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TITLE

Transversal Mode Piezoelectric Actuator

FIELD OF THE INVENTION

The present invention relates to a transversal mode piezoelectric actuator, as well  
5 as a method for forming the same.

BACKGROUND ART

Piezoelectric actuators are solid state devices which, when driven by an electric field, produce a small but accurate displacement with a large force. Compared with electromagnetic actuators, piezoelectric actuators are more compact in size,  
10 consume less power, generate less heat and have faster response times. As a result, piezoelectric actuators are widely used in precise machinery, and optical and biological applications.

There are three basic types of piezoelectric ceramic actuators currently available. The first type is a single piezoelectric ceramic bar, the second type is a biomorph  
15 structure composed of two piezoelectric plates, and the third type is a multilayer piezoelectric actuator containing a plurality of piezoelectric plates. These three types of actuators operate in different displacement modes and have different characteristics. The first type is referred to as a "transversal mode" relative to the  $d_{31}$  piezoelectric coefficient, the second type is referred to as a "bending mode"  
20 relative to the  $d_{31}$  piezoelectric coefficient, and the third type is referred to as a "longitudinal mode" with respect to the  $d_{33}$  piezoelectric coefficient.

Fabrication of the first type of actuator, the transversal mode piezoelectric actuator, is relatively simple. Two electrodes are prepared on parallel surfaces of the bar, perpendicular to the desired displacement direction. Then, an electric  
25 field is applied to the electrodes to pole the bar to be piezoelectric responsive.

After poling, a piezoelectric actuator showing the converse piezoelectric effect is obtained. That is, an applied electric field results in the bar extending or contracting in a transverse direction to the applied field, parallel to the electrode surface. However, at present, the bar has a minimum thickness imposed by  
5 limitations in ceramics processing technology, and also the required strength of the actuator. As a result, the applied voltage required for this type of actuator is very high.

Construction of the third type of actuator, the multilayer piezoelectric actuator operating in a longitudinal mode, is more complex. It is formed by laminating  
10 many piezoelectric plates, where each piezoelectric plate has electrodes on both surfaces. The top and bottom plates of the actuator act as protective layers, being thicker than the inner piezoelectric plates to provide the required strength. The outer two surfaces of the actuator act as insulators and are not covered by metal electrodes. The electrodes provided between adjacent piezoelectric plates,  
15 referred to as the internal electrodes, are generally arranged in an inter-digital arrangement when viewed in cross-section. The internal electrodes are each connected to one of two external electrodes, with adjacent internal electrodes being connected to different external electrodes, such that the polarisation direction of each two adjacent piezoelectric plates is opposite. In this way, an  
20 applied electric field results in each piezoelectric plate extending or contracting in a direction longitudinal to the applied electric field. As a result, the displacement of the actuator is enhanced by the number of piezoelectric plates.

Initially, fabrication was achieved by bonding together several poled piezoelectric plates using an epoxy. However, actuators made by this method still require a  
25 high driving voltage, because it is difficult to make piezoelectric plates thin enough by normal ceramic processing. In addition, defects such as mechanical creep and serious delimitation may exist in the actuator due to the bond of the epoxy.

More recently, improved fabrication techniques for longitudinal mode monolithic multilayer piezoelectric actuators (LM-MMPA) have become available, which are based on the tape-casting method and co-firing technology for ceramics and internal metal electrodes. Examples of this technique are described in US  
5 Patents 5,507,898 and 5,245,743.

The fabrication process using the tape-casting method for the LM-MMPA is as follows. Piezoelectric powders with some organic binders, plasticizer and solvent are milled into a slurry. The slurry is then cast onto a green sheet on a running organic film. After drying, the green sheet is stripped and punched into  
10 appropriate sizes. The internal electrodes are then printed on one surface of the green sheet. These green sheets with electrodes are laminated and pressed together into a body, where the interdigital internal electrode arrangement is adopted. After cofiring the body at high temperature, a monolithic body with a multilayer structure is achieved. Two external electrodes are connected to the  
15 interdigital internal electrodes in an alternating manner. The body is then poled at high temperature. The LM-MMPA is then ready for testing.

Recent references about modified structures for piezoelectric actuators appeared in the following papers:

- Chen Liang et al., Smart Mater.Struct., vol.5, pp. 171-186, 1996;
- 20 • Seigo Hayashi, Jpn. J. Appl. Phys., vol.30, pp. 2285-2288, 1991;
- Pilgrim.S. W et al., Ferroelectrics vol. 160, 305-316, 1994;
- M. Marutake and M. Yokosuka, Jpn. J. Appl. Phys., vol 34 pp. 5284-5287, 1995;
- Robert G. L., Smart. Mater. Struct. Vol.6, R1PR42, 1997;
- 25 • Xu Q. C. et al., Ferroelectrics Vol. 160, pp.337-346, 1994.

Notwithstanding the above advancements in manufacturing processors for LM-MMPA, transversal mode piezoelectric actuators still utilise a single piezoelectric bar, and hence still require a high driving voltage. If the bar thickness is reduced to decrease the driving voltage, the strength and driving force of the actuator is  
5 also reduced.

An object of this invention is to provide a transversal mode piezoelectric actuator, and a method of producing the same, to overcome or at least reduce the effects of the shortcomings described above.

### SUMMARY OF THE INVENTION

10 In accordance with one aspect of this invention, there is provided a transversal mode piezoelectric actuator, comprising: a plurality of layers of piezoelectric material arranged in a laminated manner to define a body having end surfaces and upper and lower surfaces; an electrode provided between each pair of adjacent layers and on the upper surface and lower surface of the body; adjacent  
15 electrodes arranged to produce an electric field therebetween; a protective layer provided on at least one end of the body; and a layer of elastic material provided on the upper and lower surfaces of the body.

Preferably, there are an even number of layers of piezoelectric material.

Preferably, said layers of piezoelectric material are formed from an electrostrictive  
20 material.

Preferably, said piezoelectric material is either PZN-PZ-PT or PBNN.

Preferably, said electrodes are formed from Ag-Pd-Au or Ag-Pd for the piezoelectric materials PZN-PZ-PT and PBNN, respectively.

Preferably, said electrodes provided on the upper and lower surfaces of the body  
25 are formed from Ag.

Preferably, the electrodes are provided in an interdigital arrangement with adjacent electrodes extending to opposing ends of the body.

Preferably, the electrodes at each end are connected to a common electrical potential.

- 5 Preferably, electrodes on the upper and lower surfaces of the body are connected to electrodes at one end of the body. More preferably, said one end corresponds with the displacement surface of the actuator.

Preferably, said protective layer is formed from a rigid material. More preferably, said rigid material is a ceramics material.

- 10 Preferably, a protective layer is provided on both ends of the body.

Preferably, said layer of elastic material is formed on all surfaces of the body other than the ends thereof.

Preferably, said layer of elastic material is formed from an insulating material.

Preferably, said elastic material is silicon rubber that is solid at room temperature.

- 15 In accordance with a further aspect of this invention, there is provided a method for producing a transversal mode piezoelectric actuator, comprising the steps of:

producing a plurality of layers of piezoelectric material and providing an electrode on one surface of each layer;

arranging said layers in a laminated manner;

- 20 cofiring said layers to form a monolithic body;

providing electrodes on the upper and lower surfaces of the body;

providing a layer of elastic material on the upper and lower surfaces of the body to cover the electrodes;

providing a protective layer on the ends of the body.

Preferably, the plurality of layers are produced using a tape-casting process.

- 5 Preferably, said step of arranging the plurality of layers of piezoelectric material includes the step of providing a layer of piezoelectric material without an electrode provided thereon, whereby the upper and lower surfaces of the body do not have electrodes thereon during the step of cofiring.

- 10 Preferably, before cofiring, said laminated layers are cut into appropriate sizes at a temperature of 50-100° C.

Preferably, said layers of material are formed from PZN-PZ-PT and said electrodes are formed of Ag-Pd-Au, said step of cofiring being performed at a temperature of substantially 1270°C.

- 15 Alternatively, said layers of material are formed from PBNN, and said electrodes are formed of Ag-Pd and said step of cofiring is performed at a temperature of substantially 1140°C.

Preferably, said step of providing electrodes on upper and lower surfaces of the body includes the steps of providing an Ag paste on said upper and lower surfaces and firing at 650°C.

- 20 Preferably, the step of providing electrodes further includes the step of providing Ag paste on the ends of the body to form external electrodes upon firing.

Preferably, the electrodes on the upper and lower surfaces are connected to the external electrode on one end of the body.

Preferably, the electrodes are arranged in an inter-digital form, with adjacent electrodes extending to opposite ends of the body.

Preferably, said method further includes the step of poling said body, comprising the steps of connecting the electrodes on the upper and lower surface and the  
5 external electrode connected therewith to the earth of an electrical source, and connecting the other external electrode to the positive output of said electrical source.

Preferably, the step of poling occurs after the step of providing the protective layer and the layer of elastic material.

10 Preferably, the step of providing the layer of elastic material comprises providing said layer on all surfaces other than the ends of the body.

Preferably, electrostrictive material is used in place of piezoelectric material.

#### BRIEF DESCRIPTION OF THE DRAWINGS

The invention will be described with reference to the following drawings, in which:

15 Figure 1 is a cross-section view of a prior art longitudinal mode monolithic multilayer piezoelectric actuator; and

Figure 2 is a cross-section view of a transversal mode monolithic multilayer piezoelectric actuator in accordance with the present invention.

#### DETAILED DESCRIPTION OF THE DRAWINGS

20 Figure 1 shows a longitudinal mode monolithic multilayer piezoelectric actuator (LM-MMPA).

The piezoelectric actuator 10 of the prior art comprises piezoelectric layers 12 arranged in a laminated manner with internal electrodes 14 provided between adjacent piezoelectric layers 12. The piezoelectric layers 12 are provided between inactive layers 16A and 16B. The inactive layers 16A and 16B are  
5 relatively thick compared with the piezoelectric layers 12. The inactive layers 16A and 16B do not contribute to the displacement of the actuator 10, but are simply there to protect the piezoelectric layers 12 from damage. The inactive layers 16A and 16B are typically formed from an insulating, hard material such as ceramics.

External electrodes 18A and 18B are provided at each side of the piezoelectric  
10 layers 12. The internal electrodes 14 are arranged in an inter-digital manner as shown in the drawing, with adjacent electrodes 14 being connected to opposing external electrodes 18A and 18B in an alternating manner. An insulating layer 20A and 20B is formed over the external electrode 18A and 18B, respectively.

When an electric field is applied to the piezoelectric layers 12 via the electrodes  
15 18A, 18B and 14, each piezoelectric layer 12 extends or contracts in a longitudinal direction relative to the electric field as shown by the arrow 'A'. The total displacement of the actuator 10 is enhanced by the number of piezoelectric layers 12.

Generally, the piezoelectric actuator 10 is positioned with the inactive layer 16B  
20 connected to a fixed surface 22, whereupon the outermost surface 24 of the inactive layer 16A becomes the displacement surface. That is, when an electric field is applied to the piezoelectric layers 12, the displacement surface 24 is longitudinally displaced relative to the fixed surface 22. The piezoelectric layers 12 and the inactive layers 16A and 16B are formed using the tape-casting method  
25 as described above.

In this regard, it is to be noted that even if the inactive layers 16A and 16B are formed from material which may be piezoelectric if subject to a poling process, such layers 16A and 16B still do not contribute to the displacement of the

displacement surface 24 since electrodes are not provided on each surface of the inactive layers 16A and 16B. Accordingly, applying an electric field via the external electrodes 18A and 18B does not apply an electric field across the inactive layers 16A and 16B, and accordingly no piezoelectric response is  
5 obtained from these layers.

In practice, the inactive layers 16A and 16B are typically formed by laminating several layers of material without the electrodes connected thereto.

The embodiment of the invention is shown in figure 2. The embodiment relates to a transversal mode monolithic multilayer piezoelectric actuator (TM-MMPA) 30  
10 comprising piezoelectric layers 32 arranged in a laminated manner. An internal electrode 34 is provided between each pair of adjacent piezoelectric layers 32. The piezoelectric layers 32 define a body 36 having ends 38A and 38B and upper and lower surfaces 40A and 40B respectively.

The internal electrodes 34 are arranged in an inter-digital manner with adjacent  
15 electrodes 34 extending to the ends 38A and 38B in an alternating manner. An external electrode 42A and 42B is provided at each of the ends 38A and 38B respectively. The external electrodes 42A and 42B electrically connect the internal electrodes 34 extending to the respective end 38A or 38B.

Further, electrodes 44A and 44B are provided on the upper and lower surfaces  
20 40A and 40B, respectively. The electrodes 44A and 44B are in electrical contact with the external electrode 42A. The electrodes 44A and 44B are formed in a consistent manner with the inter-digital arrangement of the internal electrodes 34. Accordingly, the internal electrodes 34 adjacent to the electrodes 44A and 44B are connected to the external electrode 42B.

25 Conveniently, an electric field can be applied to the actuator 30 via the external electrode 42B and any one of the electrodes 44A or 44B or the external electrode 42A.

Each end 38A and 38B is covered by a protective layer 46 formed from hard, ceramics material. Each protective layer 46 covers the corresponding external electrode 42A or 42B. The protective layers 46 are attached to the electrode 42A and 42B by an epoxy.

- 5 The upper and lower surfaces 40A and 40B are covered with an elastic layer 48. The elastic layer 48 is formed from a relatively soft, insulating material and covers all external surfaces of the body 36 not covered by the protective layers 46.

The use of an elastic layer 48 permits transverse displacement of the body 36. In contrast, if a rigid material were used to form the layers 48, transverse expansion  
10 and contraction of the body 36 would be opposed by the rigid structure of the layers 48. As a result, the actuator 30 exhibits greater displacement in the transverse direction than that of LM-MMPA. In the embodiment shown in figure 2, the protective layer 46 at the end 38B is attached to a fixed surface 50, whereupon the outermost surface of the protective layer 46 at the end 38A  
15 becomes the displacement surface. This arrangement is particularly advantageous where a positive DC or a unipolar AC voltage is applied to the actuator 30. In this arrangement, the ground signal from the electric source is connected to the electrodes 44A and 44B and the external electrodes 42, whilst the positive voltage from the signal source is connected to the external electrode  
20 42B. In this manner, the positive voltages are confined to being close to the fixed surface 50.

The fabricating process of the actuator 30 is described as below: slurries of piezoelectric powder are at first obtained by mixing piezoelectric powders with an organic vehicle and are then tape-casted into green sheets. After drying, the  
25 green sheets are punched into rectangular pieces of appropriate sizes. An internal electrode is printed on one surface of the sheets. The rectangular pieces are then laminated and a green sheet without an electrode printed on its surfaces is placed on top. The laminated sheets are then pressed into a compacted body

under a high pressure, whereupon a multilayer body with an even number of layers is obtained.

The thickness of each layer is the same, and the internal electrodes are arranged in an interdigital form. On the surface of the top and bottom layer, which face to the outside of the actuator, metal electrodes are prepared. A layer of elastic, insulating material is then formed on the metal electrodes, which should not hinder the transversal movement of the TM-MMPA.

The ends of the body are then covered by a hard material, such as ceramics to act as protective layer. Poling the multilayer body is achieved by connecting the external electrode 42A and 42B to the earth and the positive voltage of a poling electric source, respectively. All of the layers, including the top and bottom layers are then piezoelectric response.

In the practical fabrication, both a soft and a hard piezoelectric material may be used. The transversal displacement properties of the present TM-MMPA will be demonstrated by comparison to the first type of piezoelectric actuators and the LM-MMPA: the soft and hard piezoelectric material chosen are  $\text{Pb}(\text{Zn}_{1/3}\text{Nb}_{2/3})_{0.25-0.30}\text{Zr}_{0.35-0.40}\text{Ti}_{0.30-0.35}\text{O}_3$  (PZN-PZ-PT with Perovskite structure) and  $(\text{Ba}_{0.65}\text{Pb}_{0.35})_{4-5}(\text{Na}_{0.88}\text{Li}_{0.12})_{1-2}\text{Nb}_{10}\text{O}_{30}$  (PBNN with Tungsten Bronze structure), respectively, with a sintering temperature of about 1270°C and 1140°C, respectively.

The slurry of piezoelectric powders with the organic vehicle is in the weight ratio (the solid ceramics/ organic vehicle) between 65-80 : 35-20, the internal electrode adopted is Ag-Pd-Au and Ag-Pd paste for former and latter material, respectively. A compacted body is obtained in a temperature range of 50-100°C under a pressure between 20-50MP, and Ag paste is used as the external electrode and is fired at 650°C to get Ag external electrodes.

The size of the PZN-PZ-PT TM-MMPA used in the example is as follows: the length is 8.5mm, the active area is 2.1 x 1.5mm; the layer thickness is about 0.105mm, and so piezoelectric layers are used. The size and layer thickness of the PZN-PZ-PT LM-MMPA are the same as these of the PZN-PZ-PT TM-MMPA, respectively, but only 16 active piezoelectric layers are able to be accommodated in this size because of the presence of the inactive layers. The size of the first type of the PZN-PZ-PT piezoelectric bar actuator is the same as that of TM-MMPA, the piezoelectric bar thickness is 1.5mm (electrodes surface are perpendicular to thickness direction).

10 For the PBNN piezoelectric ceramics, the size of the PBNN TM-MMPA used in the example is: the length is 12mm, the active area is 2.0x3.0mm; the layer thickness is about 0.160mm, and the number of piezoelectric layers is 18. The size and layer thickness of the PBNN LM-MMPA are the same as these of PBNN TM-MMPA, respectively, but only 14 piezoelectric layers could be accommodated in this size; the size of the first type of PBNN piezoelectric bar actuator is the same as that of TM-MMPA, the piezoelectric bar thickness is 2.0mm (electrodes surface are perpendicular to thickness direction).

The results show that for both actuators made from soft and hard piezoelectric materials, the transversal displacement of the TM-MMPA is 2~3 times larger than that of the LM-MMPA when the TM-MMPA and the LM-MMPA have the same applied electric field or voltage, and reaches a comparable displacement to that of the first type of actuator when the TM-MMPA and the first type of actuator have the same applied electric field, which means that the applied voltage of the TM-MMPA is significantly lower than that of the first type of actuator (in the present case the applied voltages for the PZN-PN-PT and PBNN TM-MMPA are about 1/14 and 1/12 of the voltage applied to the first type actuator, respectively).

Therefore, the present TM-MMPA is suitable for applications requiring transversal mode displacement with lower driving voltages than existing transversal mode bar activators.

CLAIMS

1. A transversal mode piezoelectric actuator, comprising: a plurality of layers of piezoelectric material arranged in a laminated manner to define a body having end surfaces and upper and lower surfaces; an electrode provided  
5 between each pair of adjacent layers and on the upper surface and lower surface of the body; adjacent electrodes arranged to produce an electric field therebetween; a protective layer provided on at least one end of the body; and a layer of elastic material provided on the upper and lower surfaces of the body.
- 10 2. An actuator as claimed in claim 1, wherein the electrodes are provided in an interdigital arrangement with adjacent electrodes extending to opposing ends of the body.
3. An actuator as claimed in claim 2, wherein the electrodes at each end are connected to a common electrical potential.
- 15 4. An actuator as claimed in claim 2, wherein electrodes on the upper and lower surfaces of the body are connected to electrodes at one end of the body.
5. An actuator as claimed in claim 4, wherein said one end corresponds with the displacement surface of the actuator.
6. An actuator as claimed in claim 1, wherein said protective layer is formed  
20 from a rigid material.
7. An actuator as claimed in claim 6, wherein said rigid material is a ceramics material.
8. An actuator as claimed in claim 1, wherein a protective layer is provided on both ends of the body.



9. An actuator as claimed in claim 1, wherein said layer of elastic material is formed on all surfaces of the body other than the ends thereof.
10. An actuator as claimed in claim 1, wherein said layer of elastic material is formed from an insulating material.
- 5 11. An actuator as claimed in claim 1, wherein there are an even number of layers of piezoelectric material.
12. An actuator as claimed in claim 1, wherein said layers of piezoelectric material are formed from an electrostrictive material.
13. An actuator as claimed in claim 1, wherein said piezoelectric material is either  
10 PZN-PZ-PT or PBNN.
14. An actuator as claimed in claim 13, wherein said electrodes are formed from Ag-Pd-Au or Ag-Pd for the piezoelectric materials PZN-PZ-PT and PBNN, respectively.
15. An actuator as claimed in claim 1, wherein said electrodes provided on the  
15 upper and lower surfaces of the body are formed from Ag.
16. A method for producing a transversal mode piezoelectric actuator, comprising the steps of:
- producing a plurality of layers of piezoelectric material and providing an electrode on one surface of each layer;
- 20 arranging said layers in a laminated manner;
- cofiring said layers to form a monolithic body;
- providing electrodes on the upper and lower surfaces of the body;



providing a layer of elastic material on the upper and lower surfaces of the body to cover the electrodes;

providing a protective layer on the ends of the body.

17. A method as claimed in claim 16, wherein the plurality of layers are produced  
5 using a tape-casting process.
18. A method as claimed in claim 16, wherein said step of arranging the plurality of layers of piezoelectric material includes the step of providing a layer of piezoelectric material without an electrode provided thereon, whereby the upper and lower surfaces of the body do not have electrodes thereon during  
10 the step of cofiring.
19. A method as claimed in claim 16, wherein before cofiring, said laminated layers are cut into appropriate sizes at a temperature of 50-100° C.
20. A method as claimed in claim 16, wherein said layers of material are formed from PZN-PZ-PT and said electrodes are formed of Ag-Pd-Au, said step of  
15 cofiring being performed at a temperature of substantially 1270°C.
21. A method as claimed in claim 16, wherein said layers of material are formed from PBNN, and said electrodes are formed of Ag-Pd and said step of cofiring is performed at a temperature of substantially 1140°C.
22. A method as claimed in claim 16, wherein said step of providing electrodes  
20 on upper and lower surfaces of the body includes the steps of providing an Ag paste on said upper and lower surfaces and firing at 650°C.
23. A method as claimed in claim 16, wherein the step of providing electrodes further includes the step of providing Ag paste on the ends of the body to form external electrodes upon firing.



24. A method as claimed in claim 23, wherein the electrodes on the upper and lower surfaces are connected to the external electrode on one end of the body.
25. A method as claimed in claim 16, wherein the electrodes are arranged in an interdigital form, with adjacent electrodes extending to opposite ends of the body.
26. A method as claimed in claim 24, wherein said method further includes the step of poling said body, comprising the steps of connecting the electrodes on the upper and lower surface and the external electrode connected therewith to the earth of an electrical source, and connecting the other external electrode to the positive output of said electrical source.
27. A method as claimed in claim 26, wherein the step of poling occurs after the step of providing the protective layer and the layer of elastic material.
28. A method as claimed in claim 16, wherein the step of providing the layer of elastic material comprises providing said layer on all surfaces other than the ends of the body.
29. A method as claimed in claim 16, wherein electrostrictive material is used in place of piezoelectric material.

