A hybrid piezoelectric energy harvesting transducer system includes: (a) first and second symmetric, pre-curved piezoelectric elements mounted separately on a frame so that their concave major surfaces are positioned opposite to each other; and (b) a linear piezoelectric element mounted separately on the frame and positioned between the pre-curved piezoelectric elements. The pre-curved piezoelectric elements and the linear piezoelectric element are spaced from one another and communicate with energy harvesting circuitry having contact points on the frame. The hybrid piezoelectric energy harvesting transducer system has a higher electromechanical energy conversion efficiency than any known piezoelectric transducer.
FIG. 1
HYBRID PIEZOELECTRIC ENERGY HARVESTING TRANSUCER SYSTEM

CROSS-REFERENCE TO RELATED APPLICATION

This application claims the benefit of U.S. Provisional Application No. 60/699,106, filed on Jul. 14, 2005 for "Hybrid Force/Stress Amplified Piezoelectric Energy Transducer System".

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

The U.S. Government has a paid-up license in this invention and the right in limited circumstances to require the patent owner to license others on reasonable terms as provided for by the terms of Cooperative Agreement No. NCC-1-02043 awarded by the National Aeronautics and Space Administration.

BACKGROUND OF THE INVENTION

1. Field of the Invention
This invention relates generally to energy harvesting systems. It relates particularly to piezoelectric transducers for the conversion of mechanical energy to electrical energy.

2. Description of Related Art
Mobile computing, communication, and sensing devices have grown significantly in the past decade, as have various sensor networks, now used in a broad spectrum of applications. The demand has been increasing for a lightweight power supply having low volume, a high energy density, and a long lifetime. For a large integrated system such as an aircraft or ship, central electric power can be supplied to sensors and control units at each component; however, wiring from the central power source has been a big burden for these systems, and there have been concerns about system maintenance and reliability. A distributed system such as an environmental monitoring system requires thousands of various sensors, signal processing units, and local power supplies. Electronics consumers have long desired compact and long lifetime power supplies for small systems such as body wear (cell phone, PALM, DVD player, etc.)

Research and development efforts to address these problems can be divided into two main areas: batteries and energy harvesting. Advances in various batteries have indeed enhanced the capabilities of many devices; however, the operating lifetime of a battery-powered system limits system deployment time.

Energy harvesting is then, an alternative approach to reclaim energy from available sources in the system’s environment and to convert it into electrical energy to power a control system. Several exploited ambient sources include solar, heat/thermal, electromagnetic, RF, and mechanical vibration sources. Of these, mechanical vibration sources are varied in their origin, and the amount of power to be harvested therefrom is abundant. Electromagnetic and piezoelectric transducers are two major devices for energy harvesting in vibration environments. Piezoelectric transduction is well known to have a higher energy density and less environmental interference than its electromagnetic counterpart.

Progress has been made in piezoelectric transducers for the conversion of mechanical energy (mechanical shock, strain, stress, vibrations, and acoustic waves) to electric energy. Piezoelectric transduction mechanisms studied so far include piezoelectric stack transducers, unimorph/bimorph transducers, and flextensional transducers. Of these, flextensional transducers have shown a higher energy conversion efficiency in comparison to the others because strain/stress amplification mechanisms are employed by configurational design.

However, when pure compliant amplification mechanisms are used, energy waste still exists, indicating that more efficient electromechanical transduction mechanisms should be developed. On the other hand, piezoelectric materials play an important role in electromechanical transducers for energy harvesting. Piezo-ceramics, electroactive polymers(EAPs), and single crystal piezoelectric materials are the primary available materials at present. Of these, the EAP stack transducers previously reported show significantly high power output; however, net power output is small due to the consumption of the input DC-Bias field to convert the EAP from electric to piezoelectric status.

Piezoelectric transducers with a very high energy conversion efficiency are required in broad variety of advanced technologies, but they are yet unavailable in the art.

BRIEF SUMMARY OF THE INVENTION

It is accordingly the primary object of the present invention to provide what is not available in the art, viz., a hybrid force/stress amplified mechanism having a higher electromechanical energy conversion efficiency than any known piezoelectric transducer.

This primary object and its attending benefits are fully achieved by the provision of a hybrid piezoelectric energy harvesting transducer system which includes: (a) first and second symmetric, pre-curved piezoelectric elements in the form of sheets which are mounted separately at their ends on a frame so that concave major surfaces of these elements are positioned opposite to each other; (b) a linear piezoelectric element in the form of a sheet having no curvature and mounted separately at its ends on the frame and positioned thereon between the first and second pre-curved piezoelectric elements; (c) the first and second pre-curved piezoelectric elements and the linear piezoelectric element being spaced from one another and all communicating with energy harvesting circuits which have contact points located on the frame upon which all of the piezoelectric elements are mounted.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

For a more complete understanding of the present invention, including its primary object and attending benefits, reference should be made to the Detailed Description of the Invention, which is set forth below. This Detailed Description should be read in the light of the accompanying Drawings, wherein:

FIG. 1 is a schematic depicting a preferred embodiment of a hybrid piezoelectric energy harvesting transducer system according to the present invention;

FIG. 2 is a schematic depicting a flextensional piezoelectric energy harvesting transducer system of the related art;

FIG. 3A and FIG. 3B are schematics illustrating force/stress distributions in the pre-curved piezoelectric elements of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

The present invention is a hybrid force/stress amplified mechanism having a higher electromechanical energy conversion efficiency than any known piezoelectric transducer.
Referring now to the Drawings, FIG. 1 schematically depicts a preferred embodiment 1 according to the present invention. This embodiment 1 includes a first symmetric, pre-curved piezoelectric element 11 and a second symmetric, pre-curved piezoelectric element 12, both of which are in the form of sheets, and each of which has a convex and a concave major surface. Elements 11 and 12 are mounted separately at their ends on frame 13 so that their concave major surfaces are positioned opposite to each other.

Embodiment 1 also includes linear piezoelectric element 14, which is mounted separately at its ends on frame 13, and positioned on frame 13 between first pre-curved piezoelectric element 11 and second pre-curved piezoelectric element 12, and spaced therebetween.

Piezoelectric elements 11, 12, and 14 all communicate with electrical energy harvesting circuitry 15, which is well-known to those having skill in this art. Electrical energy harvesting circuitry 15 has contact points located on frame 13, upon which piezoelectric elements 11, 12, and 14 are mounted. Since the phase of element 14 may be different from elements 11 and 12, the electric circuitry for element 14 will be different.

When a contracting force \( F_{x1} \) is applied to the center of pre-curved elements 11 and 12 in a direction perpendicular to the convex surfaces thereof, an amplified contracting force \( F_{x2} \) is produced along the pre-curved elements 11 and 12 in a direction at right angles to the applied contracting force. Moreover, an equivalent stretching force \( F_{x2} \) is produced on linear piezoelectric element 14.

Furthermore, when a stretching force \( F_{y2} \) is applied to the center of elements 11 and 12 in a direction perpendicular to the concave surfaces thereof, an amplified stretching force \( F_{x2} \) is produced along elements 11 and 12 in directions at right angles to the applied stretching force \( F_{y2} \). Moreover, an equivalent contracting force \( F_{x2} \) is produced on element 14.

Each of the piezoelectric elements 11, 12, and 14 induce electrical energy simultaneously when a contracting force or a stretching force is applied thereto.

It is advantageous if the pre-curved and linear piezoelectric elements are made from a piezoelectric material which is one or more of piezoelectric ceramics, piezoelectric single crystals, piezoelectric polymers, and piezoelectric composites. They may be single elements or multilayer stacks having one kind or more than one kind of material therein.

When employed, piezoelectric ceramics are one or more of lead zirconate titanate, barium titanate, lead magnesium niobate-lead titanate ceramic, lead zirconate niobate-lead titanate ceramic, lead titanate, and lead lanthanum zirconate titanate.

When employed, piezoelectric single crystals are one or more of lead magnesium niobate-lead titanate single crystal, lead zirconate niobate-lead titanate single crystal, barium titanate single crystal, strontium barium niobate single crystal, lithium niobate single crystal, lithium tantalite single crystal, and lead barium niobate single crystal.

When employed, piezoelectric polymers are one or more of polyvinylidene fluoride, poly(vinylidene fluoride-trifluoroethylene), and polyimides, among others.

A hybrid force/stress amplified piezoelectric energy harvesting transducer system 1 is shown in FIG. 1. Elements 11 and 12 are symmetric pre-curved piezoelectric elements; element 14 is a linear piezoelectric element. When a contracting force \( F_{x1} \) is applied to the center of elements 11 and 12 along the Y direction, the system will produce an amplified contracting force \( (2F_{x1}) \) along each of the pre-curved elements 11 and 12, and an equivalent stretching force \( (-2F_{x1}) \) on element 14. On the other hand, when a stretching force \( F_{y2} \) is applied to the center of elements 11 and 12 along Y direction, the system will produce an amplified stretching force \( (Fx2) \) along the X direction on each of the pre-curved elements 11 and 12 and an equivalent contracting force \( (-2Fx2) \) on element 14. The amplification coefficient (k) is dependent on the pre-curved condition and the elastic properties of the elements 11 and 12.

The relation of \( F_x \) and \( F_y \) can be expressed as (\( F_x \) and \( F_y \) are mean static forces for the following comparisons and example calculations)

\[
F_x = \frac{F_y}{2} \tan(\theta) = M \frac{F_y}{2}
\]

Where \( \theta \) is the angle between the curved element 11 and the Y axis, and M is the magnification of the force/stress in the system.

Properly pre-curved conditions can increase the amplification coefficient by more than 100 times.

The curvature will follow this relationship:

\[
z(z) = z(b)
\]

\[
z(x_1, y_1) = z(x_2, y_2) \text{ for all } x_1, y_1, x_2, y_2
\]

It is optimized during a specific design according to the technical requirement and the properties of the materials used in the device, to get high performance without damaging the device.

There are three special cases to be considered first, since they may give relatively uniform force/stress distribution in the curved elements:

Case 1: \( b_0 > 0 \) in FIG. 3A.

Conventional flextensional transducer is closest to this case.

\[
z = \left| \frac{L_o}{2} - b \right| \tan\left( \frac{\pi}{2} - \theta \right) \text{ for } |b| \leq \frac{L_o}{2}
\]

\[
z = \left| \frac{L_o}{2} - b_0 \right| \tan\left( \frac{\pi}{2} - \theta \right) \text{ for } |b| \leq \frac{b_0}{2}
\]

Case 2: \( b_0 = 0 \) in FIG. 3A.

\[
z = \left| \frac{L_o}{2} - d \right| \tan\left( \frac{\pi}{2} - \theta \right)
\]

Complex Curvatures
Case 3: as shown in FIG. 3B.

\[
z = \left( \frac{L_o}{2} - x \right)^2
\]

For this case, the stress will uniformly distribute in the curved elements.

The piezoelectric elements 11, 12, and 14 can be any piezoelectric material (e.g., ceramic, single crystal, or polymer) multilayer stacks, or single elements.

Piezoelectric Ceramic Materials

Lead zirconate titanate (PZT) (the most popular one),
Barium titanate (BaTiO$_3$),
lead magnesium niobate-lead titanate ceramic (1-x)PbMg$_1$/3Nb$_2$/3O$_3$-xPbTiO(3) (PMN-xPT),
lead zinc niobate-lead magnesium niobate-lead titanate ceramics [PbZn$_{1/3}$Nb$_{2/3}$O$_3$-PbMg$_{1/3}$Nb$_{2/3}$O$_3$-PbTiO$_3$ (PZN-PMN-PT)],
lead lanthanum zirconate titanate (PLZT).

Piezoelectric Single Crystal
Lead magnesium niobate-lead titanate single crystal (1-x) PbMg$_1$/3Nb$_2$/3O$_3$-xPbTiO(3) (PMN-PT) (the most popular one),
Lead zinc niobate-lead magnesium niobate-lead titanate single crystal [PbZn$_{1/3}$Nb$_{2/3}$O$_3$-PbMg$_{1/3}$Nb$_{2/3}$O$_3$-PbTiO$_3$ (PZN-PT)],
Strontium Barium niobate crystal,
Lithium niobate (LiNbO$_3$) crystal,
Lithium tantalate (LiTaO$_3$),
Lead barium niobate (PBN) crystal.

Piezoelectric Polymers
Polyvinylidene Fluoride (PVDF) (the most popular one),
Poly(viny1idene fluoride-trifluoroethylene) [P(VDF-TrFE)] copolymer,
Polyimide and polyimide based nano composites.

The capacitance (C$_A$) of the center active element 17 is

\[ C_A = \varepsilon_0 \varepsilon A \frac{S}{h_A} = \varepsilon_0 \varepsilon \frac{LW}{h_A} \]  

where \( C_A \) is the capacitance of the element 17, \( \varepsilon_0 \) permittivity of vacuum, and \( \varepsilon \) dielectric constant of the piezoelectric material.

The energy output (\( P_A \)) for element 17 is

\[ P_A = \frac{Q_A^2}{2C} = \frac{d_{31}^2 k^2 F_y^2 h_A}{2 \varepsilon_0 \varepsilon LF_y} \]  

For each of the elements 11 and 12 the produced charge is

\[ Q_{11} = Q_{12} = \frac{1}{2} d_{31} k^2 F_y h \]  

The capacitance of each of the elements 11 and 12 is

\[ C_{11} = C_{12} = \varepsilon_0 \varepsilon A \frac{S}{h} = \varepsilon_0 \varepsilon \frac{W_{11} h}{h} \]  

The energy output for each of the elements 11 and 12 is

\[ P_{11} = P_{12} = \frac{Q_{11}^2}{2C_{11}} = \frac{d_{31}^2 k^2 F_y^2}{8 \varepsilon_0 \varepsilon W_{11}} \]  

The total energy output for the present hybrid energy harvesting system is

\[ P_{total} = 2P_{11} + P_{A} = \frac{d_{31}^2 k^2 F_y^2}{4 \varepsilon_0 \varepsilon W_{11}} + \frac{d_{31}^2 k^2 F_y^2 h_A}{2 \varepsilon_0 \varepsilon LF_y} \]  

The improvement ratio for the present hybrid transducer system is
If $h = h_A/2$

Then,

$$x = 1 + \left(\frac{d_32 L}{d_31 h_A}\right)^2$$

For instance, $L = 20$ mm, $h_A = 4$ mm, $d_32 = 750$ pC/N, and $d_31 = 360$ pC/N

Then,

$$x = 109$$

For PMN-PT single crystal, $d_32 = 2000$ pC/N, and $d_31 = 1000$ pC/N

Then,

$$x = 101$$

If one replaces the $d_31$ element 14 with a $d_32$ multilayer stack (n layer) at same dimension, the produced charge for element 14 is

$$Q_{14} = d_32 L F_p = d_32 n k F_p$$

Capacitance is,

$$C_1 = \varepsilon_0 \frac{S}{t} = \frac{W h_A}{t}$$

And, the output energy is

$$P_A = Q_1^2 \frac{2C_1}{C_A} = \frac{d_32 n k F_p^2 t}{2\varepsilon_0 \varepsilon W h_A}$$

The improvement ratio is

$$\chi' = \left(\frac{d_32 L}{d_31 h_A}\right)^2$$

For the above example of the PZT the improvement ratio is 216 times and the Single crystal is 200 times.

In summary, the energy harvesting capability of the present hybrid transducer system has the capability of an improvement ratio of over 100 times, comparing with either a conventional piezoelectric flextrensional transducer or a conventional piezoelectric multilayer stack transducer with a proper pre-curved design.

EXAMPLE 1

A piezoelectric single crystal (piezoelectric constant $d_32 = 1000$ pC/N, $d_31 = 2000$ pC/N, and dielectric constant $\varepsilon = 8000$) multilayer stack elements-based hybrid force/stress amplified piezoelectric energy harvesting transducer system according to the present invention has the following parameters:

Effective length of the transducer: $L_0 = 10$ mm

Width of the transducer: $W = 60$ mm

Element 14: a single layer

Element 14 Dimensions: 10 mm long
4 mm high

60 mm wide

The pre-curved elements 11 and 12 are multilayer stacks (100 layers of 0.1 mm thick single crystal) with dimensions of 10 mm long, 2 mm high, and 60 mm wide. If the force amplification constant is $k = 100$, and applied force, $F_p = 80$ N, the induced electric energy is 0.3035 (Joules/cycle). If we place 10 elements of this kind of device in each of a soldier’s heels, and assume the average weight of a soldier is 80 kg (800 N) and the average walking pace is two steps/second, then the harvested electric energy is 6.07 (Watts) for a normal soldier’s walk.

EXAMPLE 2

A piezoelectric single crystal (piezoelectric constant $d_32 = 2000$ pC/N, and dielectric constant $\varepsilon = 8000$) multilayer stack elements-based hybrid force/stress amplified piezoelectric energy harvesting transducer system according to the present invention has the following parameters:

Effective length of the transducer: $L_0 = 10$ mm

Width of the transducer: $W = 60$ mm

Element 14: a multilayer stack (100 layers of 0.1 mm-thick single crystal)

Element 14 Dimensions: 10 mm long
4 mm high

60 mm wide

The pre-curved elements 11 and 12 are multilayer stacks (100 layers of 0.1 mm thick single crystal) with dimensions of 10 mm long, 2 mm high, and 60 mm wide. If the force amplification constant is $k = 100$, and applied force, $F_p = 80$ N, the induced electric energy is 0.601 (Joules/ cycle). If we place 10 elements of this kind of device in each of a soldier’s heels, and assume the average weight of a soldier is 80 kg (800 N), and the average walking pace is two steps/second, then the harvested electric energy is 12.02 (Watts) for a normal soldier’s walk.
EXAMPLE 3

A piezoelectric PVDF polymer (piezoelectric constant d_{33}=-35 pC/N, dielectric constant \varepsilon=11) multilayer stack elements-based hybrid force/stress amplified piezoelectric energy harvesting transducer system according to the present invention has the flowing parameters.

Effective length of the transducer: L_0=10 mm
Width of the transducer: W=60 mm
Element 14: a multilayer stack (1000 layers of 0.01 mm-thick single crystal)
Element 14 Dimensions: 10 mm long
4 mm high
60 mm wide

The pre-curved elements 11 and 12 are multilayer stacks (1000 layers of 0.01 mm thick single crystal) with dimensions of 10 mm long, 2 mm high, and 60 mm wide. If the force amplification constant is k=100 and applied force, F_0=80 N, the induced electric energy is 0.0308 (Joules/cycle). If we place 10 elements of this kind of device in each of a soldier’s heels, and assume the average weight of a soldier is 80 kg (800N) and the average walking pace is two steps/second, then the harvested electric energy is 0.616 (Watts) for a normal soldier’s walk.

CONCLUSION

The present hybrid force/stress amplified piezoelectric energy harvesting transducers utilize active materials based on strain/stress amplified mechanisms instead of compliant amplification in order to more efficiently convert mechanical energy into electric energy. Advanced single crystal piezoelectrics, electroactive polymers, and their composites are used in such transducers. The present transducers feature low volume, light weight, and high mechanical-to-electric power conversion efficiency. Specifically, both contraction and expansion components in the present transducer are made of advanced active materials, while piezoelectric energy harvesting transducers developed so far have only adopted one active component—either contraction or expansion.

In conventional piezoelectric transducers with amplification mechanisms, vibration energy transferred to the compliant amplification components is converted into heat and wasted. Vibration energy transferred to the active amplification components in the present transducer, however, is converted into electric energy simultaneously, thus leading to increased energy conversion efficiency. The present device does not need a power supply, nor does it consume other resources except the motion of force/stress; consequently, it will most likely function for an essentially unlimited period of time.

Energy harvesting devices according to the present invention can be used in a broad spectrum of applications, such as various military applications, wireless sensor networks, wireless communications, and handheld computers.

We claim:
1. A hybrid piezoelectric energy harvesting transducer system, which system comprises:
   a. first and second symmetric, pre-curved piezoelectric elements in the form of sheets, each of which presents a convex and a concave major surface, the first and second symmetric, precurved piezoelectric elements being mounted separately at their ends on a frame so that the concave major surfaces of the piezoelectric elements are positioned opposite to each other;
   b. a linear piezoelectric element in the form of a sheet having no curvature, the linear piezoelectric element mounted separately at its ends on the frame and positioned thereon between the first and second pre-curved piezoelectric elements and spaced therebetween;
   c. the first and second pre-curved piezoelectric elements and the linear piezoelectric element all communicating with electrical energy harvesting circuitry having contact points which are located on the frame where the individual piezoelectric elements are mounted thereon; so that when a contracting force is applied to the center of the precurved piezoelectric elements in a direction perpendicular to the convex surfaces thereof, an amplified contracting force is produced along the precurved piezoelectric elements in a direction at right angles to the applied contracting force, and an equivalent stretching force is produced on the linear piezoelectric element; and when a stretching force is applied to the center of the pre-curved piezoelectric elements in a direction perpendicular to the concave surfaces thereof, an amplified stretching force is produced along the pre-curved piezoelectric elements in a direction at right angles to the applied stretching force, and an equivalent contracting force is produced on the linear piezoelectric element; each piezoelectric element inducing electrical energy simultaneously when a contracting force or a stretching force is applied thereto.

2. The hybrid piezoelectric energy harvesting transducer system of claim 1, wherein the pre-curved and linear piezoelectric elements comprise a piezoelectric material selected from the group consisting of piezoelectric ceramics, piezoelectric single crystals, piezoelectric polymers, and piezoelectric composites.

3. The hybrid piezoelectric energy harvesting transducer system of claim 2, wherein the pre-curved and linear piezoelectric elements are selected from the group consisting of single elements and multilayer stacks having one kind or more than one kind of piezoelectric material contained therein.

4. The hybrid piezoelectric energy harvesting transducer system of claim 2, wherein the piezoelectric ceramics are selected from the group consisting of lead zirconate titanate, barium titanate, lead magnesium niobate-lead titanate ceramic, lead zinc niobate—lead magnesium niobate—lead titanate ceramic, lead titanate, and lead lanthanum zirconate titanate.

5. The hybrid piezoelectric energy harvesting transducer system of claim 2, wherein the piezoelectric single crystals are selected from the group consisting of lead magnesium niobate—lead titanate single crystal, lead zinc niobate—lead titanate single crystal, barium titanate single crystal, strontium barium niobate single crystal, lithium niobate single crystal, lithium tantalate single crystal, and lead barium niobate single crystal.

6. The hybrid piezoelectric energy harvesting transducer system of claim 2, wherein the piezoelectric polymers are selected from the group consisting of polyvinylidene fluoride, poly(vinylidene fluoride-trifluoroethylene), and polyimides and polyimide based nano composites.