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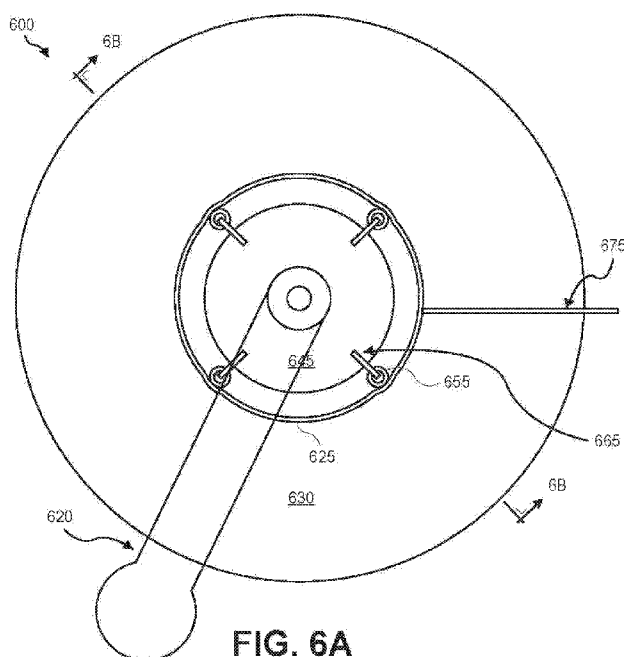
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[Continued on next page]

(54) Title: PIEZOELECTRIC ENERGY HARVESTER FOR HUMAN MOTION



(57) Abstract: An exemplary energy harvester 600 includes a piezoelectric ring 625, an eccentric mass 620 that rotates in response to external motion, and a piezoelectric stress inducer 645, 655 coupled with the eccentric mass and the piezoelectric ring. The piezoelectric stress inducer deforms the piezoelectric ring in response to rotational motion of the eccentric mass, causing the piezoelectric ring to generate electrical energy.



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PIEZOELECTRIC ENERGY HARVESTER FOR HUMAN MOTION

TECHNICAL FIELD

[0001] The present disclosure relates generally to energy harvesters, and more particularly, piezoelectric energy harvesters for human motion. Specifically, rotational momentum produced during bodily activity is converted to electrical energy which may be used by low consumption devices.

BACKGROUND

[0002] Kinetic energy harvesting, which involves converting mechanical energy from human motion into electrical energy, provides promising means for powering electronic devices, particularly in wearable, implantable, and/or portable devices. Although existing energy harvesters have been generally adequate for their intended purposes, they have not been entirely satisfactory in all respects.

BRIEF DESCRIPTION OF DRAWINGS

[0003] The present disclosure is best understood from the following detailed description when read with the accompanying figures. It is emphasized that, in accordance with the standard practice in the industry, various features are not drawn to scale and are used for illustration purposes only. In fact, the dimension of the various features may be arbitrarily increased or reduced for clarity of discussion.

[0004] FIGURES 1A–1D are simplified views of an exemplary energy harvester according to various aspects of the present disclosure;

[0005] FIGURES 2A–2D are simplified views of an exemplary energy harvester according to various aspects of the present disclosure;

[0006] FIGURE 3 is a simplified view of an exemplary energy harvester according to various aspects of the present disclosure;

[0007] FIGURE 4 is a simplified view of an exemplary energy harvester according to various aspects of the present disclosure;

[0008] FIGURE 5 is a simplified block diagram of an exemplary energy harvesting system according to various aspects of the present disclosure; and,

[0009] FIGURE 6A-6B is a simplified block diagram of an exemplary energy harvesting system according to various aspects of the present disclosure.

OVERVIEW OF EXAMPLE EMBODIMENTS

[0010] Energy harvesters disclosed herein are configured to maximize transfer of mechanical energy from motion, such as human motion, to piezoelectric energy harvesting mechanisms, which generate electrical energy. An exemplary energy harvester includes a piezoelectric diaphragm, an

eccentric mass that rotates in response to external motion, and a piezoelectric stress inducer coupled with the eccentric mass and the piezoelectric diaphragm. The piezoelectric stress inducer deforms the piezoelectric ring in response to rotational motion of the eccentric mass, causing the piezoelectric diaphragm to generate electrical energy. The disclosed energy harvesters can be implemented for powering electronic devices, particularly wearable devices, internet of things, and/or healthcare applications.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS

[0011] Kinetic energy harvesting, which involves converting mechanical energy from human motion into electrical energy, provides promising means for powering electronic devices. If properly harnessed, human motion can be implemented to supplement or replace batteries used for powering electronic devices, particularly in wearable, portable, and/or implantable devices, internet of things, and/or healthcare applications. Kinetic energy harvesters can employ various energy harvesting mechanisms, such as electromagnetic energy harvesting mechanisms (which generate electrical energy from electromagnetic fields) and piezoelectric harvesting mechanisms (which generate electrical energy from mechanical stress applied to piezoelectric materials). Piezoelectric energy harvesting mechanisms exhibit greater power output than electromagnetic energy harvesting mechanisms, particularly for micro-scale kinetic energy harvesters. However, since human motion is typically random and occurs at extremely low frequencies (for example, a few Hertz), challenges exist with how to effectively transfer mechanical energy from human motion to piezoelectric materials for generating electrical energy. The present disclosure provides energy harvesters configured to maximize transfer of mechanical energy from human motion to piezoelectric energy harvesting mechanisms.

[0012] FIGURE 1A is a simplified top diagrammatic view of an exemplary energy harvester 10 according to various aspects of the present disclosure, FIGURE 1B is a simplified cross-sectional view of energy harvester 10 along line 1B--1B of FIGURE 1A according to various aspects of the present disclosure; FIGURE 1C is a magnified top diagrammatic view of a portion of energy harvester 10 in FIGURE 1A according to various aspects of the present disclosure; and FIGURE 1D is a magnified top diagrammatic view of a portion of energy harvester 10 according to various aspects of the present disclosure. Energy harvester 10 converts mechanical energy into electrical energy. In various implementations, energy harvester 10 captures (scavenges) and transforms mechanical energy from motion (such as human motion) into electrical energy, which can be stored and managed for powering electronic devices. For example, energy harvester 10 can be implemented to power a wearable, portable, and/or implantable device, supplementing or even replacing batteries typically implemented for powering such devices. Energy harvester 10 can be implemented for providing power in electronics applications, internet of things applications, healthcare applications, and/or other

applications. For ease of discussion, FIGURES 1A–1D will be described concurrently, and FIGURES 1A–1D have been simplified for the sake of clarity to better understand the inventive concepts of the present disclosure. Additional features can be added in energy harvester 10, and some of the features described can be replaced, modified, or eliminated in other embodiments of energy harvester 10.

[0013] Energy harvester 10 includes a piezoelectric energy harvesting mechanism that converts (transfers) mechanical energy, such as that from human motion, into electrical energy. The piezoelectric energy harvesting mechanism includes an eccentric mass 20 and a piezoelectric diaphragm 25 arranged in a housing 30. As described below, eccentric mass 20 applies mechanical stress to piezoelectric diaphragm 25 as eccentric mass 20 (alternatively referred to as an eccentric rotating mass) freely rotates around an axis of rotation R in response to motion, causing piezoelectric diaphragm 25 to generate electrical energy. Piezoelectric diaphragm 25 includes any material that generates electrical energy (for example, accumulates charge) in response to applied mechanical stress or pressure. Conversely, the material generates mechanical strain in response to applied electrical energy, such as an applied electrical field. This phenomenon is referred to as piezoelectric effect. Exemplary piezoelectric materials include lead zirconate titanate (PZT), polyvinylidene difluoride (PVDF), quartz, other suitable piezoelectric material, or combination thereof. In FIGURE 1A, though eccentric mass 20 is depicted as a semicircle, and piezoelectric diaphragm 25 is depicted as a piezoelectric ring or piezoelectric circle, the present disclosure contemplates eccentric mass 20 and piezoelectric diaphragm 25 having any shape and/or configuration that facilitates the energy harvesting mechanisms described herein. In some implementations, piezoelectric diaphragm 25 includes more than one piezoelectric component, such as more than one piezoelectric ring. In some implementations, piezoelectric diaphragm 25 includes more than one piezoelectric section. For example, in some implementations, piezoelectric diaphragm 25 includes four piezoelectric material sections configured to form a circle, where each piezoelectric material section is configured as a quarter of the circle.

[0014] In FIGURES 1A–1C, energy harvester 10 includes a piezoelectric stress inducer 40 that connects mechanical energy collected by eccentric mass 20 to piezoelectric diaphragm 25. Piezoelectric stress inducer 40 is coupled with eccentric mass 20, and eccentric mass 20 drives (controls operation/movement of) piezoelectric stress inducer 40 as eccentric mass 20 rotates around axis of rotation R. Piezoelectric stress inducer 40 physically contacts piezoelectric diaphragm 25, deforming (deflecting) piezoelectric diaphragm 25 when piezoelectric stress inducer 40 moves in response to rotational motion of eccentric mass 20. Piezoelectric stress inducer 40 includes a proof mass 45, a bearing 50, proof masses 55, bearings 60, and proof mass connectors 65. Proof mass 45 is rotationally connected to bearing 50, such that proof mass 45 rotates around bearing 50. Each proof mass 55 is rotationally connected to a respective bearing 60, such that proof masses 55 rotate around

respective bearings 60. In various implementations, proof mass 45 and proof masses 55 are rotors. Proof mass connectors 65 connect rotational motion of proof mass 45 with proof masses 55. For example, in FIGURE 1C, proof mass connector 65 connects proof mass 45 to bearing 60, such that rotational motion of proof mass 45 causes rotational motion of proof mass 55 via bearing 60. Proof mass connectors 65 can have any connecting and/or linking components that link rotational motion of proof mass 45 with rotational motion of proof masses 55. Proof masses 55 physically contact piezoelectric diaphragm 25, such that proof masses 55 mechanically stress piezoelectric diaphragm 25 as proof masses 55 move in response to rotational motion of proof mass 45. Configuring proof masses 55 to rotate around respective bearings 60 reduces friction between proof masses 55 and piezoelectric diaphragm 25 as proof masses 55 roll along piezoelectric diaphragm 25 in response to rotational motion of proof mass 45.

[0015] Alternatively, as depicted in FIGURE 1D, proof masses 55 may be replaced with proof masses 70, where piezoelectric stress inducer 40 includes proof mass 45, bearing 50, and proof masses 70. In FIGURE 1D, each proof mass 70 is connected to proof mass 45, such that rotational motion of proof mass 45 causes motion of proof masses 70. In various implementations, proof mass 45 is a rotor, and proof masses 70 are rolling balls. Any connecting and/or linking components can be implemented to link rotational motion of proof mass 45 with motion of proof masses 70. Proof masses 70 physically contact piezoelectric diaphragm 25, such that proof masses 70 mechanically stress piezoelectric diaphragm 25 as proof masses 70 move in response to rotational motion of proof mass 45. Configuring proof masses 70 to roll in relation to proof mass 45 can further reduce friction between proof masses 70 and piezoelectric diaphragm 25 as proof masses 70 roll along piezoelectric diaphragm 25 in response to rotational motion of proof mass 45. In some implementations, piezoelectric stress inducer 40 can include a combination of proof masses 55 and proof masses 70. The present disclosure contemplates any number, shape, configuration, and/or combination for bearings 50, proof masses 55, bearings 60, proof mass connectors 65, and/or proof masses 70 that facilitate the energy harvesting mechanisms described herein.

[0016] In operation, eccentric mass 20 applies mechanical stress on piezoelectric diaphragm 25 via piezoelectric stress inducer 40 as eccentric mass 20 rotates within housing 30 around axis of rotation R in response to motion, such as human motion. For example, energy harvester 10 is configured to connect rotational motion of eccentric mass 20 with rotational motion of proof mass 45 and proof masses 55 (and/or proof masses 70), allowing eccentric mass 20 to drive proof mass 45 and proof masses 55 (and/or proof masses 70). In FIGURES 1A–1C, eccentric mass 20 is rotationally connected to bearing 50, such that eccentric mass 20 rotates around bearing 50. Eccentric mass 20 is also connected to proof mass 45, so that rotational motion of eccentric mass 20 causes rotational motion of proof mass 45. As proof mass 45 rotates in response to rotational motion of eccentric mass 20, proof masses 55 rotate in response to rotational motion of proof mass 45 (for example, because

bearings 60 and proof mass connectors 65 move together with proof mass 45). Bearing 50 and bearings 60 allow rotational motion of eccentric mass 20 to drive proof masses 55, as bearing 50 and bearings 60 also rotate around the same point (for example, axis of rotation R) as eccentric mass 20. Because proof masses 55 remain in physical contact with piezoelectric diaphragm 25, as long as eccentric mass 20 rotates in response to a tiniest of movement, proof masses 55 will cause stress variation on piezoelectric diaphragm 25. Proof masses 55 roll along piezoelectric diaphragm 25, deflecting or deforming piezoelectric diaphragm 25, which causes piezoelectric diaphragm 25 to generate electrical energy. Essentially, since proof masses 55 contact piezoelectric diaphragm 25 and apply stress to piezoelectric diaphragm in response to motion of eccentric mass 20, energy harvester 10 can generate power in response to any motion of eccentric mass 20 (in other words, no minimum degree of rotation is required). In various implementations, eccentric mass 20 has a mass (in some examples, as heavy as possible) that maximizes transfer of mechanical energy from external motion (such as human motion) to piezoelectric diaphragm 25. Energy harvester 10 thus generates power from piezoelectric diaphragm 25 in response to rotational motion of eccentric mass 20. Any appropriate electronics circuitry can harvest electrical energy generated by piezoelectric diaphragm 25, which can be used for powering a load or stored, for example, by capacitors and/or batteries.

[0017] FIGURE 2A is a simplified top diagrammatic view of an exemplary energy harvester 10A according to various aspects of the present disclosure, FIGURE 2B is a simplified cross-sectional view of energy harvester 10A along line 2B–2B in FIGURE 2A according to various aspects of the present disclosure; FIGURE 2C is a magnified top diagrammatic view of a portion of energy harvester 10A in FIGURE 2A according to various aspects of the present disclosure; and FIGURE 2D is a magnified top diagrammatic view of a portion of energy harvester 10A in FIGURE 2A according to various aspects of the present disclosure. Energy harvester 10A converts mechanical energy into electrical energy. In various implementations, energy harvester 10A captures (scavenges) and transforms mechanical energy from motion (such as human motion) into electrical energy, which can be stored and managed for powering electronic devices. For example, energy harvester 10A can be implemented to power a wearable, portable, and/or implantable device, supplementing or even replacing batteries typically implemented for powering such devices. Energy harvester 10A can be implemented for providing power in electronics applications, internet of things applications, healthcare applications, and/or other applications. For ease of discussion, FIGURES 2A–2D will be described concurrently. FIGURES 2A–2D have been simplified for the sake of clarity to better understand the inventive concepts of the present disclosure. Additional features can be added in energy harvester 10A, and some of the features described can be replaced, modified, or eliminated in other embodiments of energy harvester 10A.

[0018] Energy harvester 10A of FIGURES 2A–2D is similar in many respects to energy harvester 10 of FIGURES 1A–1C. Accordingly, similar features in FIGURES 1A–1C and FIGURES

2A–2D are identified by the same reference numerals for clarity and simplicity. To increase power output, energy harvester 10A includes a piezoelectric diaphragm that includes more than one piezoelectric ring for generating electrical energy. For example, energy harvester 10A includes piezoelectric diaphragm 25 and a piezoelectric diaphragm 25A, which can collectively be referred to as a piezoelectric ring. In FIGURES 2A–2D, a piezoelectric stress inducer includes piezoelectric stress inducer 40 configured to connect mechanical energy collected by eccentric mass 20 to piezoelectric diaphragm 25, and a piezoelectric stress inducer 40A configured to connect mechanical energy collected by eccentric mass 20 to piezoelectric diaphragm 25A. For example, piezoelectric stress inducer 40A includes a proof mass 75, proof masses 85, bearings 90, and proof mass connectors 95. Proof mass 75 is connected to eccentric mass 20, so that rotational motion of eccentric mass 20 causes rotational motion of proof mass 75. Each proof mass 85 is rotationally connected to a respective bearing 90, such that proof masses 85 rotate around respective bearings 90. In various implementations, proof mass 75 and proof masses 85 are rotors. Proof mass connectors 95 connect rotational motion of proof mass 75 with proof masses 85. For example, in FIGURE 2D, proof mass connector 95 connects proof mass 75 to bearing 90, such that rotational motion of proof mass 75 causes rotational motion of proof mass 85 via bearing 90. Proof mass connectors 95 can have any connecting and/or linking components that link rotational motion of proof mass 75 with rotational motion of proof masses 85. Proof masses 85 physically contact piezoelectric diaphragm 25A, such that proof masses 85 mechanically stress piezoelectric diaphragm 25A as proof masses 85 move in response to rotational motion of proof mass 75. The present disclosure contemplates any number, shape, configuration, and/or combination for bearings 50, proof masses 55, bearings 60, proof mass connectors 65, proof masses 75, proof masses 85, bearings 90, and/or proof mass connectors 95 that facilitate the energy harvesting mechanisms described herein.

[0019] To further increase power output, energy harvester 10 can implement the piezoelectric energy harvesting mechanisms described above with other power generation mechanisms, such as electromagnetic energy harvesting mechanisms and/or electrostatic energy harvesting mechanisms. In such configurations, as rotating eccentric mass 20 causes piezoelectric diaphragm 25 to generate electricity, rotating eccentric mass 20 can simultaneously cause magnetic flux changes and/or electrostatic charge changes.

[0020] FIGURE 3 is a simplified cross-sectional view of an exemplary energy harvester 200 according to various aspects of the present disclosure according to various aspects of the present disclosure. Energy harvester 200 is configured to convert simultaneously mechanical energy into electrical energy. In various implementations, energy harvester 200 captures (scavenges) and transforms mechanical energy from motion (such as human motion) into electrical energy, which can be stored and managed to provide power in electronics applications. Energy harvester 200 includes a piezoelectric energy harvesting mechanism 205, which generates electrical energy in response to

mechanical stress, and an electromagnetic energy harvesting mechanism 210, which generates electrical energy in response to an electromagnetic field. Rotational motion of eccentric mass 20 can simultaneously provide the mechanical stress and the electromagnetic field necessary respectively for piezoelectric energy harvesting mechanism 205 and electromagnetic energy harvesting mechanism 210 to generate electrical energy. Piezoelectric energy harvesting mechanism 205 can be configured as the piezoelectric energy harvesting mechanisms described above with reference to FIGURES 1A–1D and FIGURES 2A–2C. For example, piezoelectric energy harvesting mechanism 205 can include piezoelectric diaphragm 25 and piezoelectric diaphragm 25A, which generate electrical energy in response to mechanical stress applied thereto by eccentric mass 20 via piezoelectric stress inducer 40. Electromagnetic energy harvesting mechanism 210 generates electrical energy in response to a change in magnetic flux caused by rotational motion of eccentric mass 20. For example, electromagnetic energy harvesting mechanism 210 can include a magnetic layer 215 and coils 220 disposed over a substrate 225. Magnetic layer 215 is rotationally connected to bearing 50, such that magnetic layer 215 rotates around bearing 50. Eccentric mass 20 can drive magnetic layer 215, where rotational motion of eccentric mass 20 causes rotational motion of magnetic layer 215 (which serves as a rotor). Rotational motion of magnetic layer 215 generates magnetic flux changes through coils 220 (which serve as stators), causing coils 220 to generate electrical energy. In various implementations, electromagnetic energy harvesting mechanism 210 can be configured as described in Romero, E. et al, “Rotational Energy Harvester for Body Motion”, Micro Electro Mechanical Systems (MEMS), 2011 IEEE 24th International Conference on pages 1325–1328 (23–27 Jan. 2011), the entire disclosure of which is incorporated herein by reference. In such implementations, piezoelectric energy harvesting mechanism 205 and electromagnetic energy harvesting mechanism 210 can use the same eccentric mass, eccentric mass 20, and the same bearing, bearing 50, for generating electrical energy. FIGURE 3 has been simplified for the sake of clarity to better understand the inventive concepts of the present disclosure. Additional features can be added in energy harvester 200, and some of the features described can be replaced, modified, or eliminated in other embodiments of energy harvester 200.

[0021] FIGURE 4 is a simplified cross-sectional view of an exemplary energy harvester 300 according to various aspects of the present disclosure according to various aspects of the present disclosure. Energy harvester 300 is configured to convert simultaneously mechanical energy into electrical energy. In various implementations, energy harvester 300 captures (scavenges) and transforms mechanical energy from motion (such as human motion) into electrical energy, which can be stored and managed to provide power in electronics applications. Energy harvester 300 includes a piezoelectric energy harvesting mechanism 305, which generates electrical energy in response to mechanical stress, and an electrostatic energy harvesting mechanism 310, which generates electrical energy in response to an electrostatic charge. Rotational motion of eccentric mass 20 can simultaneously provide the mechanical stress and the electrostatic charge necessary respectively for

piezoelectric energy harvesting mechanism 305 and an electrostatic energy harvesting mechanism 310 to generate electrical energy. Piezoelectric energy harvesting mechanism 305 can be configured as the piezoelectric energy harvesting mechanisms described above with reference to FIGURES 1A–1D and FIGURES 2A–2C. For example, piezoelectric energy harvesting mechanism 305 can include piezoelectric diaphragm 25 and piezoelectric diaphragm 25A, which generate electrical energy in response to mechanical stress applied thereto by eccentric mass 20 via piezoelectric stress inducer 40. Electrostatic energy harvesting mechanism 310 can generate electrical energy in response to a change in electrostatic charge caused by rotational motion of eccentric mass 20. In various implementations, electrostatic energy harvesting mechanism 310 can be configured as a triboelectric energy harvesting mechanism. For example, electrostatic energy harvesting mechanism 310 can include a material layer 315, a material layer 320, and an electrode layer 325 disposed over a substrate 330. Material layer 315 is rotationally connected to bearing 50, such that material layer 315 rotates around bearing 50. Eccentric mass 20 can drive material layer 315, where rotational motion of eccentric mass 20 causes rotational motion of material layer 315 (which serves as a rotor). Rotational motion of material layer 315 generates triboelectrification through material layer 320 and electrodes 325 (which serve as a stator), causing electrodes 325 to generate electrical energy. In various implementations, triboelectric energy harvesting mechanism 210 can be configured as described in Zhu, G. et al, “Radial-arrayed rotary electrification for high performance triboelectric generator”, Nature Communications, Article No. 3426 (4 Mar 2014), the entire disclosure of which is incorporated herein by reference. In such implementations, piezoelectric energy harvesting mechanism 305 and electrostatic energy harvesting mechanism 310 can use the same eccentric mass, eccentric mass 20, and the same bearing, bearing 50, for generating electrical energy. FIGURE 4 has been simplified for the sake of clarity to better understand the inventive concepts of the present disclosure. Additional features can be added in energy harvester 300, and some of the features described can be replaced, modified, or eliminated in other embodiments of energy harvester 300.

[0022] FIGURE 5 is a simplified block diagram of an exemplary energy harvesting system 400 according to various aspects of the present disclosure according to various aspects of the present disclosure. Energy harvesting system 400 can be implemented in a wearable, portable, and/or implantable device, where energy harvesting system 400 powers the wearable, portable, and/or implantable device from human motion. Energy harvesting system 400 includes an energy harvester component 405, a power management component 410, an energy storage component 415, and an application component 420. Energy harvester component 405 includes any of the energy harvesters described above with reference to FIGURES 1–4. Power management component 410 is configured to manage (distribute) electrical energy generated by energy harvester component 405. Power management component 410 can transfer electrical energy generated by energy harvester component 405 to energy storage component 415 or directly to application component 420. Energy storage

component 415 is configured to store electrical energy, which can be used for powering application component 420. Application component 420 includes any load powered by electrical energy generated and/or stored by energy harvesting system 400. For example, application component 420 is a wireless sensor node in a wireless network system. In another example, application component 420 is a transceiver of an electronic device. In yet another example, application component 420 is any electronic circuit and/or electronic component powered by electrical energy generated by energy harvesting system 400. Application component 420 is powered by electrical energy from power management component 410 and/or from energy storage component 415. FIGURE 5 has been simplified for the sake of clarity to better understand the inventive concepts of the present disclosure. Additional features can be added in energy harvesting system 400, and some of the features described can be replaced, modified, or eliminated in other embodiments of energy harvesting system 400.

[0023] According to one or aspects of the present disclosure, FIGURE 6A is a lateral view of an energy harvester 600 which implements a pendulum 620 as an eccentric mass. Energy harvester 600 comprises housing 630, electrode 675, annulus 625, bearing member 645, armature 665, bearing 655 and pendulum 620.

[0024] As is known in the art, pendulum 620 is a weight suspended from a pivot disposed in the center of bearing member 645 so that it can swing freely. When pendulum 620 is displaced sideways from its resting, equilibrium position, it is subject to a restoring force due to gravity that will accelerate it back toward the equilibrium position. When released, the restoring force combined with the pendulum's mass causes it to oscillate about the equilibrium position, swinging back and forth.

[0025] In some embodiments, a longer lever arm is used on pendulum 620. This produces a greater restoring torque at bearing member 645 at the cost of a longer period, pursuant to:

$$T = 2\pi \sqrt{\frac{l}{g}}$$

where, T is the period, l is the length and g is the local acceleration of gravity.

[0026] The present disclosure contemplates the tuning harvester 600 such that it is similar to the gate frequency of an individual thereby maximizing pendulum 620 movement and consequent harvested energy.

[0027] Bearing member 645 can be a disc of any suitable sturdy but conductive material. In some embodiments, bearing member is made from steel. While in others, bearing member 645 is a high tensile strength polymer coated in a conductive copper. Bearing member's 645 purpose is to transfer torque exerted by pendulum 620 to armature(s) 665.

[0028] Armature 665 carries a radial load from bearing member 645 to bearing 655. Similar in suitable materials to bearing member 645, armature 665 is constructed from high tensile strength, conductive materials. Armature 665 is subjected to compressive stress and shearing stress due to the

torque exerted by bearing member 645 which is opposed by friction at the bearing 655/annulus 625 interface.

[0029] Annulus 625 is a substantially flat ring of piezoelectric material. A piezoelectric material is a solid substance that accumulates electric charge in response to applied mechanical stress. The piezoelectric effect is understood as the linear electromechanical interaction between the mechanical and the electrical state in crystalline materials with no inversion symmetry. The piezoelectric effect is a reversible process in that materials exhibiting the direct piezoelectric effect (the internal generation of electrical charge resulting from an applied mechanical force) also exhibit the reverse piezoelectric effect (the internal generation of a mechanical strain resulting from an applied electrical field). In one embodiment, annulus 625 comprises lead zirconate titanate crystals which will generate measurable piezoelectricity when their static structure is deformed by about 0.1% of the original dimension.

[0030] In some embodiments, annulus 625 represents a slice of a pipe or cylinder. In that, it is substantially circular but having somewhat flat inner and outer surfaces. In other embodiments, the inner surface is grooved in the radially direction such that it substantially mates with a ball bearing. However, any suitable shape or construction is not beyond the scope of the present disclosure.

[0031] Electrode 675 comprises any suitable conductive material. Its purpose is to carry away the electrical charge induced by pressure from bearing 655 against annulus 625. In some embodiments, electrode 675 rigidly circumscribes annulus 625 giving rise to increased pressures from bearing 655. In the present embodiment, bearing 655 is a conductive roller bearing. Roller bearings are a type of rolling-element bearing that uses cylinders (rollers) to maintain the separation between the moving parts of the bearing (as opposed to using balls as the rolling element). The purpose of a roller bearing is to reduce rotational friction and support radial and axial loads.

[0032] FIGURE 6B is a cross-sectional view of an energy harvester 600 which implements a pendulum 620 as an eccentric mass, according to one or more aspects of the present disclosure. Energy harvester 600 comprises, annulus 625, bearing member 645, armature 665, main bearing 650, bearing 655 and pendulum 620.

[0033] In practice, bearing 655 substantially presses against annulus 625 thereby engendering a piezoelectric effect. As pendulum 620 radially displaces relative to housing 630, electric charge accumulates on the inner and outer surfaces of annulus 625. The resultant potential between bearing 655 and electrode 675 can then be utilized or stored in any suitable energy storage device, e.g., capacitor, battery, etc. In some embodiments, a conductive brush disposed on housing 630 carries away the electrical charge. Known in the art, the conductive brush can be disposed to create any conduction pathway from the inner annulus 625, for example, brushing the bearing member 645. This is why it is useful, although not necessary, to have bearing 655, armature 665 and bearing member 645 all be substantially conductive.

[0034] In various implementations, the various components of the FIGURES can be implemented on a board of an associated electronic device. The board can be a general circuit board that can hold various components of an internal electronic system of the electronic device and, further, provide connectors for other peripherals. More specifically, the board can provide the electrical connections by which the other components of the system can communicate electrically. Any suitable processors (inclusive of digital signal processors, microprocessors, supporting chipsets, etc.), memory elements, etc. can be suitably coupled to the board based on particular configuration needs, processing demands, computer designs, other considerations, or a combination thereof. Other components, such as external storage, sensors, controllers for audio/video display, and peripheral devices may be attached to the board as plug-in cards, via cables, or integrated into the board itself.

[0035] In various implementations, the various components of the FIGURES can be implemented as stand-alone modules (for example, a device with associated components and circuitry configured to perform a specific application or function) or implemented as plug-in modules into application specific hardware of electronic devices. Note that particular embodiments of the present disclosure may be readily included in a system-on-chip (SOC) package, either in part, or in whole. An SOC represents an integrated circuit that integrates components of a computer or other electronic system into a single chip. It may contain digital, analog, mixed-signal, and often radio frequency functions: all of which may be provided on a single chip substrate. Other embodiments may include a multi-chip-module (MCM), with a plurality of separate ICs located within a single electronic package and configured to interact closely with each other through the electronic package. In various other embodiments, the various functions described herein may be implemented in one or more semiconductor cores (such as silicon cores) in application specific integrated circuits (ASICs), field programmable gate arrays (FPGAs), other semiconductor chips, or combinations thereof.

[0036] Note that the activities discussed above with reference to the FIGURES are applicable to any integrated circuits that involve signal processing, particularly those that can execute specialized software programs or algorithms, some of which may be associated with processing digitized real-time data. Certain embodiments can relate to multi-DSP signal processing, floating point processing, signal/control processing, fixed-function processing, microcontroller applications, etc. In certain contexts, the features discussed herein can be applicable to medical systems, scientific instrumentation, wireless and wired communications, radar, industrial process control, audio and video equipment, current sensing, instrumentation (which can be highly precise), and other digital-processing-based systems. Moreover, certain embodiments discussed above can be provisioned in digital signal processing technologies for medical imaging, patient monitoring, medical instrumentation, and home healthcare. This could include pulmonary monitors, accelerometers, heart rate monitors, pacemakers, etc. Other applications can involve automotive technologies for safety systems (e.g., stability control systems, driver assistance systems, braking systems, infotainment and

interior applications of any kind). Furthermore, powertrain systems (for example, in hybrid and electric vehicles) can use high-precision data conversion products in battery monitoring, control systems, reporting controls, maintenance activities, etc. In yet other example scenarios, the teachings of the present disclosure can be applicable in the industrial markets that include process control systems that help drive productivity, energy efficiency, and reliability. In consumer applications, the teachings of the signal processing circuits discussed above can be used for image processing, auto focus, and image stabilization (e.g., for digital still cameras, camcorders, etc.). Other consumer applications can include audio and video processors for home theater systems, DVD recorders, and high-definition televisions. Yet other consumer applications can involve advanced touch screen controllers (e.g., for any type of portable media device). Hence, such technologies could readily be a part of smartphones, tablets, security systems, PCs, gaming technologies, virtual reality, simulation training, etc.

WHAT IS CLAIMED IS:

1. An energy harvester comprising:
a piezoelectric ring;
an eccentric mass that rotates in response to external motion; and
a piezoelectric stress inducer coupled with the eccentric mass and the piezoelectric ring,
wherein the piezoelectric stress inducer deforms the piezoelectric ring in response to rotational motion of the eccentric mass.
2. The energy harvester of claim 1, wherein the piezoelectric stress inducer includes a proof mass configured to roll along the piezoelectric ring in response to rotational motion of the eccentric mass.
3. The energy harvester of claim 1, wherein the piezoelectric stress inducer includes:
a first proof mass connected to the eccentric mass, such that rotational motion of the eccentric mass causes rotational motion of the first proof mass; and
a second proof mass connected to the first proof mass, such that rotational motion of the first proof mass causes rotational motion of the second proof mass.
4. The energy harvester of claim 3, wherein the piezoelectric stress inducer further includes a first bearing and a second bearing, wherein the eccentric mass is rotationally connected to the first bearing and the second mass is rotationally connected to the second bearing.
5. The energy harvester of claim 3, wherein the second proof mass physically contacts the piezoelectric ring.
6. The energy harvester of claim 3, wherein the first proof mass is a rotor, and the second proof mass is a rotor.
7. The energy harvester of claim 3, wherein the first proof mass is a rotor, and the second proof mass is a rolling ball.
8. The energy harvester of claim 1, further comprising an electrostatic component configured to generate electrical energy in response to rotational motion of the eccentric mass.
9. The energy harvester of claim 8, wherein the eccentric mass and the electrostatic component are connected to a same bearing.
10. The energy harvester of claim 1, further comprising an electromagnetic component configured to generate electrical energy in response to rotational motion of the eccentric mass.
11. The energy harvester of claim 10, wherein the eccentric mass and the electromagnetic energy component are connected to a same bearing.
12. A method for generating electrical energy in response to human motion, the method comprising:
collecting, by an eccentric mass, mechanical energy from human motion; and

transferring, by rotational motion of the eccentric mass, the mechanical energy from human motion to a piezoelectric ring.

13. The method of claim 12, wherein transferring the mechanical energy includes causing the piezoelectric ring to deform in response to rotational motion of the eccentric mass.

14. The method of claim 13, wherein causing the piezoelectric ring to deform includes rolling a proof mass along the piezoelectric ring in response to rotational motion of the eccentric mass.

15. The method of claim 12, wherein transferring the mechanical energy includes:
causing a first proof mass to rotate in response to the rotational motion of the eccentric mass;
and

causing a second proof mass to rotate in response to rotational motion of the first proof mass.

16. A device for converting mechanical energy from human motion into electrical energy, the device comprising:

a piezoelectric ring;

an eccentric mass that rotates in response to human motion; and

a piezoelectric stress inducer coupled with the eccentric mass and the piezoelectric ring,

wherein the piezoelectric stress inducer physical contacts the piezoelectric ring.

17. The device of claim 16, wherein the piezoelectric stress inducer includes:

a first proof mass connected to the eccentric mass, such that rotational motion of the eccentric mass causes rotational motion of the first proof mass; and

a second proof mass connected to the first proof mass, such that rotational motion of the first proof mass causes rotational motion of the second proof mass.

18. The device of claim 17, wherein the piezoelectric stress inducer further includes a first bearing and a second bearing, wherein the eccentric mass is rotationally connected to the first bearing and the second mass is rotationally connected to the second bearing.

19. The device of claim 16, wherein the piezoelectric stress inducer includes a proof mass configured to roll along the piezoelectric ring in response to rotational motion of the eccentric mass.

20. The device of claim 16, further comprising an electromagnetic component or an electrostatic component configured to generate electrical energy in response to rotational motion of the eccentric mass.

21. A device for converting mechanical energy from human motion into electrical energy, the device comprising:

an outer assembly comprising:

a housing;

an annulus substantially comprising piezoelectric material; and,

an electrode in electrical communication with the annulus;

and, an inner assembly comprising:

- an eccentric mass;
- a bearing member connected to the eccentric mass;
- an armature connected to the bearing member; and,
- a bearing disposed at the distal end of the armature wherein, the bearing dynamically contacts the annulus;

whereby, the inner and outer assemblies rotate relative to one another about a pivot point at the center of the bearing member thereby producing some deformation in the annulus due to bearing contact.

22. The device of claim 21 wherein, the eccentric mass is substantially pendulum shaped.
23. The device of claim 21 wherein, the bearing is a roller bearing.
24. The device of claim 23 wherein, the roller bearing is electrically conductive.
25. The device of claim 24 wherein, the armature is electrically conductive.
26. The device of claim 21 wherein, the electrode circumscribes the annulus.
27. The device of claim 26 wherein, the electrode is substantially rigid such that it the annulus is pinched by the deformation.
28. The device of claim 21 wherein, the annulus exhibits a shape that of a slice of a cylinder.
29. The device of claim 28 wherein, the annulus further comprises a radial groove on it's inner surface.
30. The device of claim 29 wherein, the bearing is a ball bearing which substantially interfaces with radial groove.

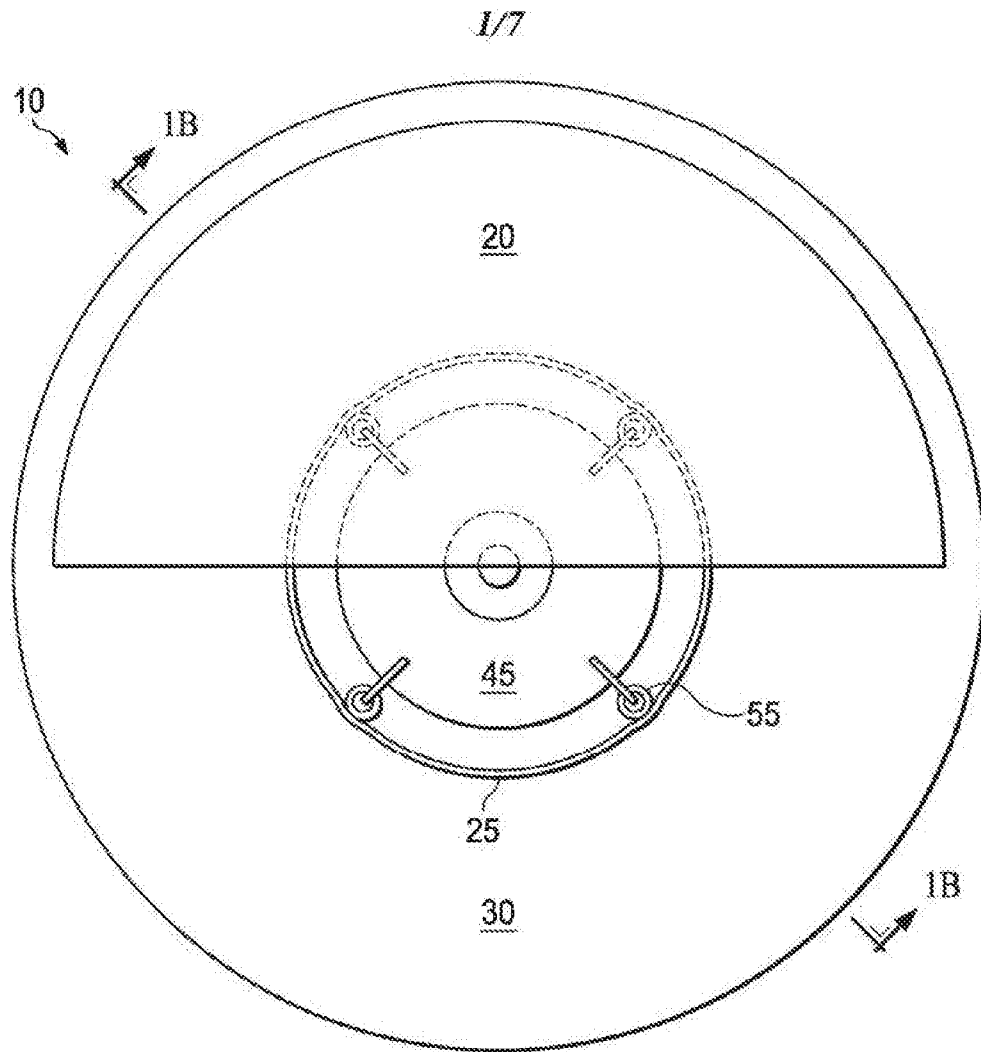


FIG. 1A

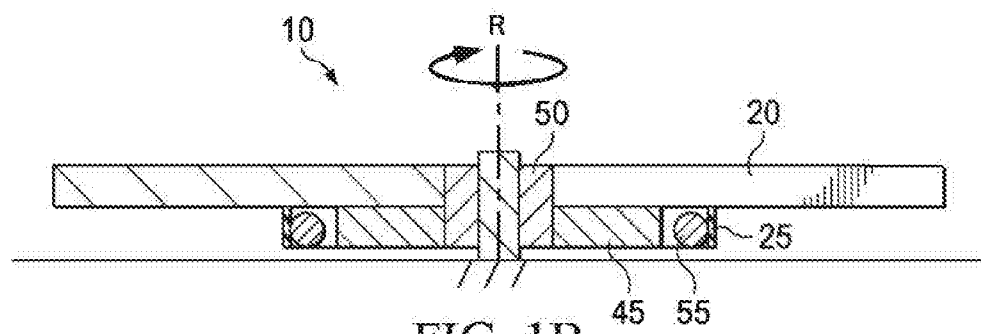
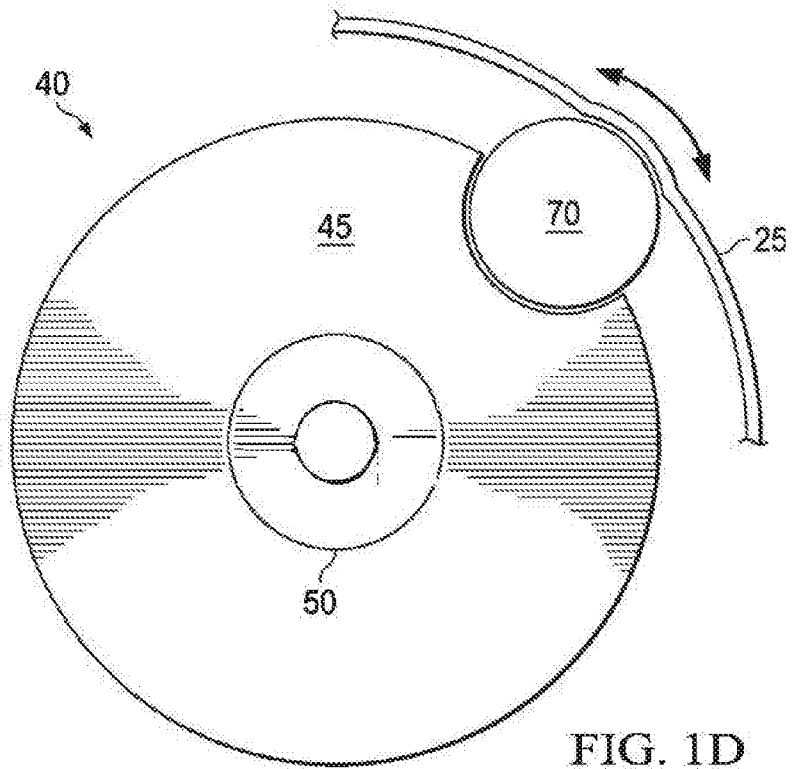
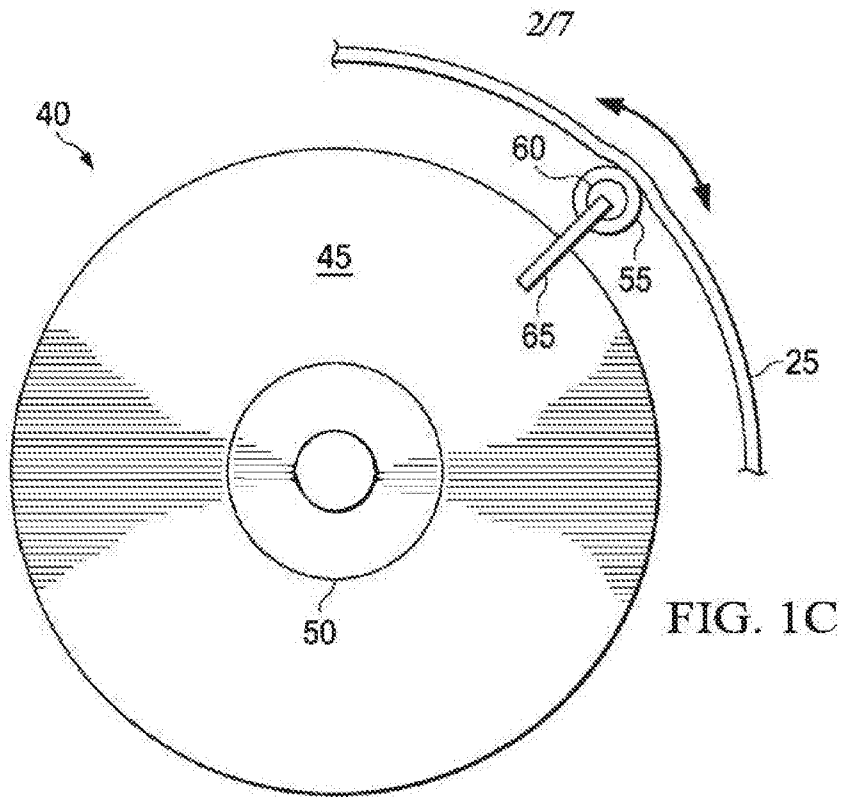


FIG. 1B



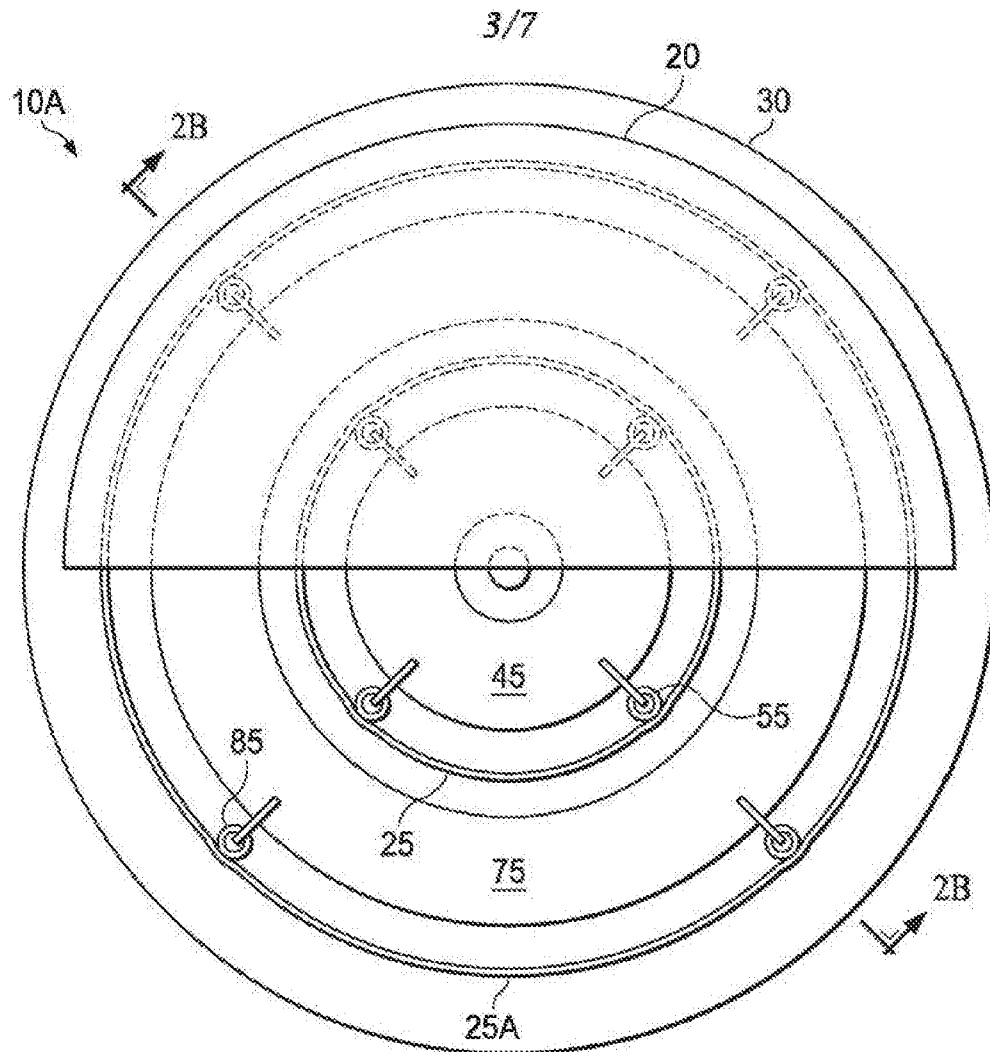


FIG. 2A

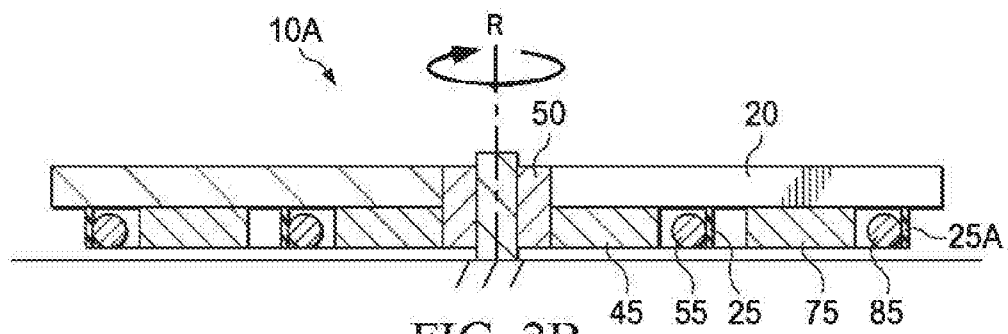
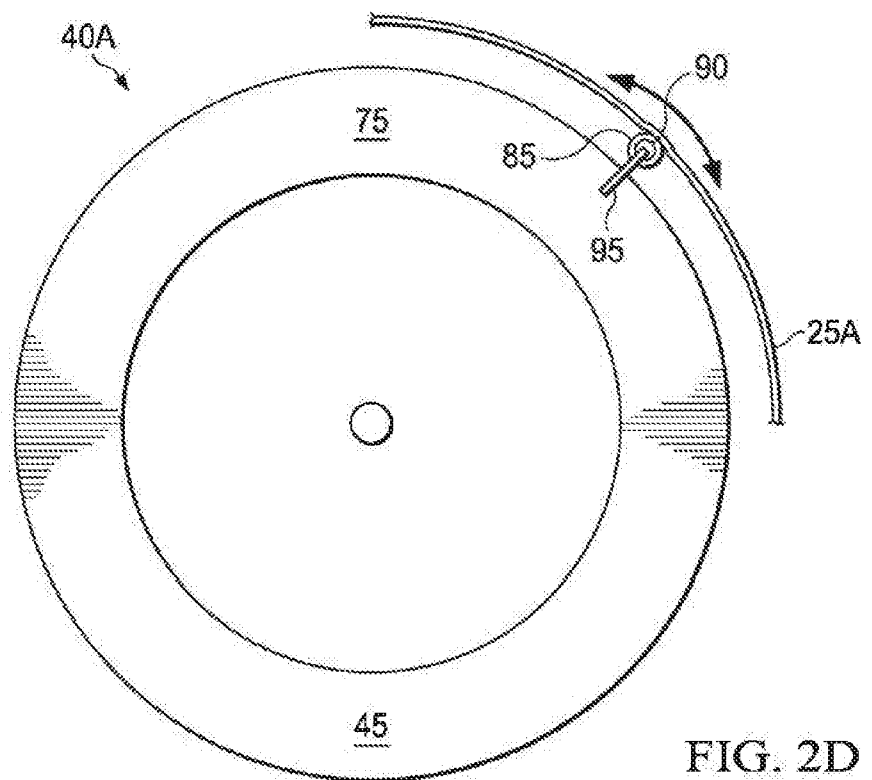
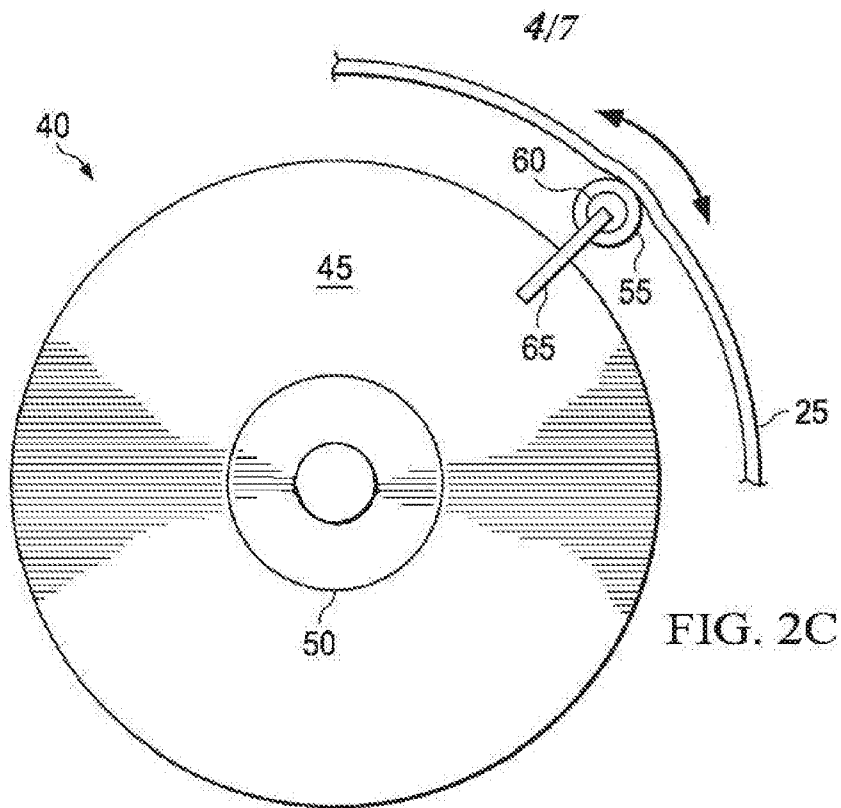


FIG. 2B



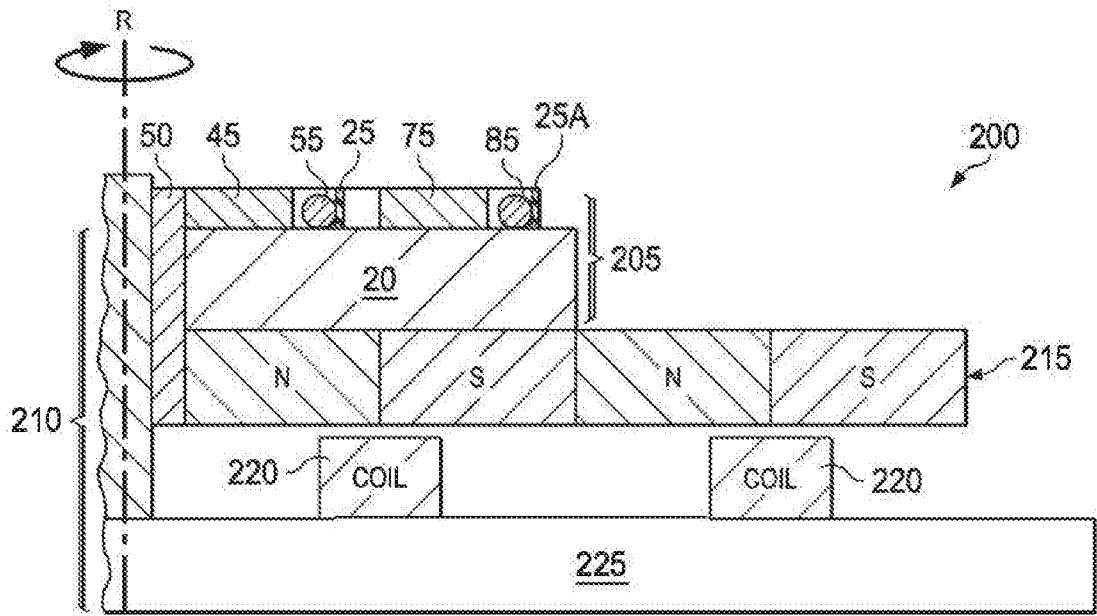


FIG. 3

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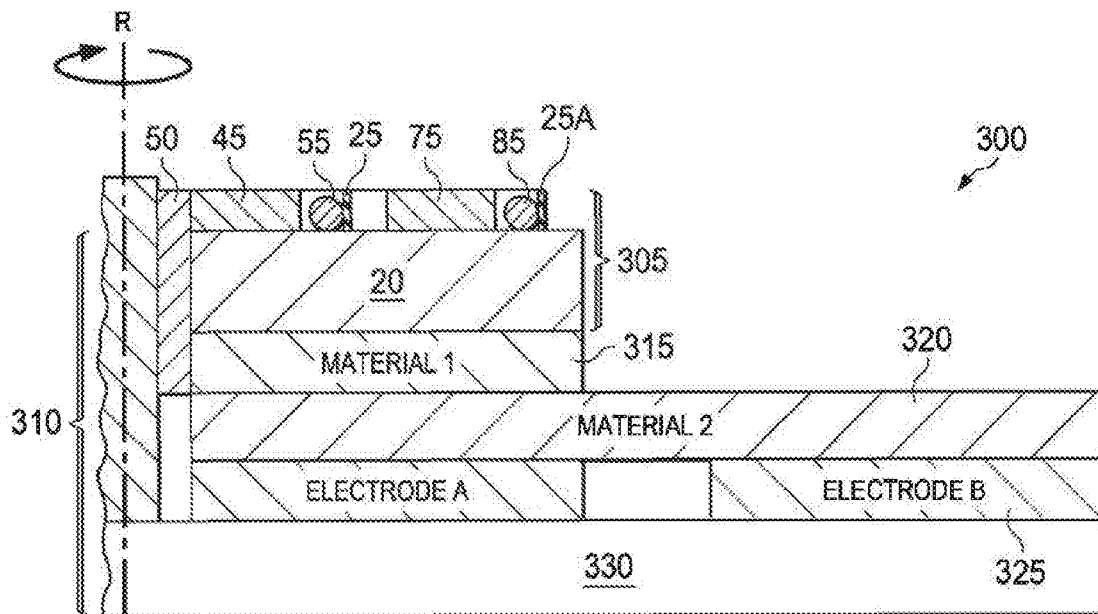


FIG. 4

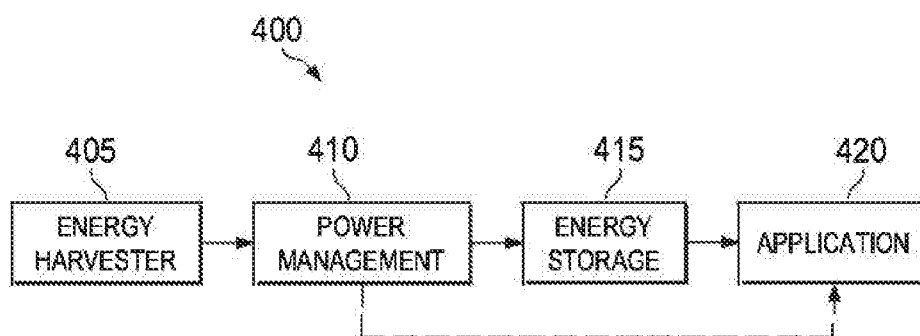
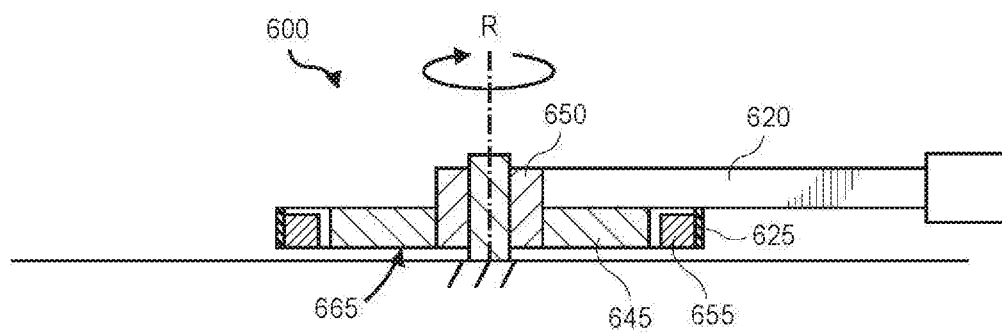
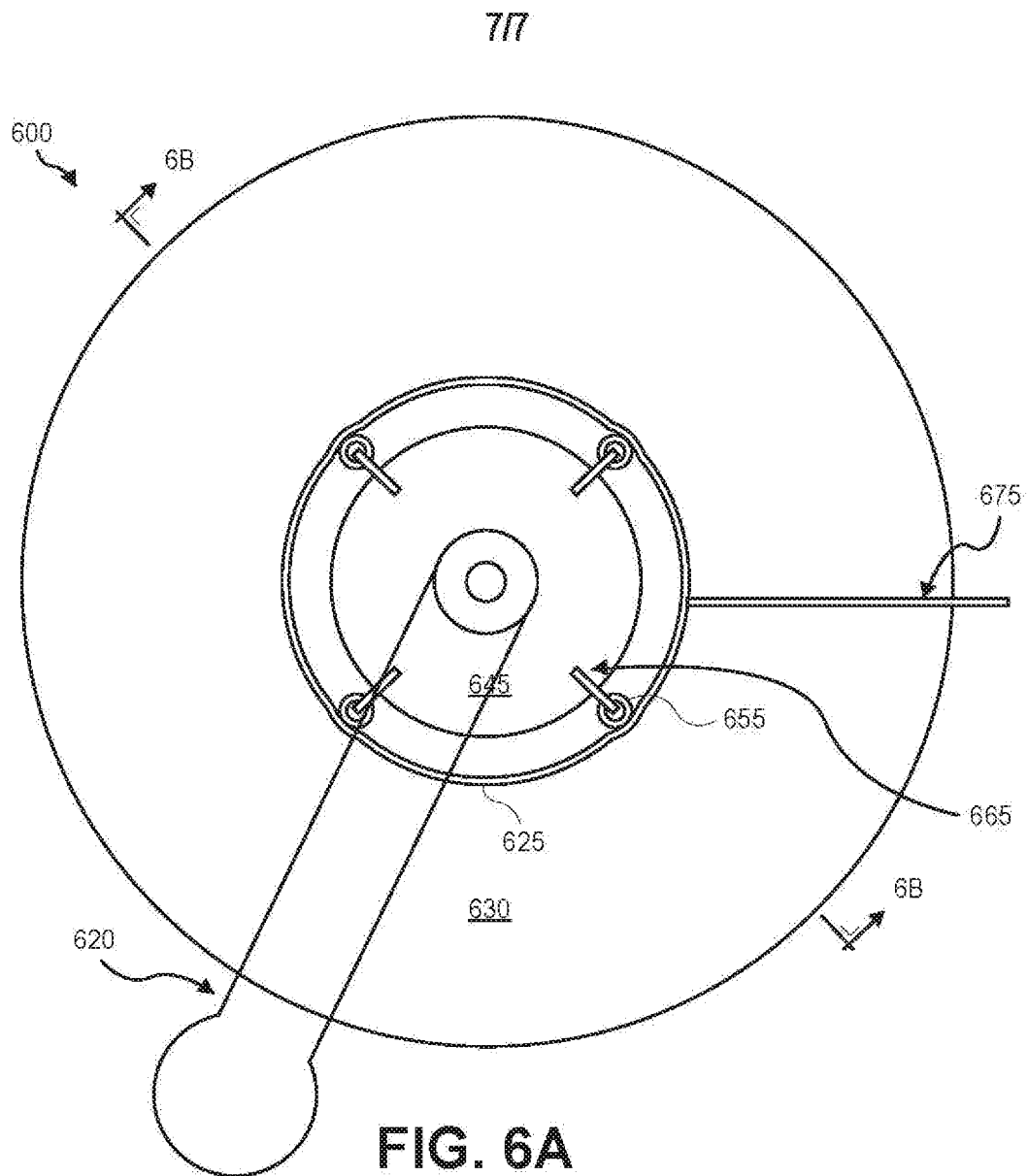


FIG. 5



INTERNATIONAL SEARCH REPORT

International application No
PCT/US2017/017341

A. CLASSIFICATION OF SUBJECT MATTER

INV. H02N2/18
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H02N

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	US 5 512 795 A (EPSTEIN MICHAEL Y [US] ET AL) 30 April 1996 (1996-04-30) abstract column 2, line 16 - column 5, line 67; figures 1-6 column 6, line 19 - column 7, line 19; figures 7,8	1-6,8, 16-28 7
Y	----- CN 103 490 667 A (UNIV NANJING AERONAUTICS) 1 January 2014 (2014-01-01) abstract paragraphs [0008] - [0011]; figures 1-3	7
A	----- CN 104 158 438 A (UNIV TIANJIN) 19 November 2014 (2014-11-19) abstract figures 1,2,5 -----	1,16,21

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

19 April 2017

Date of mailing of the international search report

20/06/2017

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
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Authorized officer

Lang, Thomas

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2017/017341

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

1-8, 16-19, 21-28(completely); 20(partially)

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. claims: 1-8, 16-19, 21-28(completely); 20(partially)

An energy harvester comprising a piezoelectric ring; an eccentric mass that rotates in response to external motion; and a piezoelectric stress inducer coupled with the eccentric mass and the piezoelectric ring, wherein the piezoelectric stress inducer deforms the piezoelectric ring in response to rotational motion of the eccentric mass (claim 1), wherein the piezoelectric stress inducer includes a first proof mass connected to the eccentric mass, such that rotational motion of the eccentric mass causes rotational motion of the first proof mass; and a second proof mass connected to the first proof mass, such that rotational motion of the first proof mass causes rotational motion of the second proof mass (claim 3); wherein the first proof mass is a rotor, and the second proof mass is a rolling ball (claim 7).

2. claim: 9

The energy harvester of claim 1, further comprising an electrostatic component configured to generate electrical energy in response to rotational motion of the eccentric mass (claim 8), wherein the eccentric mass and the electrostatic component are connected to a same bearing (claim 9).

3. claims: 10, 11(completely); 20(partially)

The energy harvester of claim 1, further comprising an electromagnetic component configured to generate electrical energy in response to rotational motion of the eccentric mass (claims 10, 11); or a device for converting mechanical energy from human motion into electrical energy, the device comprising a piezoelectric ring; an eccentric mass that rotates in response to human motion; and a piezoelectric stress inducer coupled with the eccentric mass and the piezoelectric ring, wherein the piezoelectric stress inducer physical contacts the piezoelectric ring (claim 16); further comprising an electromagnetic component configured to generate electrical energy in response to rotational motion of the eccentric mass (claim 20, first alternative).

4. claims: 12-15

A method for generating electrical energy in response to human motion, the method comprising collecting, by an eccentric mass, mechanical energy from human motion; and

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

transferring, by rotational motion of the eccentric mass, the mechanical energy from human motion to a piezoelectric ring.

5. claims: 29, 30

A device for converting mechanical energy from human motion into electrical energy, the device comprising an outer assembly comprising a housing; an annulus substantially comprising piezoelectric material; and an electrode in electrical communication with the annulus; and an inner assembly comprising an eccentric mass; a bearing member connected to the eccentric mass; an armature connected to the bearing member; and a bearing disposed at the distal end of the armature wherein, the bearing dynamically contacts the annulus; whereby, the inner and outer assemblies rotate relative to one another about a pivot point at the center of the bearing member thereby producing some deformation in the annulus due to bearing contact (claim 21); wherein the annulus exhibits a shape that of a slice of a cylinder (claim 28); wherein the annulus further comprises a radial groove on its inner surface (claims 29-30)

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2017/017341

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5512795	A	30-04-1996	AU 5117796 A 02-10-1996
			US 5512795 A 30-04-1996
			WO 9628854 A1 19-09-1996

CN 103490667	A	01-01-2014	NONE

CN 104158438	A	19-11-2014	NONE
