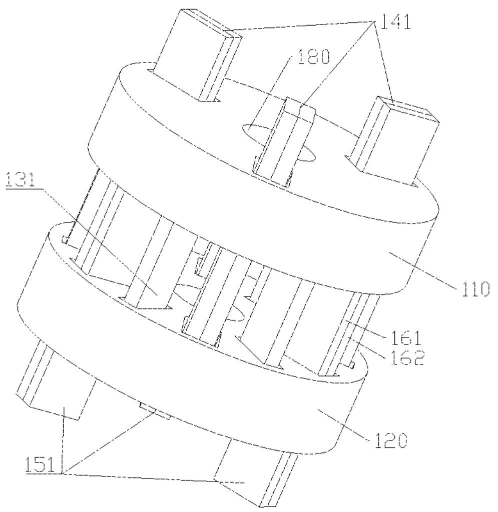


Fig. 10

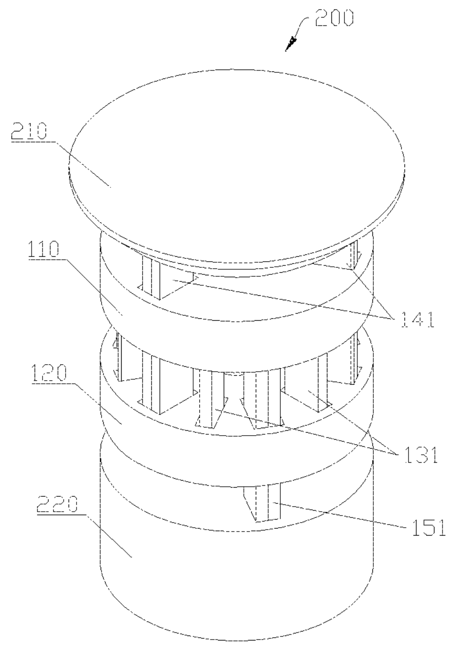
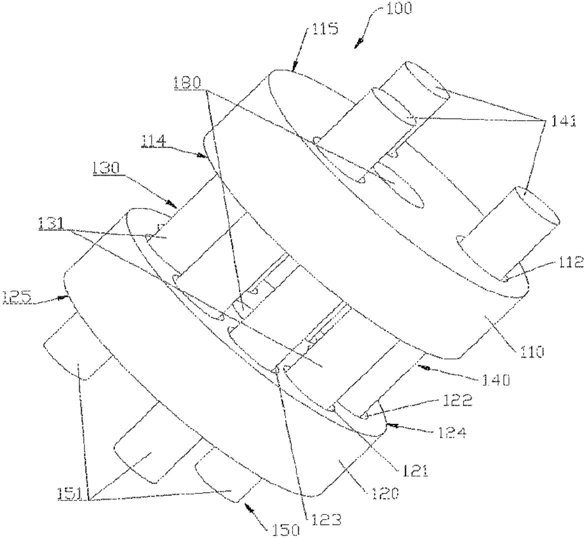


Fig. 11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