An electroactive device comprises at least two layers of material, wherein at least one layer is an electroactive material and wherein at least one layer is of non-uniform thickness. The device can be produced in various sizes, ranging from large structural actuators to microscale or nanoscale devices. The applied voltage to the device in combination with the non-uniform thickness of at least one of the layers (electroactive and/or non-electroactive) controls the contour of the actuated device. The effective electric field is a mathematical function of the local layer thickness. Therefore, the local strain and the local bending/torsion curvature are also a mathematical function of the local thickness. Hence the thinnest portion of the actuator offers the largest bending and/or torsion response. Tailoring of the layer thicknesses can enable complex motions to be achieved.

35 Claims, 5 Drawing Sheets
US 7,015,624 B1
Page 2

U.S. PATENT DOCUMENTS

<table>
<thead>
<tr>
<th>Patent Number</th>
<th>Date</th>
<th>Inventors</th>
</tr>
</thead>
<tbody>
<tr>
<td>4,399,986 A *</td>
<td>8/1983</td>
<td>Collins</td>
</tr>
<tr>
<td>4,400,634 A *</td>
<td>8/1983</td>
<td>Micheron</td>
</tr>
<tr>
<td>4,438,386 A *</td>
<td>3/1984</td>
<td>Gyugyi</td>
</tr>
<tr>
<td>4,457,636 A *</td>
<td>7/1984</td>
<td>Nusser</td>
</tr>
<tr>
<td>4,814,659 A</td>
<td>3/1989</td>
<td>Sawada</td>
</tr>
<tr>
<td>4,868,447 A</td>
<td>9/1989</td>
<td>Lee et al.</td>
</tr>
<tr>
<td>5,440,320 A</td>
<td>8/1995</td>
<td>Lach et al.</td>
</tr>
<tr>
<td>6,297,579 B1 *</td>
<td>10/2001</td>
<td>Martin et al.</td>
</tr>
</tbody>
</table>

FOREIGN PATENT DOCUMENTS

<table>
<thead>
<tr>
<th>Country</th>
<th>Patent Number</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>EP</td>
<td>59121889</td>
<td>7/1984</td>
</tr>
<tr>
<td>EP</td>
<td>11238919</td>
<td>8/1999</td>
</tr>
<tr>
<td>GB</td>
<td>2 046 936 A</td>
<td>4/1980</td>
</tr>
<tr>
<td>JP</td>
<td>11-238919</td>
<td>8/1999</td>
</tr>
</tbody>
</table>

OTHER PUBLICATIONS


Web page (http://members.aol.com/rhoa&yll2/scifbl.text, Jul. 25, 2000, 2 pgs.


* cited by examiner
\[ t = f(l) \]
\[ t = f(w) \]
\[ t = f(l, o) \]

FIG. 6
NON-UNIFORM THICKNESS ELECTROACTIVE DEVICE

CLAIM OF BENEFIT OF PROVISIONAL APPLICATION

Pursuant to 35 U.S.C. §119, the benefit of priority from provisional application 60/161,113, with a filing date of Oct. 22, 1999, is claimed for this non-provisional application.

ORIGIN OF THE INVENTION

The invention described herein was made by an employee of the United States Government and a National Research Council Research Associate and may be used, by or for the Government for governmental purposes without the payment of any royalties thereon or therefor.

CROSS REFERENCE TO RELATED CASES


BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention is generally related to the field of electroactive actuators. More specifically, it relates to an electroactive actuator having at least one layer of non-uniform thickness.

2. Description of the Related Art

Actuation devices are used for many applications, including aerospace, fluid flow and biomedical. Space applications include robotics, miniature rovers, and the shaping, tuning, positioning, controlling and deforming of membrane structures. Membrane inflatable and deployable space structures are used by the government and commercially as reflectors, antennas, solar arrays, satellites, solar sails, etc. Although actuation devices are widely used, many challenges exist which limit their performance for high precision applications. Factors affecting precision include surface smoothness, deviation from desired surface profile, surface deformations due to thermal fluctuations, and accurate membrane positioning. Additionally, hydrofoils and airfoils that can optimize their surface shape at varying flow rates are desirable to, for example, increase lift, reduce noise levels, lower vibrations and reduce drag. Other potential uses of actuation devices include precise positioning of display panels and optical index layers. To operate most effectively in the aforementioned applications, actuation devices require sufficient force and strain, and often need to produce complex motions that may include both bending and torsion.

Conventional piezoelectric ceramic, polymer, and composite actuators (including piezoelectric, electrostrictive, and electrostatic) lack the combination of sufficient strain and force to most effectively perform the aforementioned functions. Previous concepts for shaping and tuning membrane structures have primarily involved the use of piezoelectric ceramic materials. These ceramic piezoelectrics have the major problems of large mass, high density, low strain and high brittleness. Generally, piezoceramics also need additional mechanical devices to achieve a shaping, tuning, positioning, controlling or deforming function. In contrast to electroceramics, electroactive polymers are emerging as new actuation materials due to their enhanced strain capabilities.

Electrostrictive polymer-polymer actuators or other electroactive polymer actuators that provide enhanced strain capabilities can shape, tune, position, control and deform membrane structures, as well as perform in other applications, in ways not previously possible with other materials. An example of such an electrostrictive polymer-polymer actuator is described in the patent application entitled "Polymer-Polymer Bilayer Actuator," Ser. No. 09/696,524, filed Oct. 23, 2000, hereby incorporated by reference. The greater strain capability provides further possibilities for small-scale applications and integration into skin surfaces. The electroactive actuators can coincide with specific contours to optimize, for example, shapes for fluid flow, reflection and other membrane uses.

Existing devices capable of providing complex motion response utilize surface electrode patterning and/or polymer laminates having tailored lamina properties and orientations, such as described in U.S. Pat. No. 4,868,447. It is desirable to obtain complex motion response without requiring tailored surface electrode or laminate design.

STATEMENT OF THE INVENTION

Accordingly, an object of the present invention is to provide an electroactive device having controlled local strain and curvature.

Another object is to provide an electroactive device having a response contour which varies across the device.

Another object is to provide an electroactive device that can produce complex motions.

A further object is to provide an electroactive device with enhanced strain capabilities.

Additional objects and advantages of the present invention are apparent from the drawings and specification that follow.

SUMMARY OF THE INVENTION

In accordance with the present invention, the foregoing and other objects and advantages are attained by providing an electroactive device having at least two layers of material, wherein at least one layer is an electroactive material and wherein at least one layer is of non-uniform thickness. The device can be produced in various sizes, ranging from large structural actuators to microscale or nanoscale devices. The applied voltage to the device in combination with the non-uniform thickness of at least one of the layers (electroactive and/or non-electroactive) controls the contour of the actuated device. The effective electrical field is a mathematical function (E = V/D, where E is electrical field, V is voltage and D is thickness) of the local layer thickness. Therefore, the local strain and the local bending/torsion curvature are also a mathematical function of the local thickness. Hence the thinnest portion of the actuator offers the largest bending and/or torsion response. Tailoring of the layer thicknesses can enable complex motions to be achieved.

In a preferred embodiment, one or more electroactive layers of non-uniform thickness control the curvature of the device. The most responsive portions of the device will be at the thinnest portions of the electroactive layers, where the highest electric fields result. In other embodiments, the curvature can be controlled by varying the thickness of the...
non-electroactive layer or by varying the thickness of both
the electroactive layer(s) and non-electroactive layer.

The electroactive device described herein will provide
enabling technology to allow variable contouring of the
device to expand electroactive actuator use in applications
such as motion control, position control, tension control,
curvature control, biomedical pulse control, surface flow
dynamic control, display panels, optical alignment, optical
filters, micro-electromechanical systems, and nano-electro-
mechanical systems. More specifically, it can be utilized in
membrane inflatable and deployable structures, and be used
for shaping surfaces such as hydrofoils and airfoils to
optimize shape for different flow rates. Furthermore, the
device could serve to provide precise positioning of an
optical index layer for a liquid crystal display and provide
positioning control of display panels to reduce glare.

Advantages of using polymers for the electroactive
layer(s) include low weight, unified materials-device body,
simple operation, long lifetime, flexibility, toughness, and
ease of processing. However, use of layers (electroactive
and/or non-electroactive) of non-uniform thickness to con-
trol the curvature can be applied to any materials that can
cooperatively produce a sufficient force and strain combi-
nation for particular shaping, tuning, positioning, controlling
and deforming applications.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete appreciation of the invention and the
many of the attendant advantages thereof will be readily
attained by reference to the following detailed description
when considered in connection with the accompanying drawings, wherein:

FIG. 1A illustrates a view of an embodiment of a
non-uniform thickness actuator, showing the most respon-
sive portions located at the thinnest points of the active layer
closer to the free end.

FIG. 1B illustrates a side view of an embodiment of a
non-uniform thickness actuator, showing the most respon-
sive portions located at the thinnest points of the active layer
closer to the cantilevered end.

FIG. 2 illustrates a side view of a non-uniform thickness
actuator fixed at one end, with the thickness of the active layer
decreasing towards the fixed end.

FIGS. 3A-3C illustrate a cross section of a typical hydro-
foil or airfoil with a non-uniform thickness actuator, in
actuated and non-actuated configurations, attached to the
surface of the foil.

FIG. 3D illustrates a cross section of a typical hydrofoil
or airfoil with a non-uniform thickness actuator integrated
into the foil.

FIG. 4 illustrates an embodiment of a non-uniform thick-
ness actuator having stacked electroactive layers, wherein
the stacks on either side of the bond interface are alternately
activated.

FIG. 5 illustrates an embodiment of a non-uniform thick-
ness actuator having multiple electroactive layers.

FIG. 6 illustrates thickness variation of a single layer of
an actuator.

DETAILED DESCRIPTION OF THE
INVENTION

Referring now to the drawings, and more particularly to
FIGS. 1A and 1B, an electroactive device according to the
present invention is shown and referenced generally by the
numeral 100. Electroactive layer 112 is of non-uniform
thickness and is bonded to non-electroactive layer 114,
which has uniform thickness. A layer should be understood
to be a sheet, strip, film, plate, or the like, which may have
various configurations such as planar, annular, and spiral.

Although either or both layers can be of non-uniform thick-
ness, nonuniformity of the electroactive layer thickness will
produce the greatest strain, and hence displacement capa-
bility of the device. Electroactive layer 112 can be any
material that responds to electrical activation, including a
polymer, ceramic or composite, and is selected based upon
the response desired. A preferred material is the elec-
tric actuator elastomer described and claimed in “Electros-

cative Actuator”, Ser. No. 9/696,527, filed Oct. 23,
2000, hereby incorporated by reference. Another preferred
embodiment is the polymer-polymer actuator described and
claimed in “Polymer-Polymer Bilayer Actuator”, Ser. No.
9/696,524, filed Oct. 23, 2000, also hereby incorporated by
reference, wherein the active polymeric web has non-un-
iform thickness. Non-electroactive layer 114 must have a
mechanical modulus sufficient to obtain the desired response
in conjunction with electroactive layer 112. For equal thick-
ness of the electroactive layer 112 and non-electroactive
layer 114, the mechanical modulus of the non-electroactive
layer 114 is preferred to be equal to or lower than the
mechanical modulus of the electroactive layer 112 in order
to achieve maximum bending displacement. Candidate
materials include polymers, ceramics, composites, and met-
als.

The layers 112 and 114 are bonded using chemical,
physical, mechanical, or biological bonding means. The
preferred bonding means provide ease in processing, mini-
mized thickness, as well as the desired stiffness and dura-
bility. Especially preferred is a chemical adhesive that is cast
cured at room temperature. The bonding layer thickness
depends on the whole configuration of the device, including
the material selections for the electroactive and non-elec-
 troactive layers, as well as the device’s displacement and
stress induced at the bonding interfaces. The thinnest bond-
ing layer that satisfies the device requirements is preferred.
Epoxy resin is a suitable chemical adhesive.

Layers 112 and 114 are fixedly mounted at 116 and
electrically connected to a drive voltage (not shown). When
no voltage is supplied, the device remains in the non-
activated position 120. In FIG. 1A, when voltage is supplied,
electrical signals are supplied across the thickness of layer
112, and the electroactive response of layer 112 causes
device 100 to bend to position 140. The electrical signals are
supplied via one or more electrodes 130 disposed on each of
the upper and lower surfaces of layer 112. These electrodes
130 can be disposed via a single layer across the surface or
via multiple or patterned electrodes, depending on the
desired response. One example of suitable electrodes 130 are
gold electrodes, although any material having significant
conductivity (generally greater than 10$^{3}$ S/m) and fatigue
resistance can be used. A conductive polymer having
mechanical elasticity comparable to the electroactive mate-
rial and good adherence to the electroactive material is
preferred for the electrode material. Some examples of
suitable electrodes are polypyrrole and polyaniline. The
drive voltage is dependent on the number of device layers,
as well as on the desired displacement, and can range from
several volts to several kV.

The most responsive area of device 100 is position 140 at
the thinnest portion of electroactive layer 112. Similarly, in
FIG. 1B, the most responsive area of device 100 is position
150, at the thinnest portion of electroactive layer 112. In
other embodiments the non-electroactive layer 114 may be
The thicknesses are optimized based on the application requirements. The thickness of the layers 112 and 114 depend upon the desired response. For multiple electroactive device layers, the thicknesses of the layers, the moduli of the layers, and the material selection is tailored to achieve desired results.

Referring to FIGS. 2A and 2B, another embodiment of the electroactive device according to the present invention is shown and referenced generally by the numeral 200. Electroactive layer 212 is narrowed at each end and is bonded along its length to non-electroactive layer 214, which has uniform thickness. Device 200 is fixedly attached at 280 to a structure 235 on which the actuator functions. Furthermore, device 200 can be attached to the support layer 235 by chemical or mechanical means. Electroactive layer 212 is electrically connected to a drive voltage (not shown). When no voltage is supplied, as illustrated in FIG. 2A, the device 200 remains in its non-activated position. When voltage is supplied, as illustrated in FIG. 2B, the electroactive response of layer 212 causes device 200 to bend to its activated position. The most responsive areas of the device 200 are at the thinnest portions of layer 212, nearest ends 280 and 290.

FIGS. 3A through 3C depict an embodiment in which a non-uniform electroactive device is used to optimize characteristics of a hydrofoil or airfoil. Such optimization may include the formation of traveling waves. Cross-Section 300 represents a typical airfoil or hydrofoil. One or more non-uniform thickness electroactive actuators 310 are affixed to the airfoil or hydrofoil, preferably at the leading edge. In the activated positions 320 and 330, the actuators form a curvatures that alter the flow stream 340. FIG. 3B illustrates the actuator displacement resulting from the actuator being fixed at 350 to the airfoil or hydrofoil. Electrode 360 through 390 and 400 form a second stack 400. The first stack 470 and second stack 480 are bonded via bonding layer 460. The first stack 470 and second stack 480 are alternately activated. Although electroactive layers 400 through 450 can be different materials, consistent materials are preferred to obtain greater control of the device.

FIG. 3C illustrates an embodiment having multiple electroactive layers 400 through 450. Electroactive layers 400 through 410 form a first stack 470 and electroactive layers 430 through 450 form a second stack 480. The first stack 470 and second stack 480 are bonded via bonding layer 460. First stack 470 and second stack 480 are alternately activated. Although electroactive layers 400 through 450 can be different materials, consistent materials are preferred to obtain greater control of the device.

FIG. 5 illustrates an embodiment having three electroactive layers 510 through 530 and a single non-electroactive layer 540. Such a multiple electroactive layer arrangement may be used to obtain greater output force and greater strain/displacement for a given drive voltage.

Referring now to FIG. 6, the thickness variation of one or more layers is chosen to achieve a desired contour. The thickness of a layer can vary as any function of length (t=W(1)), any function of width (t=W(w)), or as any function of both length and width (t=W(l,w)). This thickness variation acts in cooperation with and/or enhances the contour that could be achieved by material choice, electrode design, or orientation of layers.

What is claimed is:

1. An electroactive device, comprising:
   a. at least two layers of material, each layer having a length, width and thickness dimension, wherein at least one layer is an electroactive material and wherein at least one layer of electroactive material is of non-uniform thickness, further wherein the thickness of each non-uniform thickness layer varies along one or some of the non-uniform thickness layer's length and width; and means for bonding the layers to one another.
   b. The electroactive device of claim 1, wherein at least one layer of electroactive material further comprises means to supply electrical signals across the thickness thereof.
The electroactive device of claim 2, when the means to supply electrical signals is at least one electrode positioned on each of the upper and lower surfaces of the at least one layer of electroactive material.

The electroactive device of claim 3, wherein the at least one electrode is a conductive polymer material having elasticity comparable to the at least one layer of electroactive material and having good adherence to the at least one electroactive material.

The electroactive device of claim 2, wherein the applied amplitude of the electrical signals controls the range of device motion.

The electroactive device of claim 1, wherein non-uniform thickness of at least one layer enables a controlled contouring of the activated device.

The electroactive device of claim 6, wherein the controlled contouring comprises bending of the activated device.

The electroactive device of claim 6, wherein the controlled contouring comprises torsion of the activated device.

The electroactive device of claim 1, wherein the non-uniform thickness of at least one electroactive layer is a function of at least one dimension of the layer.

An electroactive device, comprising:

at least two layers of material, each layer having a length, width and thickness dimension, wherein at least one layer is an electroactive material and wherein at least one layer is of non-uniform thickness, and means for bonding the layers to one another;

wherein the cross-section of at least one non-uniform layer is defined by a function of both the distance along the length of the layer and the distance along the width of the layer.

An electroactive device, comprising:

at least two layers of material, each layer having a length, width and thickness dimension, wherein at least one layer is an electroactive material and wherein at least one layer is of non-uniform thickness; and means for bonding the layers to one another;

wherein the cross-section of at least one non-uniform layer is defined by a function of the distance along the width of the layer.

The electroactive device of claim 1, wherein the at least one device is a component of a nano-electromechanical system.

The electroactive device of claim 1, wherein the at least one device is of non-uniform thickness; and

means for bonding the layers to one another;

wherein the cross-section of at least one non-uniform layer is defined by a function of the distance along the length of the layer.

The electroactive device of claim 1, wherein the at least one device is a membrane to be deformed.

The electroactive device of claim 1, wherein the at least one device is a conductive polymer material having elasticity comparable to the at least one layer of electroactive material and having good adherence to the at least one electroactive material.

The electroactive device of claim 1, wherein the surface to be modified is an optical index layer for a liquid crystal display.