

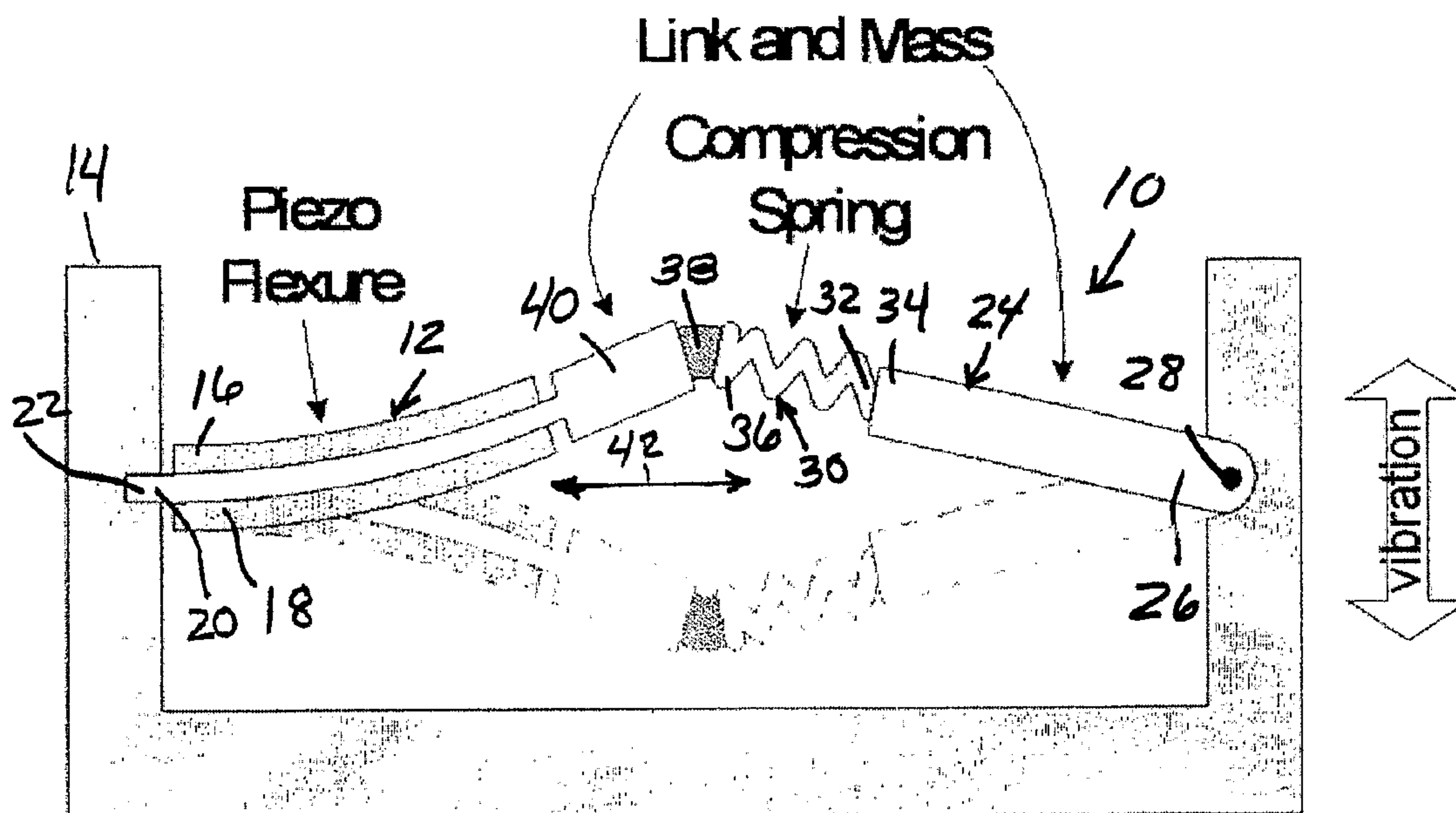


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(54) Title: STRAIN ENERGY SHUTTLE APPARATUS AND METHOD FOR VIBRATION ENERGY HARVESTING



Two Stable Positions Shown

(57) **Abrégé/Abstract:**

An apparatus for use in low frequency vibration energy harvesting (VEH) and with actuators requiring a low deflection force. The apparatus includes a piezo flexure that is loaded with a compressive pre-load force to place the piezo flexure under compression. The piezo flexure may be supported at an intermediate point or at one end thereof. The compressive pre-load force flexes the piezo flexure into one or the other of two stable positions, these positions being offset on opposite sides of a longitudinal centerline representing the position of the piezo flexure that would be produced without the compressive pre-load force applied thereto. The compressive pre-load effectively provides a negative spring constant which "softens" the piezo flexure and enhances a responsiveness of the piezo flexure to low frequency vibration energy. The piezo flexure also operates over a much wider frequency bandwidth than conventional systems incorporating a tip mass.

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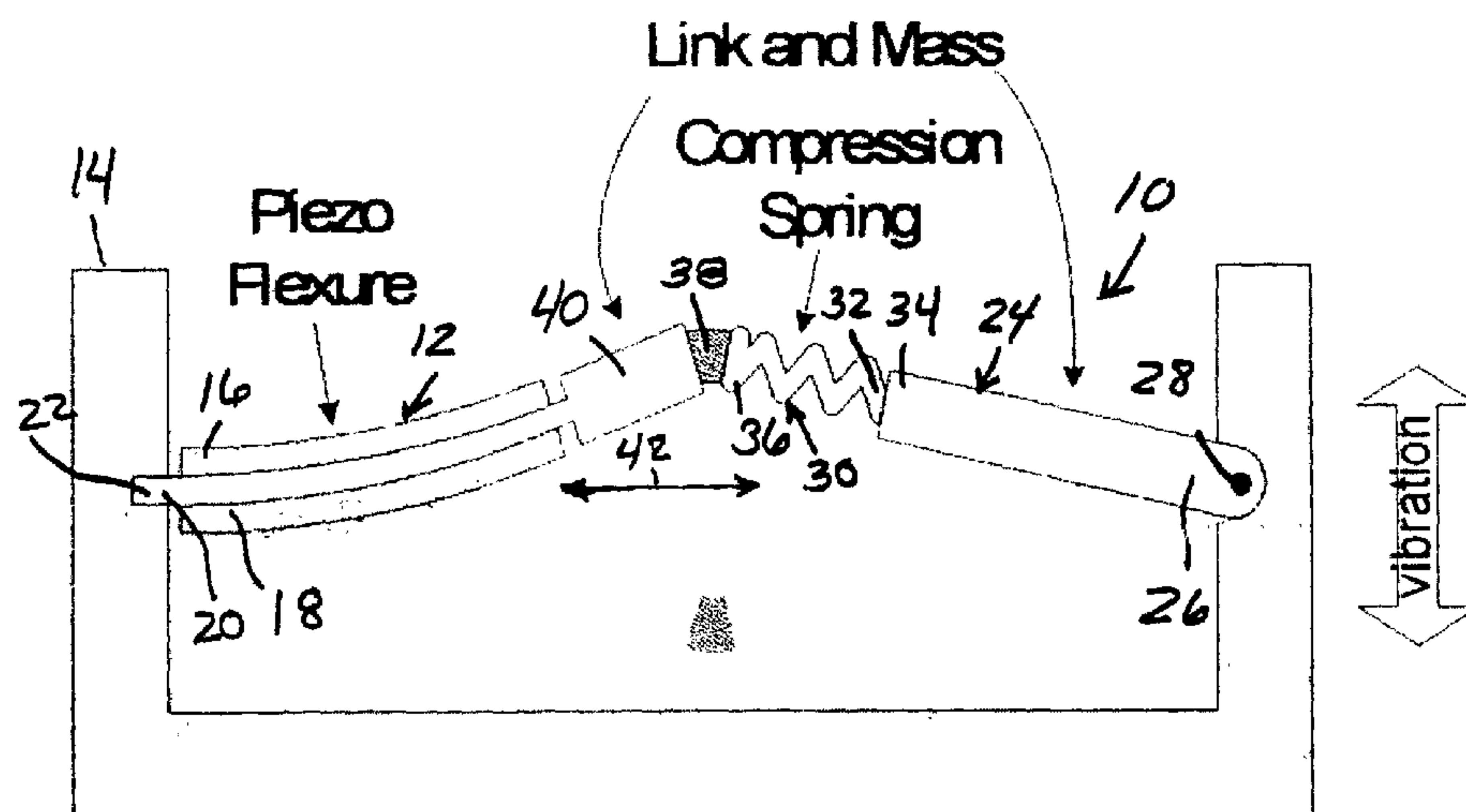
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STRAIN ENERGY SHUTTLE APPARATUS AND METHOD FOR VIBRATION ENERGY HARVESTING

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FIELD OF THE INVENTION

[0002] This invention relates to vibration energy harvesting devices, and more particularly to an apparatus which is ideally suited for harvesting low frequency vibration energy from a vibrating structure.

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BACKGROUND OF THE INVENTION

[0003] Many environments offer a vibration rich environment that is ideal for harvesting vibration energy. Such environments often exist in aircraft and automotive applications where the vibration experienced by an aircraft or automotive vehicle represents energy that could be used to power sensors or other remotely located devices, provided such energy can be harvested by a suitable device.

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[0004] Vibration energy harvesting (VEH) can be accomplished by developing relative motion, and hence energy, between a vibrating structure and a reaction mass coupled to the structure. This mechanical energy can be converted into electrical energy by developing cyclic stress in a piezo electric structure. A simple form of this device is a cantilever beam that has piezo material attached to the surface. This is illustrated in Figure 1. A reaction mass is attached to the tip of the beam to increase performance. When subjected to vibration, the tip of the beam tends to resist motion, thus placing the piezo material under stress. This stress results in electrical charge accumulation in the piezo material that results in an increase in voltage potential between two points of the material. However, for this topology to work efficiently, vibration energy must occur at or above the beam resonance frequency. Vibration energy with frequency content below the resonance frequency will produce very little motion between the tip mass and the base.

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[0005] When the cantilever beam shown in Figure 1 is used, the stiffness of the beam, including the piezo material, beam length (L) and the tip

mass determine the lowest frequency where the VEH device will work. Additionally, piezo material is usually a ceramic and is fragile when subjected to tension loading which will limit the robustness of the VEH device and its life. Figure 2 illustrates the relative tip displacement as a function of frequency for this device. At low frequency, the tip beam moves very little relative to the vibrating structure. Accordingly, the VEH device shown in Figure 1, at low frequency, will provide very little power from low frequency vibrations. Vibration energy at resonance frequency will provide maximum VEH, but utility is limited by a very narrow bandwidth.

10 **[0006]** The limitation of needing to "tune" the system around the resonant frequency of the cantilever beam imposes a significant limitation in terms of efficient operation of the system shown in Figure 1. This is because various structures often produce vibration energy over a much wider frequency bandwidth than what the system can be tuned for. The selection of the tip mass, to essentially tune the system to operate efficiently at the resonant beam frequency, means that the system will not be efficient in harvesting energy at other frequencies above and below the resonant frequency of the cantilever beam. Accordingly, a system that is not limited to efficient harvesting of vibration energy at only the resonant beam frequency, but that is able to harvest energy over a relatively wide frequency range, would be much more effective in generating electrical power from a vibrating structure.

25 **[0007]** Accordingly, there still exists a need for an apparatus able to be used with a piezo material to improve the harvesting of vibration energy at low frequencies, and also at frequencies above and below the resonant frequency of the structure from which vibration energy is being harvested. Such an apparatus would be extremely useful for powering remotely located sensors and various other components from low frequency vibration energy experienced by a piezo, beam-like structure. Such an apparatus would effectively make it possible to provide energy harvesting from a wide variety of structures experiencing low frequency vibration where such energy harvesting would have previously not been practicable.

SUMMARY OF THE INVENTION

[0008] In one aspect, the present invention is directed to a strain energy shuttle apparatus and method. The apparatus is useful for providing low frequency vibration energy harvesting (VEH) from a piezo beam-like structure experiencing low frequency vibration energy. In one aspect, the apparatus includes a biasing element for mechanically generating a negative spring force that is added in parallel with a piezo flexure (i. e. , a piezo beam-like component). The negative spring force provided by the biasing element effectively "softens" the piezo flexure and provides the piezo flexure with substantially a zero stiffness at zero frequency. The apparatus provides important benefits for applications where softening of a piezo structure is desirable, such as where the piezo structure is being used to harvest low frequency vibration energy or as an actuator to move a separate component. In either application, the apparatus operates to overcome the inherent structural stiffness of the piezo flexure to allow much easier flexing thereof.

[0009] In one embodiment the biasing element is coupled to a cantilever beam which is in turn pivotally coupled to a supporting structure. The piezo flexure is also coupled to the structure in a manner that places the piezo flexure generally in a common plane with the biasing element. A flexure couples a free end of the piezo flexure to a free end of the biasing element. This produces two stable positions, each being laterally offset from a line extending from the point of attachment of the piezo flexure to its associated structure and the point of attachment of the cantilever beam to the structure. Precise tailoring of the force provided by the biasing element enables the piezo flexure to be moved very easily by low frequency vibration energy from one of the two stable positions to the other and back again.

Once moved from one stable position to the other, the piezo flexure will oscillate around the new stable position, thereby generating additional power.

[0010] In another embodiment, an apparatus is disclosed that makes use of a piezo flexure having a support substrate with at least one piezoceramic wafer secured thereon. The support substrate is supported at an intermediate point of its length. A biasing element is operatively associated with the support substrate to apply a compressive force to the

substrate sufficient to deflect the substrate and the piezoceramic wafer mounted thereon into one of two stable positions on opposite sides of a centerline that extends through the substrate when it is not being subjected to a compressive pre-stress force. The compressive force provided by the biasing element serves to "soften" the inherent structural stiffness of the piezoceramic wafer and enhance its responsiveness to vibration energy, and particularly to low frequency vibration energy.

[0011] In one aspect a plurality of biasing elements are disposed longitudinally parallel to and along a longitudinal axis of the support substrate on opposite sides of the piezoceramic wafer. The support substrate is also supported at an approximate mid-point thereof on a base assembly that experiences the vibration energy. Opposite ends of the support substrate are secured to link arms, with each of the biasing elements being attached between the link arms on opposite longitudinal sides of the support substrate. This arrangement imparts a compressive stress to the piezoceramic wafer that softens the wafer and deflects the opposite ends of the wafer into one of two stable positions. Most importantly, the compressive force significantly enhances the response of the piezo electric material to low frequency vibration energy.

[0011a] In accordance with another aspect of the invention there is provided a vibration energy harvesting apparatus. The apparatus includes a piezoelectric wafer, and a support for supporting the piezoelectric wafer and allowing oscillating motion of the piezoelectric wafer. The apparatus also includes a biasing element operatively associated with the support and the piezoelectric wafer for applying a compressive pre-load force to the piezoelectric wafer sufficient to deflect the wafer from a linear orientation into one of two stable non-linear orientations, to soften the piezoelectric wafer to assist in initiating oscillating movement of the piezoelectric wafer in response to vibration energy experienced by the support, between the two stable positions.

[0011b] In accordance with another aspect of the invention there is provided an energy harvesting apparatus. The apparatus includes a support substrate, a piezoelectric wafer secured to a surface of the support substrate,

and a base for supporting the support substrate in a manner to enable oscillating motion of the support substrate and the piezoelectric wafer. The apparatus also includes a biasing element operatively associated with opposite longitudinal ends of the support substrate for supplying a mechanical compressive pre-load force to the piezoelectric wafer, sufficient to deflect the wafer into one of two flexed orientations in the absence of vibration energy, to thus soften the piezoelectric wafer to facilitate oscillating motion of the wafer in response to vibration experienced by the base.

[0011c] In accordance with another aspect of the invention there is provided a method for vibration energy harvesting. The method involves disposing a piezoelectric wafer on a support substrate, supporting the support substrate to enable oscillating motion of the support substrate, applying a compressive stress to the support substrate that is sufficient to deflect the piezoelectric wafer from a central, non-flexed position, into one of two flexed positions, the compressive stress operating to soften the piezoelectric wafer to enhance a response of the wafer to vibration energy.

[0011d] In accordance with another aspect of the invention there is provided a method for forming an actuator using a piezoelectric wafer. The method involves supporting the piezoelectric wafer on a support substrate to enable motion of the piezoelectric wafer, and placing the support substrate and the piezoelectric wafer under a compressive pre-load stress sufficient to hold the piezoelectric wafer in a flexed, non-linear configuration, the compressive pre-load operating to soften the wafer and enhance a sensitivity of the piezoelectric wafer to vibration energy.

[0011e] In accordance with another aspect of the invention there is provided an energy harvesting apparatus. The apparatus includes a support substrate, a piezoelectric wafer secured to a surface of the support substrate, and a base for supporting the support substrate in a manner to enable oscillating motion of the support substrate and the piezoelectric wafer, the base including a frame for supporting the support substrate from an approximate midpoint thereof. The apparatus also includes a pair of biasing elements operatively associated with opposite longitudinal ends of the support substrate, and disposed on opposite lateral sides of the support substrate,

and generally longitudinally aligned with a plane of the midpoint of the support substrate, for supplying a mechanical compressive pre-load force to the piezoelectric wafer and the support substrate that is sufficient to deflect outer ends of the support substrate into one of two flexed orientations that are laterally offset from the plane of the midpoint of the support structure, in the absence of vibration energy, to thus soften the piezoelectric wafer to facilitate oscillating motion of the wafer in response to vibration experienced by the base.

[0011f] In accordance with another aspect of the invention there is provided a method for vibration energy harvesting. The method involves disposing a piezoelectric wafer on a support substrate, and supporting the support substrate from a midpoint thereof to enable oscillating motion of a pair of outer ends of the support substrate, and arranging a pair of biasing elements generally parallel to the support substrate on opposite lateral sides of the support substrate. The method also involves securing opposite ends of each of the biasing elements to the outer ends of the support structure, such that the biasing elements apply a compressive stress to the support substrate that is sufficient to deflect the outer ends of the support substrate, and thus the piezoelectric wafer, from a central, non-flexed position, into one of two flexed positions laterally spaced apart from midpoint, the compressive stress operating to soften the piezoelectric wafer to enhance a response of the wafer to vibration energy.

[0011g] In accordance with another aspect of the invention there is provided a method for forming an actuator using a piezoelectric wafer. The method involves supporting the piezoelectric wafer on a support substrate to enable motion of the piezoelectric wafer, and supporting the support substrate from a midpoint thereof such that outer longitudinal ends thereof are free to move. The method also involves using a pair of biasing elements disposed on opposite lateral sides of the support substrate and longitudinally aligned with a midpoint of the support substrate, and operatively coupled to the outer ends of the support substrate, to place the support substrate and the piezoelectric wafer under a compressive pre-load stress sufficient to hold the piezoelectric wafer in one of two stable flexed, non-linear configurations, the

compressive pre-load operating to soften the wafer and enhance motion of the outer ends of the support substrate to enhance a sensitivity of the piezoelectric wafer to vibration energy.

5 **[0011h]** In accordance with another aspect of the invention there is provided an electrically driven actuator apparatus. The apparatus includes an electronically responsive piezoelectric wafer, and a support for supporting the piezoelectric wafer while allowing oscillating motion of a midpoint of the piezoelectric wafer. The apparatus also includes a biasing element operatively associated with an end of the piezoelectric wafer for applying a compressive pre-load force to the end of the piezoelectric wafer sufficient to deflect the midpoint of the piezoelectric wafer into one of two stable non-linear orientations, and to assist in moving the midpoint between the two stable non-linear positions, and the biasing element associated with the end of the piezoelectric wafer being free to flex in an arcuate path in response to vibration experienced by the piezoelectric wafer, to enhance a sensitivity of the piezoelectric wafer and oscillating motion of the midpoint of the piezoelectric wafer in response to the vibration.

10 **[0011i]** In accordance with another aspect of the invention there is provided a piezoelectric drive motor. The motor includes a support structure, and a substrate forming a beam, the beam having a non-linear shape and having opposing ends. The motor also includes a first piezoelectric layer secured to a first surface of the beam, the first piezoelectric layer operable to deflect the beam when a voltage is applied to the first piezoelectric layer. The motor also includes first and second biasing elements secured to respective opposing end portions of the substrate and supported from the support structure, the substrate being secured between free ends of the biasing elements so as to be supported by the biasing elements, with the biasing elements exerting a compressive stress on associated free ends of the substrate. The biasing elements are each further able to flex in an arcuate path to and adapted to enhance sensitivity of the first piezoelectric layer to the voltage to assist in causing deflection of a midpoint of the beam between two stable positions.

5 **[0012]** In accordance with another aspect, the present invention thus significantly assists in overcoming the inherent structural stiffness of a piezo flexure. The apparatus makes the piezo flexure highly susceptible to very low frequency vibration energy which would otherwise not be sufficient to cause sufficient flexing or bending of the piezo flexure for low frequency vibration energy harvesting applications. A significant advantage is that vibration energy

harvesting can be accomplished over a significantly wider frequency bandwidth than what is possible with conventional cantilever beam VEH devices using a tip mass.

5 **[0013]** Further areas of applicability of the present invention will become apparent from the detailed description provided hereinafter. It should be understood that the detailed description and specific examples are intended for purposes of illustration only and are not intended to limit the scope of the invention.

10 BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The present invention will become more fully understood from the detailed description and the accompanying drawings, wherein:

[0015] Figure 1 is a view of a prior art energy harvesting device incorporating a conventional tip mass disposed at a free end of a piezo beam-
15 like structure;

[0016] Figure 2 is a graph of the tip displacement of the beam shown in Figure 1 relative to frequency;

[0017] Figure 3 is a view of a preferred embodiment of the present invention incorporated for use with a piezo flexure;

20 **[0018]** Figure 4 is a perspective view of an alternative preferred embodiment of the present invention, making use of a pair of apparent biasing elements to soften the piezoelectric flexure of the assembly; and

[0019] Figure 5 is a side view of the assembly of Figure 4; and

[0020] Figure 6 is a side view of the assembly of Figure 4 illustrating
25 the two stable positions.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0021] The following description of the preferred embodiment(s) is merely exemplary in nature and is in no way intended to limit the invention, its
30 application, or uses.

[0022] Referring to Figure 3, an apparatus 10 in accordance with a preferred embodiment of the present invention is shown. The apparatus is

used for enabling low frequency vibration energy harvesting (VEH) through the use of a piezo flexure 12 which is supported fixedly from a vibrating structure 14. The piezo flexure essentially forms a beam-like structure, and in one preferred form comprises a piezo bimorph flexure. The piezo flexure 12 includes piezo layers 16 and 18 formed on opposite sides of a flexible supporting substrate 20. The substrate 20 includes an end 22 which is fixedly coupled to the structure 14. The substrate 20 can be plastic, metal or any other flexible material that allows the piezo layers 16 and 18 to be bonded thereto.

10 **[0023]** The apparatus 10 further includes a link or cantilever beam 24 which is pivotally coupled at a first end 26 via a pivot pin 28 or other suitable coupling element such that the beam 24 is able to pivot about pin 28 in response to vibration experienced by the structure 14. A biasing element 30 is fixedly coupled at one end 32 to a free end 34 of the beam 24 and at an
15 opposite end 36 to a flexure 38. The flexure 38 is in turn coupled to a free end 40 of the piezo flexure 12. Flexure 38 may comprise any suitable coupling element or material which enables relative movement between the end 36 of the biasing element 30 and the free end 40 of the piezo flexure 12. In one preferred form the biasing element 30 comprises a compression coil
20 spring, but it will be appreciated that any biasing element capable of providing a force directed against the piezo flexure 12 could be incorporated.

[0024] The coupling of the cantilever beam 24 to the free end 40 of the piezo flexure 12 (via the biasing element 30) produces an arrangement wherein the piezo flexure 12 has two stable positions, with one being shown
25 in solid lines in Figure 3 and the other being indicated in phantom. Each of the stable positions of the piezo flexure 12 are laterally offset from a longitudinal mid line 42 extending between the point of attachment of the fixed end 22 of the piezo flexure 12 and the pivot pin 28 supporting the cantilever beam 24. The mid-line 42 can be viewed as a position of equilibrium, albeit
30 an unstable one. This geometry essentially produces a geometric cotangent function between the piezo flexure 12 and the biasing element 30. In effect,

the piezo flexure 12 experiences a spring constant that is the negative of the spring constant provided by biasing element 30.

[0025] The apparatus 10 significantly reduces the force required to move the piezo flexure 12 between the two stable positions shown in Figure 3. Put differently, the biasing element 30 and cantilever beam 24 operate to significantly “soften” the piezo layers 16 and 18 to overcome the inherent structural stiffness of each. By tailoring the spring constants of the biasing element 30 and the piezo flexure 12, the energy required to switch conditions and cause movement of the piezo flexure 12 out of one stable position and into the other stable position can be matched to the electrical load which the piezo flexure 12 is electrically coupled to. When properly matched, the apparatus 10 is highly efficient. Under such a condition, the energy delivered to the electrical load is equal to the stress-strain hysteresis observed in the piezo flexure 12.

[0026] The apparatus 10 has a significantly lower frequency of operation than a conventional energy harvesting device, such as that shown in Figure 1. The frequency of operation of the apparatus 10 is determined in part by the stiffness of the piezo flexure 12 and the mass of the piezo flexure. The relationship between the angular tip deflection (i.e., of tip 38) of the piezo flexure 12 and an applied torque is given by equation 1 below:

[0027] Equation 1: $T_{\text{PiezoFlexure}} = \theta_{\text{PiezoFlexure}} * K_{\text{PiezoFlexure}}$

[0028] $T_{\text{PiezoFlexure}} = \sigma_{\text{PiezoFlexure}} * K_{\text{PiezoFlexure}}$

[0029] The biasing element 30 (i.e., compression spring) applies a non-linear torque to the piezo flexure 12 which is represented by equation 2 below:

[0030] Equation 2: $T_{\text{PiezoFlexure} / \text{Spring}} = L * F_{\text{Spring}} * \sin(\theta_{\text{PiezoFlexure}})$

[0031] The torque applied to the piezo flexure 12 deforms the piezo flexure 12 to an angle whereat the piezo flexure 12 is stable at two locations as shown in Figure 3. The torque required to change the state of the piezo flexure 12 from $+\theta$ to $-\theta$ is the difference between the torque generated by the biasing element in equation 1 and the torque given in equation 2, and is represented by the following Equation 3:

$$\begin{aligned}
T_{Tot} &= T_{PiezoFlexure} - T_{PiezoFlexure / Spring} \\
&= \theta_{PiezoFlexure} * K_{PiezoFlexure} - L * \sin(\theta_{PiezoFlexure}) \\
&\quad (F_{max} - 2 * L * (1 - \cos(\theta_{PiezoFlexure}))) * K_{spring}
\end{aligned}$$

5 **[0032]** The difference in torque is the effective “softening” of the piezo flexure 12. Equation 4 represents the deflection of the biasing element 30 (i.e., the spring) as a function of piezo flexure angle θ :

[0033] Equation 4: $\delta_{spring} = 2 * L(1 - \cos(\theta_{PiezoFlexure}))$

[0034] Equation 5 defines the maximum spring force F_{max} :

10 **[0035]** $F_{max} = [F_{Spring}]_{\theta=0}$

[0036] Also, a compression spring exhibits a force-distance relationship expressed by equation 6:

[0037] $F_{Spring} = -K_{spring} * \delta_{spring} + F_{max}$

[0038] This relationship, when applied to the apparatus 10, results in two stable angles. The torque necessary to change the positions is a strong function of the spring constant, where a softer spring produces a lower reset force (i.e., a force required to move the piezo flexure 12 from one stable position to the other). Equation 3, above, clearly shows the non-linear nature of the torque versus θ relationship.

20 **[0039]** An additional advantage of the apparatus 10 is that the two stable positions produce a frequency conversion between low frequency vibration and the high frequency nature of the stable angle locations. Put differently, once external vibration energy has caused the piezo flexure 12 to move from one stable position to the other, the piezo flexure 12 will oscillate around the stable location that it has just moved to, allowing the piezo material 16 and 18 of the piezo flexure 12 to harvest the strain energy over many cycles.

[0040] While the apparatus 10 has been described in connection with “softening” a piezo flexure for vibration energy harvesting applications, it will also be appreciated that the apparatus 10 can be readily incorporated in an actuator. For example, the apparatus 10 is extremely well suited to

applications requiring large deflections of the piezo flexure and low force, such as with an aerodynamic flow control synthetic jet actuator or a low frequency audio speaker. In this embodiment the apparatus 10 is designed such that the torque required to change the state of the apparatus 10 is within the capability of the piezo material to provide torque. Applying a voltage to the piezo materials 16 and 18 on the piezo flexure 12 causes the apparatus 10 to change states producing significantly larger displacements than would occur if the piezo flexure was energized without the biasing element 30. Typical increases in motion of the piezo flexure 12 with the present invention can be ten to twenty times that obtained with a simple, conventional piezo flexure unassisted by any spring force.

[0041] It will also be appreciated that for both energy harvesting and actuation applications, the use of other materials besides piezo electric materials is possible. For example, electromagnetic, electrostatic and magnostictive transduction technology can be used.

[0042] Referring to Figures 4 and 5, a VEH apparatus 100 is illustrated in accordance with another preferred embodiment of the present invention. VEH apparatus 100 generally comprises a piezo flexure assembly 102 supported on a base 103. The flexure assembly 102 includes a pair of piezoelectric wafers 104 and 106 disposed on opposite sides of a support substrate 108. In one preferred form the piezoelectric wafers 104, 106 each comprise piezoceramic wafers. The flexure assembly 102 further includes a pair of link arms 110 and 112 and a pair of biasing elements 114 and 116 coupled between the link arms 110, 112.

[0043] The entire flexure assembly 102 is supported on the base 103 from a pair of upstanding boss portions 115 and 117. Conventional threaded fasteners 118 and 120 extend through openings 122 and 124 in support arms 126 and 128 of the support substrate 108 to thus suspend the entire flexure assembly 102 above the base 103. The support arms 126 and 128 are located at an approximate midpoint of the support substrate 108, but the support arms could also be offset so as to be closer to one or the other of the link arms 110, 112 and thus not disposed at the approximate longitudinal

midpoint. The substrate 108 can be made of spring steel, beryllium copper, brass, glass epoxy composite or graphite epoxy composite, or any other suitable material.

5 **[0044]** With specific reference to Figure 5, the attachment of the biasing element 114 to each link arm 110 and 112 can be seen in greater detail. The same arrangement is used to couple the opposite ends of biasing element 116 to the link arms 110 and 112. Each link arm 110 and 112 includes a slot 130, 131 formed along a portion of its length. Each slot 130, 131 is further disposed along a midpoint of the overall thickness of its
10 respective link arm 110 or 112. Slot 130 has a height sufficient to receive an end 132 of the support substrate 108 therein. Slot 131 similarly is sized to receive end 133 of the support substrate 108. Ends 132 and 133 are each adhered or otherwise secured in their respective slots 130 or 131 such that they are not removable from either link arm 110 or 112.

15 **[0045]** The link arm 110 further includes a pair of pins 134 that extend through spaced apart openings 136 in the link arm 110. Link arm 112 similarly includes a pair of pins 135 that extend through openings 137 in link arm 112. The pins 134 essentially form a channel through which one end 138A of a flexure component 138 can be secured. Pins 135 similarly form a
20 channel for securing an end 139A of a second flexure component 139. End 138A of the flexure component has a cross-sectional thickness that is greater than an end 138B so that end 138A cannot simply be pulled out from between the pins 134. End 139A of flexure component 139 is constructed in identical fashion with a thickness greater than end 139B so that it cannot be removed
25 from between pins 135. However, this coupling arrangement allows free pivoting movement of ends 138A and 139A about their respective pins 134 and 135 with a minimal degree of friction and while limiting stress at this area of its associated flexure component 138 or 139.

30 **[0046]** Referring further to Figures 4 and 5, each end 138B, 139B of the flexure components 138 and 139 include a opening 140A, 140B which receives an end 142, 143 of the biasing element 114. In practice, any suitable means for attaching the ends 142, 143 of biasing element 114 can be

employed. Biasing element 116 is coupled in the same fashion. The link arms 110 and 112 may be made from a variety of materials but preferably are comprised of aluminum, steel, glass or graphite epoxy. Biasing element 114 is illustrated as a coil spring, but in practice any form of spring that is coupled
5 between the link arms 110 and 112 that serves to place the piezoelectric wafers 104 and 106 in compression may be employed.

[0047] With further specific reference to Figure 4, link arm 110 includes a notch forming ears 110A, while link arm 112 similarly includes a notch forming ears 112A. The ears 110A and 112A provide stress transition
10 regions that maintain stiffness across those areas where the opposite ends of the support substrate 108 are coupled to their respective link arms 110, 112. The gap formed between each link arm 110 and 112 and the adjacent ends of the piezoceramic wafers 104, 106, produces a low bending stiffness region along the flexure 102 that would otherwise reduce performance of the
15 apparatus 100. The ears 110A and 112A of each link arm 110 and 112, respectively, thus provide increased bending stiffness to offset this.

[0048] With further reference to Figure 5, each of the piezoelectric wafers 104, 106 may vary significantly in thickness, length and width to suit the needs of a particular application. However, in one preferred form, each
20 piezoelectric wafer 104 and 106 has a thickness of about 0.005" - 0.02" (0.127 mm - 0.508 mm). In one preferred form, the length and width of the piezoelectric wafers 104 and 106 is about 1.8" (45.72 mm) and about 0.6" (15.24 mm) respectively. The actual energy per bending cycle generated by the apparatus 100 is a function of piezoceramic volume that is under stress.
25 A thicker piezoceramic wafer will provide a higher energy content, but this energy will be in the form of high voltage and low charge as compared to a thinner material. Although more energy is available from thicker piezoceramic material, the conversion electronics that are needed to capture this energy are significantly more complex and less efficient than that required for use with a
30 thinner piezoceramic wafer. Thinner piezoceramic material produces a lower voltage but much higher charge. Merely as an example, typical capacitance

and voltages produced by a piezoceramic wafer, per cycle of oscillation, are as follows:

- 0.02" thick PZT 5A – 10nF at 200 volts (harder to convert);
5 0.005" thick PZT 5A – 100nF at 30 volts (easily converted);
Total energy is $CV^2/2$ per bending cycle.

[0049] Referring to Figure 6, the oscillating motion of the flexure assembly 102 can be seen in response to a vibration force. The compressive
10 force generated by the biasing elements 114, 116 is sufficient to maintain the flexure assembly 102 in a deflected (i.e., bowed) orientation at one of two stable positions 144 or 146. Longitudinal line 148 represents the plane the flexure assembly 102 would reside in without the compressive force from the biasing elements 114, 116. When in either of positions 144 or 146, the flexure
15 assembly 102 is highly responsive to low frequency vibration energy and is easily deflected to the other stable position by such energy. The spring force provided by the biasing elements can be tailored to provide the required sensitivity for a specific VEH application.

[0050] The present invention thus forms a means to significantly
20 "soften" a piezo flexure which enables the piezo flexure to be used in low frequency vibration energy harvesting applications where such a flexure would otherwise be too structurally stiff to harvest the vibration energy. A significant benefit of the present invention is that it can be used over a wider frequency bandwidth than previously developed VEH devices incorporating a
25 tip mass on the free end of the piezo flexure. The capability of operating over a wider bandwidth allows the invention 10 to more efficiently harvest vibration energy from the structure and to generate a greater voltage output from the vibration energy than would be possible with a conventional piezo flexure.

[0051] While various preferred embodiments have been described,
30 those skilled in the art will recognize modifications or variations which might be made without departing from the inventive concept. The examples illustrate the invention and are not intended to limit it. Therefore, the

description and claims should be interpreted liberally with only such limitation as is necessary in view of the pertinent prior art.

**THE EMBODIMENTS OF THE INVENTION IN WHICH AN EXCLUSIVE
PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS FOLLOWS:**

1. A vibration energy harvesting apparatus, comprising:

5 a piezoelectric wafer;

a support for supporting said piezoelectric wafer and allowing oscillating motion of said piezoelectric wafer; and

10 a biasing element operatively associated with said support and said piezoelectric wafer for applying a compressive pre-load force to said piezoelectric wafer sufficient to deflect said wafer from a linear orientation into one of two stable non-linear orientations, to soften said piezoelectric wafer to assist

15 in initiating oscillating movement of said piezoelectric wafer in response to vibration energy experienced by said support, between said two stable positions.
2. The apparatus of claim 1, wherein said support comprises: a flexible

20 substrate on which said piezoelectric wafer is secured; and a base secured to said flexible substrate.
3. The apparatus of claim 1, wherein said support comprises:

25 a flexible substrate on which said piezoelectric wafer is secured;

a base for supporting said substrate;

a pair of link arms secured to opposite ends of said flexible

30 substrate; and

wherein the biasing element is coupled at opposite ends thereof to the link arms to place the piezoelectric wafer under

compression such that the flexible substrate has two stable flexed conditions.

4. The apparatus of claim 3, wherein:

5

at least one of said link arms includes a first pair of spaced apart retaining pins; and

10

a first coupling flexure having a first end and a second end, said first end being retained by said first pair of retaining pins and said second end being coupled to one end of said biasing member.

5. The apparatus of claim 4, wherein a second one of said pair of link arms includes a second pair of spaced apart retaining pins; and

15

20

wherein said apparatus further includes a second coupling flexure having a first end and a second end, said first end of said second coupling flexure being coupled to said second link arm and said second end of said second coupling flexure being coupled to an end of said biasing element opposite said one end.

6. The apparatus of claim 1, wherein said support supports said piezoelectric wafer from an intermediate point along a length thereof.

25

7. The apparatus of claim 1, wherein said support supports said piezoelectric wafer at an approximate midpoint thereof.

30

8. The apparatus of claim 1, wherein a pair of said biasing elements are operatively associated with said support and said piezoelectric wafer and extend parallel to said piezoelectric wafer and within a common longitudinal plane within which said piezoelectric wafer resides.

9. The apparatus of claim 1, further including :

a cantilever beam supported for pivoting motion at one end thereof from said support; and

5

wherein said cantilever beam has a free end coupled to one end of said biasing element.

10. The apparatus of claim 9, further comprising a flexure element disposed between said free end of said cantilever beam and said piezoelectric wafer.

10

11. The apparatus of claim 1, wherein:

15

said support comprises a flexible substrate on which said piezoelectric wafer is secured;

20

a base for supporting said flexible substrate at one end thereof to enable oscillating pivotal motion of said piezoelectric wafer relative to said base.

12. The apparatus of claim 1, further comprising a pair of said piezoelectric wafers mounted on opposing surfaces of said support.

25

13. The apparatus of claim 1, wherein:

30

said support comprises a flexible substrate on which said piezoelectric wafer is secured, and a base for supporting a first end of said flexible substrate to enable oscillating pivotal movement of said piezoelectric wafer about said first end; and

wherein said biasing element is operatively coupled between a second end of said flexible substrate and said base.

14. The apparatus of claim 13, further comprising a cantilever beam disposed in between said base and biasing member, said cantilever beam being pivotally coupled at a first end to said base.
- 5
15. The apparatus of claim 14, further comprising a flexure member disposed in between a second end of said cantilever beam and said biasing element.
- 10
16. The apparatus of claim 14, wherein said biasing element comprises a coil spring.
17. An energy harvesting apparatus comprising:
- 15
- a support substrate;
- a piezoelectric wafer secured to a surface of said support substrate;
- 20
- a base for supporting said support substrate in a manner to enable oscillating motion of said support substrate and said piezoelectric wafer; and
- 25
- a biasing element operatively associated with opposite longitudinal ends of said support substrate for supplying a mechanical compressive pre-load force to said piezoelectric wafer, sufficient to deflect said wafer into one of two flexed orientations in the absence of vibration energy, to thus soften said piezoelectric wafer to facilitate oscillating motion of said
- 30
- wafer in response to vibration experienced by said base.

18. The apparatus of claim 17, wherein said base comprises a frame having a boss portion for supporting said support substrate from an approximate midpoint thereof.
- 5 19. The apparatus of claim 17, further comprising a pair of link arms coupled to opposite longitudinal ends of said support substrate; and wherein said biasing element is coupled between said link arms.
- 10 20. The apparatus of claim 17, further comprising a pair of said piezoelectric wafers secured to opposing surfaces of said support substrate.
- 15 21. The apparatus of claim 19, wherein a pair of said biasing elements are disposed parallel to said support substrate and each coupled at opposite ends thereof to portions of said link arms.
22. The apparatus of claim 17, wherein said biasing element comprises a coil spring.
- 20 23. The apparatus of claim 17, wherein said piezoelectric wafer comprises a piezoelectric ceramic wafer.
- 25 24. The apparatus of claim 17, further comprising a cantilever beam disposed in between a first end of said support substrate and said base.
- 30 25. The apparatus of claim 17, wherein said support substrate is supported at a first longitudinal end by said base for oscillating motion relative to said base.
26. The apparatus of claim 25, wherein said biasing element is operatively coupled to said base and to a second longitudinal end of said support

substrate to thus place said biasing element generally longitudinally in line with said support substrate when said piezoelectric wafer is at rest.

5 **27.** The apparatus of claim 17, further comprising a flexure element disposed in between said biasing element and said support substrate.

28. A method for vibration energy harvesting, comprising:

10 disposing a piezoelectric wafer on a support substrate;

 supporting said support substrate to enable oscillating motion of said support substrate;

15 applying a compressive stress to said support substrate that is sufficient to deflect said piezoelectric wafer from a central, non-flexed position, into one of two flexed positions, said compressive stress operating to soften said piezoelectric wafer to enhance a response of said wafer to vibration energy.

20 **29.** The method of claim 28, further comprising securing said support surface in a manner to enable oscillating motion of opposite longitudinal ends of said piezoelectric wafer.

25 **30.** The method of claim 28, further comprising supporting said support surface in a manner to enable oscillating motion of one longitudinal end of said piezoelectric wafer.

31. The method of claim **28**, wherein applying a compressive stress comprises using a biasing element operatively coupled to said piezoelectric wafer to apply said compressive stress.

32. A method for forming an actuator using a piezoelectric wafer, comprising:

supporting the piezoelectric wafer on a support substrate to enable motion of said piezoelectric wafer; and

placing said support substrate and said piezoelectric wafer under a compressive pre-load stress sufficient to hold said piezoelectric wafer in a flexed, non-linear configuration, said compressive pre-load operating to soften said wafer and enhance a sensitivity of the piezoelectric wafer to vibration energy.

33. The method of claim **32**, wherein placing said piezoelectric wafer under a compressive pre-load stress comprises using a biasing element to generate said compressive pre-load stress.

34. The method of claim **32**, further comprising supporting said support substrate to enable motion of opposite longitudinal ends of said piezoelectric wafer.

35. The method of claim **32**, further comprising supporting said support substrate to enable motion of one longitudinal end of said piezoelectric wafer (s).

36. An energy harvesting apparatus comprising:

a support substrate;

a piezoelectric wafer secured to a surface of said support substrate;

a base for supporting said support substrate in a manner to enable oscillating motion of said support substrate and said piezoelectric wafer;

5

said base including a frame for supporting said support substrate from an approximate midpoint thereof; and

10

a pair of biasing elements operatively associated with opposite longitudinal ends of said support substrate, and disposed on opposite lateral sides of said support substrate, and generally longitudinally aligned with a plane of said midpoint of said support substrate, for supplying a mechanical compressive pre-load force to said piezoelectric wafer and said support substrate that is sufficient to deflect outer ends of said support substrate into one of two flexed orientations that are laterally offset from said plane of said midpoint of said support structure, in the absence of vibration energy, to thus soften said piezoelectric wafer to facilitate oscillating motion of said wafer in response to vibration experienced by said base.

15

20

37. The apparatus of claim 36, wherein said frame including a boss portion for supporting said support substrate from said approximate midpoint thereof.

25

38. The apparatus of claim 36, further comprising a pair of link arms coupled to opposite longitudinal ends of said support substrate; and

30

wherein said biasing elements are each coupled between said link arms.

39. The apparatus of claim 36, further comprising a pair of said piezoelectric wafers secured to opposing surfaces of said support substrate.
- 5 40. The apparatus of claim 38, wherein said pair of said biasing elements are disposed parallel to said support substrate and each coupled at opposite ends thereof to portions of said link arms.
- 10 41. The apparatus of claim 36, wherein each said biasing element comprises a coil spring.
42. The apparatus of claim 36, wherein said piezoelectric wafer comprises a piezoelectric ceramic wafer.
- 15 43. A method for vibration energy harvesting, comprising:
disposing a piezoelectric wafer on a support substrate;

supporting said support substrate from a midpoint thereof to enable oscillating motion of a pair of outer ends of said support
20 substrate; and

arranging a pair of biasing elements generally parallel to said support substrate on opposite lateral sides of said support substrate, and securing opposite ends of each of said biasing
25 elements to said outer ends of said support structure, such that said biasing elements apply a compressive stress to said support substrate that is sufficient to deflect said outer ends of said support substrate, and thus said piezoelectric wafer, from a central, non-flexed position, into one of two flexed positions
30 laterally spaced apart from midpoint, said compressive stress operating to soften said piezoelectric wafer to enhance a response of said wafer to vibration energy.

44. The method of claim **43**, further comprising securing said support surface in a manner to enable oscillating motion of opposite longitudinal ends of said piezoelectric wafer.

5 **45.** A method for forming an actuator using a piezoelectric wafer, comprising:
supporting the piezoelectric wafer on a support substrate to enable
motion of said piezoelectric wafer;

10 supporting said support substrate from a midpoint thereof such that
outer longitudinal ends thereof are free to move; and

15 using a pair of biasing elements disposed on opposite lateral sides of
said support substrate and longitudinally aligned with a midpoint of said
support substrate, and operatively coupled to said outer ends of said
support substrate, to place said support substrate and said piezoelectric
20 wafer under a compressive pre-load stress sufficient to hold said
piezoelectric wafer in one of two stable flexed, non-linear configurations,
said compressive pre-load operating to soften said wafer and enhance
motion of said outer ends of said support substrate to enhance a
sensitivity of said piezoelectric wafer to vibration energy.

46. An electrically driven actuator apparatus, comprising:

25 an electronically responsive piezoelectric wafer;

a support for supporting said piezoelectric wafer while allowing
oscillating motion of a midpoint of said piezoelectric wafer; and

30 a biasing element operatively associated with an end of said
piezoelectric wafer for applying a compressive pre-load force to

said end of said piezoelectric wafer sufficient to deflect said midpoint of said piezoelectric wafer into one of two stable non-linear orientations, and to assist in moving said midpoint between said two stable non-linear positions; and

5

said biasing element associated with said end of said piezoelectric wafer being free to flex in an arcuate path in response to vibration experienced by said piezoelectric wafer, to enhance a sensitivity of the piezoelectric wafer and oscillating motion of said midpoint of said piezoelectric wafer in response to said vibration.

10

47. The apparatus of claim **46**, wherein said biasing element comprises a coil spring.

15

48. The apparatus of claim **46**, further comprising:

a substrate forming a beam, and said piezoelectric wafer being secured to a surface of said substrate, and said biasing element being in abutting contact with said substrate.

20

49. The apparatus of claim **48**, wherein a first end of said beam is secured to said support, and a second end of said beam is disposed against said biasing element, such that said second end is able to oscillate between said two nonlinear orientations.

25

50. The apparatus of claim **48**, wherein said beam forms a non-linear shape.

30

51. The apparatus of claim **50**, wherein said beam forms a re-curve shape.

52. A piezoelectric drive motor, comprising:

a support structure;

5 a substrate forming a beam, the beam having a non-linear shape and having opposing ends;

10 a first piezoelectric layer secured to a first surface of said beam, the first piezoelectric layer operable to deflect the beam when a voltage is applied to said first piezoelectric layer; and
first and second biasing elements secured to respective opposing end portions of said substrate and supported from said support structure, said substrate being secured between free ends of said biasing elements so as to be supported by said
15 biasing elements, with said biasing elements exerting a compressive stress on associated free ends of said substrate, said biasing elements each further being able to flex in an arcuate path to and adapted to enhance sensitivity of the first piezoelectric layer to said voltage to assist in causing deflection
20 of a midpoint of said beam between two stable positions.

53. The motor of claim **52**, wherein said substrate comprises a plurality of independent sections disposed adjacent one another forming said non-linear shape.

25

54. The motor of claim **52**, wherein said biasing elements comprise leaf springs.

55. The motor of claim **52**, further comprising a pair of piezoelectric layers secured to opposing surfaces of said substrate.

30

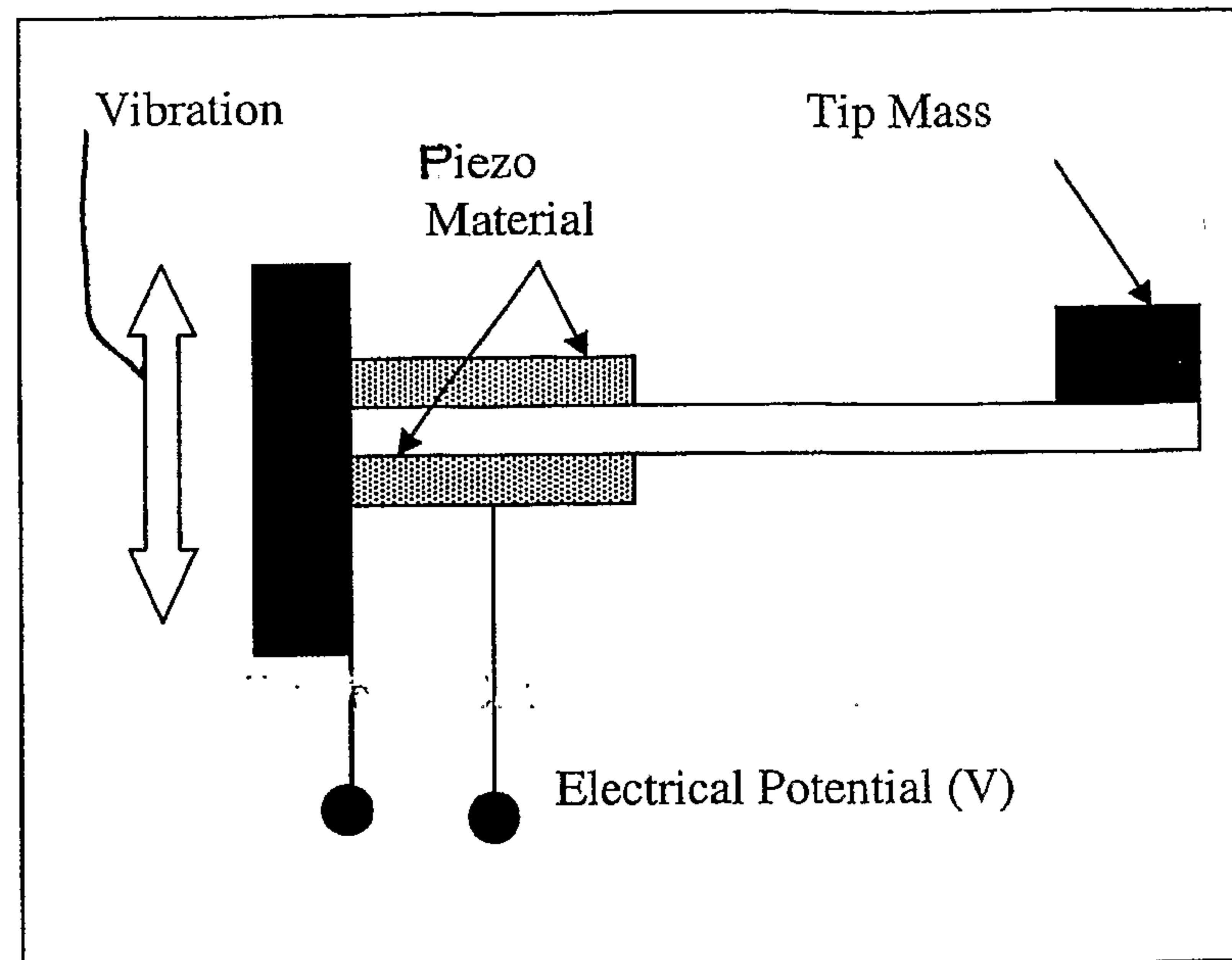
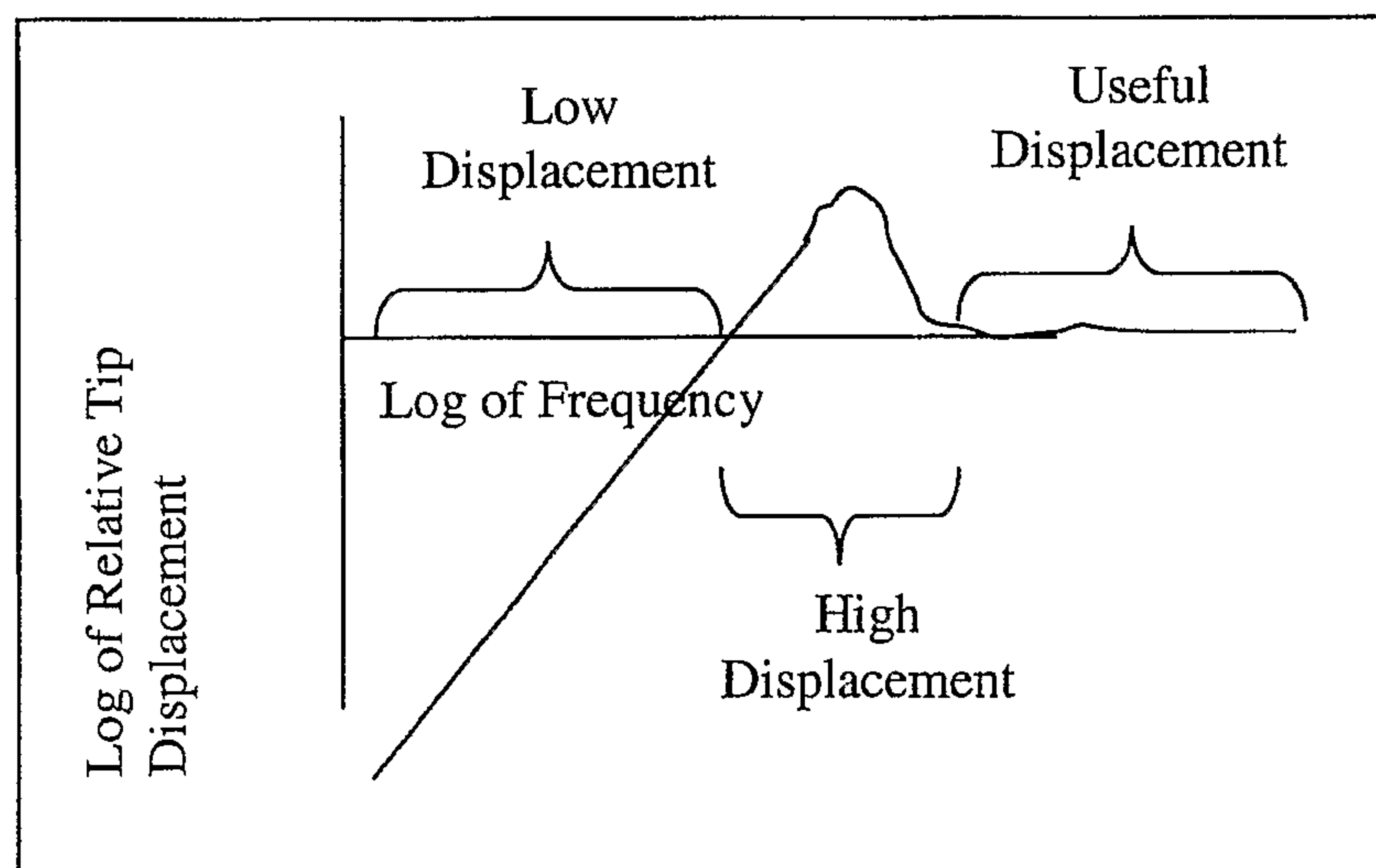
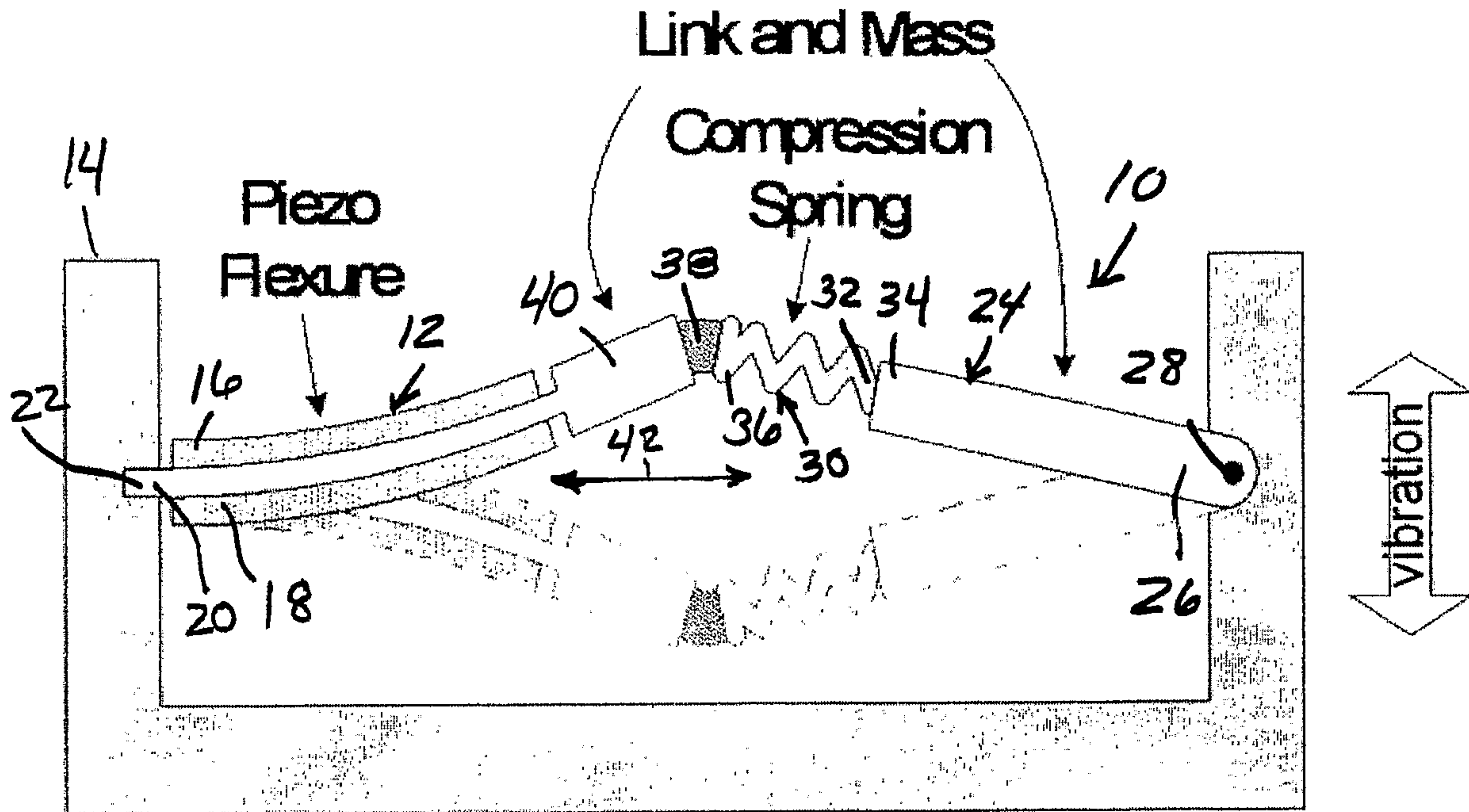


FIGURE 1

*FIGURE 2*



Two Stable Positions Shown