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(54) **Title**: INDEPENDENT TUNIG OF AUDIO DEVICES EMPLOYING ELECTROACTIVE POLYMER ACTUATORS

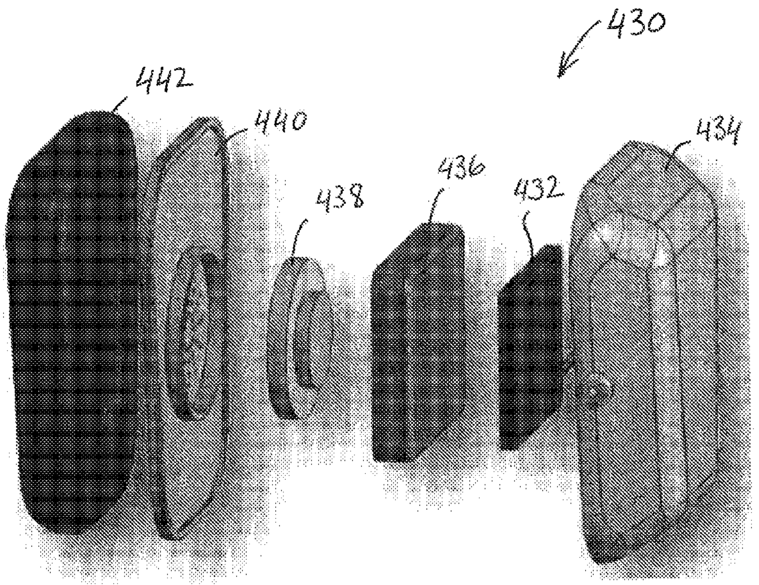

FIG. 7

(57) **Abstract**: The disclosure provides a device having first and second electroactive polymer actuators, each one of the electroactive polymer actuators comprising an electroactive polymer film, a pair of opposing compliant electrodes, and at least one mechanical output region. The mechanical output region is configured to move in response to an activation signal being applied to the electroactive polymer film to provide a movement. The first and second electroactive polymer actuators are independently tunable in frequency and amplitude to provide motion independently. Also disclosed are audio devices configured as over-the ear-headphones and in-the-ear headphones.

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INDEPENDENT TUNING OF AUDIO DEVICES EMPLOYING ELECTROACTIVE POLYMER ACTUATORS

CROSS REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit, under 35 USC § 119(e), of United States provisional patent application numbers: 61/805,269, filed March 26, 2013, entitled "IN-EAR HEADPHONES WITH DIELECTRIC ELASTOMER ACTUATORS," 61/813,886, filed April 19, 2013, entitled "EARPHONE DESIGN TO INTEGRATE DIELECTRIC ELASTOMER," 61/846,669, filed July 16, 2013, entitled "INDEPENDENT TUNING OF VIVITOUCH AND VOLUME LEVELS FOR HEADPHONES," and 61/868,245, filed August 21, 2013, entitled "RELAXATION HEADPHONES USING VIVITOUCH ACTUATORS" the entire disclosure of each of which is hereby incorporated by reference.

FIELD OF THE INVENTION

[0002] In various embodiments, the present disclosure relates generally to electroactive polymer devices. More particularly, the present disclosure relates to independently tunable electroactive polymer devices such as audio devices.

BACKGROUND OF THE INVENTION

[0003] A tremendous variety of devices used today rely on actuators of one sort or another to convert electrical energy to mechanical energy. Conversely, many power generation applications operate by converting mechanical action into electrical energy. Employed to harvest mechanical energy in this fashion, the same type of device may be referred to as a generator. Likewise, when the structure is employed to convert physical stimulus such as vibration or pressure into an electrical signal for measurement purposes, it may be characterized as a sensor. Yet, the term "transducer" may be used to generically refer to any of the devices.

[0004] A number of design considerations favor the selection and use of advanced dielectric elastomer materials, also referred to as "electroactive polymers," for the fabrication of transducers. These considerations include potential force, power density, power conversion/consumption, size, weight, cost, response time, duty cycle, service requirements, environmental impact, etc. As such, in many applications, electroactive polymer technology offers an ideal replacement for piezoelectric, shape-memory alloy and electromagnetic devices such as motors and solenoids.

[0005] An electroactive polymer transducer comprises two electrodes having deformable characteristics and separated by a thin elastomeric dielectric material. When a voltage difference is applied to the electrodes, the oppositely charged electrodes attract each other thereby compressing the polymer dielectric layer therebetween. As the electrodes are pulled closer together, the dielectric polymer film becomes thinner (the Z-axis component contracts) as it expands in the planar directions (along the X- and Y-axes), i.e., the displacement of the film is in-plane. The electroactive polymer film may also be configured to produce movement in a direction orthogonal to the film structure (along the Z-axis), i.e., the displacement of the film is out-of-plane. U.S. Pat. No. 7,567,681 discloses electroactive polymer film constructs which provide such out-of-plane displacement- also referred to as surface deformation or as thickness mode deflection.

[0006] The material and physical properties of the electroactive polymer film may be varied and controlled to customize the deformation undergone by the transducer. More specifically, factors such as the relative elasticity between the polymer film and the electrode material, the relative thickness between the polymer film and electrode material and/or the varying thickness of the polymer film and/or electrode material, the physical pattern of the polymer film and/or electrode material (to provide localized active and inactive areas), the tension or pre-strain placed on the electroactive polymer film as a whole, and the amount of voltage applied to or capacitance induced upon the film may be controlled and varied to customize the features of the film when in an active mode.

[0007] Recent advances in headphone technology have incorporated electroactive polymer actuators into headphones to enhance audio quality as described in PCT Publication No. WO/2012/173669, the entire disclosure of which is hereby incorporated by reference. The headphones comprise at least one conventional acoustic speaker which provides a sonic response by providing sound waves that travel through the ear canal to vibrate the ear drum as well as at least one electroactive polymer actuator that induces vibrations in the bone and tissue surrounding the ear which are experienced as a conductive audio response through bone conduction. The at least one electroactive polymer actuator is driven by a high voltage signal that is derived from the same low-voltage audio signal that drives the acoustic speaker although it may have been processed to enhance specific regions of the frequency spectrum, particularly low frequencies that are difficult to achieve with acoustic speakers. While over-the-ear and on-ear headphones comprising electroactive polymer actuators have been demonstrated, it has been more difficult to incorporate these actuators into in-ear headphones or earphones.

[0008] While independent volume tuning of individual acoustic speakers on stereo headphones already exists, incorporation of electroactive polymer actuator technology for headphones and audio devices generally is still new. Conventional technology for headphones and audio devices generally does not allow custom tuning of electroactive polymer actuator generated conductive audio responses and volume level control independent of the sonic audio response and volume for each side of a pair of headphones or speakers, generally.

[0009] It is known that low frequency phenomena can induce improved states of relaxation. Coupling low frequency vibrations or sounds to the human body can help people to better relax. Some conventional methods use large chairs or apparatus that are not easily moved or transported. Other methods use standard headphones and sound waves in an attempt to have transportable relaxation apparatus. In some cases, sound waves with different frequencies are introduced in each ear to elicit a binaural response. Because conventional headphones do not directly produce sound waves at the frequencies of interest, most acoustic methods use frequency differences of fairly high frequencies (for example, 400 Hz and 405 Hz to get a 5 Hz difference). Most other methods of adding vibration use eccentric rotating masses attached to electric motors. These are not dynamic and result in monotonic vibrations with a very narrow range of operating frequencies. The incorporation of electroactive polymer actuators that can be independently driven over a broad range of amplitudes and frequencies of interest can enable many new applications.

SUMMARY OF THE INVENTION

[0010] Accordingly, the present invention provides various devices integrated with electroactive polymer actuators to provide independently controllable or tunable acoustic and conductive audio stimulation. In one embodiment, a device comprises at least two electroactive polymer actuators that are spatially separated, wherein each actuator is driven with a signal controlling frequency and amplitude. In one embodiment, a different drive signal is used for each actuator. The different drive signals may be chosen such that they provide an interference beat at yet a third set of frequencies.

[0011] In another embodiment, the device is an audio device that further comprises at least one acoustic speaker which is optionally driven at a set of frequencies and amplitude different from at least one of the electroactive polymer actuators. The drive signals of the electroactive polymer actuators may be chosen such that they provide an interference beat and may provide a binaural conductive audio response. The conductive audio response may be entirely distinct from the sonic audio response from the acoustic speaker. In one embodiment, the conductive audio response is designed to couple to brain waves that can lead to stress relief, relaxation or stimulation of a user of the audio device.

[0012] In another embodiment, the audio device is an over-the-ear or on-ear headphone. In another embodiment, the audio device is an in-ear headphone or earphone. The earphone may have a configuration which decouples the sound tube from the earphone case to accommodate an electroactive polymer actuator and accompanying high voltage leads.

[0013] Electroactive polymer devices that can be used with these designs include, but are not limited to planar, diaphragm, thickness mode, roll, and passive coupled devices (hybrids) as well as any type of electroactive polymer device described in the commonly assigned patents and applications cited herein.

[0014] These and other advantages and benefits of the present invention will be apparent from the Detailed Description of the Invention herein below.

BRIEF DESCRIPTION OF THE FIGURES

[0015] The present invention will now be described for purposes of illustration and not limitation in conjunction with the figures, wherein:

[0016] FIGS. 1A and 1B illustrate a top perspective view of a transducer before and after application of a voltage in accordance with the present invention;

[0017] FIG. 2A illustrates an exemplary electroactive polymer cartridge in accordance with the present invention;

[0018] FIG. 2B illustrates an exploded view of an electroactive polymer actuator, inertial mass and actuator housing in accordance with the present invention;

[0019] FIG. 3 is a cutaway view of an electroactive polymer system to illustrate the principle of operation in accordance with the present invention;

[0020] FIG. 4 is a schematic diagram of an electroactive polymer system to illustrate the principle of operation in accordance with the present invention;

[0021] FIG. 5 is an exploded side view of an audio device comprising independent control of frequency and volume levels for each channel in accordance with the present invention;

[0022] FIG. 6 is a level control switch for independent control of volume and vibration levels for each channel of the audio device shown in FIG. 5;

[0023] FIG. 7 is an exploded view of an audio device comprising an independently tunable electroactive polymer actuator in accordance with the present invention;

[0024] FIG. 8 is a cross-sectional view of the audio device shown in FIG. 7;

[0025] FIG. 9 is a diagram of a electroactive polymer /acoustic audio device in accordance with the present invention;

[0026] FIG. 10 is a block diagram of an electronic topology for an independently tunable actuator electronic system in accordance with the present invention;

[0027] FIG. 11 is a graphical depiction of acoustic response of a headphone with electroactive polymer actuators turned on;

[0028] FIG. 12 is a graphical depiction of acoustic response of the headphones with electroactive actuators of FIG. 11 turned on and actuator gains set to minimum;

[0029] FIG. 13 is a graphical depiction of acceleration of headphone ear cups versus frequency measured on a Head And Torso Simulator (HATS);

[0030] FIG. 14 is a graphical depiction of acceleration of headphone ear cups comprising electroactive polymer actuators versus frequency measured on a human test subject;

[0031] FIG. 15 is a cross-sectional view of a hub-mounted audio device located inside the ear canal in accordance the present invention;

[0032] FIG. 16 is a cross-sectional view of a wall mounted audio device located inside the ear canal in accordance with the present invention;

[0033] FIG. 17 is a cross-sectional view of a fully potted audio device located inside the ear canal in accordance with the present invention;

[0034] FIG. 18 is a diagram of a conventional earphone;

[0035] FIG. 19 is a diagram of an earphone in accordance with the present invention;

[0036] FIGS. 20A-20D illustrate placement of electroactive polymer actuator in an ear bud in accordance with the present invention;

[0037] FIG. 21 is a graphical depiction of frequency response of the ear bud shown in FIGS. 20A-20D in accordance with the present invention;

[0038] FIG. 22 illustrates an improved potting fixture for placing the electroactive polymer actuator into ear buds in accordance with the present invention;

[0039] FIGS. 23A-23D illustrate an electroactive polymer actuator placement in an ear bud in accordance with the present invention;

[0040] FIG. 24 is a graphical depiction of a finite element analysis rough draft model prediction of movement of the electroactive polymer actuator within the ear bud;

[0041] FIG. 25A is a graphical depiction of measured movement consistent with the prediction shown in FIG. 24 in accordance with the present invention;

[0042] FIG. 25B is a sectional view of the ear bud and the electroactive polymer actuator mounted therein in accordance with the present invention;

[0043] FIG. 26 is illustrates high potential voltage (HiPot) testing of an electroactive polymer actuator enhanced ear bud in accordance with the present invention;

[0044] FIG. 27 shows an electroactive polymer actuator enhanced ear bud made according to the process described in connection with FIG. 26;

[0045] FIGS. 28A-28C illustrate some additional movement strategies such as a piston mode (FIG. 28A), a bender mode (FIG. 28B) and a basket mode (FIG. 28C) in accordance with the present invention;

[0046] FIGS. 29A and 29B illustrate potential issues arising out of the piston mode movement shown in FIG. 28A;

[0047] FIGS. 30 and 31 illustrate the bender mode previously discussed in connection with FIG. 28B;

[0048] FIG. 32A is an exploded view of a unimorph electroactive polymer actuator including relative dimensions thereof in accordance with the present invention;

[0049] FIG. 32B is an assembled view of the unimorph electroactive polymer actuator shown in FIG. 32A;

[0050] FIG. 33 is an assembled view of several unimorph electroactive polymer actuators shown in FIGS. 32A and 32B in accordance with the present invention;

[0051] FIG. 34 is a graphical depiction of measured movement of roll bender electroactive polymer actuators;

[0052] FIG. 35A illustrates spring rate on tension roll from loaded hoops in accordance with the present invention;

[0053] FIG. 35B is a graphical depiction of force as a function of stretch ratio; and

[0054] FIG. 36 illustrates a diagram of the human ear.

DETAILED DESCRIPTION OF THE INVENTION

[0055] Examples of electroactive polymer devices, their applications, and methods of manufacturing are described, for example, in U.S. Pat. Nos.: 7,394,282; 7,378,783; 7,368,862; 7,362,032; 7,320,457; 7,259,503; 7,233,097; 7,224,106; 7,211,937; 7,199,501; 7,166,953; 7,064,472; 7,062,055; 7,052,594; 7,049,732; 7,034,432; 6,940,221; 6,911,764; 6,891,317; 6,882,086; 6,876,135; 6,812,624; 6,809,462; 6,806,621; 6,781,284; 6,768,246; 6,707,236; 6,664,718; 6,628,040; 6,586,859; 6,583,533; 6,545,384; 6,543,110; 6,376,971; 6,343,129; 7,952,261; 7,911,761; 7,492,076; 7,761,981; 7,521,847; 7,608,989; 7,626,319; 7,915,789; 7,750,532; 7,436,099; 7,199,501; 7,521,840; 7,595,580; 7,567,681; 7,595,580; 7,608,989; 7,626,319; 7,750,532; 7,761,981; 7,911,761; 7,915,789; 7,952,261; 8,183,739; 8,222,799; 8,248,750, and in U.S. Patent Application Publication Nos.: 2007/0200457; 2007/0230222; 2011/0128239; 2012/0126959; 2012/0126667; 2012/0206248; 2013/0002587; 2013/0194082; and in PCT Publication Nos.: WO/2011/097020; WO/2012/099850; WO/2012/099854; WO/2012/118916; WO/2012/120009; WO/2012/122438; WO/2012/122440; WO/2012/122440; WO/2012/129357; WO/2012/136503; WO/2012/148644; WO/2012/156423; WO/2012/173669; WO/2012/175533; WO/2013/037508; WO/2013/049485; WO/2013/059560; WO/2013/059562; WO/2013/103470; WO/2013/142552; WO/2013/148641; WO/2013/155377; WO/2013/192143; WO/2014/006005; WO/2014/028819; WO/2014/028822; WO/2014/028825; the entirety of each of which is incorporated herein by reference.

[0056] Before explaining the embodiments of the inventive electroactive polymer based devices in detail, it should be noted that the disclosed embodiments are not limited in application or use to the details of construction and arrangement of parts illustrated in the accompanying drawings and description. The disclosed embodiments may be implemented or incorporated in other embodiments, variations and modifications, and may be practiced or carried out in various ways. Further, unless otherwise indicated, the terms and expressions employed herein have been chosen for the purpose of describing the embodiments for illustrative purposes and for the convenience of the reader and are not intended for the purposes of limiting any of the embodiments to the particular ones disclosed. Further, it should be understood that any one or more of the disclosed embodiments, expressions of embodiments, and examples can be combined with any one or more of the other disclosed embodiments, expressions of embodiments, and examples, without limitation. Thus, the combination of an element disclosed in one embodiment and an element disclosed in another embodiment is considered to be within the scope of the present disclosure and appended claims.

[0057] FIGS. 1-4 provide a brief description of electroactive polymer structures. Accordingly, the description now turns to FIGS. 1A and 1B, which illustrate an example of an electroactive polymer film or membrane **10** structure. A thin elastomeric dielectric film or layer **12** is sandwiched between compliant or stretchable electrode plates or layers **14** and **16**, thereby forming a capacitive structure or film. The length “L” and width “w” of the dielectric layer, as well as that of the composite structure, are much greater than its thickness “t”. Preferably, the dielectric layer has a thickness in the range from about 10 μm to about 100 μm, with the total thickness of the structure in the range from about 15 μm to about 10 cm. Additionally, it is desirable to select the elastic modulus, thickness, and/or the geometry of electrodes **14**, **16** such that the additional stiffness they contribute to the actuator is generally less than the stiffness of the dielectric layer **12**, which has a relatively low modulus of elasticity, i.e., preferably less than about 100 MPa and more preferably less than about 10 MPa, but is likely thicker than each of the electrodes. Electrodes suitable for use with these compliant capacitive structures are those capable of withstanding cyclic strains greater than about 1% without failure due to mechanical fatigue.

[0058] As shown in FIG. 1B, when a voltage is applied across the electrodes, the unlike charges in the two electrodes **14**, **16** are attracted to each other and these electrostatic attractive forces compress the dielectric film **12** (along the Z-axis). The dielectric film **12** is thereby caused to deflect with a change in electric field. As electrodes **14**, **16** are compliant, they change shape with dielectric layer **12**. In the context of the present disclosure, "deflection" refers to any displacement, expansion, contraction, torsion, linear or area strain, or any other deformation of a portion of dielectric film **12**. Depending on the architecture, e.g., a frame in which capacitive structure **10** is employed (collectively referred to as a "transducer"), this deflection may be used to produce mechanical work. Various transducer architectures are disclosed and described in the above-identified patent references.

[0059] With a voltage applied, the transducer film **10** continues to deflect until mechanical forces balance the electrostatic forces driving the deflection. The mechanical forces include elastic restoring forces of the dielectric layer **12**, the compliance or stretching of the electrodes **14**, **16** and any external resistance provided by a device and/or load coupled to transducer **10**. The resultant deflection of the transducer **10** as a result of the applied voltage may also depend on a number of other factors such as the dielectric constant of the elastomeric material and its size and stiffness. Removal of the voltage difference and the induced charge causes the reverse effects.

[0060] In some cases, the electrodes **14** and **16** may cover a limited portion of dielectric film **12** relative to the total area of the film. This may be done to prevent electrical breakdown around the edge of the dielectric or achieve customized deflections in certain portions thereof. Dielectric material outside an active area (the latter being a portion of the dielectric material having sufficient electrostatic force to enable deflection of that portion) may be caused to act as an external spring force on the active area during deflection. More specifically, material outside the active area may resist or enhance active area deflection by its contraction or expansion.

[0061] The dielectric film **12** may be pre-strained. The pre-strain improves conversion between electrical and mechanical energy, i.e., the pre-strain allows the dielectric film **12** to deflect more and provide greater mechanical work. Pre-strain of a film may be described as the change in dimension in a direction after pre-straining relative to the dimension in that direction before pre-straining. The pre-strain may include elastic deformation of the dielectric film and be formed, for example, by stretching the film in tension and fixing one or more of the edges while stretched. The pre-strain may be imposed at the boundaries of the film or for only a portion of the film and may be implemented by using a rigid frame or by stiffening a portion of the film.

[0062] The transducer structure of FIGS. 1A and 1B and other similar compliant structures and the details of their constructs are more fully described in many of the referenced patents and publications disclosed herein.

[0063] FIG. 2A illustrates an exemplary electroactive polymer cartridge **12** having an electroactive polymer transducer film **26** placed between rigid frame **8** where the electroactive polymer film **26** is exposed in openings of the frame **8**. The exposed portion of the film **26** includes three working pairs of thin elastic electrodes **32** on either side of the cartridge **12** where the electrodes **32** sandwich or surround the exposed portion of the film **26**. The electroactive polymer film **26** can have any number of configurations. However, in one example, the electroactive polymer film **26** comprises a thin layer of elastomeric dielectric polymer (e.g., made of acrylate, silicone, urethane, thermoplastic elastomer, hydrocarbon rubber, fluoroelastomer, copolymer elastomer, or the like).

[0064] When a voltage difference is applied across the oppositely-charged electrodes **32** of each working pair (i.e., across paired electrodes that are on either side of the film **26**), the opposed electrodes attract each other thereby compressing the dielectric polymer layer **26** therebetween. The area between opposed electrodes is considered the active area. As the electrodes are pulled closer together, the dielectric polymer **26** becomes thinner (i.e., the Z-axis component contracts) as it expands in the planar directions (i.e., the X- and Y-axes components expand) (See Figs. 1B for axis references). Furthermore, in variations where the electrodes contain conductive particles, like charges distributed across each electrode may cause conductive particles embedded within that electrode to repel one another, thereby contributing to the expansion of the elastic electrodes and dielectric films. In alternate variations, electrodes do not contain conductive particles (e.g., textured sputtered metal films). The dielectric layer **26** is thereby caused to deflect with a change in electric field. As the electrode material is also compliant, the electrode layers change shape along with dielectric layer **26**.

[0065] As stated elsewhere herein, deflection refers to any displacement, expansion, contraction, torsion, linear or area strain, or any other deformation of a portion of dielectric layer **26**. This deflection may be used to produce mechanical work. As shown, the dielectric layer **26** can also include one or more mechanical output regions or bars **34**. The regions or bars **34** can optionally provide attachment points for either an inertial mass (as described below) or for direct coupling to a substrate in the electronic media device.

[0066] In fabricating a transducer, an elastic film **26** can be stretched and held in a pre-strained condition usually by a rigid frame **8**. In those variations employing a four-sided frame, the film can be stretched bi-axially. It has been observed that pre-strain improves the dielectric strength of the polymer layer **26**, thereby enabling the use of higher electric fields and improving conversion between electrical and mechanical energy, i.e., the pre-strain allows the film to deflect more and provide greater mechanical work. Preferably, the electrode material is applied after pre-straining the polymer layer, but may be applied beforehand. The two electrodes provided on the same side of layer **26**, referred to herein as same-side electrode pairs, i.e., electrodes on the top side of dielectric layer **26** and electrodes on a bottom side of dielectric layer **26**, can be electrically isolated from each other. The opposed electrodes on the opposite sides of the polymer layer form two sets of working electrode pairs, i.e., electrodes spaced by the electroactive polymer film **26** form one working electrode pair and electrodes surrounding the adjacent exposed electroactive polymer film **26** form another working electrode pair. Each same-side electrode pair can have the same polarity, whereas the polarity of the electrodes of each working electrode pair is opposite each other. Each electrode has an electrical contact portion configured for electrical connection to a voltage source.

[0067] In this variation, the electrodes **32** are connected to a voltage source via a flex connector **30** having leads **22, 24** that can be connected to the opposing poles of the voltage source. The cartridge **12** also includes conductive vias **18, 20**. The conductive vias **18, 20** can provide a means to electrically couple the electrodes **8** with a respective lead **22** or **24** depending upon the polarity of the electrodes.

[0068] The cartridge **12** illustrated in FIG. 2A shows a 3-bar actuator configuration. However, the devices and processes described herein are not limited to any particular configuration, unless specifically claimed. Preferably, the number of the bars **34** depends on the active area desired for the intended application. The total amount of active area, e.g., the total amount of area between electrodes, can be varied depending on the mass that the actuator is trying to move and the desired frequency of movement. In one example, selection of the number of bars is determined by first assessing the size of the object to be moved, and then the mass of the object is determined. The actuator design is then obtained by configuring a design that will move that object at the desired frequency range. Clearly, any number of actuator designs is within the scope of the disclosure.

[0069] An electroactive polymer actuator for use in the processes and devices described herein can then be formed in a number of different ways. For example, the electroactive polymer can be formed by stacking a number of cartridges **12** together, having a single cartridge with multiple layers, or having multiple cartridges with multiple layers. Manufacturing and yield considerations may favor stacking single cartridges together to form the electroactive polymer actuator. In doing so, electrical connectivity between cartridges can be maintained by electrically coupling the vias **18**, **20** together so that adjacent cartridges are coupled to the same voltage source or power supply.

[0070] The cartridge **12** shown in FIG. 2A includes three pairs of electrodes **32** separated by a single dielectric layer **26**. In one variation, as shown in FIG. 2B, two or more cartridges **12** are stacked together to form an electroactive actuator **14** that is coupled to an inertial mass **50**. Alternatively, the electroactive actuator **14** can be coupled directly to the electronic media device through an intermediary attachment plate or frame. As discussed below, the electroactive actuator **14** may be placed within a cavity **52** that allows for movement of the actuator as desired. The pocket **52** may be directly formed in a housing of a case. Alternatively, pocket **52** may be formed in a separate case **56** positioned within the housing of the device. If the latter, the material properties of the separate case **56** may be selected based upon the needs of the actuator **14**. For example, if the main body of the housing assembly is flexible, the separate case **56** can be made rigid to provide protection to the electroactive actuator and/or the mass **50**. In any event, variations of the device and processes described herein include size of the cavity **52** with sufficient clearance to allow movement of the actuator **14** and/or mass **50** but a close enough tolerance so that the cavity **52** barrier (e.g., the housing or separate case **56**) serves as a limit to prevent excessive movement of the electroactive actuator **14**. Such a feature prevents the active areas of the actuator **14** from excessive displacement that can shorten the life of the actuator or otherwise damage the actuator.

[0071] FIGS. 3-4 provide a description of an electroactive polymer based module suitable for use in the devices such as headphones. FIG. 3 is a partial cutaway view of an electroactive polymer system that may be integrally incorporated to provide motion effects. Accordingly, in one embodiment the system comprises an electroactive polymer module **200**.

An electroactive polymer actuator **222** is configured to slide an output plate **202** (e.g., sliding surface) relative to a fixed plate **204** (e.g., fixed surface) when energized by a voltage "V." The plates **202**, **204** are separated by steel balls, and have features that constrain movement to the desired direction, limit travel, and withstand drop tests. For integration into headphones, the top plate **202** may be attached to an inertial mass.

[0072] Segmenting the electroactive polymer actuator **222** within a given footprint into (n) sections is a convenient method for setting the passive stiffness and blocked force of the electroactive polymer system. A pre-stretched dielectric is held in place by the rigid material that defines an external frame such as the fixed plate **204** and one or more windows within the frame. Inside each window is an output bar **212** of the same rigid frame material, and on one or both sides of the output bar **212** are electrodes **208**. Alternatively, an adhesive may replace the rigid frame material as disclosed in co-assigned PCT Publication No. WO/2012/099854; the entire disclosure of which is hereby incorporated by reference.

[0073] Applying the potential difference (V) across the dielectric on one side of the output bar **212** creates electrostatic pressure in the elastomer which causes the electrode area to expand and exert force on the output bar **212**. This force scales with the effective cross section of the electroactive polymer actuator **222**, and therefore increases linearly with the number of segments, each of which adds to the effective width of the actuator. The passive spring rate scales with n^2, as each additional segment effectively stiffens the device twice, first by shortening it in the stretching direction (X) and second by adding to the width (Y) that resists displacement. Both spring rate and blocked force scale linearly with the number of dielectric layers (m).

[0074] Among the advantages of electroactive polymer modules **200** is the ability to generate low frequency vibrations inside the ear cup housings that can be felt substantially immediately by the user. In addition, electroactive polymer modules **200** consume low power, and are well suited for customizable design and performance options. The electroactive polymer module **200** is representative of electroactive polymer modules developed by Artificial Muscle, Inc., of Sunnyvale, CA, USA.

[0075] Still with reference to FIG. 3, many of the design variables of the electroactive polymer module **200**, (e.g., thickness, footprint) may be fixed by the needs of module integrators while other variables (e.g., number of dielectric layers, operating voltage) may be constrained by cost. Because actuator geometry – the allocation of footprint to rigid supporting structure versus active dielectric – does not impact cost much, it may be a reasonable way to tailor performance of the electroactive polymer module **200** to an application where the module **200** is integrated with headphones or other device.

[0076] Computer implemented modeling techniques can be employed to gauge the merits of different actuator geometries, such as: (1) Mechanics of the Handset/User System; (2) Actuator Performance; and (3) User Sensation. Together, these three components provide a computer-implemented process for estimating the capability of candidate designs and using the estimated capability data to select an electroactive polymer design suitable for mass production. The model predicts the capability for two kinds of effects: long effects (e.g. gaming and music), and short effects (e.g. key clicks). "Capability" is defined herein as the maximum sensation a module can produce in service. Such computer-implemented processes for estimating the capability of candidate designs are described in more detail in commonly assigned PCT Publication No. WO/2011/102898, the entire disclosure of which is hereby incorporated by reference.

[0077] FIG. 4 is a schematic diagram of an electroactive polymer system **300** designed to illustrate the principle of operation of electroactive polymer modules. The electroactive polymer system **300** comprises a power source **302**, shown as a low voltage direct current (DC) battery for illustrative purposes, electrically coupled to an electroactive polymer module **304**. In accordance with the present disclosure, the power source (V_{Batt}) represents the output of an audio signal source configured to generate low frequency audio signals below about 200 Hz, for example, and in one embodiment between about 2 Hz to about 200 Hz, where the term "about" stands for ±10%. The electroactive polymer module **304** comprises a thin elastomeric dielectric element **306** disposed (e.g., sandwiched) between two conductive electrodes **308A, 308B**. The conductive electrodes **308A, 308B** are stretchable (e.g., conformable) and may be printed on the top and bottom portions of the elastomeric dielectric element **306** using any suitable technique, such as, for example screen printing.

[0078] The electroactive polymer module **304** is activated by coupling the battery **302** (e.g., signal source) to an actuator circuit **310** by closing a switch **312**. The actuator circuit **310** converts the low DC voltage V_{Batt} signal into a higher DC voltage V_{in} signal suitable for driving the electroactive polymer module **304**. In accordance with the present disclosure, an additional circuit may be located within the opening **124** defined by the housing **118**, where the circuit is configured to convert the low voltage low frequency audio signal from the audio signal source, to a higher voltage signal suitable for driving the electroactive polymer actuator **122** as shown in FIGS. 1A-1B.

[0079] Returning to FIG. 4, when the voltage V_{in} is applied to the conductive electrodes **308A, 308B** the elastomeric dielectric element **306** contracts in the vertical direction (V) and expands in the horizontal direction (H) under electrostatic pressure. The contraction and expansion of the elastomeric dielectric element **306** can be harnessed as motion. The amount of motion or displacement is proportional to the input voltage V_{in}. The motion or displacement may be amplified by a suitable configuration of electroactive polymer actuators.

[0080] The following description is directed to independent tuning of amplitude and frequency of motion and volume levels for headphones. FIG. 5 is an exploded side view of an electroactive polymer device **400** comprising independent tuning of motion and volume levels for each channel in accordance with present invention. As shown in FIG. 5, the electroactive polymer device is shown in the form of a headphone. The electroactive polymer device **400** comprises a headband **402** and first and second ear cushions $\mathbf{404_1}$, $\mathbf{404_2}$, first and second speakers $\mathbf{406_1}$, $\mathbf{406_2}$, first and second drive electronics $\mathbf{408_1}$, $\mathbf{408_2}$, first and second electroactive polymer actuators $\mathbf{410_1}$, $\mathbf{410_2}$, and first and second ear cups $\mathbf{412_1}$, $\mathbf{412_2}$. The "first" components correspond to a first channel of the electroactive polymer device **400** and the "second" components correspond to the second channel of the electroactive polymer device **400**.

[0081] FIG. 6 is a level control switch **420** for independent control of volume and motion levels for each channel of the audio device **400** shown in FIG. 5. The level control switch **420** comprises four separate switches $\mathbf{422_1}$, $\mathbf{422_2}$, $\mathbf{424_1}$, $\mathbf{424_2}$, to control left speaker $\mathbf{406_1}$ volume, right speaker $\mathbf{406_2}$ volume, left electroactive polymer actuator $\mathbf{410_1}$, and right electroactive polymer actuator $\mathbf{410_2}$, respectively.

[0082] With reference to both FIGS. 5 and 6, the level control switch **420** provides independent control of motion from the electroactive polymer actuators $\mathbf{410_1}$, $\mathbf{410_2}$ and sound volume from the speakers $\mathbf{406_1}$, $\mathbf{406_2}$ for the electroactive polymer device **400**. The level control switch **420** comprises a first volume control switch $\mathbf{422_1}$ to control the volume level of the first speaker $\mathbf{406_1}$ and a second volume control switch $\mathbf{422_2}$ to control the volume level of the second speaker $\mathbf{406_2}$ independently. The level control switch **420** also comprises a first vibration control switch $\mathbf{424_1}$ to control the motion level of the first electroactive polymer actuators **410**$_1$ and a second vibration control switch **424**$_2$ to control the motion level of the second electroactive polymer actuators **410**$_2$ independently.

[0083] Accordingly, the present invention allows custom and independent tuning of the motions produced by the electroactive polymer actuators **410**$_1$, **410**$_2$ and the sound volume and content produced by the speakers **406**$_1$, **406**$_2$ for each side of the electroactive polymer device **400**. As shown in FIG. 6, for example, using the 1 to 10 level control switch **422**$_1$ the user could tune the sound volume level of the first speaker **406**$_1$ to 6 and using the 1 to 10 level control switch **424**$_1$ the user could tune the motion level of the first electroactive polymer actuator **410**$_1$ to 8 on the first side (e.g., right side). At the same, using the 1 to 10 level control switch **422**$_2$ the user could tune the sound volume level of the second speaker **406**$_2$ to 4 and using the 1 to 10 level control switch **424**$_2$ the user could tune the motion level of the second electroactive polymer actuator **410**$_2$ to 3 on the second side (e.g., left side).

[0084] The combination of independent volume and motion tuning control can be advantageous for individuals that are hard of hearing because the technology allows someone to feel their music including frequencies that a person may not be able to hear. Furthermore, being able to independently tune the electroactive polymer actuators **410**$_1$, **410**$_2$ is advantageous because users may have asymmetric hearing loss. For example, someone with hearing loss may have 80% hearing loss in the right ear and have only 60% hearing loss in the left ear. Thus, someone with that profile may want to turn up the volume level as well as the electroactive polymer actuator level on the right side but turn down the volume level and the electroactive polymer actuator level on the left side, relative to the right side. Even if an individual does not have hearing loss, they may prefer to experience different levels of motion by the electroactive polymer actuator (conductive audio response) on one ear versus the other.

[0085] It will be appreciated that the level control switch **420** mechanism for the electroactive polymer device **400** speaker volume level as well as electroactive polymer actuator level may be integrated either directly into the electroactive polymer device **400** ear cups **412**$_1$, **412**$_2$ or as a separate wired or wireless controller.

[0086] The following description is directed to relaxation headphones including electroactive polymer actuators. Low frequency phenomena may induce improved states of relaxation (see, PHOTOSONIX and ILIGHTZ products as examples). Thus, coupling low frequency vibrations or sounds to the human body may better help people to relax. Some methods use large chairs or apparatus which is not easily moved or easily transported. Other techniques use standard headphones and sound waves in an attempt to provide a transportable relaxation apparatus. Because conventional headphones do not directly produce sound waves at the frequencies of interest, most acoustic methods use frequency differences of fairly high frequencies, for example 400 Hz and 405 Hz, to obtain a 5 Hz difference. In addition, a sonic audio response due to sound waves may not be as effective at coupling into a human body as a conductive audio response which can be transmitted by the skeletal system.

[0087] FIG. 7 is an exploded view of a device **430** comprising an electroactive polymer actuator **432** in accordance with the present invention. FIG. 8 is a cross-sectional view of the audio device **430** shown in FIG. 7 in accordance with the present invention. With reference now to both FIGS. 7 and 8, the audio device **430** comprises an electroactive polymer actuator **432** attached to an exterior portion of a sound cavity cover **436**. A speaker **438** is located within the cavity defined by the sound cavity cover **436**. A speaker housing **440** is rigidly attached to an ear cup housing **434** and supports the speaker **438**, the sound cavity cover **436**, and the electroactive polymer actuator **432** therebetween. A cushion **442** may be attached to the speaker housing **440**.

[0088] Still with reference to both FIGS. 7 and 8, there are many different device (e.g., headphone) architectures including over-the-ear (circumaural) and on-the-ear (supra-aural) configurations. In addition, the acoustic cavity may be: (1) open; (2) closed; or (3) closed with an acoustic port. The electroactive polymer actuator **432** (e.g., electroactive polymer motion element or module) can be used in over-ear and on-ear headphones to improve the user experience by enhancing the low frequency content of the audio. Preferably, the electroactive polymer actuator **432** is coupled directly to the sound cavity cover **436** portion of the audio device **430**, which is rigidly attached to the speaker housing **440** and the cushion **442**. As shown, the surface outside of the sound cavity cover **436**, behind the speaker **438**, may be utilized to mount the electroactive polymer actuator **432**.

[0089] The electroactive polymer actuator **432** may be integrated in over-the-ear and on-the-ear headphones to improve the user experience by enhancing the low frequency content of the audio being played. The electroactive polymer actuator **432** may preferably be attached to a rigid flat surface, such as the back of the sound cavity cover **436**, on one side and to a suspended mass on the other side. The electroactive polymer actuator **432** moves the mass relative to the speaker housing **440**, according to the low frequency portion of the audio signals it receives. A suspended mass attached to the speaker housing **440** through the electroactive polymer actuator **432** results in a mass-spring-damper system. The movement direction of the electroactive polymer actuator **432** may be best when oriented in parallel plan relative to the ear, orthogonal to the axis of the acoustic driver (to minimize acoustic artifacts).

[0090] Accordingly, the electroactive polymer device depicted in FIGS. 7 and 8 may be employed to create binaural frequencies that humans may feel. The created effect influences the theta brainwaves of humans inducing the brain to enter a state of deep relaxation.

[0091] As illustrated in FIGS. 7 and 8, the device **430** includes a pair of headphones in which a pair of electroactive polymer actuators **432** has been mounted. An inertial mass of about 26 g may be added to each of the electroactive polymer actuators **432** to produce soothing motion (vibration) phenomena in the headphones **430**. Stereo electronics, discussed below in connection with FIGS. 9-11, provide for full independent left and right side motion (vibration) and left and right side sound level control, as discussed above in connection with FIGS. 4 and 5, to provide the relaxing experience to the user.

[0092] Lower mechanical resonant frequencies are used as compared to headphones optimized for music listening. For example, in one embodiment, the resonant frequency was selected around 44 Hz, even though lower frequencies are achievable.

[0093] As discussed above, most other methods of adding vibration use eccentric rotating masses attached to electric motors which cannot be controlled over a wide arbitrary range of frequencies and amplitude. Such techniques are not dynamic and result in monotonic motion centered around a single frequency. The electroactive polymer actuators **432** are dynamic and can be controlled to a wide variety of sensations and effects. With electroactive polymer actuators **432**, the device **430** may generate frequencies that cannot be heard but be felt by humans to influence the theta brainwaves. Relaxation experts may be able to design better programs using such an electroactive polymer actuator **432** enabled low-frequency device **430**. Humans may enter a relaxation state for their body and brain on a button press and using a mobile device.

[0094] It should be understood that although the discussion above centers on the application of low-frequency stimuli to induce a relaxation state for the user, the present invention may also be used with drive signals designed to provide stimulation or increased alertness in the user and more generally to provide stress relief for the user.

[0095] Most audio content can be delivered as a two-channel, real-time analog signal such as stereo music, for example. In other instances, the audio content may be delivered as streaming digital information. The analog audio signals may be processed to extract meaningful content. This real-time content may be directed to the electroactive polymer actuators **432** to produce compelling motion/acoustic effects.

[0096] FIGS. 9-11 describe an electronics system design that may be employed to operate the electroactive polymer devices **400, 430** described in connection with FIGS. 4-8. As to each device **400, 430**, the electronics system may require a unique implementation based on its features and specific design, therefore the electronics system described herein is generic.

[0097] Accordingly, turning now to FIG. 9, there is shown a diagram of a electroactive polymer /acoustic audio device **500** in accordance with one embodiment of the present invention. Preferably, the audio source **502** delivers audio content as two two-channel real-time analog signals. In other instances, the audio source **502** may deliver streaming digital information. The audio source **502** includes any one of a PC, IPOD, IPHONE, USB, 3.5 mm, stereo, among other audio sources **502**. The audio source **502** outputs a one or two channel acoustic signal **504** and a one or two channel motion signal **506**. The acoustic and motion signals **504, 506** are processed to extract meaningful content. The acoustic signal **504** is processed by acoustic electronic system **508** and the motion signal **506** is processed by an actuator electronic system **514**. The user may provide input **526** in any of the audio source **502**, the acoustic electronic system **508**, or the actuator electronic system **514**.

[0098] The acoustic electronic system **508** may comprise relatively simple audio electronics or more sophisticated digital signal processing (DSP) electronic circuits. In some embodiments, the acoustic electronic system **508** may comprise passive or active noise canceling circuits. The acoustic electronic system **508** includes a left channel output section $\mathbf{510_1}$ and a right channel output section $\mathbf{510_2}$ to independently drive left and right speakers $\mathbf{512_1}$, $\mathbf{512_2}$, respectively. Thus, the left and right speakers $\mathbf{512_1}$, $\mathbf{512_2}$ produce stereo sound with independent volume level control. In one embodiment, however, one output signal may be used to drive both speakers $\mathbf{512_1}$, $\mathbf{512_2}$ at once. Both amplitude and frequency of the low voltage electrical signals output from the left channel output section $\mathbf{510_1}$ and the right channel output section $\mathbf{510_2}$ are independently tunable.

[0099] The motion signal **506** is processed by the actuator electronic system **514** to extract meaningful content. The actuator electronic system **514** comprises a signal processing section **522** and a high voltage amplifier section **524**. The signal processing section **522** receives the motion signal **506** from the audio source **502** and prepares the signal for feeding into the high voltage amplifier section **524**. The high voltage amplifier section **524** includes a left channel output section **516**$_1$ and a right channel output section **516**$_2$ to independently drive left and right electroactive polymer actuators **518**$_1$, **518**$_2$, respectively, in the direction indicated by arrows **520**$_1$, **520**$_2$, respectively. The real-time motion signal **506** is thus directed to the electroactive polymer actuators **518**$_1$, **518**$_2$ to produce compelling motion effects. In one embodiment, however, one output signal may be used to drive both electroactive polymer actuators **518**$_1$, **518**$_2$ at once. Both amplitude and frequency of the high voltage electrical signals output from the left channel output section **516**$_1$ and the right channel output section **516**$_2$ are independently tunable.

[0100] FIG. 10 is a block diagram **600** of an electronic topology for an independently tunable actuator electronic system in accordance with the present invention. The actuator electronic system **600** is suitable for independently driving electroactive polymer actuators, such as the electroactive polymer actuators **518**$_1$, **518**$_2$ described in connection with FIG. 9. As shown in FIG. 10, the block diagram **600** of the electronic circuit for generating low frequency motion signals **614L**, **614R** for driving the electroactive polymer actuators **616L**, **616R**, respectively. A variety of signal conditioning, amplifying, compensating, and driving circuits are also implemented. In particular, an analog audio signal module **602** receives analog motion signals from a differential amplifier source, or any suitable source. In one embodiment, the differential amplifier may be implemented with any suitable integrated circuit amplifier.

[0101] From the analog audio signal module **602**, the signal is passed to a low frequency digital filter module **606**. The low frequency digital filter module **606** may be implemented using any suitable circuit technique and may comprise a microcontroller and a programmable gate array circuit, among other digital or analog processing circuit elements. In one embodiment, the low frequency digital filter module **606** may be implemented with any suitable programmable system, such as, for example a programmable system-on-chip controller.

[0102] A low frequency amplifier module **608** amplifies the output of the low frequency digital filter **606** and the output is passed to the programmable gate array circuit. In one embodiment, the low frequency amplifier module **608** may be implemented using any suitable integrated circuit amplifier.

[0103] The output of the low frequency digital filter **606** is provided to a non-linear inverse transform circuit (square root circuit) such as an inverse polynomial circuit **610**, which provides the electronic audio signal compensation to remove unwanted distortions in the audio signal used to move the electroactive polymer actuators. In other words, the inverse polynomial circuit **610** approximates an inverse function to linearize the electroactive polymer actuators, for example. In various embodiments, the inverse polynomial circuit **610** may be implemented using integrated circuits, programmable circuits, piecewise linear circuits and/or any combinations thereof. In one embodiment a piecewise linear circuit can be used to approximate a non-linear function, such as sine, square-root, logarithmic, exponential, and the like, for example. The quality of the approximation depends on the number of segments employed by the piecewise linear circuit and the strategy used in determining the segments. There are two approaches to building piecewise linear circuits: (1) non-linear voltage dividers with diodes (or transistors) used to switch between the segments and (2) summing the outputs of a chain of saturating amplifiers. Both of these approaches may be employed and are technically equivalent although each has its advantages and disadvantages.

[0104] The diode approach has the advantage of simplicity but the disadvantages include temperature dependence on the switching thresholds and relatively slow response. The saturating amplifier method has the disadvantage of complexity but the advantages of minimal temperature dependence on thresholds and high speed. In various embodiments, the inverse polynomial circuit **610** may be implemented as a compression or an expansion circuit, each type having a different circuit topology. A compression circuit compresses the dynamic range of an input signal whereas an expansion circuit expands the dynamic range. Examples of compression circuits include square-root, logarithmic, and sine and generally employ non-linear voltage divider techniques. One example of an expansion circuit is an exponential function.

[0105] In other embodiments, a combination of compression and expansion circuits may be employed to implement the inverse polynomial circuit **610** to linearize electroactive polymer actuators, for example. One embodiment of a piecewise linear circuit using diode switching to approximate an inverse square-root function may be employed. The output of the inverse polynomial circuit **610** is provided to a high voltage power amplifier **612** for amplification to a level sufficient to drive the electroactive polymer actuator module. Preferably, the voltage required to drive the electroactive polymer actuator module may range from a few hundred volts (V) to several thousand volts (kV), with a nominal driving voltage of about 1 kV. A left channel output **614L** of the high voltage amplifier **612** is provided to a left reflex actuator and mass **616L**, e.g., to an electroactive polymer actuator located in a left ear cup of the headphones. A right channel output **614R** of the high voltage amplifier **612** is provided to a right reflex actuator and mass **616R**, e.g., to an electroactive polymer actuator located in a right ear cup of the headphones. In one embodiment, single phase actuators can be improved using a square root circuit in the sensory enhanced headphones comprising electroactive polymer actuators. Non-linear control techniques also may be employed in multi-phase actuators, for example.

[0106] Accordingly, as described in connection with FIGS. 5-10, in one embodiment of the present invention provides an apparatus for applying binaural frequencies that a human can feel. For example, if a person is in beta stage (highly alert) and a stimulus of 10Hz is applied to his/her brain for some time, the brain frequency is likely to change towards the applied stimulus. The effect will feel relaxing to the person; a phenomenon known as "frequency following response."

[0107] Electroactive polymer actuators and driving techniques described in connection with FIGS. 5-10 may be used to generate motion signals to stimulate the brain using a binaural technique. The stimulus may be applied using binaural beats. If the left element is presented with a steady tone of 500Hz and the right element a steady tone of 510Hz, these two tones combine in the brain. The difference, 10Hz, is perceived by the brain and is a very effective stimulus for brainwave entrainment. This 10Hz is formed entirely by the brain. The devices described in connection with FIGS. 5-10 mat be employed to move one side of a person's head with a first motion signal at a first frequency (f_1) and the other side of the person's head with a second motion signal at a second frequency (f_2). The left and right motion signals do not mix together, but rather constructively interfere to create a binaural beat with a frequency roughly equal to the frequency difference ($\Delta f = f_2 - f_1$) which is perceived by brain. .

[0108] For example, to obtain a motion stimulus of 10Hz, motion signals of 50Hz and 60Hz, or 40Hz and 50Hz, or 80Hz and 90Hz should be applied. The electronic system **600** described in FIG. 10 is configured to respond to signals between ~1Hz and ~150Hz. The electroactive polymer actuators have a mechanical resonance around 44 Hz when placed on a human subject. Optimum frequencies are in approximately the 20 Hz to 80 Hz range.

[0109] It will be appreciated that the motion level in each channel can be independently controlled to customize the binaural effect using electroactive polymer actuators. In one embodiment, where the devices have independently controlled acoustic and motion levels, the binaural stimulus may be enhanced using a combination of audible frequencies and motion frequencies to generate binaural stimulus to the brain. Table 1 below depicts the effect of binaural beats.

[0110] TABLE 1

State	Frequency range	State of mind
Delta	0.5 Hz - 4Hz	Deep sleep
Theta	4Hz - 8Hz	Drowsiness (also first stage of sleep)
Alpha	8Hz - 14Hz	Relaxed but alert
Beta	14Hz - 30Hz	Highly alert and focused

[0111] FIGS. 11-14 are graphical depiction of test results conducted with a modified ATH-M50 Headphones. The headphones included three bar/two layer actuators installed into flexure modules using a 26 g inertial mass, as described by way of example in FIGS. 2A and 2B. Only one bar of three was connected to the mass which reduced the spring constant by a factor of three. This resulted in a significantly lower mechanical resonant frequency than the typical headphones used for audio enhancement. The acoustic volume levels and actuator motion levels may be operated independently or together as described in connected with FIGS. 5-10. This is a full stereo system with independent gains on both actuators. At minimum gain setting, 100 mV peak-to-peak ("pk-pk") produces full output to the actuators. At maximum gain setting, 25 mV pk-pk produces full output to the actuators. A quick check of the acoustic response after modification shows no significant differences from a standard ATH-M50 headphone. A chirp frequency response from 20 Hz-20 kHz is shown below. The test signal is 200 mV pk-pk and a logarithmic sweep occurring in one second.

[0112] FIG. 11 is a graphical depiction **700** of acoustic response of a headphone with electroactive polymer actuators turned on. Frequency (Hz) is shown along the horizontal axis on a logarithmic scale and Acoustic Response |y(f)| is shown along the vertical axis.

[0113] FIG. 12 is a graphical depiction **710** of acoustic response of the headphones with electroactive actuators in FIG. 11 turned on and actuator gains set to minimum. Frequency (Hz) is shown along the horizontal axis on a logarithmic scale and Acoustic Response |y(f)| is shown along the vertical axis.

[0114] FIG. 13 is a graphical depiction **720** of acceleration of headphone ear cups versus frequency measured on a Head And Torso Simulator (HATS). Frequency (Hz) is shown along the horizontal axis on a logarithmic scale and Acceleration (g) is shown along the vertical axis. The resonant frequency measured on HATS (B&K 4128c Head and Torso Simulator) was about 53 Hz but measures around 44 Hz when placed on a human test subject (see FIG. 14). The vertical scaling on FIG. 13 is 0.0312 was 0.1 g peak (0.2 g's peak-to-peak). Left and right vertical (Y) axis and horizontal (X) axis acceleration was measured versus vibration frequency of the electroactive polymer actuator. As shown in FIG. 12, four curves were plotted: the left X-axis **726**, the left Y-axis **722**, the right X-axis **728**, and the right Y-axis **724**. Because the electroactive polymer actuators were configured to move primarily in the X-direction relative to the Y-direction, as shown in FIG. 12, the right X-axis and the left X-axis **726** accelerations were greater than the corresponding right Y-axis **724** and left Y-axis **722** accelerations.

[0115] FIG. 14 is a graphical depiction **730** of acceleration of headphone ear cups comprising electroactive polymer actuators versus frequency measured on a human test. Frequency (Hz) is shown along the horizontal axis on a logarithmic scale and Acceleration (g) is shown along the vertical axis. The resonant frequency measured is about 44 Hz when placed on a human test subject. The vertical scaling on FIG. 13 is 0.0312 is 0.1 g peak (0.2 g's peak-to-peak). As shown in FIG. 13, four curves are plotted: the left X-axis **736**, the left Y-axis **732**, the right X-axis **738**, and the right Y-axis **734**. Because the electroactive polymer actuators were configured to move primarily in the X-direction relative to the Y-direction, as shown in FIG. 12, the right X-axis and the left X-axis **726** accelerations were greater than the corresponding right Y-axis **724** and left Y-axis **722** accelerations.

[0116] The following description of the present invention is directed to integration of an electroactive polymer actuator into an ear bud insert of an earphone. The assembly safely shields the electroactive polymer actuator and high voltage wires to minimize the risk of shock. FIGS. 15-17 illustrate three approaches to conforming an integrated electroactive polymer actuator/ear bud into an ear.

[0117] FIG. 15 is a cross-sectional view of a hub-mounted audio device **800** located inside the ear canal **808** in accordance with one embodiment of the present invention. The hub-mounted audio device **800** comprises a wall **806** and a potted electroactive polymer actuator **804** mounted about a hub **802**. As shown in FIG. 15, an inner portion **810** of the potted electroactive polymer actuator **804** contacts an outer surface **812** abut the perimeter of the hub **802** and outer portions **814** of the electroactive polymer actuator **804** contact inner portions of the wall **806** whereas other surfaces **816**, **817** of the electroactive polymer actuator **804** do not contact the wall **806** and rather define openings **818**, **819** between the wall **806** and the outer surfaces **816**, **817**. The openings **818**, **819** are separated by the hub **802** and potted electroactive polymer **804**.

[0118] FIG. 16 is a cross-sectional view of a wall-mounted audio device **820** located inside the ear canal **808** in accordance with one embodiment of the present invention. The wall-mounted audio device **820** comprises a wall **826** and a potted electroactive polymer actuator **824** mounted to the wall **826** rather than a hub **822**. As shown in FIG. 16, an outer surface **828** of the potted electroactive polymer **824** contacts an inner portion of the wall **826** about the perimeter thereof. Portions **830** on an inner surface of the potted electroactive polymer **824** contact the hub **822** and defines openings **832**, **834** between portions **836**, **838** of the potted electroactive polymer actuator **824** and outer surfaces of the hub **822**.

[0119] FIG. 17 is a cross-sectional view of a fully potted audio device **840** located inside the ear canal **808** in accordance with one embodiment of the present invention. The fully potted audio device **840** comprises a hub **842**, a potted electroactive polymer actuator **844**, and a wall **846**. The potted electroactive polymer actuator **844** occupies the entire space between the inner surface **848** of the wall **846** and the outer surface **852** of the hub **842**. Accordingly, the outer surface **850** of the potted electroactive polymer actuator **844** is in contact with the inner surface **848** of the wall **846** and the inner surface **854** of the potted electroactive polymer actuator **844** is in contact with the outer surface **852** of the hub **842**.

[0120] FIG. 18 is a diagram of a conventional earphone **860**. The conventional earphone **860** includes a rigid case back **862**, a rigid case front **864**, and a flexible rubber ear bud **866**. A rigid sound tube **868** is molded into the rigid case front **864**. The conventional earphone **860**

is built using two pieces, with the rigid sound tube **868** rigidly attached to the rigid front case **864** of the earphone **860**.

[0121] FIG. 19 is a diagram of an earphone **870** in accordance with the present invention. The earphone **870** comprises a rigid case back **872**, a rigid case front **874**, and a flexible rubber ear bud **876**. In accordance with this embodiment of the present invention, however, a rigid sound tube **878** is formed as an integral feature of the otherwise flexible rubber ear bud **876**. During assembly, the end **884** of the sound tube **878** is attached to the rigid case front **874**, for example using adhesive, snap-fit, or ultrasonic welding. This provides a straightforward means of routing high-voltage leads **880** (HV+), 882 (GND) into the case front **874** and case back **872** during assembly.

[0122] Accordingly, the new configuration of the earphone **870** described in FIG. 19 decouples the rigid sound tube **878** from the rigid front case **874** of the earphone **870** to accommodate an electroactive polymer actuator and accompanying high voltage leads **880**, **882**. This embodiment of the present invention integrates the dielectric elastomer actuator into the ear bud **876** insert portion of the earphone **870** as described in connection with FIGS. 15-17. The assembly safely shields the electroactive polymer actuator and the high voltage wires **880**, **882** to minimize the risk of shock.

[0123] As shown in FIG. 19, the high voltage wires **880**, **882** are routed inside the protective rigid case front **872** at the earliest possible point, minimizing shock hazard. Furthermore, the earphone **870** provides a rigid foundation for building up the flexible ear bud **876**, enabling better precision when molding in or otherwise integrating the electroactive polymer actuator into the ear bud **876**, as discussed in connection with FIGS. 15-17. Finally, the earphone **870** configuration shown in FIG. 19 enables the designers to control space that was previously taken up by the rigid "sound tube" of the rigid case front and the "hub" of the flexible ear bud. As space is at a premium in the ear canal, it is helpful to be able to minimize the radial thickness of these passive parts, and leave more room for the electroactive polymer actuator.

[0124] FIGS. 20A-20D illustrate placement of electroactive polymer actuator **890** in an ear bud **876** in accordance with the present invention. The ear bud **876** is coupled to the rigid front case **874**. The high-voltage wires **880**, **882** are electrically coupled to the electroactive polymer **890** and in FIGS. 20A, 20B are seen exiting the end of the rigid front case **874**. As shown in FIG. 20D, the electroactive polymer **890** are located within a cavity **892** formed inside the flexible ear bud **876**. As shown in FIG. 20D, the electroactive polymer **890** are in contact with the wall of the ear bud **876** but not the hub **892**.

[0125] FIG. 21 is a graphical depiction of frequency response of the ear bud **876** shown in FIGS. 20A-20D in accordance with the present invention. The acoustic response was adequate. The tactile response was low when held in fingertips, there was no sensation at ~f=20-100 Hz and were detectable at ~f=100-200 Hz. Future configurations inspired by these results include addition of strain relief at soft-stiff transition - Soft = ear bud **876** and electroactive polymer actuator **890**; Stiff = wire-wrap leads **880, 882**. For measurements, a cast silicone ear and canal was considered ideal as it would match body stiffness: (Shore 00 35). An LDM laser was shined through the silicone to measure movement of a laser dot on the ear bud surface. The LDM laser was moved to get multiple points.

[0126] For electrical insulation, zero-defect isolation of ~1-1.8 kV is required and the insulation must not over-constrain movement. Because the ear bud **876** surface has compound curvature, it requires precise molds and fixtures. Other desirable methods of manufacturing the ear bud **876** include machining or 3D printing.

[0127] FIG. 22 illustrates an improved potting fixture **900** for placing the electroactive polymer actuator **890** into ear buds **876** in accordance with the present invention. As shown, the electroactive polymer **876** and the high voltage wires **880, 882** located through various openings **902** formed on a cover portion of the potting fixture **900**. The ear buds **876** are aligned along corresponding receiving holes **906** formed in a bottom case portion **908** of the potting fixture **900**. As shown in FIG. 22, the electroactive polymer **890** electrically coupled to the high voltage wires **880, 882** are inserted into openings **910** formed in the ear buds **876** and the entire assembly is then inserted into receiving holes **906** in the bottom case **908** where the assembly is potted.

[0128] FIGS. 23A-23D are photographs showing an electroactive polymer actuator **890** placement in an ear bud **876** in accordance with the present invention. In FIG. 23A, the electroactive polymer actuator **890** electrically coupled to high-voltage wires **880, 882** is shown to the left of a sectioned portion of the ear bud **876**. A detail view of the sectioned ear bud **876** is shown in FIG. 23C. FIGS. 23B and 23D show sectional views of the electroactive polymer actuator **890** mounted inside the ear bud **876**.

[0129] FIG. 24 is a graphical depiction of a finite element analysis rough draft model prediction of movement of the electroactive polymer actuator **890** within the ear bud **876**.

[0130] FIG. 25A is a graphical depiction **920** of measured movement consistent with the prediction shown in FIG. 24 in accordance with the present invention. FIG. 25B is a sectional view of the ear bud **876** and the electroactive polymer actuator **890** mounted therein in accordance with the present invention. A medium ear bud **876** with a 20 layer electroactive polymer actuator **890**, one slab, potted in a potting compound, 1.8 kV, free stroke was used to generate the data for FIG. 25A. The angle θ was varied from -5 degrees to 60 degrees and the measurements plotted in the graph **920** shown in FIG. 25A were taken at -5 degrees, 10 degrees, 30 degrees, and 60 degrees. With reference to both FIGS. 25A and 25B, the solid triangles (▲) represent 60 degrees; the solid circles (●) represent 30 degrees; the solid squares (■) represent 10 degrees; and the solid diamonds (♦) represent -5 degrees. The amplitude distribution was consistent with finite element rough draft shown in FIG. 24. The direction also agreed (field on radius reduced), whereas the peak amplitude was lower than the model.

[0131] FIG. 26 is a photograph depicting the results of high potential voltage (HiPot) testing of an electroactive polymer actuator enhanced ear bud in accordance with the present invention. The procedure is as follows: contact with Al foil **922**; repeat 5x to ensure all surface tested. Voltage=3600 DC (2x operating voltage). Time =1000 sec. No failures (N=2 samples). A device made in this manner is illustrated in FIG. 27 and had V=1.6kV (35 V/μm), a frequency=60-120 Hz. The tactile sensation was detected in pinch grip (3/3 subjects). A tactile sensation was detected in the ear canal (3/3 subjects) and was reported to be not annoying (3/3).

[0132] FIGS. 28A-28C illustrate some additional movement strategies such as a piston mode (FIG. 28A), a bender mode (FIG. 28B) and a basket mode (FIG. 28C) in accordance with the present invention. As shown in FIG. 28A, in piston mode the motion is along the longitudinal axis defined by the electroactive polymer actuator **930**. As shown in FIG. 28A, excitation by a voltage potential causes electroactive polymer actuator **930** to elongate by Δd in the longitudinal direction defined by the electroactive polymer actuator **930**. In FIG. 28B, in bender mode the electroactive polymer actuator **932** bends under a force F like a beam for a displacement in the Y direction of Δy relative to x_0 by an angle of θ_m. In the basket mode shown in FIG. 28C, the electroactive polymer **934** is shaped like a basket and is capable of expanding and collapsing under the influence of a high-voltage potential between the HV+ and GND wires.

[0133] FIGS. 29A and 29B illustrate some potential issues arising out of the piston mode movement depicted in FIG. 28A. In the piston mode, the electroactive polymer actuator **930** stack or roll may buckle instead of elongating in the longitudinal direction defined by the electroactive polymer actuator **930**.

[0134] FIGS. 30 and 31 illustrate the bender mode previously discussed in connection with FIG. 28B. In FIG. 30, the bending angle θ is determined and in FIG. 31, the Δy displacement is determined. As shown in FIG. 30, the straight beam **932** is represented by the expression:

[0135] $S_2 = (r_1+t)\theta$

[0136] and the bent beam **934** is represented by the expression:

[0137] $S_1 = r_1\theta = \ell$

[0138] The angle θ is small ~3.2° and is calculated according to the following:

[0139] In FIG. 31 it is shown that for a small angle $\theta_m \approx \theta$, $\Delta y = 0.57$mm and is calculated according to the following:

Small angle approx

$$\theta_m \approx \theta$$

$$\Delta y \approx x_0 \sin\theta$$

$$\Delta y \cong x_0 \sin\left(\frac{\ell(\lambda - 1)}{t}\right)$$

$$\Delta y \cong [0.010\,\text{m}]\sin\left(\frac{[0.010\,\text{m}](1.017 - 1)}{[0.003\,\text{m}]}\right)$$

$$\Delta y \cong 0.00057\,\text{m} = 0.57\,\text{mm}$$

[0140]

[0141] FIG. 32A is an exploded view of a unimorph electroactive polymer actuator **940** including relative dimensions thereof in accordance with the present invention. FIG. 32B is an assembled view of the unimorph electroactive polymer actuator **940** shown in FIG. 32A. With reference now to both FIGS. 32A and 32B, the unimorph electroactive polymer actuator **940** comprises an electroactive polymer roll **942**, an electrically insulated sheet **944**, and an electrical conductor 946. Although a set of suitable dimensions for implementing a unimorph electroactive polymer actuator **940** is disclosed in connection with the present invention, such dimensions should not be construed in a limiting manner. Rather, such dimensions may be modified for any suitable applications without departing from the overall scope of the present invention.

[0142] FIG. 33 is photograph showing several unimorph electroactive polymer actuators **940**.

[0143] FIG. 34 is a graphical depiction **942** of measured movement of roll bender electroactive polymer actuators. Theory: Δx=0.57 mm; Observed: Δx=0.25-0.35 mm; Fblock=0.025 N.

[0144] FIG. 35A illustrates spring rate on tension roll from loaded hoops **945** in accordance with the present invention. FIG. 35B is a graphical depiction **947** of force as a function of stretch ratio. From pure geometry, about a 30% increase in force can be achieved using a linear spring on the hoop. But this would require a great fattening of the electroactive polymer actuator. 10 degrees is about acceptable. But this only gives strain of 1.5%. Many smaller hoops at about 40 degrees could be acceptable. -20 degrees gives 6% strain; 30 degrees gives 15% strain; 40 degrees gives 30% strain. Nonlinear (strain softening) hoop spring could increase the steepness of the negative rate.

[0145] The force F is calculated as follows:

$$F_y = -ky$$

$$F_{10} = \frac{F_y}{\sin\theta}$$

$$F_{12} = F_{10}\cos\theta$$

$$F_{12} = F_y\cot\theta$$

$$|F_{12}| = kd\sin\theta\cot\theta = kd\cos\theta$$

$$x = d\cos\theta$$

[0146] An average human ear canal is about 26 mm in length and 7 mm in diameter. The outer part of the canal consists of a cartilaginous soft body and a 0.5 - 1.0 mm thick skin with glands and hair follicles. The glands produce ear wax, which has an important role in keeping the ear canal clean and protecting it from bacteria, fungi and insects. The outer soft part of the canal forms one third to one half of total canal length. The remaining inner part of the canal rests on the opening of the bony skull and the skin in this part of the canal is tightly applied to the bone. The skin here is approximately 0.2 mm thick and it may be easily injured or ruptured.

[0147] FIG. 36 is a diagram of the human ear **1000**. Applied sound pressure **1002** at the ear canal entrance **1004**, radiated sound pressure at the ear canal entrance **1004**, applied force or displacement at the actuator attachment points **1008**, and displacement of the footplate center in the direction of the longitudinal stapes axis **1010** are shown.

[0148] The foregoing examples of the present invention are offered for the purpose of illustration and not limitation. It will be apparent to those skilled in the art that the embodiments described herein may be modified or revised in various ways without departing from the spirit and scope of the invention. The scope of the invention is to be measured by the appended claims.

[0149] It is to be appreciated that the embodiments described herein illustrate example implementations, and that the functional elements, logical blocks, program modules, and circuits elements may be implemented in various other ways which are consistent with the described embodiments. Furthermore, the operations performed by such functional elements, logical blocks, program modules, and circuits elements may be combined and/or separated for a given implementation and may be performed by a greater number or fewer number of components or program modules. As will be apparent to those of skill in the art upon reading the present disclosure, each of the individual embodiments described and illustrated herein has discrete components and features which may be readily separated from or combined with the features of any of the other several embodiments without departing from the scope of the present disclosure. Any recited method can be carried out in the order of events recited or in any other order which is logically possible.

[0150] It will be appreciated that those skilled in the art will be able to devise various arrangements which, although not explicitly described or shown herein, embody the principles of the present disclosure and are included within the scope thereof. Furthermore, all examples and conditional language recited herein are principally intended to aid the reader in understanding the principles described in the present disclosure and the concepts contributed to furthering the art, and are to be construed as being without limitation to such specifically recited examples and conditions. Moreover, all statements herein reciting principles, embodiments, and embodiments as well as specific examples thereof, are intended to encompass both structural and functional equivalents thereof. Additionally, it is intended that such equivalents include both currently known equivalents and equivalents developed in the future, i.e., any elements developed that perform the same function, regardless of structure. The scope of the present disclosure, therefore, is not intended to be limited to the exemplary embodiments and embodiments shown and described herein. Rather, the scope of present disclosure is embodied by the appended claims.

[0151] Groupings of alternative elements or embodiments disclosed herein are not to be construed as limitations. Each group member may be referred to and claimed individually or in any combination with other members of the group or other elements found herein. It is anticipated that one or more members of a group may be included in, or deleted from, a group for reasons of convenience and/or patentability.

[0152] While certain features of the embodiments have been illustrated as described above, many modifications, substitutions, changes and equivalents will now occur to those skilled in the art. It is therefore to be understood that the appended claims are intended to cover all such modifications and changes as fall within the scope of the disclosed embodiments and appended claims.

[0153] Various aspects of the subject matter described herein are set out in the following numbered clauses:

[0154] 1. An electroactive polymer device comprising: first and second electroactive polymer actuators which are spatially separated, each of the electroactive polymer actuators comprising an electroactive polymer film, at least one pair of opposing compliant electrodes, and at least one mechanical output region, wherein the mechanical output region is configured to move in response to an activation signal being applied to the electroactive polymer film; wherein the first electroactive polymer actuator is configured to receive a first high voltage electrical signal and the second electroactive polymer actuator is configured to receive a second high voltage electrical signal, wherein the first and second high voltage electrical signals are independently tunable in both frequency and amplitude.

[0155] 2. The electroactive polymer device according to Clause 1, wherein the first high voltage electrical signal has a first frequency track and the second high voltage electrical signal has a second frequency track, wherein the first frequency track is not the same as the second frequency track.

[0156] 3. The electroactive polymer device according to clause 2, wherein the frequencies of the first and second frequency tracks are approximately in the range of ~1Hz and ~150Hz.

[0157] 4. The electroactive polymer device according to any of clauses 1 to 3 wherein the electroactive polymer device is an audio device further comprising at least one acoustic speaker which is configured to receive a first low voltage electrical signal that is tunable in both frequency and amplitude independently from the electroactive polymer actuators.

[0158] 5. The electroactive polymer device according to clause 4 further comprising at least a second acoustic speaker which is configured to receive a second low voltage electrical signal that is tunable in both frequency and amplitude independently from the electroactive polymer actuators.

[0159] 6. The electroactive polymer device according to clause 5, wherein amplitude and frequency of each of the first and second low voltage electrical signals is independently tunable for each of the first and second acoustic speakers.

[0160] 7. The electroactive polymer device according to one of clauses 1 to 6, wherein the device comprises one of an over-the-ear headphone, an inside-the-ear headphone, an in-the-ear audio device, a personal sound amplification device, a stress relief aid, a relaxation aid, a stimulation aid, and a hearing aid.

[0161] 8. The electroactive polymer device according to any of clauses 1 to 7 wherein the first and second electroactive polymer actuators are situated to provide motion on separate locations on a user's head and are driven to provide a binaural beat that is approximately the difference between the frequencies of the first and second electroactive polymer actuators.

[0162] 9. The electroactive polymer device according to one of clauses 1 to 8, wherein the device comprises an in-the-ear device, further comprising: a first hub; a first wall; and wherein the first electroactive polymer actuator located between the hub and the wall.

[0163] 10. The in-the-ear device according to clause 9, wherein the first electroactive polymer actuator is potted in a potting compound and is mounted to the hub and defines at least one cavity between an interior surface of the wall and an exterior surface of the electroactive polymer actuator or wherein the first electroactive polymer actuator is potted in a potting compound and mounted to the wall and defines at least one cavity between an interior surface of the electroactive polymer actuator and an exterior surface of the hub, or wherein the first electroactive polymer actuator is potted in a potting compound and is mounted to the wall and the hub to fill the space defined between an interior surface of the wall and an exterior surface of the hub.

[0164] 11. The in-the-ear device according to clause 9, further comprising: a second hub; a second wall; and wherein the second electroactive polymer actuator located between the hub and the wall.

[0165] 12. The electroactive polymer device according to one of clauses 1 to 11, wherein the device comprises an in-the-ear audio device, further comprising: a first rigid case back; a first rigid case front; a first flexible rubber ear bud; wherein the first electroactive polymer actuator is located within the flexible ear bud.

[0166] 13. The in-the-ear audio device according to clause 12, further including a rigid sound tube formed as an integral feature of the flexible rubber ear bud, wherein the rigid sound tube is configured to attach to the rigid case front.

[0167] 14. The in-the-ear audio device according to clause 12, further comprising: a second rigid case back; a second rigid case front; a second flexible rubber ear bud; wherein the second electroactive polymer actuator located within the flexible ear bud.

[0168] 15. A method of driving the device according to any of clauses 1 to 14 wherein the first and second electroactive polymer actuators are driven to provide a conductive audio response that couples to brain waves to induce one of mental relaxation or mental stimulation.

WHAT IS CLAIMED IS:

1. An electroactive polymer device comprising:

first and second electroactive polymer actuators which are spatially separated, each of the electroactive polymer actuators comprising an electroactive polymer film, at least one pair of opposing compliant electrodes, and at least one mechanical output region, wherein the mechanical output region is configured to move in response to an activation signal being applied to the electroactive polymer film;

wherein the first electroactive polymer actuator is configured to receive a first high voltage electrical signal and the second electroactive polymer actuator is configured to receive a second high voltage electrical signal, wherein the first and second high voltage electrical signals are independently tunable in both frequency and amplitude.

2. The electroactive polymer device according to Claim 1, wherein the first high voltage electrical signal has a first frequency track and the second high voltage electrical signal has a second frequency track, wherein the first frequency track is not the same as the second frequency track.

3. The electroactive polymer device according to Claim 2, wherein the frequencies of the first and second frequency tracks are approximately in the range of ~1Hz and ~150Hz.

4. The electroactive polymer device according to any of Claims 1 to 3 wherein the electroactive polymer device is an audio device further comprising at least one acoustic speaker which is configured to receive a first low voltage electrical signal that is tunable in both frequency and amplitude independently from the electroactive polymer actuators.

5. The electroactive polymer device according to Claim 4 further comprising at least a second acoustic speaker which is configured to receive a second low voltage electrical signal that is tunable in both frequency and amplitude independently from the electroactive polymer actuators.

6. The electroactive polymer device according to Claim 5, wherein amplitude and frequency of each of the first and second low voltage electrical signals is independently tunable for each of the first and second acoustic speakers.

7. The electroactive polymer device according to one of Claims 1 to 6, wherein the device comprises one of an over-the-ear headphone, an inside-the-ear headphone, an in-the-ear audio device, a personal sound amplification device, a stress relief aid, a relaxation aid, a stimulation aid, and a hearing aid.

8. The electroactive polymer device according to any of Claims 1 to 7 wherein the first and second electroactive polymer actuators are situated to provide motion on separate locations on a user's head and are driven to provide a binaural beat that is approximately the difference between the frequencies of the first and second electroactive polymer actuators.

9. The electroactive polymer device according to one of Claims 1 to 8, wherein the device comprises an in-the-ear device, further comprising:
a first hub;
a first wall; and
wherein the first electroactive polymer actuator located between the hub and the wall.

10. The in-the-ear device according to Claim 9, wherein the first electroactive polymer actuator is potted in a potting compound and is mounted to the hub and defines at least one cavity between an interior surface of the wall and an exterior surface of the electroactive polymer actuator or wherein the first electroactive polymer actuator is potted in a potting compound and mounted to the wall and defines at least one cavity between an interior surface of the electroactive polymer actuator and an exterior surface of the hub, or wherein the first electroactive polymer actuator is potted in a potting compound and is mounted to the wall and the hub to fill the space defined between an interior surface of the wall and an exterior surface of the hub.

11. The in-the-ear device according to Claim 9, further comprising:
a second hub;
a second wall; and
wherein the second electroactive polymer actuator located between the hub and the wall.

12. The electroactive polymer device according to one of Claims 1 to 11, wherein the device comprises an in-the-ear audio device, further comprising:
a first rigid case back;
a first rigid case front;
a first flexible rubber ear bud;
wherein the first electroactive polymer actuator is located within the flexible ear bud.

13. The in-the-ear audio device according to Claim 12, further including a rigid sound tube formed as an integral feature of the flexible rubber ear bud, wherein the rigid sound tube is configured to attach to the rigid case front.

14. The in-the-ear audio device according to Claim 12, further comprising:
a second rigid case back;
a second rigid case front;
a second flexible rubber ear bud;
wherein the second electroactive polymer actuator located within the flexible ear bud.

15. A method of driving the device according to any of Claims 1 to 14 wherein the first and second electroactive polymer actuators are driven to provide a conductive audio response that couples to brain waves to induce one of mental relaxation or mental stimulation.

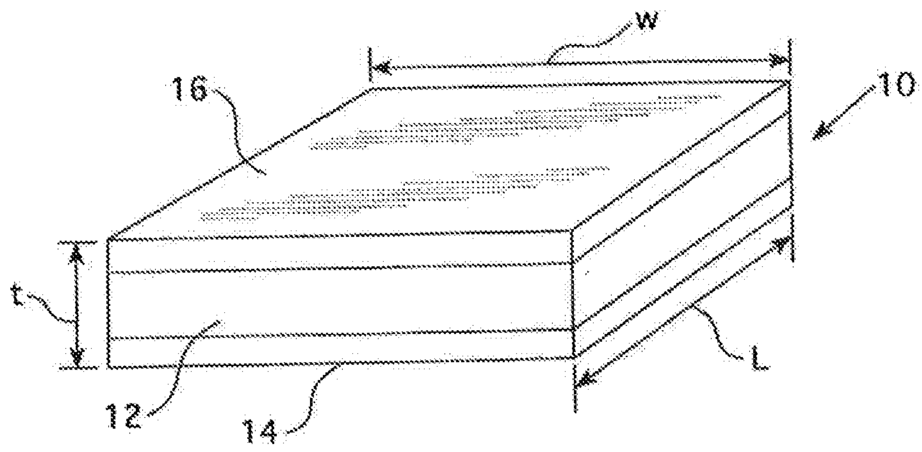

FIG. 1A

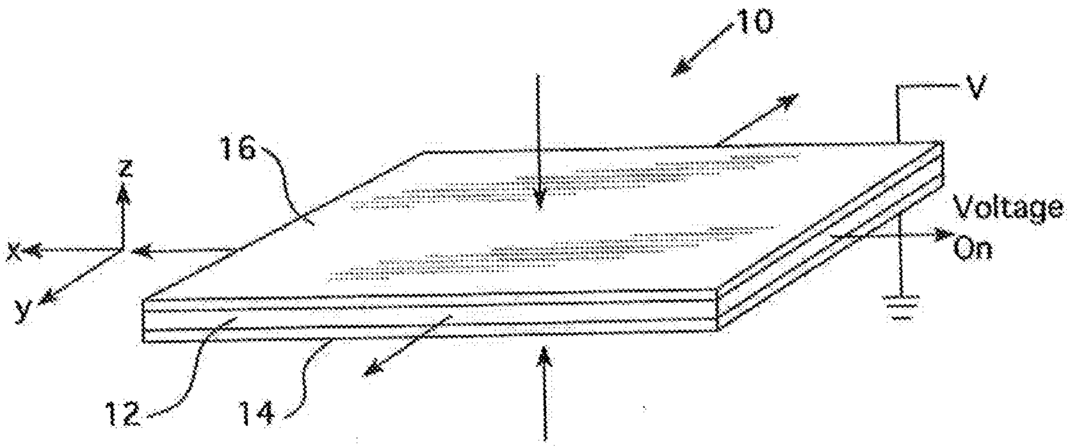

FIG. 1B

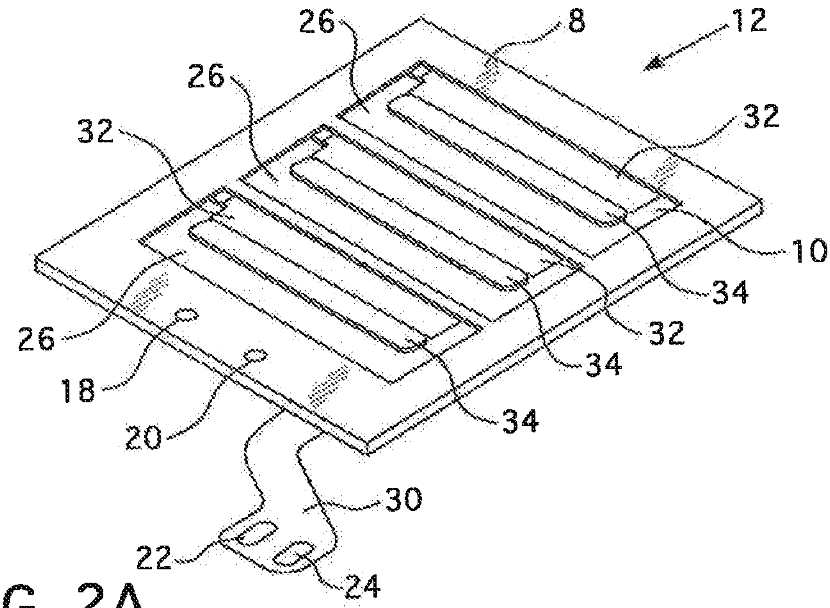

FIG. 2A

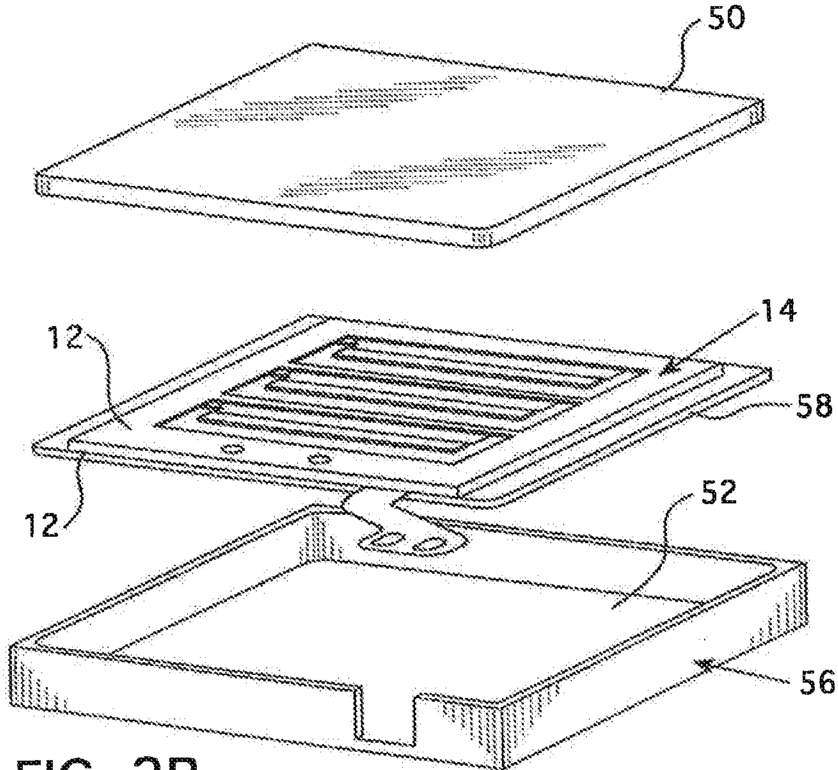

FIG. 2B

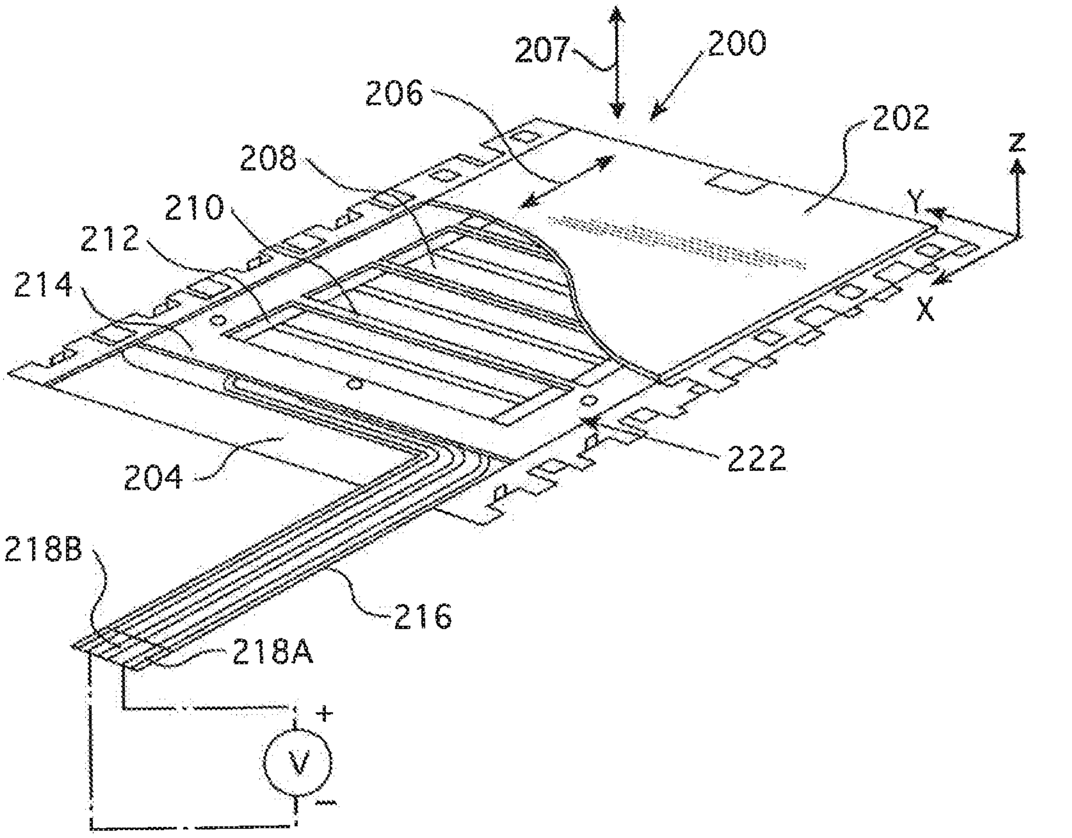
207
200
206
202
208
z
Y
210
212
214
X
222
204
218B
216
218A
+
V
−

FIG. 3

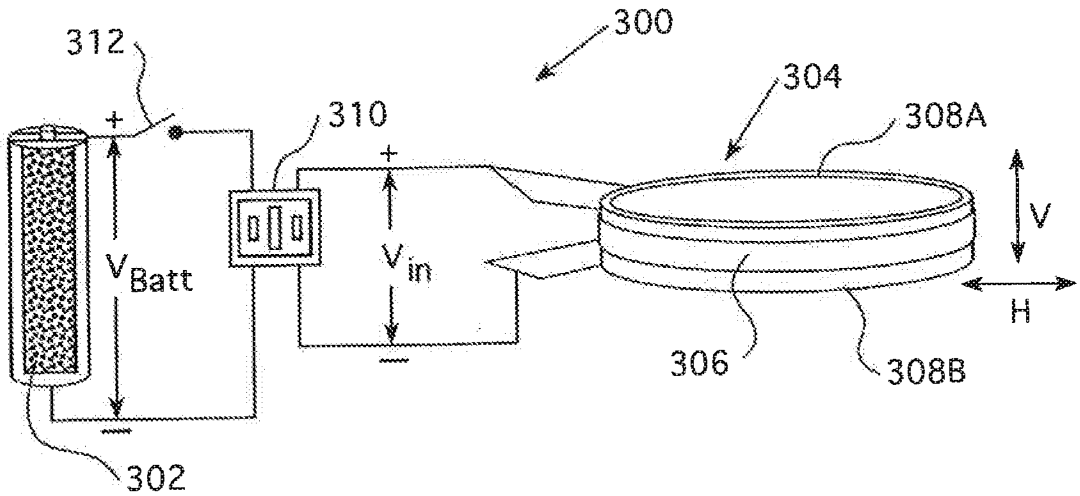
300
312
304
310
308A
+
+
V
V_{Batt}
V_{in}
H
306
308B
302

FIG. 4

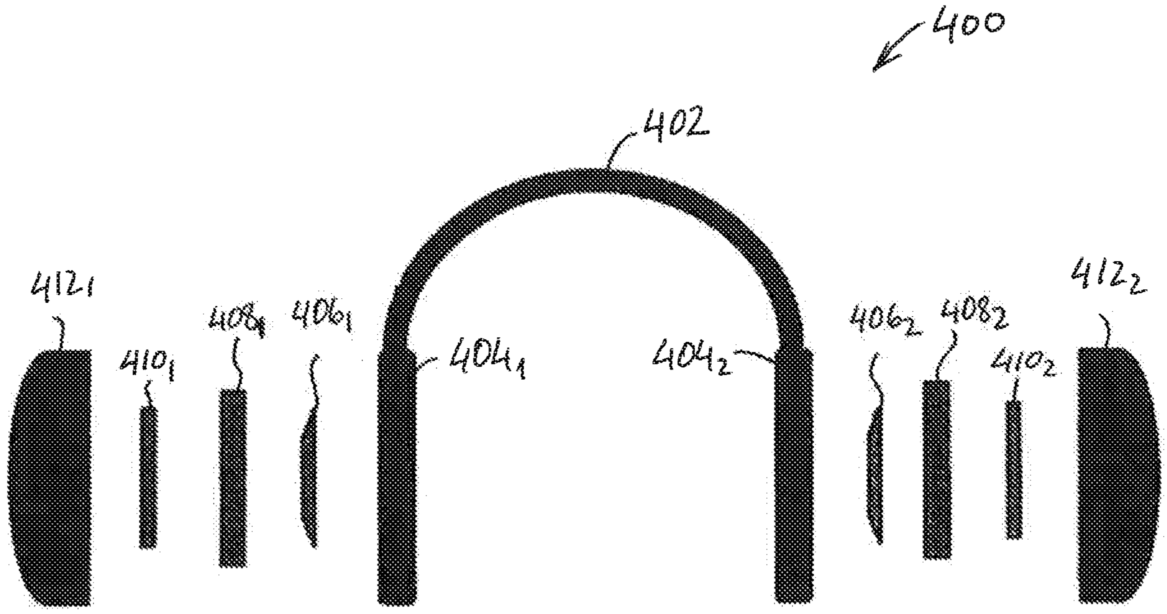
400
402
4121
4122
4101
4081
4061
4041
4042
4062
4082
4102

FIG. 5

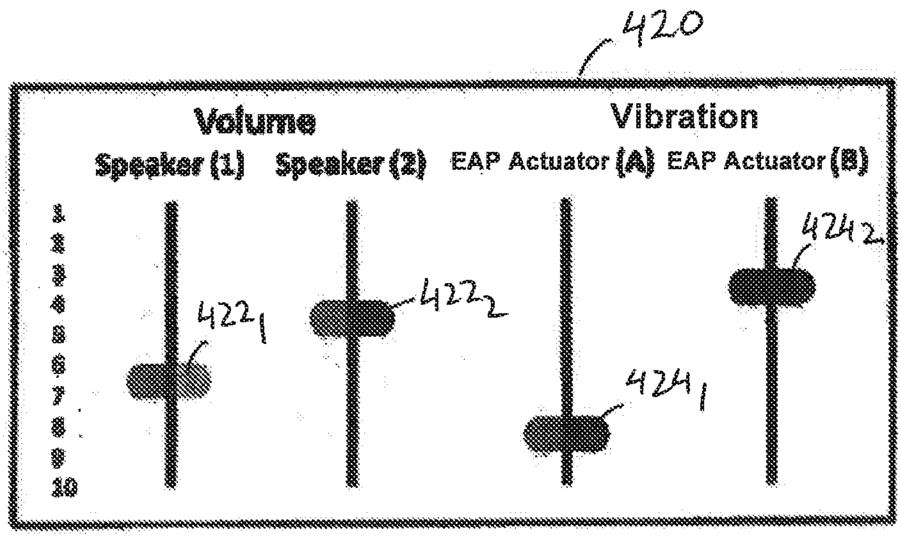
420
Volume
Vibration
Speaker (1)
Speaker (2)
EAP Actuator (A)
EAP Actuator (B)
1
2
3
4
5
6
7
8
9
10
4221
4222
4241
4242

FIG. 6

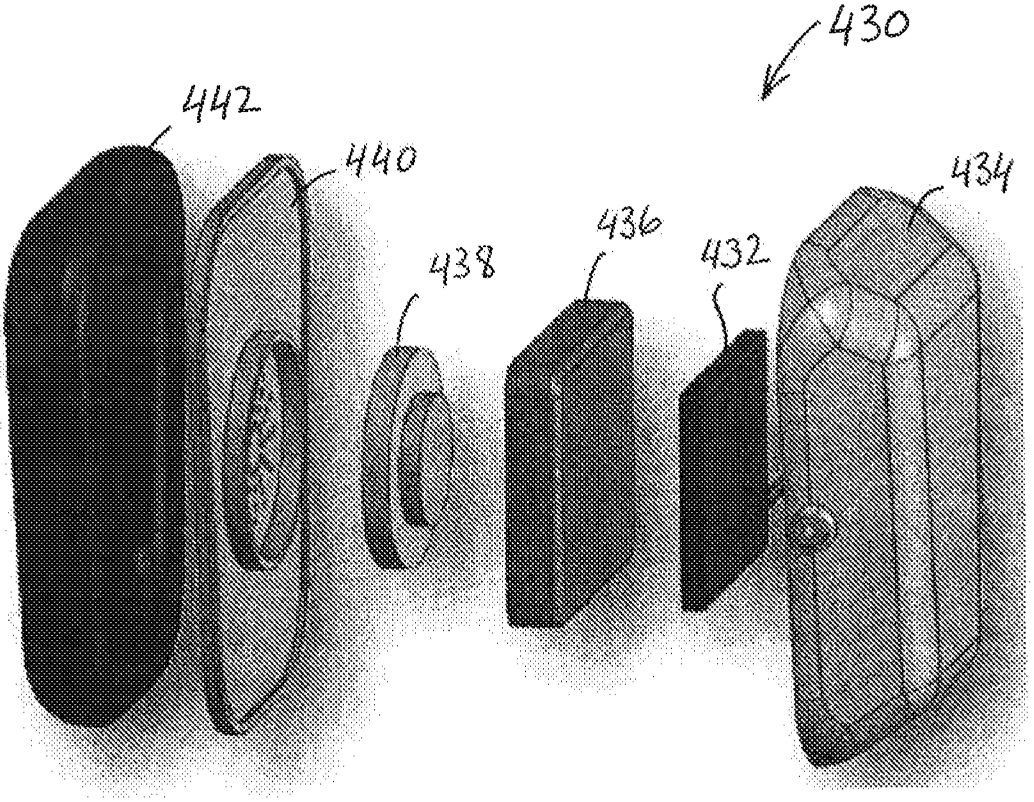

FIG. 7

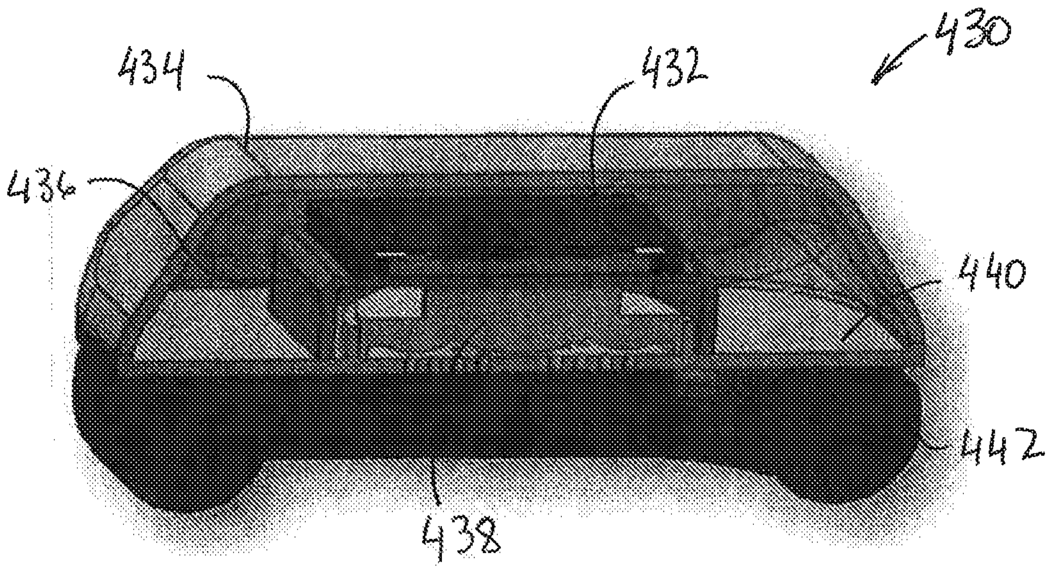

FIG. 8

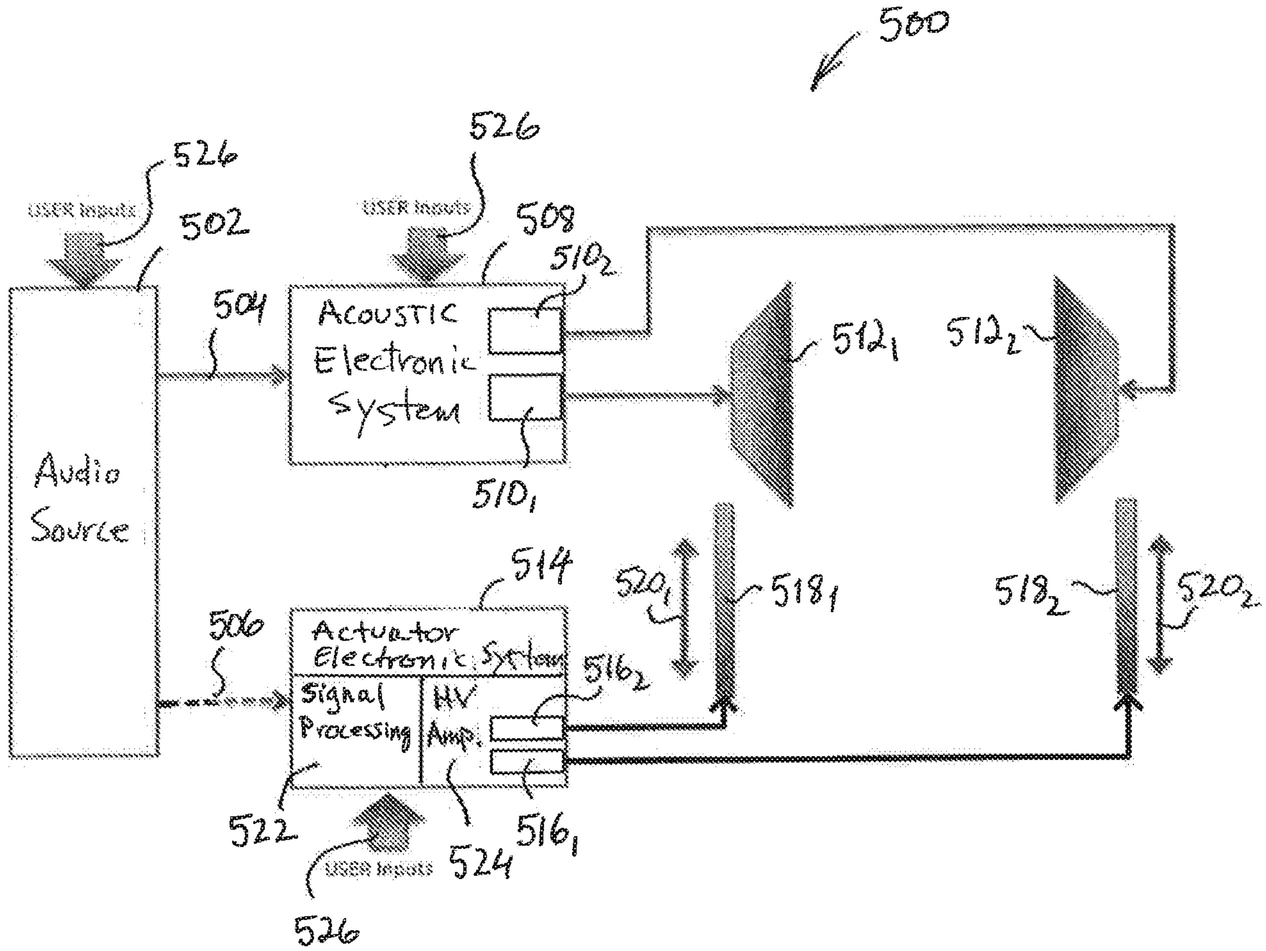
500
526
USER Inputs
502
526
USER Inputs
508
510₂
504
Acoustic Electronic System
512₁
512₂
Audio Source
510₁
514
520₁
518₁
518₂
520₂
506
Actuator Electronic System
516₂
Signal Processing
HV Amp.
522
516₁
524
USER Inputs
526

FIG. 9

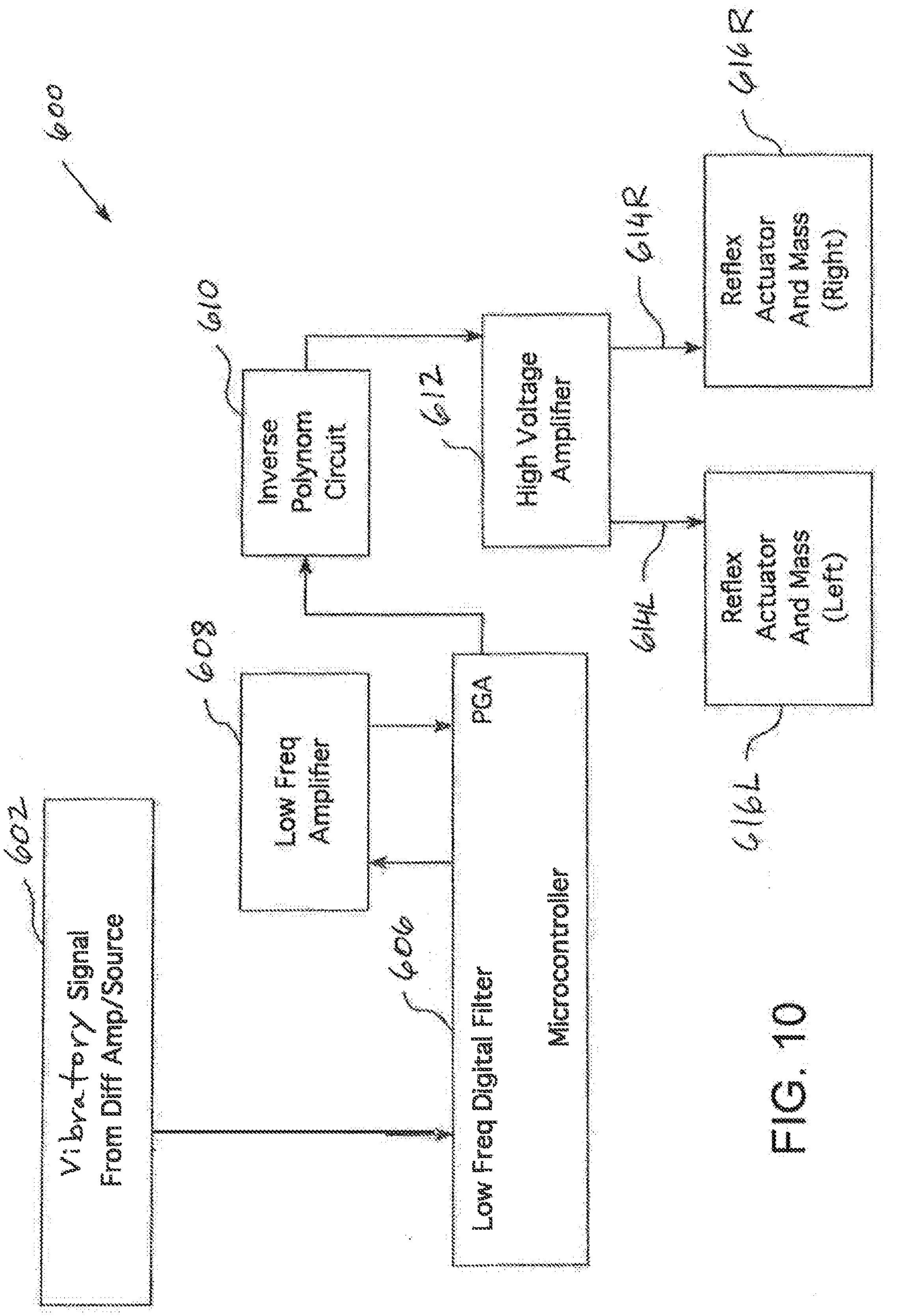
600
602
Vibratory Signal From Diff Amp/Source
606
Low Freq Digital Filter
Microcontroller
PGA
608
Low Freq Amplifier
610
Inverse Polynom Circuit
612
High Voltage Amplifier
614R
614L
616R
Reflex Actuator And Mass (Right)
616L
Reflex Actuator And Mass (Left)

FIG. 10

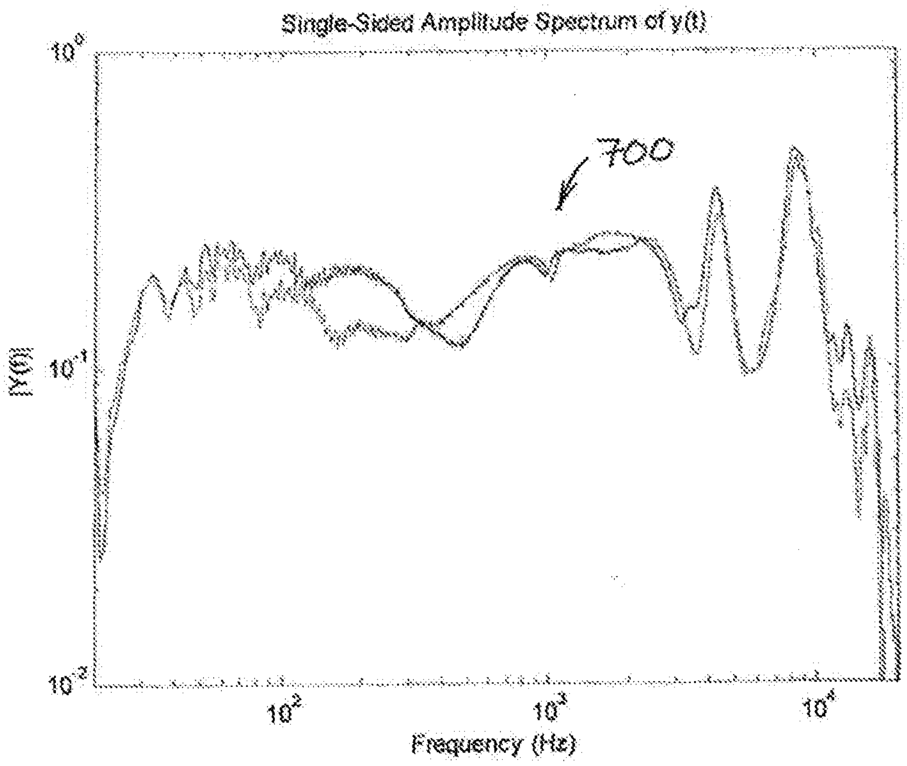
Single-Sided Amplitude Spectrum of y(t)
700
|Y(f)|
10^0
10^{-1}
10^{-2}
10^2
10^3
10^4
Frequency (Hz)

FIG. 11

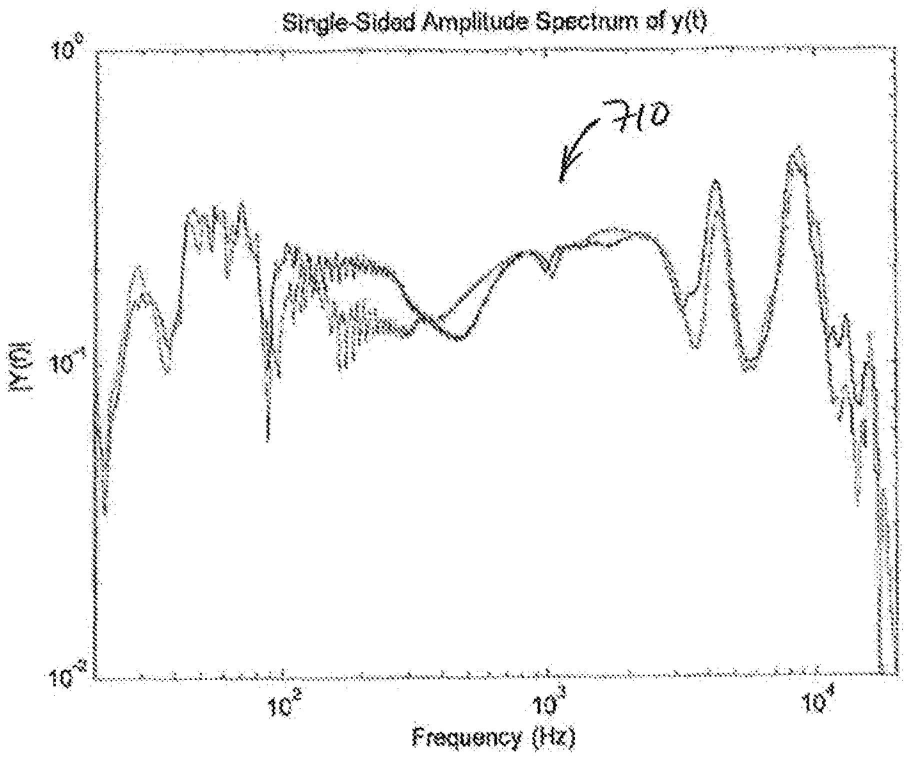
Single-Sided Amplitude Spectrum of y(t)
710
|Y(f)|
10^0
10^{-1}
10^{-2}
10^2
10^3
10^4
Frequency (Hz)

FIG. 12

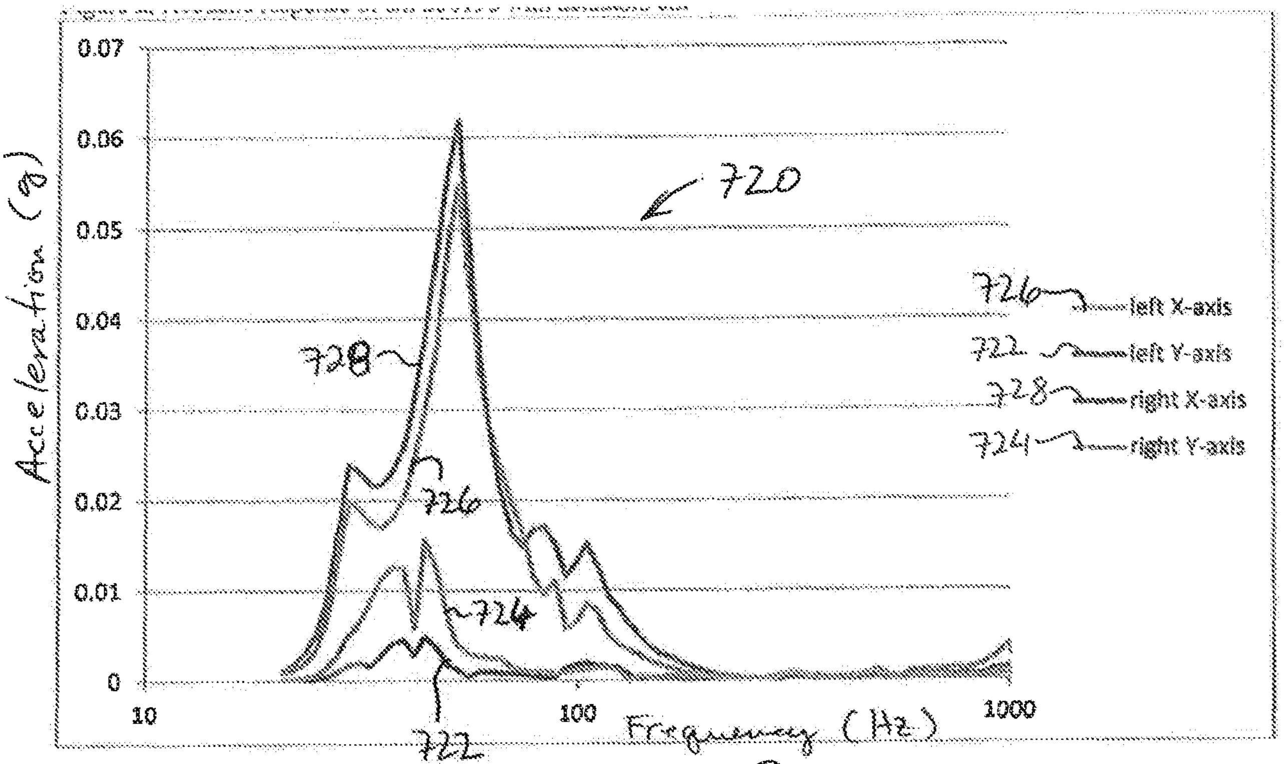
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
10
100
1000
Acceleration (g)
Frequency (Hz)
720
726
722
728
724
left X-axis
left Y-axis
right X-axis
right Y-axis

FIG. 13

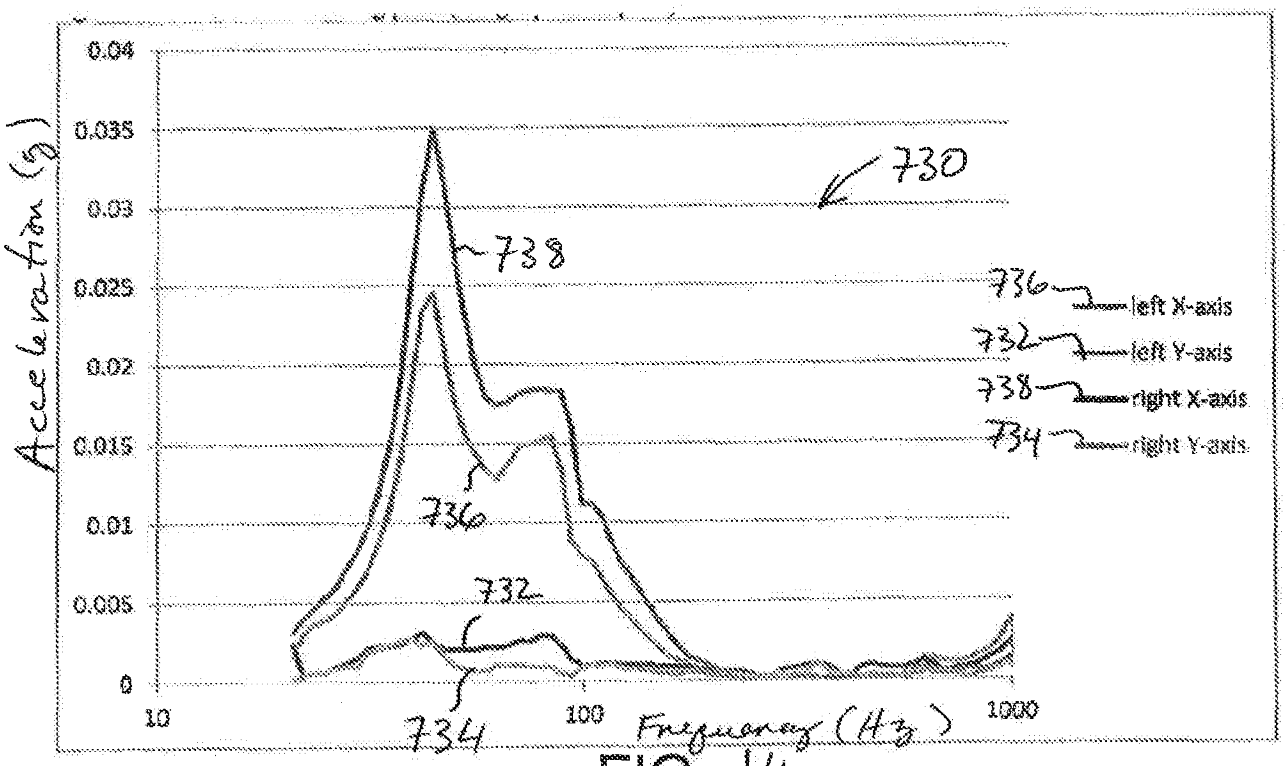
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
10
100
1000
Acceleration (g)
Frequency (Hz)
730
738
736
732
734
left X-axis
left Y-axis
right X-axis
right Y-axis

FIG. 14

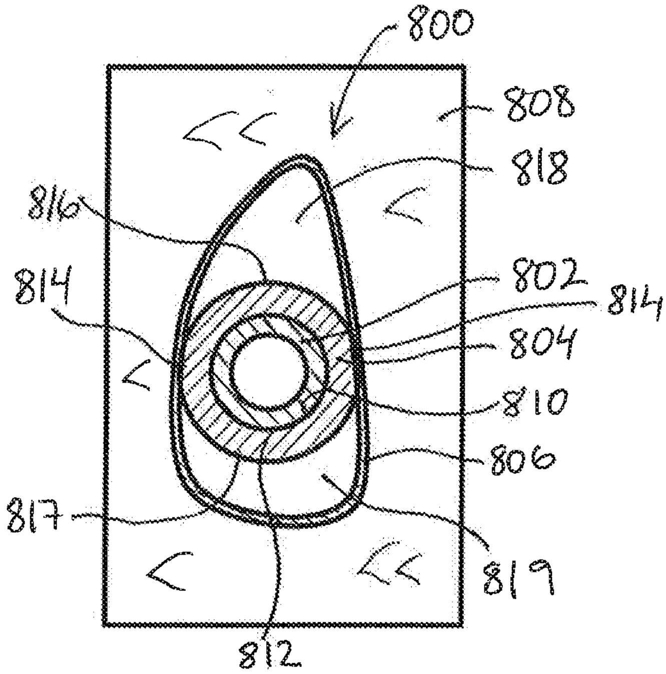

FIG. 15

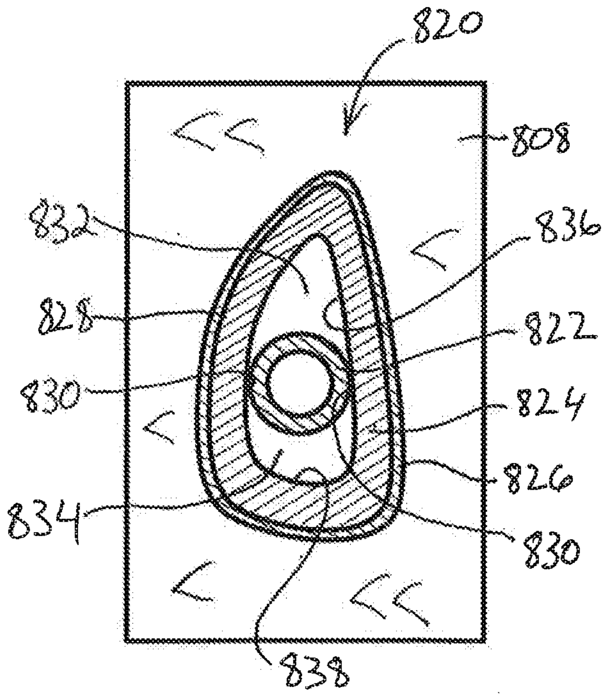

FIG. 16

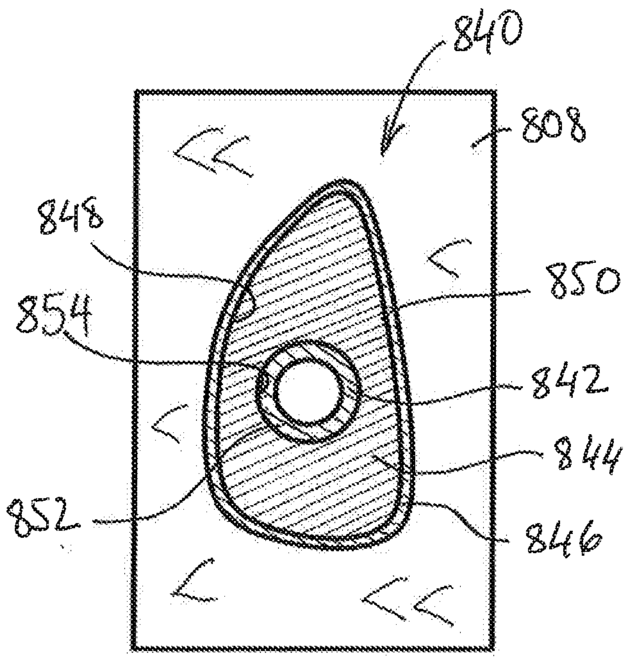

FIG. 17

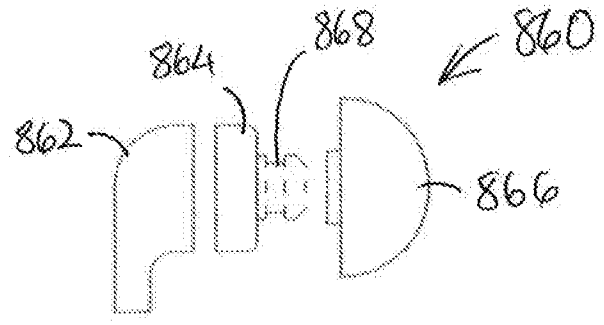

FIG. 18

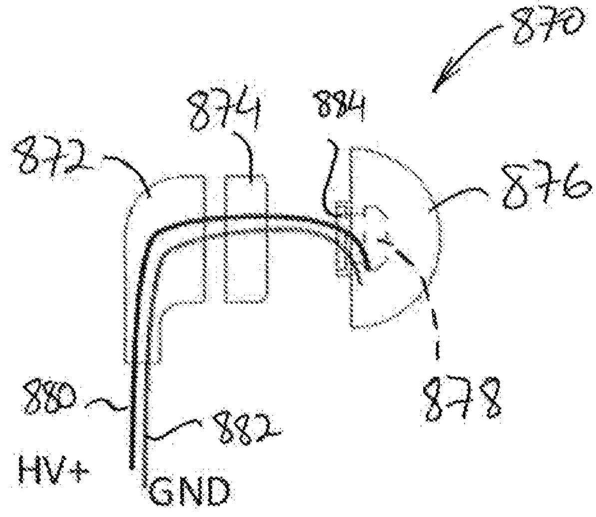

FIG. 19

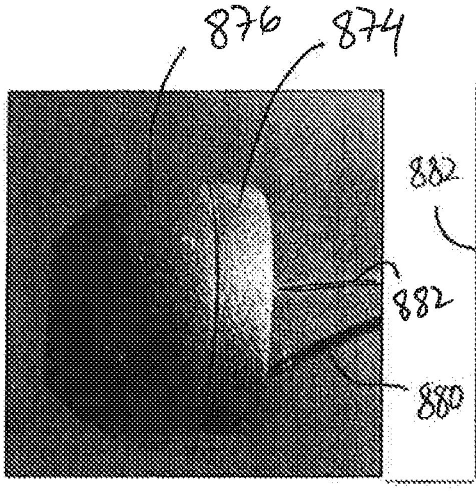

FIG. 20A

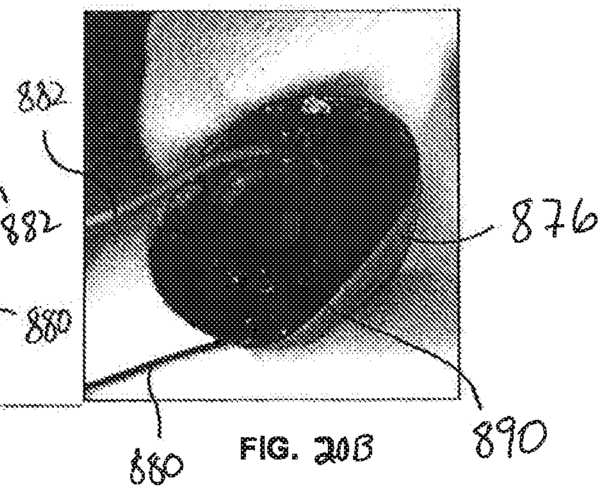

FIG. 20B

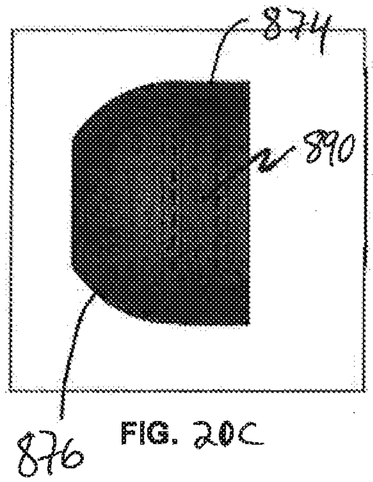

FIG. 20C

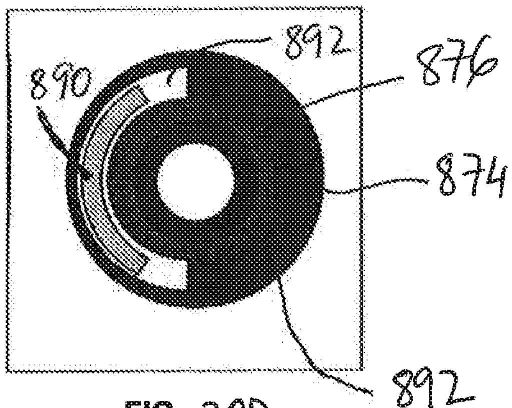

FIG. 20D

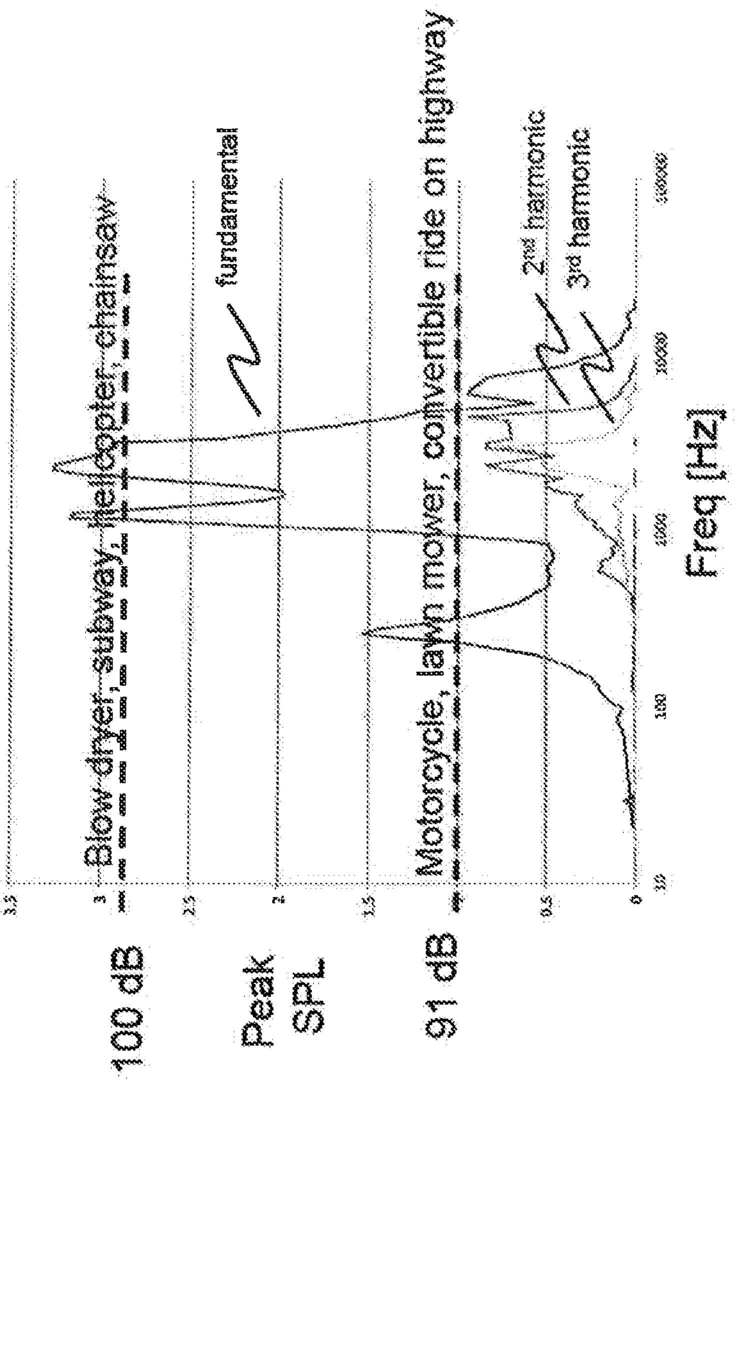
Blow dryer, subway, helicopter, chainsaw
fundamental
Motorcycle, lawn mower, convertible ride on highway
2nd harmonic
3rd harmonic
100 dB
Peak
SPL
91 dB
3.5
3
2.5
2
1.5
1
0.5
0
Freq [Hz]

FIG 21

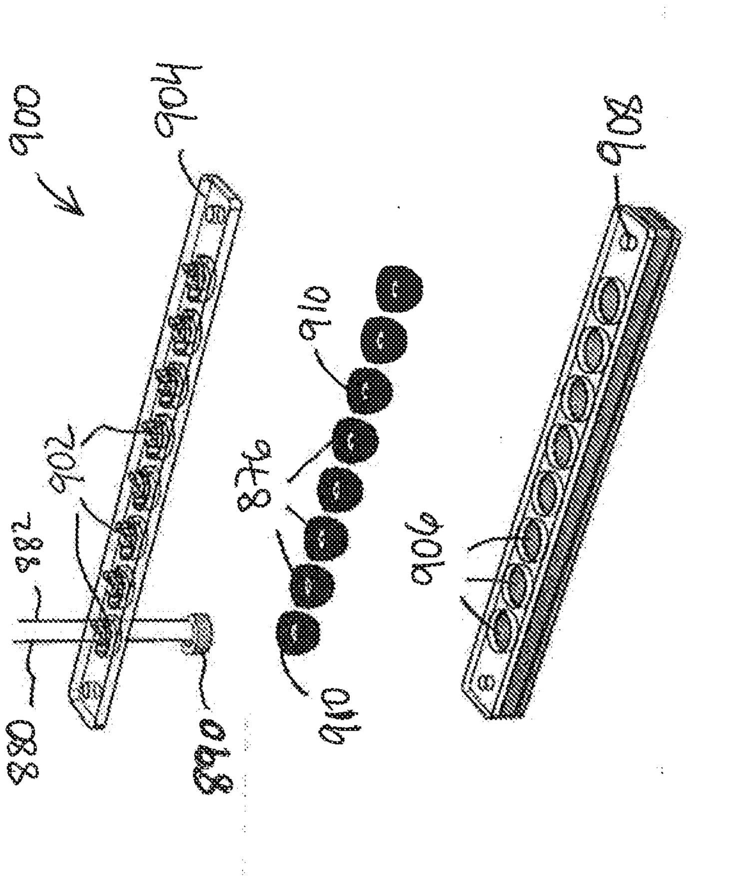

FIG. 22

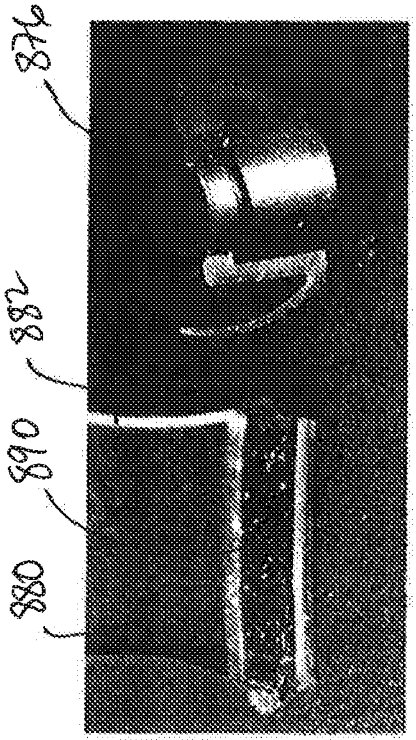

FIG. 23A

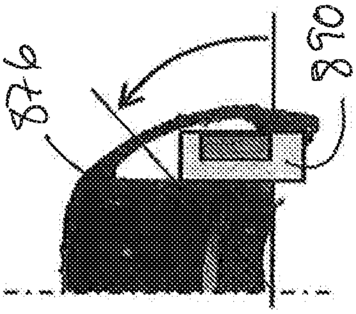

FIG. 23B

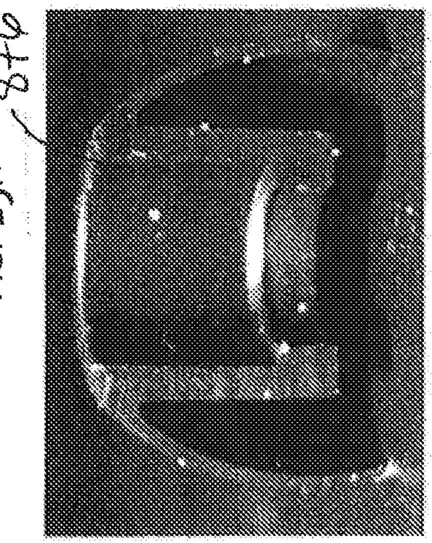

FIG. 23C

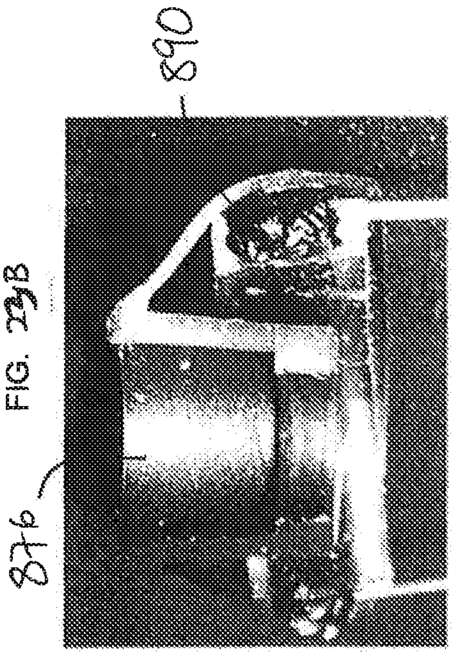

FIG. 23D

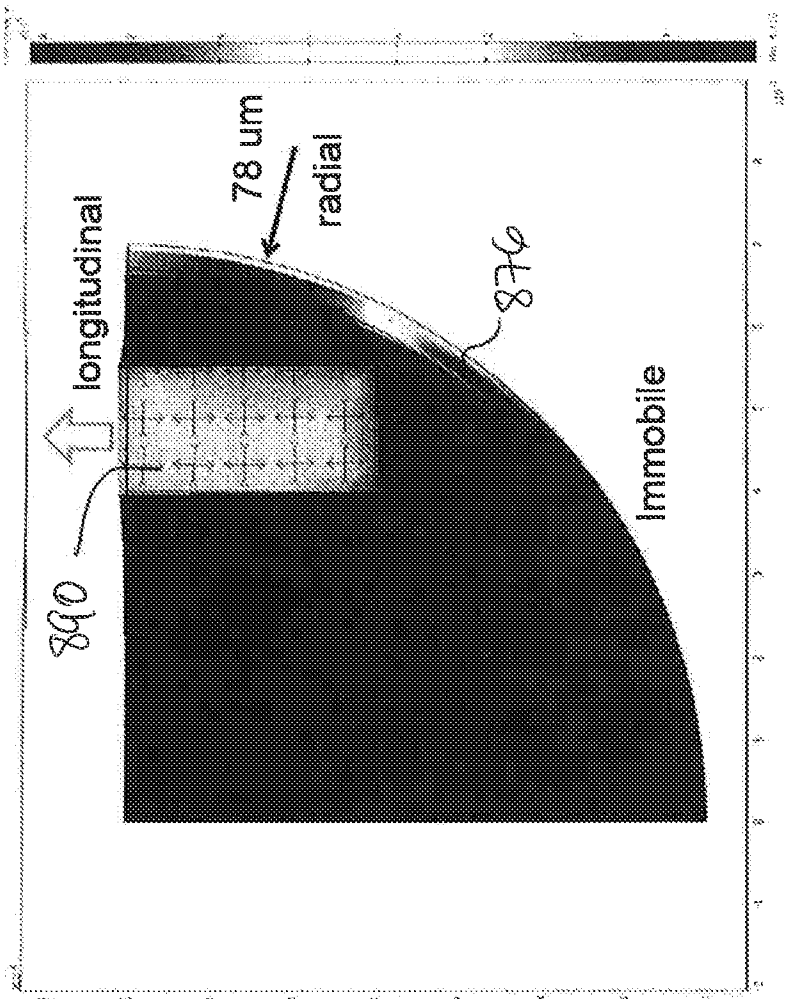

FIG. 24

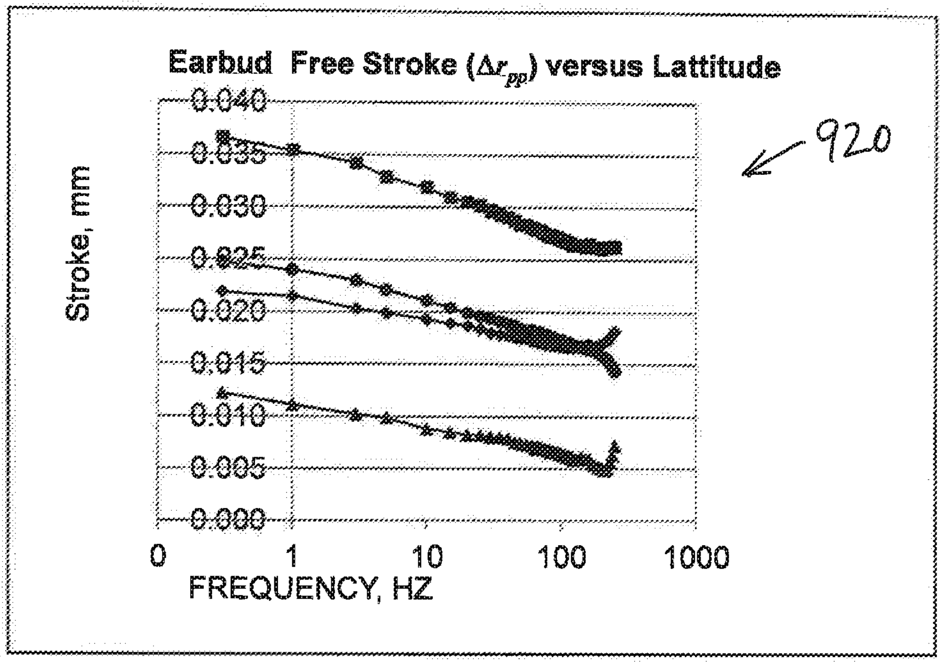

FIG. 25A

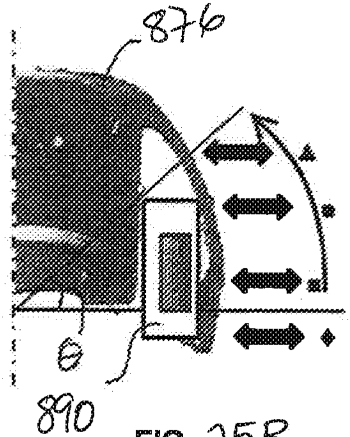

FIG. 25B

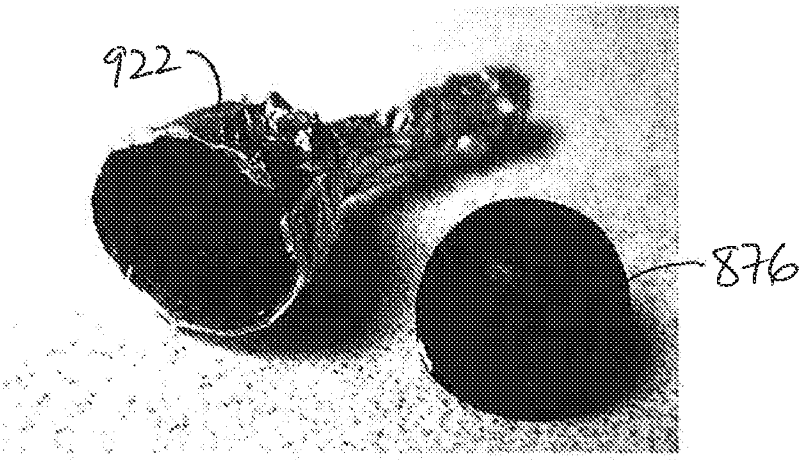

FIG. 26

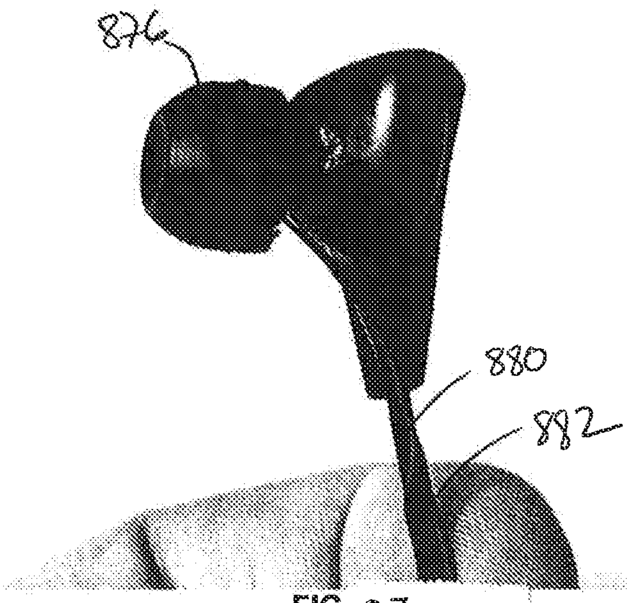

FIG. 27

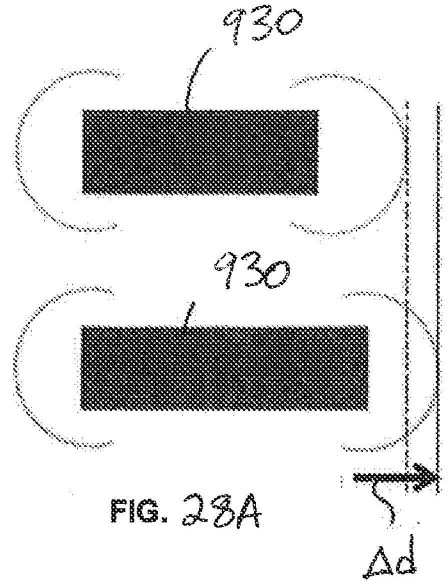

FIG. 28A

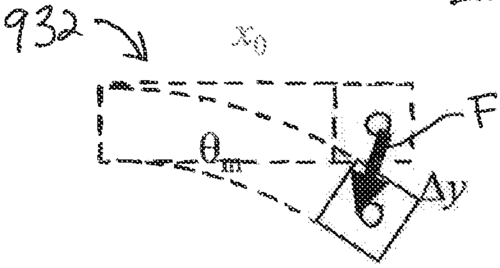

FIG. 28B

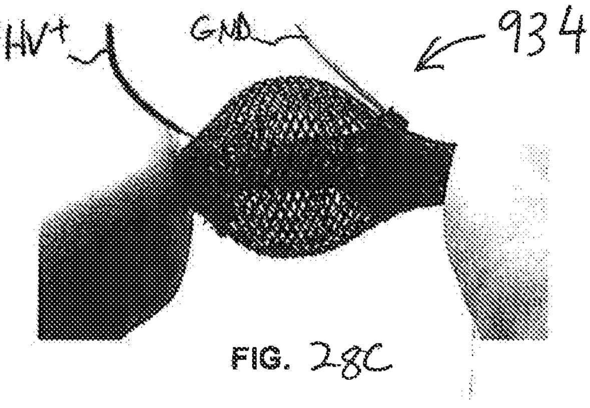

FIG. 28C

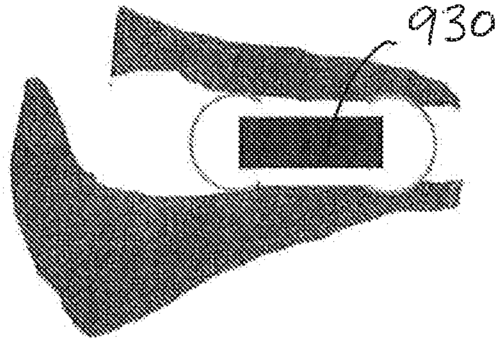

FIG. 29A

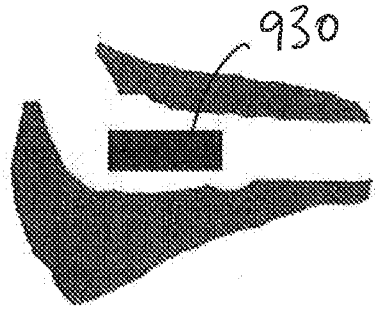

FIG. 29B

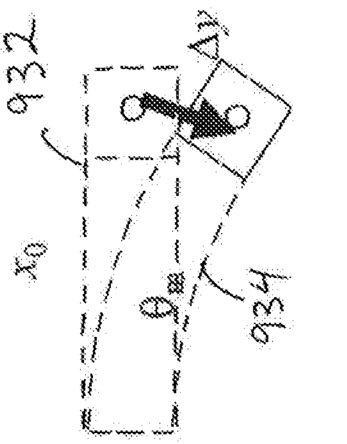

FIG. 31

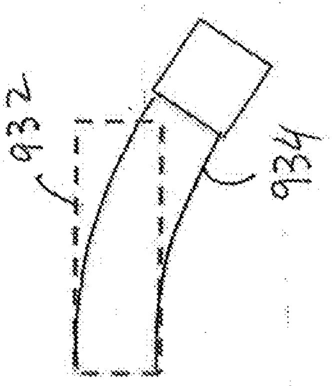

FIG. 30

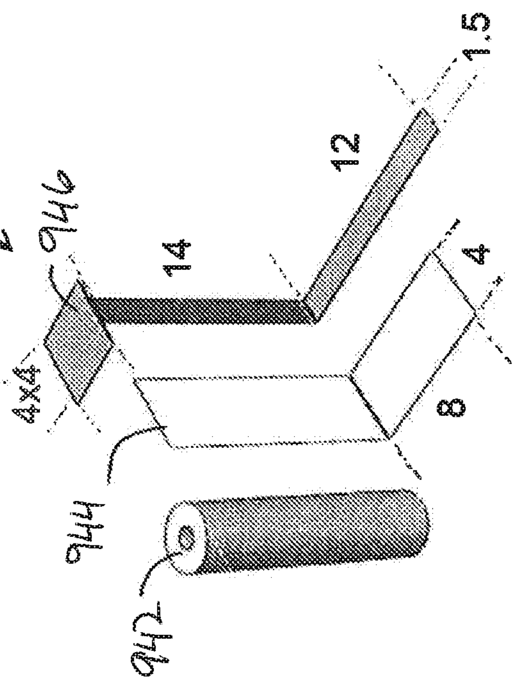

FIG. 32A

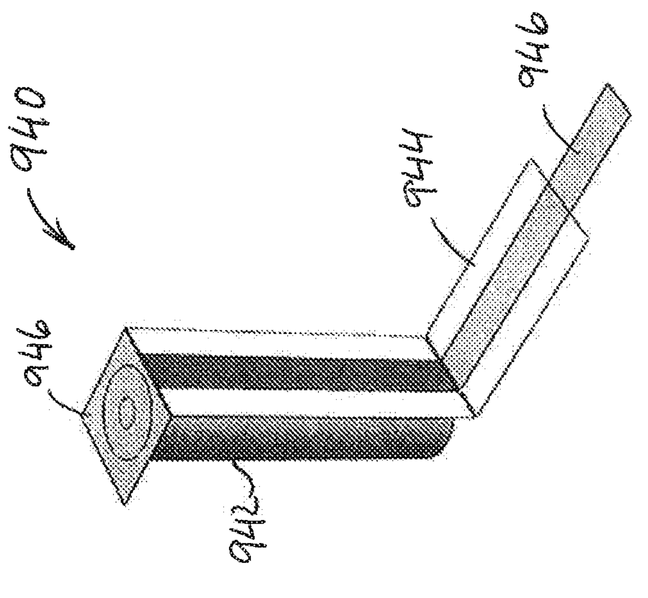

FIG. 32B

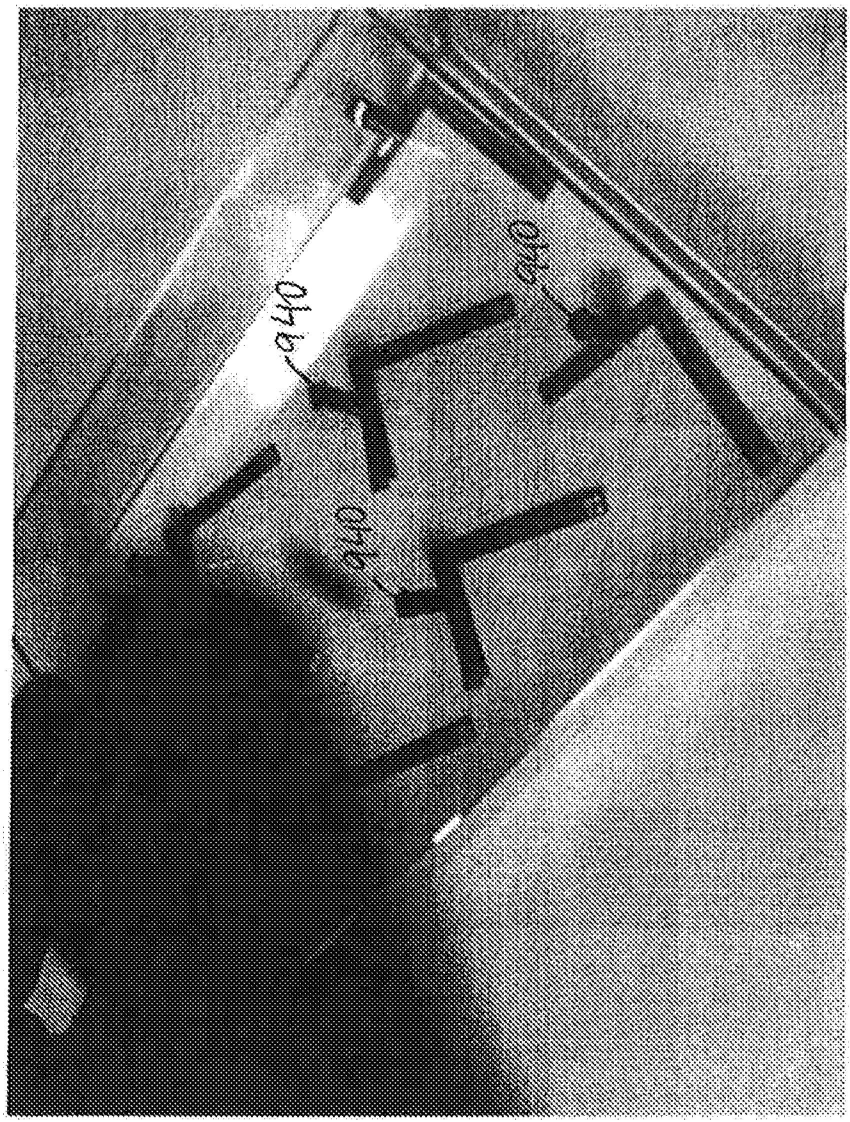

FIG. 33

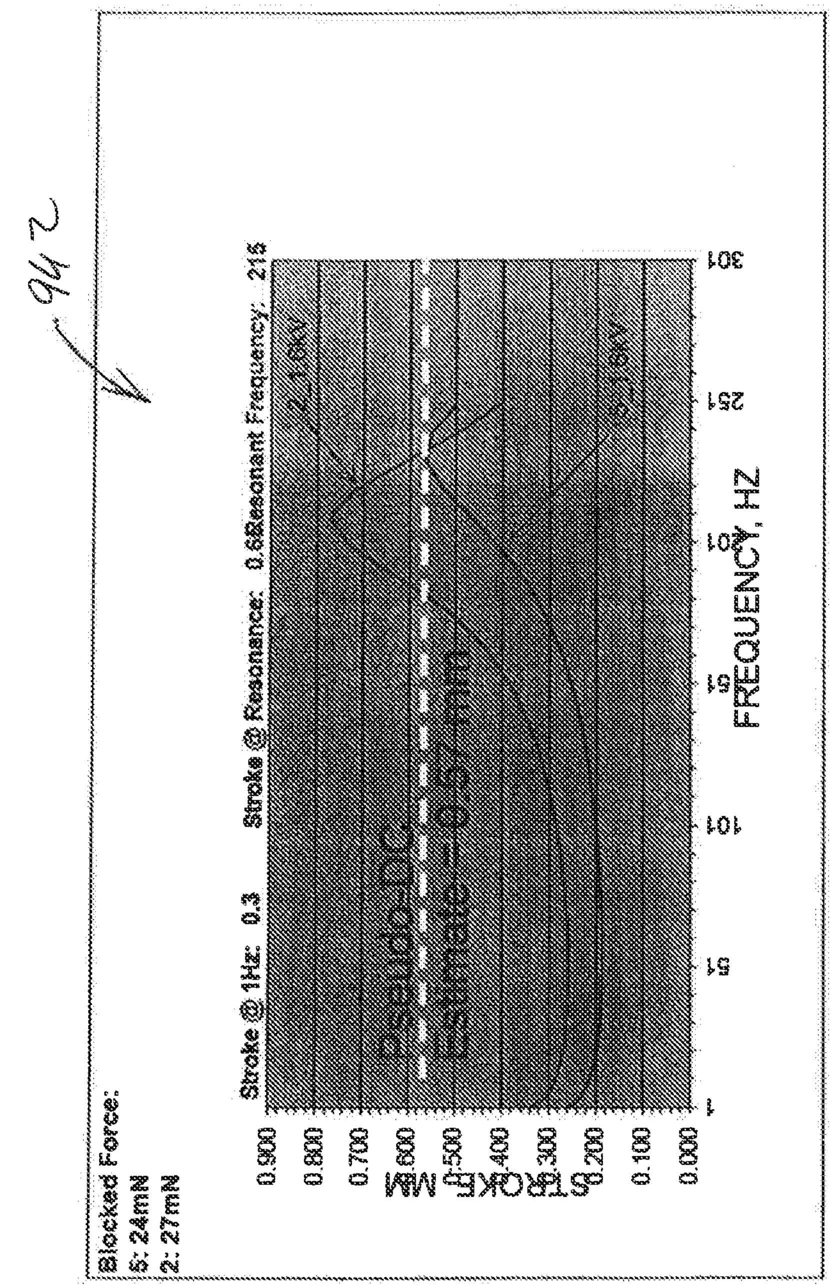
942
Blocked Force:
S: 24mN
2: 27mN
Stroke @ 1Hz: 0.3
Stroke @ Resonance: 0.6
Resonant Frequency: 215
STROKE MM
FREQUENCY, HZ

FIG. 34

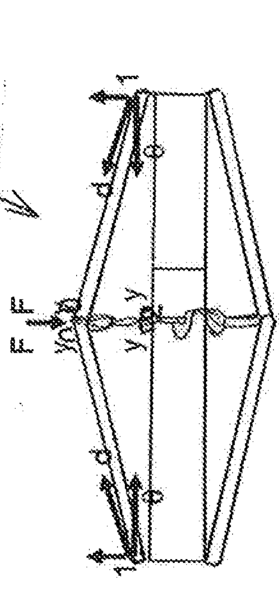

FIG. 35A

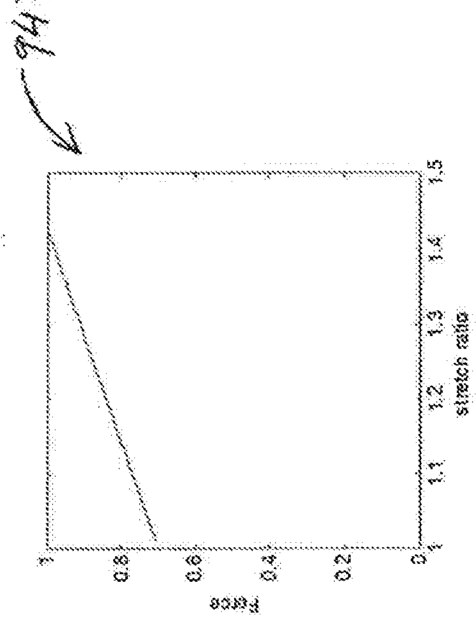

FIG. 35B

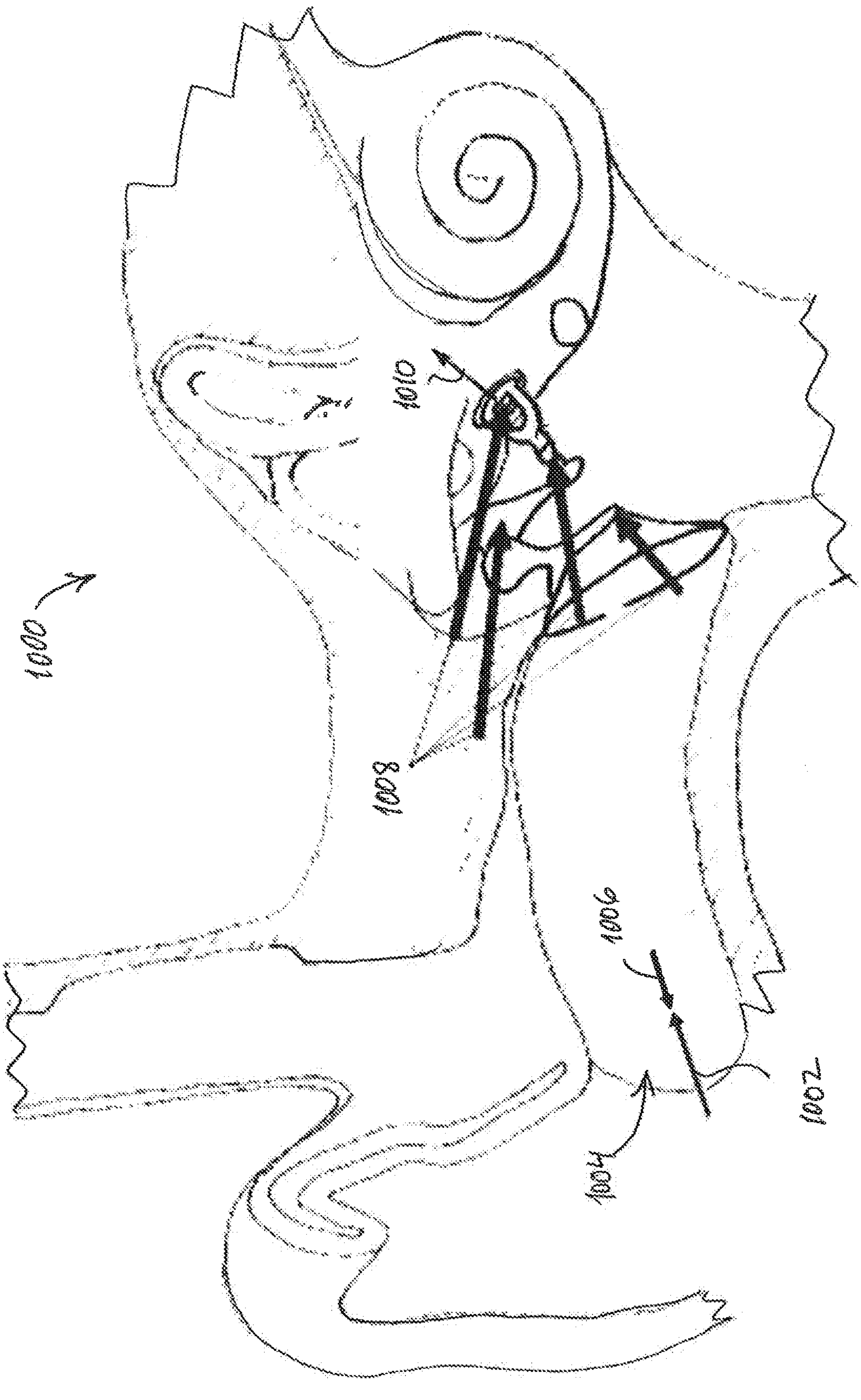

FIG. 36