

AUDIO DEVICES HAVING ELECTROACTIVE POLYMER ACTUATORS**CROSS REFERENCE TO RELATED APPLICATION**

This application claims the benefit, under 35 USC § 119(e), of
5 United States provisional patent application numbers: 61/497,556, filed
June 16, 2011, entitled "ELECTRO-MECHANICAL SYSTEM FOR
SIMULATING LOW FREQUENCY AUDIO SENSATIONS"; and
61/564,437, filed November 29, 2011, entitled "ACOUSTIC NOISE
REDUCTION TECHNIQUES FOR TACTILE HEADPHONE
10 ACTUATORS"; the entire disclosure of each of which is hereby
incorporated by reference.

FIELD OF THE INVENTION

In various embodiments, the present disclosure relates generally to
electro-mechanical systems for simulating low frequency audio sensations.
15 More particularly, the present disclosure relates to audio devices equipped
with electroactive polymer actuators or transducers. In particular, the
present disclosure relates to headphones equipped with electroactive
polymer actuators and mechanical and electrical acoustic noise reduction
modules.

BACKGROUND OF THE INVENTION

20 Conventional acoustic headphones include a pair of ear cups
intercoupled by a headband. The ear cups include loudspeakers mounted
within a housing portion of the ear cups and held in place close to a user's
ears. The headphones include electrical wires to connect the
25 loudspeakers to an audio signal source such as an audio amplifier, radio,
CD player, portable media player, computer, tablet, mobile device, or
gaming console. Some versions of conventional headphones also include
electronic circuits for signal conditioning and processing the acoustic
signal received from the audio signal source. Versions of audio
30 headphones that do not include a headband and are specifically designed

to be placed directly in the user's ear are also known as earphones or colloquially as earbuds.

Conventional audio signals include acoustical frequency components in the range of about 20 Hz to about 20 kHz. Most acoustic reproduction systems (home audio, headphones, earbuds, telephones, speakers) cannot cover the entire audio frequency range effectively and typically perform poorly at low frequencies (below about 200 Hz). Accordingly, large acoustical radiators are employed to accurately reproduce low frequency audio signals. Typically, these devices are physically large and consume a significant amount of power. One example of an acoustical radiator is a subwoofer cabinet used in home theater systems. It is difficult to implement low frequency audio content into relatively small acoustic reproduction devices such as headphones. Some methods of doing so require essentially sealing the air volume around the listener's ear and using directly coupled air pressure waves. This method is effective but also poses uncomfortable pressures even at modest sound levels. At higher sound levels it can even become dangerous and cause short or long term hearing loss.

Bone conduction is the conduction of sound to the inner ear through the bones of the skull (http://en.wikipedia.org/wiki/Bone_conduction). Bone conduction is why a person's voice sounds different to him/her when it is recorded and played back. Because the skull conducts lower frequencies better than air, people perceive their own voices to be lower and deeper than others do. Bone conduction also explains why a recording of one's own voice sounds higher than one is accustomed to. Bone conduction is said to have been discovered by the composer Ludwig van Beethoven, who was almost deaf. Beethoven supposedly found a way to hear music through his jawbone by biting a rod attached to his piano.

Some hearing aids employ bone conduction, achieving an effect equivalent to hearing directly by means of the ears. A headset is

ergonomically positioned on the temple and cheek and an electromechanical transducer, which converts electric signals into mechanical vibrations, sends sound to the internal ear through the cranial bones. Likewise, a microphone can be used to record spoken sounds via bone conduction. The first description of a bone conduction hearing aid was provided in U.S. Pat. No. 1,521,287.

Bone conduction devices may be categorized into three types: hands-free headsets or headphones; hearing aids and assistive listening devices; and specialized communication devices (e.g. underwater & high-noise environments). Bone conduction devices have several advantages over traditional headphones: such devices are "ears-free", thus providing extended use comfort and safety; have high sound clarity in very noisy environments; may be used with hearing protection; and may provide the perception of stereo sound.

Among the devices' disadvantages: some implementations require more power than headphones; and some devices may provide less clear recording & playback than traditional headphones and microphone because of reduced frequency bandwidth.

An example of a bone conduction speaker is a rubber over-molded piezo-electric flexing disc about 40mm across and 6mm thick which is used by scuba divers. A connecting cable is molded into the disc, resulting in a tough, water-proof assembly. In use, the speaker is strapped against one of the dome-shaped bone protrusions behind the ear. As would be expected, the sound produced seems to come from inside the user's head, but can be surprisingly clear and crisp.

Bone conduction audio devices are not limited to headsets or headphones but can also be used on other parts of the body wherever the device can be coupled to the skeletal system.

The present disclosure provides improved audio devices such as headphones with electro-mechanical systems such as electroactive polymer actuators for simulating low frequency audio sensations. The

improved audio devices comprise mechanical and electrical acoustic noise reduction modules.

Another application that may be addressed by the present invention lies in sensory enhanced audio devices where information other than audio signals is conveyed to the user. An early example of a sensory enhanced headphone to convey coded signals is described in U. S. Pat. No. 1,531,543.

SUMMARY OF THE INVENTION

In one embodiment, the present disclosure applies to a sensory enhanced audio device. The audio device includes an electroactive polymer actuator array comprising at least one elastomeric dielectric element disposed between first and second electrodes. A tray may be configured to receive the electroactive polymer actuator array and a mass coupled to the electroactive polymer actuator array. A circuit is electrically coupled to the electroactive polymer actuator array. The circuit is to generate a drive signal preferably in the frequency range of about 2 Hz to about 200 Hz to cause the electroactive polymer actuator array to move or vibrate according to the drive signal. The electroactive polymer actuators shake (vibrate) the ear cups in the case of headphones, the vibrations tracking the incoming low frequency audio, thereby giving the sensation of low frequency audio without creating high pressure acoustical waves, which are potentially dangerous to the eardrum. The electroactive polymer actuators disclosed herein enhance the "listening" experience of conventional audio devices, such as headphones. With an appropriate drive signal, the actuator array can also be used to convey information unrelated to the audio signal. 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

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

FIG. 1 is a perspective view of a sensory enhanced headphone according to one embodiment of the present invention;

FIG. 2 is a perspective view of the left ear cup shown in FIG. 1 according to one embodiment;

5 FIG. 3 is a front view of the left ear cup shown in FIG. 1 according to one embodiment;

FIG. 4 is a perspective view of the right ear cup shown in FIG. 1 according to one embodiment;

10 FIG. 5 is a back view of the right ear cup shown in FIG. 1 according to one embodiment;

FIG. 6 is a sectional view of the right ear cup taken along section line 6—6 as shown in FIG. 4 according to one embodiment;

FIG. 7 is a sectional view of the right ear cup taken along section line 6—6 as shown in FIG. 4 according to one embodiment;

15 FIG. 8 is a front view of the ear cup shown in FIGS. 6 and 7 according to one embodiment;

FIG. 9 is a cutaway view of an electroactive polymer system according to one embodiment;

20 FIG. 10 is a schematic diagram of one embodiment of an electroactive polymer system to illustrate the principle of operation;

FIGS. 11A, 11B, 11C illustrate three possible configurations, one/three/six bar electroactive polymer actuator arrays, according to various embodiments;

25 FIG. 12 is an exploded view of one embodiment of an electroactive polymer actuator system for an acoustic headphone system according to one embodiment;

FIG. 13 illustrates an electroactive polymer actuator and speaker element according to one embodiment;

30 FIG. 14 illustrates the electroactive polymer actuator shown in FIG. 13 without the mass shown FIG. 13 to show the underlying electroactive polymer actuator array, according to one embodiment;

FIG. 15 illustrates the electroactive polymer actuator shown in FIG. 14 with the tray removed, according to one embodiment;

FIG. 16 illustrates the electroactive polymer actuator shown in FIG. 14 with the mass and the cartridge portion of the electroactive polymer actuator array removed to show just the tray and a bottom rigid frame element, according to one embodiment;

FIG. 17 illustrates a top view of an electroactive polymer actuator according to one embodiment;

FIG. 18 illustrates a sectional view of the electroactive polymer actuator shown in FIG. 17 taken along section line 18—18, according to one embodiment;

FIG. 19 is a perspective view of an electroactive polymer actuator, according to one embodiment;

FIG. 20 is a back view of the electroactive polymer actuator shown in FIG. 19, according to one embodiment;

FIG. 21 is a sectional view of the electroactive polymer actuator shown in FIG. 19 taken along section line 21—21, according to one embodiment;

FIG. 22 is a perspective view of the electroactive polymer actuator shown in FIG. 19 with the top plate removed to show the underlying mass located within a suspension tray of the flexure suspension system, according to one embodiment;

FIG. 23 is a perspective view of the electroactive polymer actuator shown in FIG. 22 with the mass removed to show the underlying adhesive layer located above the electroactive polymer actuator array 724, according to one embodiment;

FIG. 24 is a perspective view of the electroactive polymer actuator shown in FIG. 23 with the flexure tray removed to better show the base plate and the underlying 3-bar electroactive polymer actuator array, according to one embodiment;

FIG. 25 is a perspective view of the electroactive polymer actuator shown in FIG. 24 with the electroactive polymer actuator array removed to show the underlying base plate and the adhesive layer, according to one embodiment;

5 FIG. 26 is a perspective view of the electroactive polymer actuator shown in FIG. 25 with the adhesive layer and flex circuit removed to show the underlying base plate and apertures, according to one embodiment;

10 FIG. 27 is a sectional view of the electroactive polymer actuator shown in FIG. 19 taken along section line 27—27, according to one embodiment;

FIG. 28 illustrates one embodiment of an electroactive polymer actuator;

15 FIG. 29 is a perspective view of the electroactive polymer actuator shown in FIG. 28 with the mass removed to show the underlying adhesive layer, according to one embodiment;

FIG. 30 illustrates a base portion of the tray with the electroactive polymer actuator array removed, according to one embodiment;

20 FIG. 31 is perspective view of the electroactive polymer actuator array portion of the electroactive polymer actuator 800, according to one embodiment;

25 FIG. 32 is a graphical representation of test data illustrating the frequency responses of an electroactive polymer actuator without a flexure suspension system and suspended mass, where Frequency (Hz) is shown along the horizontal axis and STROKE (mm) displacement is shown along the vertical axis;

30 FIG. 33 is a graphical representation of test data illustrating the frequency responses of an electroactive polymer actuator with a flexure suspension system and suspended mass, where Frequency (Hz) is shown along the horizontal axis and STROKE (mm) displacement is shown along the vertical axis;

FIG. 34 is a perspective sectional view of one embodiment of an ear cup;

FIG. 35 is a perspective sectional view of the ear cup shown in FIG. 34;

5 FIG. 36 is a front sectional view of the ear cup shown in FIG. 34;

FIG. 37 illustrates one embodiment of the ear cup shown in FIGS. 34-36 with the circumaural cushion and the housing removed to expose the underlying standalone tray mounted to a sound cavity behind a speaker;

10 FIG. 38 illustrates the ear cup shown in FIG. 37 without the standalone module housing to expose the electroactive polymer actuator array, according to one embodiment;

FIG. 39 illustrates the ear cup shown in FIG. 38 without the electroactive polymer actuator array to shown the underlying mass,
15 according to one embodiment;

FIG. 40 illustrates the ear cup shown in FIG. 39 without the underlying mass, according to one embodiment;

FIG. 41 is a bottom view of a sound cavity showing a speaker mounted therein, according to one embodiment;

20 FIG. 42 illustrates one embodiment of electroactive polymer based headphone comprising an electroactive polymer actuator contained in a first housing portion of an ear cup;

FIG. 43 is a block diagram of an electronic circuit for generating low frequency audio signals for driving the electroactive polymer actuators and
25 for reducing unwanted audio noise, according to one embodiment;

FIG. 44 is a graphical representation of harmonic distortion measurements without the use of the Inverse Polynomial Circuit (e.g., "inverse square root circuit") shown in FIG. 43, according to one embodiment;

FIG. 45 is a graphical representation of harmonic distortion measurements with the Inverse Polynomial Circuit ("square root circuit") shown in FIG. 43, according to one embodiment;

FIG. 46 illustrates one embodiment of the Inverse Polynomial Circuit (e.g., "inverse square root circuit") shown in FIG. 43, according to one embodiment;

FIG. 47 is a partial cutaway view of the electroactive polymer module shown in FIG. 12 comprising a flexure suspension system, according to one embodiment;

FIG. 48 is a schematic illustration of one embodiment of the electroactive polymer module shown in FIGS. 12 comprising the flexure suspension system shown in FIGS. 12 and 47 comprising a flexure tray, according to one embodiment;

FIG. 49 illustrates an X and Y axes vibration motion diagram for modeling the motion of the flexure suspension system shown in FIGS. 12 and 47-48 in the X and Y-directions, according to one embodiment;

FIG. 50 illustrates an X and Z axes vibration motion diagram for modeling the motion of the flexure suspension system shown in FIGS. 12 and 47-48 in the X and Z-directions, according to one embodiment;

FIG. 51 is a schematic diagram illustrating flexure tray travel stop features of the flexure suspension system shown in FIGS. 12 and 47-48, according to one embodiment;

FIG. 52 is a schematic diagram of a flexure linkage beam model, according to one embodiment;

FIG. 53 illustrates one embodiment of a flexure tray without a mass, according to one embodiment; and

FIG. 54 illustrates a segment of one embodiment of a flexure tray.

DETAILED DESCRIPTION OF THE INVENTION

Before explaining the embodiments of the inventive sensory enhanced audio devices and audio noise reduction modules 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.

The present invention provides a sensory enhanced audio device comprising an actuator system with having a mechanical Q factor less than about 10 and a circuit electrically coupled to the actuator system, wherein the circuit is to generate a drive signal to cause the actuator system to move according to the drive signal.

The present invention further provides a sensory enhanced headphone comprising at least one ear cup, an electro active polymer actuator array located within the at least one ear cup, the electroactive polymer actuator comprising at least one elastomeric dielectric element disposed between first and second electrodes and a circuit electrically coupled to the electroactive polymer actuator array, wherein the circuit is to generate a drive signal to cause the electroactive polymer actuator array to vibrate according to the drive signal.

The drive signal used to move the actuator system in the sensory enhanced audio device is derived from an audio signal. The actuator

system useful in the present invention comprises an electroactive polymer actuator array comprising at least one elastomeric dielectric element disposed between first and second electrodes.

In one embodiment, the drive signal is designed to move the actuator system in a way to convey information other than according to the audio signal. Thus, control of the intensity of the effect due to the motion of the actuator system can be separate from the control of the intensity of the audio signal. The user is able to increase, for example, the bass response of a headphone without being subjected to an increased sonic response which could potentially be uncomfortable or harmful to the user's hearing.

In one embodiment, the present disclosure provides high quality low frequency vibration content to augment limited audio based sensations. This includes sensory enhanced audio devices such as sensory enhanced headphones comprising electroactive polymer actuators, for example, as described in more detail hereinbelow. While not wishing to be bound by any particular theory, the present inventors speculate the inventive audio devices rely on a mixture of bone conduction and sound wave effects due to the inclusion of electroactive polymer actuators.

The present disclosure provides various embodiments of sensory enhanced headphones containing electroactive polymer actuators. The electroactive polymer actuators contain electroactive polymer modules based on dielectric elastomer elements. Such modules possess the bandwidth and the energy density suitable for implementing electroactive polymer actuators for use in acoustic headphones and for implementing mechanical acoustic noise reduction techniques. Such modules are made from a thin sheet with a dielectric elastomer film sandwiched between two electrode layers. When a sufficiently high voltage is applied to the electrodes, the two attracting electrodes compress the dielectric elastomer film. These modules are slim, low-powered, and can be coupled to an

inertial mass to amplify the motion produced by a drive signal derived from an audio signal source of a host device.

In addition to providing various embodiments of electroactive polymer actuators for sensory enhanced audio device implementation, in various aspects, the present disclosure also provides mechanical and electronic techniques for reducing acoustic noise from a variety of sources. Each technique is focused on different operational conditions that produce undesired acoustics and will be described separately hereinbelow.

Various embodiments of the mechanical techniques for reducing acoustic noise are disclosed. In one embodiment, the mechanical noise reduction techniques employ electroactive polymer based flexure suspension systems to minimize and eliminate unwanted modes of vibration by substantially limiting displacements to a single direction (desired direction, such as the direction of movement, for example). Test results support that stable vibrations substantially along a desired direction of movement can be achieved. The reduction in acoustic noise is highest when the desired direction is orthogonal to the acoustic radiator axis.

Embodiments of electronic techniques for reducing acoustic noise are also disclosed. In one embodiment, the electronic acoustic noise technique employs a non-linear inverse transform to remove unwanted acoustic artifacts. The basic functioning of electroactive polymer elements relies on electrostatic pressure produced by an electric field. In its simplest form, this pressure is proportional to the square of the electric field. Thus, to compensate for unwanted distortions of the actuator response, a non-linear inverse transform such as a square root circuit may be employed. This is true for isotropic, homogeneous, linear dielectric properties of electroactive polymers as disclosed in more detail hereinbelow. Other materials that are non-linear, non-isotropic, or non-homogeneous may require additional electronic and/or mechanical corrections, for example. Block diagrams depicting examples of electronic

topologies for implementing non-linear noise reduction techniques are shown and described hereinbelow.

Prior to describing the various noise reduction techniques, the disclosure turns to FIG. 1, which is a perspective view of a sensory enhanced headphone **100** according to one embodiment. In the embodiment shown in FIG. 1, the headphone **100** comprises a right ear cup **102** and a left ear cup **104** intercoupled by a headband **106**. The headband **106** may be any suitable conventional headband. The right and left ear cups **102**, **104** each comprise a corresponding exemplary right and left circumaural cushion **108**, **110**. It will be appreciated that the circumaural cushions **108**, **110** may have any shape although traditionally such cushions are circular or ellipsoid to encompass the ears. Because the circumaural cushions **108**, **110** completely surround the ear, these headphones **100** can be designed to fully seal against the head to attenuate any intrusive external noise, for example. The materials of the cushions **108**, **110**, may be chosen to modulate the degree of coupling between the headphone and the user. Each of the right and left ear cups **102**, **104** may preferably comprise circumaural cushions **108**, **110**, perforated speaker grills **112** (right only shown), and housings **114** (left only shown). The housing **114** contains a speaker, an electroactive polymer actuator, a circuit board comprising circuits to drive the actuator, and in some embodiments and mechanical and/or electronic acoustic noise reduction components. Embodiments of these elements are described hereinbelow.

FIG. 2 is a perspective view of the left ear cup **104** and FIG. 3 is a front view of the left ear cup **104**. As shown in FIGS. 2 and 3, the left ear cup **104** comprises a circumaural cushion **110** and a perforated speaker grill **116**.

FIG. 4 is a perspective view of the right ear cup **102** and FIG. 5 is a back view of the right ear cup **102**. As shown in FIGS. 4 and 5, the right ear cup **102** comprises a housing **118**.

FIGS. 6 and 7 are sectional views of the right ear cup **102** taken along section line 6—6 as shown in FIG. 4. FIG. 8 is a front view of the ear cup **102** shown in FIGS. 6 and 7. Since the left ear cup **104** is substantially similar to the right ear cup **102**, for conciseness and clarity of disclosure the remainder of this description provides focuses on the structure and function of the right ear cup **102** although such attributes may pertain equally to the left ear cup **104**.

With reference now in particular to FIGS. 6-8, in one embodiment the right ear cup **102** comprises a housing **118**, which defines an opening **124** suitable for mounting a speaker **120** and an electroactive polymer actuator **122** therein. In the embodiment illustrated in FIGS. 6-8, the actuator **122** comprises several sub-components and thus may be occasionally referred to herein as a electroactive polymer module. In particular embodiments where the actuator **122** includes three-bars, for example, the actuator **122** may be referred to as a 3-bar electroactive polymer module, without limitation. In particular embodiments where the actuator **122** comprises a flexure suspension system, for example, the actuator **122** may be referred to as an inertial electroactive polymer module, without limitation. With reference now back to FIGS. 6-8, the speaker **120** can be mounted directly behind the perforated speaker grill **112**, as shown. In other embodiments however, the location of the speaker **120** may vary and may be mounted in any suitable location within the opening **124** of the housing **118**. In one embodiment, for example, the electroactive polymer actuator **122** can be mounted to an inner wall **132** portion of the housing **118**. In one embodiment, the actuator **122** may comprise a tray **126**, an electroactive polymer actuator array **128**, and a mass **130**. In one embodiment, the tray **126** may be replaced with a flexure suspension system as discussed in more hereinbelow for minimizing, reducing, or substantially eliminating acoustic noise arising unwanted modes of vibration by substantially limiting displacements to a single desired direction of movement, for example. Electroactive polymer

actuator arrays such as the actuator **128** also may be referred to herein as an “n-bar cartridge,” where “n” stands for the number of actuator bars in the array. Thus, a 3-bar standalone cartridge refers to an electroactive polymer actuator array comprising three actuator bars that is mounted in a tray without flexure elements. Conversely, a 3-bar inertial cartridge refers to an electroactive polymer actuator array comprising three bars that is mounted in flexure suspension system. It will be appreciated that any of the disclosed headphone embodiments comprising a standalone actuator tray such as the tray **126** may be replaced with flexure suspension trays, without limitation.

With reference now to FIGS. 1-6, in one embodiment, the sensory enhanced headphones **100** comprising electroactive polymer actuators **122** according to the present disclosure are capable of producing mechanical vibrations in the audio frequency band (e.g., about 20 Hz to about 20 kHz) to provide high quality audio sensations without creating high sound pressures in the ear. In one embodiment, each of the ear cups **102**, **104** comprise the electroactive polymer actuator **122**. Each of the actuators **122** comprises a small mass **130** (preferably from 1 to 50 g, more preferably 25 g) attached to the electroactive polymer actuator array **128** forming a simple mass/spring/damper resonant system. Low frequency portions of the incoming audio are passed to an audio amplifier that is connected to the actuators **122**. The electroactive polymer actuators **122** shake (vibrate) the ear cups **102**, **104**, the vibrations tracking the incoming low frequency audio, thereby giving the sensation of low frequency audio without creating high pressure acoustical waves, which are potentially dangerous to the eardrum. The electroactive polymer actuators **122** disclosed herein enhance the “listening” experience of conventional audio headphones. The generation of low frequency (20 Hz - 200 Hz) vibrations extends the perceived frequency range of the audio headphones **100** below their normal, optimal range.

The vibrations generated by the electroactive polymer actuators **122**, however, are non-linear in nature. In addition, electroactive polymer based actuators **122** may also produce acoustic vibrations that may, or may not, be desirable. In the case of undesirable acoustic vibrations, the present disclosure also provides mechanical and electrical techniques to reduce the undesirable acoustic effects to acceptable levels. At times, the vibrations may be out-of-plane with the speaker **120**. Vibrational augmentation may be added to the sensory enhanced headphones **100**, if desired, by employing voice coils for driving suspended masses. These implementations, however, may result in high Q systems having low damping such that they vibrate longer in the same axis as the acoustic radiator, thereby introducing undesirable acoustic artifacts. In various embodiments, however, the electroactive polymer actuators **122** disclosed herein may be oriented in such a manner that the plane of vibration is perpendicular to the acoustic radiator axis, thereby significantly reducing unwanted acoustic artifacts.

The mechanical Q factor characterizes the mechanical damping of a system. It is the ratio of the reactive energy over the mechanical energy loss. As noted hereinabove, high Q systems vibrate longer creating more acoustic artifacts and less well defined effects. Low Q values indicate systems with high mechanical losses so vibrations are easily damped and the motion of the actuator system is well defined.

For optimal performance, the Q of the actuator system should be preferably below 10, more preferably below 5, and most preferably between 1.5 and 3.

As those skilled in the art are aware, QMS is a unit less measurement, characterizing the mechanical damping of the driver, that is, the losses in the suspension (surround and spider.) It varies roughly between 0.5 and 10, with a typical value around 3. High QMS indicates lower mechanical losses, and low QMS indicates higher losses. The main effect of QMS is on the impedance of the driver, with high QMS drivers

displaying a higher impedance peak. One predictor for low QMS is a metallic voice coil former. These act as eddy-current brakes and increase damping, reducing QMS and must be designed with an electrical break in the cylinder. Some speaker manufacturers have placed shorted turns at the top and bottom of the voice coil to prevent it leaving the gap, but the sharp noise created by this device when the driver is overdriven is alarming and was perceived as a problem by owners. Low QMS drivers are often built with nonconductive formers, made from paper, or various plastics.

The resonant frequency of the actuator system should be tailored to the type of effects desired. For example, a resonant frequency in the range of 80 to 90 Hz is desired to maximize the effect or "punch" of percussive effects such as kick drums. The motion of the actuator system should be orthogonal to the direction of the sound waves if a separate speaker is used. While other types of actuators such as piezoelectric transducers, voice coils, linear resonant motors, and eccentric rotating motors can be used, electroactive polymer actuators are particularly well suited to meet the above criteria for this application. They can be designed to have intrinsically low Q factors in the appropriate resonant frequency range of about 50-100 Hz while retaining fast response times and high power in a small, lightweight, and energy-efficient form factor that is more easily incorporated into a sensory enhanced audio device. They can be directly driven by the drive circuit to track and enhance an audio signal or to produce specifically tailored effects independent of the audio signal.

With the low modulus of the dielectric film in an electroactive polymer actuator, preferably less than 100 MPa, a smaller inertial mass can be used to amplify the motion of the actuator than needs to be used with higher modulus materials such as piezoelectric polymers or crystals. This lowers the overall volume and mass of the actuator system which may be an important factor in the design of portable audio devices such as headphones.

Before launching into a further description of various embodiments of the electroactive polymer actuator **122**, as shown in connection with FIGS. 6-8, for example, the description turns briefly to FIGS. 9-11 for a description of various integrated devices comprising electroactive polymer based modules suitable for use in audio devices such as headphones.

FIG. 9 is a partial cutaway view of an electroactive polymer system that may be integrally incorporated into the actuator **122** to provide the necessary vibratory motion to the headphone **100**. 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 a headphone device, the top plate **202** may be attached to an inertial mass, such as the mass **130** shown in FIGS. 6-8. In FIG. 9, the top plate **202** of the electroactive polymer module **200** includes a sliding surface configured to mount to an inertial mass or the back of a surface that can move bi-directionally as indicated by arrow **206**. Between the output plate **202** and the fixed plate **204**, the electroactive polymer module **200** comprises at least one electrode **208**, optionally at least one divider **210**, and at least one output bar **212** that attach to the sliding surface, e.g., the top plate **202**. Frame and divider segments **214** attach to a fixed surface, e.g., the bottom plate **204**. The module **200** may comprise any number of bars **212** configured into arrays to amplify the motion of the sliding surface. The electroactive polymer module **200** may be coupled to the drive electronics of an actuator controller circuit via a flex cable **216**. A voltage "V" potential difference of preferably about 1 kV (preferably anywhere up to 5 kV, more preferably between 100 V to 5 kV, more preferably between 300 V to 5 kV) may be applied to first and second electrically conductive elements **218A**, **218B** of the flex cable.

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 International PCT Patent Application No. PCT/US2012/021511, filed January 17, 2012 entitled FRAMELESS ACTUATOR APPARATUS, SYSTEM AND METHOD, which application claims the benefit, under 35 USC § 119(e), of United States provisional patent application numbers: 61/433,640 filed January 18, 2011 entitled, "FRAMELESS DESIGN CONCEPT AND PROCESS FLOW"; 61/442,913 filed February 15, 2011 entitled, "FRAME-LESS DESIGN"; 61/447,827 filed March 1, 2011, entitled, "FRAMELESS ACTUATOR, LAMINATION AND CASING"; 61/477,712 filed April 21, 2011, entitled, "FRAMELESS APPLICATION"; and 61/545,292 filed October 10, 2011, entitled, "AN ALTERNATIVE TO Z-MODE ACTUATORS"; the entire disclosure of which is hereby incorporated by reference. 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).

Advantages electroactive polymer modules **200** include 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
5 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.

Still with reference to FIG. 9, many of the design variables of the electroactive polymer module **200**, (e.g., thickness, footprint) may be fixed
10 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
15 **200** to an application where the module **200** is integrated with a headphone device, as shown in FIGS. 6-8.

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
20 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 (gaming and music), and short effects
25 (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 International PCT Patent Application No. PCT/US2011/000289, filed February 15, 2011, entitled "ELECTROACTIVE
30 POLYMER APPARATUS AND TECHNIQUES FOR QUANTIFYING

CAPABILITY THEREOF,” the entire disclosure of which is hereby incorporated by reference.

FIG. 10 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 $\pm 10\%$. 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. 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** (FIGS. 6-8). Returning to FIG. 10, 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 as described below in connection with FIGS. 11A, 11B, and 11C.

5 FIGS. 11A, 11B, 11C illustrate three possible configurations, among others, of electroactive polymer actuator arrays **400**, **420**, **440**, according to various embodiments. Various embodiments of electroactive polymer actuator arrays may comprise any suitable number of bars depending on the application and physical spacing restrictions of the application.

10 Additional bars provide additional displacement and therefore may be employed to enhance the realistic sound reproduction vibration that the user can sense immediately. The electroactive polymer actuator arrays **400**, **420**, **440** may be coupled to the drive electronics of an actuator controller circuit via a corresponding flex cable **402**, **422**, **442**.

15 FIG. 11A illustrates an example of a one bar electroactive polymer actuator array **400**. The one bar electroactive polymer actuator array **400** comprises a fixed plate **404**, an output bar **406**, and an elastomeric dielectric element **408** coupled to the fixed plate **404**.

 FIG. 11B illustrates an example of a three bar electroactive polymer
20 actuator array **420** comprising three bars **424**, **426**, **428** coupled to a fixed frame **430**. Each pair of bars is separated by a divider **432**. Each of the three bars **424**, **426**, **428** comprises an output bar **434** and an elastomeric dielectric element **436**. The three bar electroactive polymer actuator array **420** amplifies the motion of the sliding surface in comparison to the single
25 bar electroactive polymer actuator array **400** of FIG. 11A.

 FIG. 11C illustrates an example of a six bar electroactive polymer
 actuator array **440** comprising six bars **444**, **446**, **448**, **450**, **452**, **454**
 coupled to a fixed frame **456**, where each pair of bars is separated by a
 divider **458**. Each of the six bars **444**, **446**, **448**, **450**, **452**, **454** comprises
30 an output bar **460** and an elastomeric dielectric element **462**. The six bar
 electroactive polymer actuator array **440** amplifies the force on the sliding

surface in comparison to the single bar electroactive polymer actuator array **400** of FIG. 11A and the three bar electroactive polymer actuator array **420** of FIG. 11B.

The electroactive polymer actuator arrays **400**, **420**, **440** illustrated
5 in reference to FIGS. 113A-C may be integrated into a variety of
electroactive polymer actuators for headphone applications to achieve
desired effects. For example, in one embodiment, an electroactive
polymer actuator array may be configured to be mounted into an inner
surface of a housing **118** as illustrated in FIGS. 6-8. In the embodiment
10 shown in FIGS. 6-8, an electroactive polymer actuator array **128** is
integrated with the electroactive polymer actuator **122** to implement a
sensory enhanced headphone.

FIG. 12 is an exploded view of one embodiment of an electroactive
polymer module **500** comprising a flexure suspension system **502** that
15 may be employed in a sensory enhanced headphone. Examples of
flexure suspension systems that may be employed in the disclosed
embodiments can be found at commonly assigned International PCT
Patent Application No. PCT/US2012/021506, filed on January 17, 2012,
entitled "ELECTROACTIVE POLYMER FLEXURE APPARATUS,
20 SYSTEM, AND METHOD," which application claims the benefit, under 35
USC § 119(e), of United States provisional patent application numbers:
61/433,655, filed January 18, 2011, entitled "SLIDING MECHANISM AND
AMI ACTUATOR INTEGRATION"; 61/477,680, filed April 21, 2011,
entitled "Z-MODE BUMPERS"; 61/493,123, filed June 3, 2011, entitled
25 "FLEXURE SYSTEM DESIGN"; 61/493,588, filed June 6, 2011, entitled
"ELECTRICAL BATTERY CONNECTION"; and 61/494,096, filed June 7,
2011, entitled "BATTERY VIBRATOR FLEXURE WITH METAL BATTERY
CONNECTOR FLEXURE"; the entire disclosure of each of which is hereby
incorporated by reference. In one embodiment, a flexure tray **504** defines
30 an opening **510** for receiving an electroactive polymer actuator **506** (shown
in exploded view format) therein. One side of the electroactive polymer

actuator **506** can be mounted to the bottom portion of the flexure tray **504** and the other side of the actuator **506** can be coupled to a mass **508**. The electroactive polymer actuator **506** and the mass **508** are dimensioned to fit within the opening **510** defined by the tray **504**. As shown in FIG. 12,

5 the actuator **506** comprises two sets of electroactive polymer actuator arrays **512**, **512'**. In other embodiments, one electroactive polymer actuator array **512** may be employed and in other embodiments, for example, more than two sets of electroactive polymer actuator arrays **512**, **512'** may be employed in the electroactive polymer actuator **506**. As

10 shown, the first and second sets of electroactive polymer actuator arrays **512**, **512'** each comprise an output bar adhesive layer **514A**, **514A'** to couple a first set of electroactive polymer actuator arrays **514B**, **514B'** to the bottom of the mass **508**. A frame-to-frame adhesive layer **514C**, **514C'** is used to couple the first set of electroactive polymer actuator arrays

15 **514B**, **514B'** to a second set of electroactive polymer actuator arrays **514D**, **514D'**. A base frame adhesive layer **514E**, **514E'** couples the second set of electroactive polymer actuator arrays **514D**, **514D'** to the mounting surface **516** inside the tray **504**. As shown in FIG. 12, the electroactive polymer actuator **506** comprises dual three bar electroactive

20 polymer actuator arrays. In other embodiments, as described hereinbelow, any suitable number of electroactive polymer actuator arrays comprising any suitable number of bars may be employed. Although not shown in FIG. 12, either the mass **508** or the tray **504** may be physically and/or electrically connected to a printed circuit board with a flex cable

25 connector, for example. The flexure suspension system **502** can be used to implement an acoustic headphone system as described in more detail hereinbelow. Additional details of the flexure suspension system **502** are described hereinbelow in connection with FIGS. 47-54.

Having generally described various integrated devices comprising

30 electroactive polymer feedback modules that may be employed in various embodiments of the electroactive polymer actuator **122** shown in FIGS. 6-

8, the description now turns to FIGS. 13-16, which illustrate one embodiment of the electroactive polymer actuator **122**. In FIG. 13, the housing **118** and the circumaural cushion **108** portions of the ear cup **102** are not shown in order to more clearly illustrate the electroactive polymer actuator **122** and the speaker **120** elements, according to one
5 embodiment. In the illustrated embodiment, the electroactive polymer actuator **122** comprises the standalone tray **126** (e.g., in other embodiments, the tray **126** may be replaced by a flexure suspension system), which defines an opening **136** for holding the mass **130** and the
10 electroactive polymer actuator array **128** (shown in FIGS. 14-15) beneath the mass **130**. The tray **126** comprises a perimeter surface **134** for attaching the electroactive polymer actuator **122** to the inner wall **132** (FIGS. 7-8) of the housing **118**. The tray **126** includes a slot **138** to receive a flex cable to electrically couple the electroactive polymer
15 actuator array **128** to an actuator circuit.

FIG. 14 illustrates the electroactive polymer actuator **122** without the housing **118** and the circumaural cushion **108** portions of the ear cup **102** and further without the mass **130** (FIG. 13) to show the underlying electroactive polymer actuator array **128**, according to one embodiment.
20 As shown in FIG. 14, the electroactive polymer actuator array **128** is located in the tray **126**. FIG. 15 illustrates the electroactive polymer actuator shown in FIG. 14 with the tray removed, according to one embodiment. With reference to FIGS. 14-15, the electroactive polymer actuator array **128** comprises a rigid frame and dividers **142** separating
25 electrodes **148** and elastomeric dielectric elements **146**. An adhesive layer **144** is provided on a top surface of the electrodes **148** to adhesively mount a top surface of the electroactive polymer actuator array **128** to a bottom surface of the mass **130**. Because the electroactive polymer actuator array **128** comprises three sets of electrodes **148** and elastomeric
30 dielectric elements **146**, the electroactive polymer actuator array **128** may be referred to as a 3-bar cartridge.

FIG. 16 illustrates the electroactive polymer actuator **122** shown in FIG. 15 with the mass **130** and the cartridge portion of the electroactive polymer actuator array **128** removed to show just the tray **126** and a bottom rigid frame element **142**, according to one embodiment.

5 FIGS. 17 and 18 illustrate a top view and a sectional view, taken along section line 18—18, of a electroactive polymer actuator **600** according to one embodiment. The electroactive polymer actuator **600** comprises a flexure suspension system **622** and may be employed in the headphones **100** in place of the electroactive polymer actuator **122** shown
10 in FIGS. 1, 6-8 and 13-16. The flexure suspension system **622** comprises a suspension tray **608**, a mass **602**, and a electroactive polymer actuator array **624** (shown in FIG. 18). As shown in FIG. 18, the electroactive polymer actuator **600** comprises a top plate **610** located over the flexure suspension system **622** and a base plate **612** having frame and divider
15 segments **614** separating three sets of output bars **616** and elastomeric dielectric elements **618**. Accordingly, the electroactive polymer actuator **600** is a 3-bar inertial electroactive polymer module. The electroactive polymer actuator **600** comprises electroactive polymer actuators located within a suspension tray **608** of the flexure suspension system **622**. The
20 suspension tray **608** comprises suspension or flexure arms **604**, **606**. The electroactive polymer actuator **600** defines an X-Y plane of vibration. The flexure suspension system **622** limits travel primarily to one direction, e.g., along the Y axis as indicated by the arrow **620**. Limited movement in the Z direction helps to maintain clearances required for free movement in the Y
25 direction. When the electroactive polymer actuator **600** is energized by a voltage derived from a low frequency audio signal, the suspension tray **608** moves substantially along the Y axis, as indicated by the arrow **620**, and motion along the X and Z axes is substantially minimized. Thus, the electroactive polymer actuator **600** comprising the flexure suspension
30 system **622** substantially reduces or eliminates undesirable acoustic

effects. The flexure suspension system **622** also may be used to generate acoustic effects to intentionally add artifacts to sound tracks.

In one embodiment, the flexure suspension system **622** comprises at least one flexure coupled to the electroactive polymer actuator array **624**, wherein the flexure enables the flexure suspension system **622** to move in a predetermined direction when the first and second electrodes in elastomeric dielectric elements **618** are energized. In one embodiment, the flexure suspension system **622** comprises at least one travel stop to limit movement of the suspension tray **608** in the predetermined direction.

In one embodiment, the suspension tray **608** comprises the at least one flexure arm **604**, **606**. In one embodiment, the flexure tray **608** comprises at least one travel stop to limit movement of the flexure suspension system **622** in the predetermined direction. In one embodiment, at least one of the flexure arms is formed integrally with the suspension tray **608**.

FIGS. 19-27 illustrate one embodiment of an electroactive polymer actuator **700** comprising a flexure suspension system **722** similar to the flexure suspension system **622** shown in FIGS. 17 and 18. FIG. 19 is a perspective view of the electroactive polymer actuator **700** and FIG. 20 is a back view of the actuator, according to one embodiment. FIG. 21 is a sectional view of the electroactive polymer actuator **700** taken along section line 21—21 and FIG. 27 is a sectional view of the electroactive polymer actuator **700** taken along section line 27—27 as shown in FIG. 19, according to one embodiment. With reference now to FIGS. 19-21 and 27, in addition to the flexure suspension system **722**, in one embodiment, the electroactive polymer actuator **700** comprises a top plate **710**, a base plate **712**, and a slot **726** to receive a flex cable **728** to electrically couple the electroactive polymer actuator array **724** to an electronic drive circuit **740** via first and second electrically conductive elements **736A**, **736B**. The base plate **712** includes apertures **730** that reveal the output bar **716** portions of the electroactive polymer actuator array **724**.

FIG. 21 shows a mass **702** and a first adhesive layer **732** located between the electroactive polymer actuator array **724** and the base plate **712** to adhesively attach the electroactive polymer actuator **700** to the base plate **712**, according to one embodiment. A second adhesive layer **734** is located between the mass **702** and the electroactive polymer actuator array **724** to adhesively attach the electroactive polymer actuator array **724** to a bottom surface of the mass **702**.

FIG. 22 is a perspective view of the electroactive polymer actuator **700** with the top plate **710** removed to show the underlying mass **702** located within a suspension tray **708** of the flexure suspension system **722**, according to one embodiment. The suspension tray **708** comprises first and second suspension arms **704**, **706**. As discussed in connection with FIGS. 17 and 18, the suspension arms **704**, **706** formed in the suspension tray **708** enables the flexure suspension system **722** to move in a predetermined manner. For example, the suspension arms **704**, **706** of the flexure suspension system **722** limit the travel of the mass **702** in the X-Y plane primarily along the Y axis as indicated by the arrow **720**. Limited movement in the Z direction helps to maintain clearances required for free movement in the Y direction. Accordingly, when the electroactive polymer actuator **700** is energized by a higher voltage derived from a low frequency audio signal, the suspension tray **708** moves in the direction of motion indicated by arrow **720**, which is substantially along the Y axis.

FIG. 23 is a perspective view of the electroactive polymer actuator **700** shown in FIG. 22 with the mass **702** removed to show the underlying adhesive layer **734** located above the electroactive polymer actuator array **724**, according to one embodiment. The adhesive layer **734** adhesively couples the electroactive polymer actuator array **724** to a bottom surface of the mass **702**. The electroactive polymer actuator array **724** also comprises a frame and divider segments **714** that separate the three separate output bars **716** and elastomeric dielectric elements **718**. Because the electroactive polymer actuator array **724** includes three bars,

it may be referred to as a 3-bar inertial electroactive polymer module, without limitation.

FIG. 24 is a perspective view of the electroactive polymer actuator **700** shown in FIG. 23 with the flexure tray **708** removed to better show the base plate **712** and the underlying 3-bar electroactive polymer actuator array **724**, according to one embodiment. As shown in FIG. 24, the electroactive polymer actuator array **724** comprises frame and divider segments **714**, output bars **716**, elastomeric dielectric elements **718**, and an adhesive layer **734** located above the output bars **716**.

FIG. 25 is a perspective view of the electroactive polymer actuator **700** shown in FIG. 24 with the electroactive polymer actuator array **724** removed to show the underlying base plate **712** and the adhesive layer **732**, according to one embodiment. The base plate **712** comprises apertures **730** and the adhesive layer **732** located between the base plate **712** and the electroactive polymer actuator array **724**. The first and second electrical conductors **736A**, **736B** of the flex circuit **728** are electrically connected to corresponding first and second terminals **738A**, **738B**.

FIG. 26 is a perspective view of the electroactive polymer actuator **700** shown in FIG. 25 with the adhesive layer **732** and flex circuit **728** removed to show the underlying base plate **712** and apertures **730**, according to one embodiment.

FIGS. 28-31 illustrate one embodiment of an electroactive polymer actuator **800**. In one embodiment, the electroactive polymer actuator **800** comprises a tray **822**, a mass **802**, and a slot **826** formed in the tray **822**. The slot **826** is dimensioned to receive a flex cable (not shown) to electrically couple the electroactive polymer actuator array **824** to an electronic drive circuit. FIG. 30 illustrates a base portion of the tray **822** with the electroactive polymer actuator array **824** removed, according to one embodiment. The base portion of the tray **822** includes apertures **830** that reveal output bars **816** of the electroactive polymer actuator array **824**.

The mass **802** is adhesively coupled to the electroactive polymer actuator array **824** by a adhesive layer **834** located therebetween. The electroactive polymer actuator **800** defines a plane of vibration indicated by the X-Y plane. The tray **822** limits travel primarily in one direction along the Y axis as indicated by the arrow **820**. Limited movement in the Z direction helps to maintain clearances required for free movement in the Y direction. Accordingly, when the actuator **800** is energized by a higher voltage derived from a low frequency audio signal, the tray **822** moves in the direction of motion indicated by arrow **820**, which is substantially along the Y axis.

FIG. 29 is a perspective view of the electroactive polymer actuator **800** shown in FIG. 28 with the mass **802** removed to show the underlying adhesive layer **834**, according to one embodiment. As shown, the adhesive layer **834** is located above the electroactive polymer actuator array **824**, which is located beneath the mass **802**. The electroactive polymer actuator array **824** is adhesively coupled to a bottom surface of the mass **802** with the adhesive layer **834**. The electroactive polymer actuator array **824** also comprises a frame and divider segments **814** that separate the three separate output bars **816** and elastomeric dielectric elements **818** of the electroactive polymer actuator array **824**. Because the electroactive polymer actuator array **824** includes three bars, it may be referred to as a 3-bar electroactive polymer module, without limitation. FIG. 31 is perspective view of the electroactive polymer actuator array **824** portion of the electroactive polymer actuator **800**, according to one embodiment.

FIGS. 32 and 33 are graphical representations **900**, **950** of test data illustrating the frequency responses of two types of electroactive polymer actuators, respectively, where Frequency (Hz) is shown along the horizontal axis and STROKE (mm) displacement is shown along the vertical axis. The graph **900** shown in FIG. 32 shows the frequency response curve of an electroactive polymer actuator without a flexure

suspension system and suspended mass, such as the electroactive polymer actuator **122** (FIGS. 6-8 and 13) and the electroactive polymer actuator **800** (FIG. 28) that relies primarily on the motion of the electroactive polymer actuator array to move the suspended mass. At some frequencies (specifically 20Hz to 50Hz) the suspended mass wobbles because it is free to move in all directions and there is no limitation or support in the undesired directions. This phenomenon manifests itself as distortions **902**, **904** in the desired direction displacement and ultimately desired sensation. The graph **950** shown in FIG. 33 shows the frequency response curve of an electroactive polymer actuator that utilizes a flexure suspension system, such as the flexure suspension system **622**, **722** of the respective actuators **600**, **700** shown in FIGS. 17-19. Areas **952** and **954** clearly show that the undesired distortions have been successfully eliminated by the flexure suspension system **622**, **722**.

FIGS. 34-40 illustrate one embodiment of an ear cup **1000** that may be employed in the sensory enhanced headphone **100** shown in FIG. 1. FIGS. 34 and 35 are perspective sectional views of the ear cup **1000** and FIG. 36 is a front sectional view of the ear cup, according to one embodiment. With reference now in particular to FIGS. 34-36, in one embodiment the right ear cup **1000** comprises a circumaural cushion **1008** and a housing **1018**, which defines an opening **1024** suitable for mounting a speaker **1020** and a electroactive polymer actuator **1022** therein. In the embodiment illustrated in FIGS. 34-36, the electroactive polymer actuator **1022** may be referred to as an electroactive polymer module. More particularly, in the embodiment illustrated in FIGS. 34-36, the electroactive polymer actuator **1022** may be referred to as a 3-bar inertial electroactive polymer module, without limitation. As shown, the speaker **1020** can be mounted directly behind a perforated speaker grill **1012**. In other embodiments, however, the location of the speaker **1020** may vary. In one embodiment, the actuator **1022** comprises a standalone tray **1026**

configured to receive an electroactive polymer actuator array **1028** and a mass **1030** therein. The electroactive polymer actuator **1022** is mounted to a sound cavity **1050**, which is mounted directly behind the speaker **1020**. In other embodiments, the actuator **1022** may comprise a flexure suspension system, such as the flexure suspension system **622**, **722** of the respective actuators **600**, **700** shown in FIGS. 17-19, for example, to mechanically correct for minor distortions at the lower frequencies (e.g., less than 200 Hz). The actuator **1022** also comprises a electroactive polymer actuator array **1028** and a mass **1030**.

FIGS. 37-41 illustrate various elements of the ear cup **1000** with other elements removed in order to show the underlying structures, according to one embodiment. Accordingly, FIG. 37 illustrates one embodiment of the ear cup **1000** with the circumaural cushion **1008** and the housing **1018** removed to expose the underlying standalone tray **1026** mounted to the sound cavity **1050** behind the speaker **1020**.

FIG. 38 illustrates the ear cup **1000** shown in FIG. 37 without the standalone module housing **1026** to expose the electroactive polymer actuator array **1028**, according to one embodiment. The electroactive polymer actuator array **1028** comprises a rigid frame and dividers **1042** separating output bars **1048** and elastomeric dielectric elements **1046**. An adhesive layer **1044** is provided on the output bars **1048** to adhesively mount the electroactive polymer actuator array **1028** to the standalone tray **1026**. A mass **1030** may suspended from flexures (not shown) attached to standalone tray **1026**. A second adhesive layer (not shown) may be provided to adhesively mount the standalone tray **1026** to the sound cavity **1050**.

FIG. 39 illustrates the ear cup **1000** shown in FIG. 38 without the electroactive polymer actuator array **1028** to show the underlying mass **1030**, according to one embodiment. FIG. 40 illustrates the ear cup **1000** shown in FIG. 39 without the underlying mass **1030** and FIG. 41 is a

bottom view of the sound cavity **1050** showing the speaker **1020** mounted therein, according to one embodiment.

Having described various electroactive polymer headphone embodiments including mechanical techniques for reducing acoustic noise, the disclosure now turns to electronic methods of reducing the acoustic noise that can be implemented into any of the embodiments of the electroactive polymer actuators described herein. Embodiments of electronic acoustic noise reduction techniques employing non-linear inverse transforms to remove unwanted acoustic artifacts are described hereinbelow. First, however, the disclosure turns briefly to FIG. 42, which illustrates one embodiment of sensory enhanced headphone **1100** comprising an electroactive polymer actuator **1102** contained in a first housing portion **1104** of an ear cup **1110**. A circuit board **1106** comprising electronic circuits for driving the electroactive polymer actuator **1102** at low audio frequencies and for reducing unwanted acoustic noise is also shown. The circuit board **1106** may be mounted behind the electroactive polymer actuator **1102**. The entire assembly of the electroactive polymer actuator **1102** and the circuit board **1106** may be located between the first housing portion **1104** and a second housing portion **1108**.

FIG. 43 is a block diagram **1200** of an electronic circuit for generating low frequency audio signals for driving the electroactive polymer actuators and for reducing unwanted audio noise, according to one embodiment. A variety of signal conditioning, amplifying, compensating, and driving circuits are also implemented. In particular, an analog audio signal module **1202** receives analog audio signal from a differential amplifier source. In one embodiment, the differential amplifier may be implemented with any suitable integrated circuit amplifier, such as, for example an AD822 single-supply, rail-to-rail low power field effect transistor-input operational amplifier, available from Analog Devices, Inc. of Norwood, MA, or any suitable equivalent thereof.

An automatic gain control module **1204** receives the output signal from the analog audio signal module **1202** and provides automatic gain control from 0 dB to 20 dB, for example, or any suitable gain. In one embodiment, the automatic gain control module **1204** may be

5 implemented with any suitable integrated circuit amplifier such as, for example, a MAX9814 microphone amplifier with automatic gain control and low-noise microphone bias, available from Maxim Integrated Products, Inc. of Sunnyvale, CA, or any suitable equivalent thereof. In one

10 embodiment, the automatic gain control module **1204** is configured to control the volume of vibration for driving the electroactive polymer actuators in each of the ear cups differently from the volume of the actual audio sound signal. Although the vibration level for driving the

electroactive polymer actuators in each of the ear cups is different from the volume of the actual audio sound signal, the vibration level gain is

15 correlated or based on the audio sound level gain. In various embodiments, the relationship between the vibration level gain and the audio sound level gain may be linear or non-linear depending on the specific design implementation. In one embodiment, the relationship

between the gains is non-linear in order to approximate a non-linear

20 function such as sine, square-root, logarithmic, exponential, and the like. In the illustrated embodiment, the relationship between the vibration level gain and the audio sound level gain is a non-linear function that

approximates a square-root function. In other words, the vibration level gain is approximately correlated to the square-root of the audio sound

25 level gain. Thus, the electroactive polymer actuator vibrations track the incoming low frequency audio and give the sensation of low frequency audio without creating high pressure acoustical waves, which may be

potentially dangerous to the eardrum.

In one embodiment, the vibration level gain approximates a square-

30 root of the audio sound level gain as shown in TABLE 1.

TABLE 1

Audio Sound Level Gain (dB)	Audio Sound Level Gain	Vibration Level Gain (dB)	Vibration Level Gain
10	3.16	5	1.78
20	10	10	3.16
30	31.6	15	5.62
40	100	20	10

From the automatic gain control module **1204**, the signal is passed to a low frequency digital filter module **1206**. The low frequency digital filter module **1206** 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 **1206** may be implemented with any suitable programmable system, such as, for example a CY8C29466 programmable system-on-chip controller, available from Cypress Semiconductor Corporation, of San Jose, CA, or any suitable equivalent thereof.

A low frequency amplifier module **1208** amplifies the output of the low frequency digital filter **1206** and the output is passed to the programmable gate array circuit. In one embodiment, the low frequency amplifier module **1208** may be implemented using any suitable integrated circuit amplifier such as the MAX9618 low-power, zero-drift operational amplifier, available from Maxim Integrated Products, Inc. of Sunnyvale, CA, or any suitable equivalent thereof.

The output of the low frequency digital filter **1206** is provided to a non-linear inverse transform circuit (square root circuit) such as an inverse polynomial circuit **1210**, which provides the electronic audio signal compensation to remove unwanted distortions in the audio signal used to vibrate the electroactive polymer actuators. In other words, the inverse polynomial circuit **1210** approximates an inverse function to linearize the electroactive polymer actuators, for example. In various embodiments, the inverse polynomial circuit **1210** 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

5 approximation depends on the number of segments employed by the piecewise linear circuit and the strategy used in determining the segments. Generally speaking, 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

10 saturating amplifiers. Both of these approaches may be employed and are technically equivalent although each has its advantages and disadvantages.

The diode approach has the advantage of simplicity but the disadvantages include temperature dependence on the switching

15 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 **1210** may be implemented as a compression or an expansion circuit, each type having a different circuit

20 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. In other

25 embodiments, a combination of compression and expansion circuits may be employed to implement the inverse polynomial circuit **1210** to linearize electroactive polymer actuators, for example. One embodiment of a piecewise linear circuit using diode switching to approximate an inverse square-root function is described in more detail herein in connection with

30 FIG. 46.

The output of the inverse polynomial circuit **1210** is provided to a high voltage power amplifier **1212** for amplification to a level sufficient to drive the electroactive polymer actuator module. In general, the voltage required to drive the electroactive polymer actuator module may range

5 from a few hundred volts (V) to several thousand volts (kV), with a nominal driving voltage of about 1kV. A left channel output **1214L** of the high voltage amplifier **1212** is provided to a left reflex actuator and mass **1216L**, e.g., to an electroactive polymer actuator located in a left ear cup of the headphones. A right channel output **1214R** of the high voltage amplifier

10 **1212** is provided to a right reflex actuator and mass **1216R**, 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

15 also may be employed in multi-phase actuators, for example.

In one embodiment, the electronic circuit includes a visual feedback display module **1218**. In this embodiment, a blue display (e.g., light emitting diode or LED) indicates audio signals. A green display indicates processed signals. An orange/red display indicates mixed and high

20 voltage signals. Those skilled in the art will appreciate any combination of desired colors may be used to provide the visual feedback.

FIG. 44 is a graphical representation of harmonic distortion measurements **1300** without the use of the inverse polynomial circuit **1210** (e.g., "inverse square root circuit") shown in FIG. 43, according to one

25 embodiment. The bottom trace **1302** is a measured acceleration waveform at 100 Hz without the square root circuit **1210** and the top trace **1304** is the Fourier transform showing a high second harmonic **1306**.

FIG. 45 is a graphical representation of harmonic distortion measurements **1350** with the Inverse Polynomial Circuit **1210** ("square root circuit") shown in FIG. 43, according to one embodiment. The bottom

30 trace **1352** is a measured acceleration waveform at 100 Hz with the

square root circuit **1210** and the top trace **1354** is the Fourier transform showing a significantly reduced second harmonic **1356**.

FIG. 46 illustrates one embodiment of an inverse polynomial circuit **1210** described in FIG. 43 employing a piecewise linear circuit using diode switching to approximate an inverse square-root function. As described in connection with FIG. 43, other nonlinear circuit topologies may be employed to implement a linearization function to linearize the electroactive polymer actuators and the topology described in connection with FIG. 46 is but one example. Accordingly, embodiments of inverse polynomial circuits should not be limited in this context. In the embodiment illustrated in FIG. 46, the inverse polynomial circuit **1210** comprises a voltage-to-current converter circuit **1220**, a piecewise linear circuit **1230** employing a diode switching topology, and a final gain amplifier **1240**. The output voltage V_o is provided to a high voltage power amplifier **1212**, as shown in FIG. 43, for example.

The voltage-to-current converter circuit **1220** employs a first amplifier A1 and resistors R1-R4 to generate a current i that is proportional to the input voltage V_{in} , from the low frequency digital filter module **1206** in FIG. 43. The current i is provided to the piecewise linear circuit **1230**, which is configured to approximate an inverse square-root function (current-to-voltage) using R5-R15 and diodes D1-D5. The final gain amplifier **1240**, which included resistors R16-R17 and a second amplifier A2, sets the final scaling (with R16 and R17) and could be any value between 1 and 100, but typically is between 1 and 2.

In the illustrated embodiment, the piecewise linear circuit **1230** includes five segments that are switched in depending on the current i and the node voltage v_n that develops. Each segment has a breakpoint voltage that approximates a different slope based on the input voltage range of v_n . For example, the first segment has a first breakpoint voltage V_1 equal to V_A plus the diode voltage drop across D1. Similarly, the second segment has a second breakpoint voltage V_2 equal to V_B plus the

diode voltage drop across D2, and so on, up to segment five, which has a fifth breakpoint voltage V_5 equal to V_E plus the diode voltage drop across D5. Each segment has a different slope that is based on the parallel combination of resistors R5-R15. As each segment is switched in, the

5 slope changes such that the voltage v_n at the node approximates an inverse square-root function depending on the values selected for the resistors. The piecewise linear circuit **1230** also may implement a square-root or other non-linear function depending on the resistor values selected. The amplifiers A1 and A2 may be any suitable integrated circuit amplifier,

10 such as, for example, an AD823 rail-to-rail FET-input operational amplifier, available from Analog Devices, Inc. of Norwood, MA, or any suitable equivalent thereof. In one embodiment, the voltage V^+ may be +5V, for example.

In one embodiment, the resistors R1-R4 to implement the voltage-

15 to-current converter circuit **1220**, the resistors R5-R15 to implement the a piecewise linear circuit **1230**, and the resistors R16-R17 to implement the final gain amplifier **1240** are shown in TABLE 2. It will be appreciated that the values of the resistors may have different tolerances depending on the level of accuracy to be achieved and may be $\pm 10\%$, $\pm 5\%$, $\pm 1\%$, or may be

20 trimmed to any suitable value.

TABLE 2

Resistor	Value (k Ω) ($\pm 10\%$, ± 5 , ± 1 , or trimmed)
R1	2
R2	2
R3	10
R4	10
R5	3
R6	3
R7	3
R8	3
R9	3
R10	7.8
R11	5
R12	10
R13	20
R14	100
R15	1000
R16	1
R17	10

FIGS. 47-54 illustrate additional details of flexure suspension systems according to disclosed embodiments. FIG. 47 is a partial cutaway view of the electroactive polymer module **500** shown in FIG. 12 comprising a flexure suspension system, according to one embodiment.

FIG. 48 is a schematic illustration of one embodiment of the electroactive polymer module **500** shown in FIGS. 12 comprising the flexure suspension system **506** shown in FIGS. 12 and 47 comprising a flexure tray **504**, according to one embodiment. With reference to FIGS. 47 and 48, the flexure tray **504** comprises flexures **570**, travel stops **572**, **574**, and a mass **508** located within the opening defined by the flexure tray **504**. The flexures **570** and travel stops **572**, **574** can be molded into the flexure tray **504** or can be provided as separate components. As previously discussed, the flexure tray **504** is coupled to a mounting surface **568**, which acts as a mechanical ground for the flexure suspension system **502**. The flexures **570** located in one or more locations enable the flexure tray **504** to vibrate in one or more directions of motion. In the illustrated embodiment, the flexure tray **504** comprises four separate flexures **570**

that enable the flexure tray **504** to move in the X and Y-directions. The flexure tray **504** also comprises X-travel stops **572** and Y-travel stops **574** to limit travel or movement in a predetermined direction and prevent damage from shock type movement. The X- and Y-travel stops **572**, **574** are provided to constrain the motion of the flexure tray **504** in the X and Y-directions of motion, as discussed in more detail with reference to FIGS. 49 and 60 below, such that the flexure suspension system **502** can limit unwanted vibrations in undesired directions of movement.

FIG. 49 illustrates an X and Y axes vibration motion diagram **580** for modeling the motion of the flexure suspension system **502** shown in FIGS. 12 and 47-48 in the X and Y-directions, according to one embodiment. FIG. 50 illustrates an X and Z axes vibration motion diagram **582** for modeling the motion of the flexure suspension system **502** shown in FIGS. 12 and 47-48 in the X and Z-directions, according to one embodiment. With reference now to FIGS. 12 and 47-50, k_{fx} = combined stiffness of the flexures **570** and electrical connections in the X-axis, k_{ax} = active stiffness of the electroactive polymer actuator **506** in the X-axis, k_{fz} = combined stiffness of the flexures **570** and electrical connection in the Z-axis, k_{az} = stiffness of the electroactive polymer actuator **506** in the Z-axis, $m_{tray} + m_{batt}$ = total sprung mass consisting of the mass **508** and any other support structure in motion.

X-Axis Compliance

Compliance in the X-axis is one factor to consider when evaluating the performance of the flexure suspension system **502**. Combined non-actuator stiffness (k_{fx}) should be reduced as much as possible and kept below about 10% of the actuator stiffness (k_{ax}), for example. Additional stiffness from electrical interconnects should be factored into the non-actuator stiffness calculations. Stiffness of the flexures **570** in the X-axis provides suitable movement control with proper use of the travel stops **572**, **574**.

Z-Axis Compliance

Compliance in the Z-axis should be reduced as much as possible to reduce deflection of the dynamic mass due to gravity or user input, and in particular, when the flexure suspension system **502** is integrated with a touch surface (e.g., touch screen or touch pad) suspension application where unrestricted X-axis movement of the assembly should be insured during user input. Ideally the total Z-axis stiffness can be over 300X the total X-axis stiffness. If negative Z-direction (–Z-direction) travel stops are not used, the flexure **570** should be configured to withstand force and shock that may be experienced during removal of the mass **508**.

Y-Axis Compliance

With properly designed flexures **570**, compliance in the Y-axis is relatively small as the flexure **570** beams are either in compression or tension. Any compliance in the Y-axis is the result of buckling or stretching of the flexure **570**, which is undesirable in all situations. The amount of deflection in the Y-axis should be minimized to prevent damage to the flexures **570** during movement, for example.

TABLE 3 below provides total flexure stiffness based on stiffness being less than 10% of total electroactive polymer actuator **506** stiffness, according to one embodiment, where the values provided are approximate example values.

TABLE 3

Total Flexure Stiffness (Stiffness < 10% of total Electroactive Polymer Actuator Stiffness)					
Sprung Mass (m _{batt} + m _{tray})	12.5g	25g	...	125g	150g
3-Bar Actuator Layers	2	4	...	20	24
Total Actuator Stiffness (k _{ax})	2.8kN/m	5.6kN/m	...	28kN/m	30.8kN/m
Total Flexure X-Stiffness Allowance (k _{fx})	125N/m	250N/m	...	1.25kN/m	1.375kN/m

FIG. 51 is a schematic diagram **584** illustrating the flexure tray **504** travel stop **572**, **574** features of the flexure suspension system **502** shown in FIGS. 12 and 47-48, according to one embodiment. In the flexure suspension system **502** illustrated in FIG. 51, an electroactive polymer layer **586** is distributed through a plurality of screen printed electroactive polymer actuator frames **588** that are alternatively attached to the mounting surface **568** of a device and the base of the flexure tray **504** by an adhesive sheet **590**. The flexure **570** is represented symbolically for convenience and clarity. In one embodiment, the stops **572**, **574** are provided where possible while allowing free movement of the dynamic mass under normal loads. The travel stops **572**, **574** prevent over extension and damage to the flexures **570** and the electroactive polymer actuator **506**. The embodiment of the flexure **570** presented herein lends itself well to built-in travel stops **572**, **574** in all axes except for the -Z-direction where pulling of the mass **508** out of the flexure tray **504** may cause damage. A positive Z-direction (+Z-direction) stop may be implemented using the actuator frame itself, which may be suitable to survive industry standard drop testing up to 1.5m, for example.

TABLE 4 below provides flexure tray stop **572**, **574** clearances, according to one embodiment. The clearances labeled A-F in TABLE 4 below are approximate example values and correspond to similarly labeled clearances in FIG. 51.

TABLE 4

Flexure Tray Stop Clearances			
Dimension	Minimum	Average	Maximum
A	0.1 mm	0.25 mm	0.5 mm
B	0.1 mm	0.25 mm	1.0 mm
C	0.1 mm	0.25 mm	0.29 mm
D	0.2 mm	0.5 mm	1.0 mm
E	N/A	0.4/0.6 mm	N/A
F	N/A	0.13 mm	N/A

FIG. 52 is a schematic diagram **592** of a flexure linkage **594** beam model, according to one embodiment. The flexure linkages **594** can be

made from a number of materials. In one embodiment, the flexure linkages **594** may be made of plastic using an injection molded set of linkages built into the handset back-shell or a tablet battery mount frame, for example. In such embodiments, the flexure linkage material may be
5 made of a moldable plastic such as acrylonitrile-butadiene-styrene, for example, without limitation. Applications involving larger Z-direction loads and/or having limited space, flexure linkages **594** may be made of sheet metal and can be molded into a plastic frame. Alternatively, an entire stamped sheet metal subassembly can be made and used in applications
10 that require the larger Z-direction loads. The stiffness of an individual linkage **594** can be calculated using the beam model shown in FIG. 52, for example, where the deflection of the flexure linkage **594** in the X- and Z-directions (d_x and d_z) under corresponding forces (F_x and F_z) is modeled.

FIG. 53 illustrates one embodiment of a flexure tray **504** without the
15 mass **508**. The flexure tray **504** comprises a rigid outer frame **596** that is fixedly mounted to a mounting surface. In the illustrated embodiment, the rigid outer frame **596** may be fixedly mounted to the mounting surface by way of fasteners inserted through one or more apertures **598**. Typical fasteners include screws, bolts, rivets, and the like. As shown in FIG. 53,
20 the flexure tray **504** comprises flexures **570** that enable the flexure tray **504** to move in the X and Y-direction to provide a vibro-electroactive polymer stimulus of the user. Also shown are the X-travel stops **572** and Y-travel stops **574** to prevent over extension and damage to the flexures **570** and electroactive polymer actuator.

FIG. 54 illustrates a segment **599** of one embodiment of the flexure
25 tray **504**. The segment **599** shows the diameters ϕ_1 and ϕ_2 of the flexure **570** as well as the overlapping distance d_1 between two flexure segments and the distance d_2 between bent segments of the flexure **570**. TABLE 5 provides reference design flexure parameters, according to one
30 embodiment, where the values provided are approximate example values.

TABLE 5

Reference Design Flexure Parameters	
Material	P430 ABS Plus (3D printed FDM process)
Actuator	8L 3-Bar
Sprung Mass ($m_{batt} + m_{tray}$)	60g
L =	15 mm
b =	0.3 mm
h =	5 mm
$k_x =$	92 N/m
N =	6
$k_{fx(total)}$	552 N/m
$k_{tz} =$	153.3k N/m

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.

Although certain modules and/or blocks may be described by way of example, it can be appreciated that a greater or lesser number of modules and/or blocks may be used and still fall within the scope of the embodiments. Further, although various embodiments may be described in terms of modules and/or blocks to facilitate description, such modules and/or blocks may be implemented by one or more hardware components

(e.g., processors, digital signal processors, programmable logic devices, application-specific integrated circuits, circuits, registers), software components (e.g., programs, subroutines, logic) and/or combination thereof.

5 Numerous specific details have been set forth herein to provide a thorough understanding of the embodiments. It will be understood by those skilled in the art, however, that the embodiments may be practiced without these specific details. In other instances, well-known operations, components and circuits have not been described in detail so as not to
10 obscure the embodiments. It can be appreciated that the specific structural and functional details disclosed herein may be representative and do not necessarily limit the scope of the embodiments.

 It is worthy to note that any reference to “one embodiment” or “an embodiment” means that a particular feature, structure, or characteristic
15 described in connection with the embodiment is included in at least one embodiment. The appearances of the phrase “in one embodiment” or “in one aspect” in the specification are not necessarily all referring to the same embodiment.

 It is worthy to note that some embodiments may be described using
20 the expression “coupled” and “connected” along with their derivatives. These terms are not intended as synonyms for each other. For example, some embodiments may be described using the terms “connected” and/or “coupled” to indicate that two or more elements are in direct physical or electrical contact with each other. The term “coupled,” however, may also
25 mean that two or more elements are not in direct contact with each other, but yet still co-operate or interact with each other.

 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
30 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, 5 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 10 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.

The terms "a" and "an" and "the" and similar referents used in the 15 context of the present disclosure (especially in the context of the following claims) are to be construed to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context. Recitation of ranges of values herein is merely intended to serve as a shorthand method of referring individually to each separate value falling 20 within the range. Unless otherwise indicated herein, each individual value is incorporated into the specification as if it were individually recited herein. All methods described herein can be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context. The use of any and all examples, or exemplary language (e.g., 25 "such as," "in the case," "by way of example") provided herein is intended merely to better illuminate the invention and does not pose a limitation on the scope of the invention otherwise claimed. No language in the specification should be construed as indicating any non-claimed element essential to the practice of the invention. It is further noted that the claims 30 may be drafted to exclude any optional element. As such, this statement is intended to serve as antecedent basis for use of such exclusive

terminology as solely, only and the like in connection with the recitation of claim elements, or use of a negative limitation.

Groupings of alternative elements or embodiments disclosed herein are not to be construed as limitations. Each group member may be
5 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.

While certain features of the embodiments have been illustrated as
10 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.

WHAT IS CLAIMED IS:

1. A sensory enhanced audio device comprising:
an actuator system having a mechanical Q factor less than about 10; and
a circuit electrically coupled to the actuator system, wherein the circuit is to
5 generate a drive signal to cause the actuator system to move
according to the drive signal.
2. The sensory enhanced audio device according to Claim 1, wherein
the actuator system has a mechanical Q factor from about 1.5 to about 3.
- 10 3. The sensory enhanced audio device according to one of Claims 1
and 2, wherein the actuator system has a resonant frequency between
about 50 to about 100 Hz.
- 15 4. The sensory enhanced audio device according to any one of Claims
1 to 3, wherein the actuator system comprises an electroactive polymer
actuator array comprising at least one elastomeric dielectric element
disposed between first and second electrodes.
- 20 5. The sensory enhanced audio device according to any one of Claims
1 to 4, wherein the drive signal is derived from an audio signal.
6. The sensory enhanced audio device according to any one of Claims
1 to 5, further comprising an acoustic radiator and means by which the
25 motion of the actuator system is constrained to be substantially in a
direction orthogonal to the axis of the acoustic radiator axis.
7. The sensory enhanced audio device according to any one of Claims
1 to 6, wherein the drive signal generated by the circuit is in the frequency
30 range of about 2 Hz to about 200 Hz.

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8. The sensory enhanced audio device according to any one of Claims 1 to 7, further including a tray configured to receive the actuator system.

9. The sensory enhanced audio device according to one of Claims 1
5 to 8, further including a mass coupled to the actuator system.

10. The sensory enhanced audio device according to Claim 8, wherein the tray comprises at least one aperture.

10

11. The sensory enhanced audio device according to Claim 8, further comprising a sound cavity mounted to the tray.

12. The sensory enhanced audio device according to Claim 8, wherein
15 the tray comprises a suspension system to minimize unwanted modes of vibration by substantially limiting displacements to a single direction.

13. The sensory enhanced audio device according to Claim 12, wherein the suspension system comprises:
20 a suspension tray defining an opening to receive the mass and the actuator system therein; and
at least one flexure arm formed in the suspension tray;
wherein the actuator system defines an plane of vibration defined by a first and second axis and the suspension system allows movement primarily in
25 one direction along the first axis.

14. The sensory enhanced audio device according to any one of Claims 1 to 13, further comprising an inverse polynomial circuit to compute a non-linear inverse transform to remove unwanted acoustic artifacts from the
30 drive signal.

15. The sensory enhanced audio device according to any one of Claims 1 to 14, wherein the audio device is a headphone.
16. The headphone of Claim 15, wherein the headphone comprises at
5 least one ear cup including the actuator system.
17. The sensory enhanced audio device according to any one of Claims 1 to 15, wherein intensity of an effect created by motion of the actuator system is controlled independently of intensity of the audio signal.