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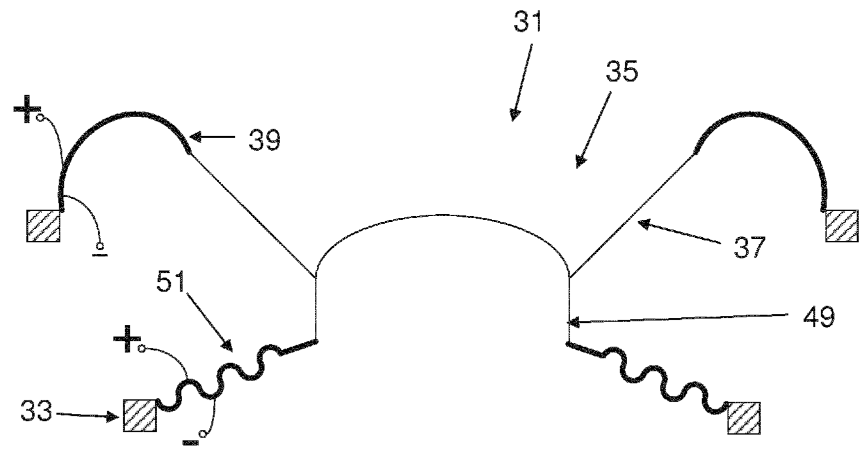

FIG. 5

(57) Abstract: A loudspeaker 31 has a frame 33, a diaphragm 37, at least a part of which does not comprise an electro-active polymer, and one or more connecting parts 39, 51 comprising an electro-active polymer and connecting the diaphragm 37 to the frame 33. The one or more connecting parts 39, 51 are operable to excite the diaphragm 37 to displace it relative to the frame 33, in order to produce sound.

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A Loudspeaker

The present invention relates to a loudspeaker.

Background

At its most basic, a loudspeaker can be considered to be an electro-acoustic transducer, which produces sound in response to electrical energy input. A loudspeaker receives electrical energy and converts this electrical energy into mechanical energy, and thus acoustic energy (i.e. sound) is generated.

A variety of different techniques have been used to convert electrical energy into acoustic energy in loudspeakers. The most widely used technique for converting electrical energy into acoustic energy in a loudspeaker is to use a so-called “moving-coil” arrangement. This technique is also widely considered to be the most efficient technique for converting electrical energy into acoustic energy in a loudspeaker.

An example of a known moving-coil type loudspeaker is shown in FIGS. 1 and 3. As shown in FIGS. 1 and 3, the loudspeaker 1 comprises a frame 3 (also called a basket) having an aperture 5 (or opening). A diaphragm 7 (i.e. that comprises a thin sheet of material that forms a partition) extends across the aperture 5 of the frame 3. The diaphragm 7 is connected to the frame 3 by a flexible surround 9 that is connected (i.e. extends) around an outer perimeter 11 of the diaphragm 7 and that is also connected (i.e. extends) around a corresponding inner perimeter of the aperture 5. The diaphragm 7 is connected around the inner perimeter of the aperture 5 by means of a gasket 12

The diaphragm 7 has a substantially conical-shaped geometry, which extends from the outer perimeter 11 to a voice coil former 13 that protrudes from a central region of the diaphragm 7. Thus, the diaphragm 7 comprises a thin sheet/layer part and a voice coil former 13. The voice coil former 13 is a hollow tube made of a thin and light-weight sheet of material (e.g. paper, or very thin aluminium) that has been rounded to form a hollow cylinder. The thin sheet/layer part of the diaphragm 7 continues over an end 15 of the voice coil former 13 to cover the opening of the hollow tube, and is glued to the voice coil former 13 at the end 15 of the voice coil former 13.

A voice coil 17 is wound around the voice coil former 13 of the diaphragm 7. The voice coil 17 can essentially be regarded as a variable electromagnet. In response to an input electrical signal, e.g. an electrical signal provided by an amplifier of an audio system, a magnetic field is generated around the voice coil 17. The polarity of the generated magnetic field depends on the direction of flow of the electrical signal through the voice coil 17, i.e. switching the direction of flow of the electrical signal causes the polarity of the generated magnetic field to be switched. The magnitude of the generated magnetic field is determined by the magnitude of the electric current passing through the voice coil 17.

The voice coil former 13 protrudes from the diaphragm 7 into an opening (or aperture) 19 defined by a permanent magnet 21 of a magnetic assembly, and accepts a part of the magnetic assembly inside the hollow tube of the voice coil former 17. This helps to enable the voice coil 17 to be positioned in the static magnetic field generated by the permanent magnet 21. A narrow air gap is present between the permanent magnet 21 and the voice coil 17 wound around the voice coil former 13.

The combination of the voice coil and the permanent magnet can be termed a “magnetic circuit”. As discussed in more detail below, the magnetic circuit is usable to drive oscillations of the diaphragm.

A spider 23, which is a flexible suspension, connects the voice coil former 13 of the loudspeaker 1 to the frame 3. The function of the spider is discussed in more detail below. As shown in FIG. 1, the spider 23 extends around substantially the whole of an outer perimeter of the voice coil former 13 and around substantially the whole of an inner perimeter of the frame 3. The spider 23 has a wavy and/or corrugated appearance/structure. The spider is glued to the voice coil former 13.

In use, when an electrical signal is passed through the voice coil 17, a magnetic field is generated around the voice coil 17 (i.e. it acts as a variable electromagnet). The interaction between this magnetic field and a static magnetic field generated by the permanent magnet 21 generates a magnetic force that causes the voice coil 17, and therefore the attached voice coil former 13 and the diaphragm 7, to move relative to the permanent magnet 21. By varying the magnitude of the electric signal passed through the voice coil 17, the magnitude of this magnetic force, and therefore the magnitude of the displacement of the diaphragm, can be varied.

The spider 23 has a first role of providing a restoring force (i.e. when it is deformed, e.g. stretched or bent, a force is generated urging it to return to its initial configuration before it was deformed) for returning the voice coil 17, and therefore the diaphragm 7, to an equilibrium position when no electric signal is passed through the voice coil 17 (i.e. after the voice coil has been displaced by a previously applied magnetic force). The surround 9 also acts to provide a restoring force for returning the diaphragm 7 to the equilibrium position.

The spider 17 also has a second role of constraining the voice coil 17 to only move axially within the opening 19 of the permanent magnet 21, i.e. along a straight axis that coincides with the symmetry axis of the loudspeaker 1 (i.e. parallel to the dotted lines shown in FIG. 1). The surround 9 also acts to constrain the voice coil to only move axially within the opening 19 of the permanent magnet 21, by helping to centre the diaphragm within the aperture 5 of the frame 3.

Constraining the voice coil 17 to only move along a linear axial direction of the loudspeaker 1 helps to maintain the air gap between the voice coil 17 and the permanent magnet 21. Maintaining an air gap is necessary because any contact between the metal parts of the voice coil 17 and metal parts of the magnetic circuit (i.e. metal parts of the permanent magnet 21) creates an unwanted sound, and therefore significantly degrades the acoustic properties of the loudspeaker 1. The flexible parts of the loudspeaker 1, i.e. the spider 23 and the surround 9, are responsible for keeping the voice coil 17 from touching the metal parts of the magnetic circuit.

In addition, constraining the voice coil 17 to only move along a linear axial direction of the loudspeaker 1 improves the quality (e.g. the fidelity) of the sound produced by the loudspeaker 1. Any unintentional sideways (i.e. perpendicular to the central symmetry axis of the loudspeaker 1) movement of the diaphragm 7 may adversely affect the quality (e.g. the fidelity) of the sound produced by the loudspeaker 1.

It is the linear (axial) movement of the voice coil 17, and therefore of the diaphragm 7, that generates acoustic energy in the form of pressure waves in the surrounding air. Therefore, the diaphragm 7 represents the primary (main) sound creating element of the loudspeaker 1, which moves to create the primary (main) sound produced by the loudspeaker 1.

This known type of loudspeaker has proven itself to be efficient due to many reasons. One of the reasons is that, in the presence of a static magnetic field, generation of the force with the magnetic circuit is an efficient way to excite the diaphragm. Therefore, the loudspeaker does not depend on any additional energy source, other than the supplied electrical signal provided by e.g. an amplifier, to generate sound.

The stiffness of the diaphragm is not only dependent on the stiffness of the material forming the diaphragm, but also on the conical-shape of the diaphragm. When the material is not formed into a particular geometry and is instead formed flat, the rigidity of the flat diaphragm solely depends on the material properties of the material from which the diaphragm is made. However, if the diaphragm is formed into a particular geometry like a cone shape, the total rigidity of the diaphragm depends both on the material properties and on the geometrical shape of the diaphragm.

It has been noted that, in some cases, the geometry of the diaphragm has more of an influence on the total rigidity of the diaphragm than the material properties of the material from which the diaphragm is made. When compared to flat panel loudspeakers, a cone-shaped diaphragm has an advantage that the cone-shaped geometry of the diaphragm leads to an increased stiffness and/or rigidity of the diaphragm. A greater stiffness and/or rigidity of the diaphragm improves the overall efficiency of the diaphragm as a means for generating acoustic energy. Thus, the conventional moving-coil type loudspeaker has increased efficiency due to the cone-shape of the diaphragm, as compared to e.g. a flat diaphragm.

Since the first introduction of moving-coil type loudspeakers, the design of the moving coil loudspeaker has been changed in a variety of different ways according to the needs of the desired applications. One of the main desired requirements recently has been to achieve the flattest and/or the thinnest moving coil loudspeaker. The extent of the flatness and/or the thickness of the loudspeaker has become one of the main differentiators between loudspeakers, and flatter and/or thinner loudspeakers have achieved marketing advantages in many different areas like automobiles, television sets, mobile audio applications and the like.

Various changes have been made to the conventional moving-coil loudspeaker shown in FIG. 1 in order to try to design a flatter loudspeaker. These changes have primarily involved arranging the positioning of the surround and the spider in such a way that they can fit into a smaller package. For example, the diaphragm has been folded or made flat in order to reduce the total height of the loudspeaker. However, these modified moving-coil loudspeakers still require the magnetic drive system to generate the forces required to produce acoustic energy. The magnetic drive system takes up a significant space, and therefore limits the minimum thickness that can be achieved with a moving-coil type loudspeaker.

Many attempts have been made to replace the magnetic circuit of a moving-coil loudspeaker, to benefit from the cone shaped diaphragm for efficiency but at the same time reduce the height of the loudspeaker by using an alternative technology to excite the diaphragm.

There are further motivations for replacing the magnetic circuit of a moving-coil loudspeaker. The efficiency of a moving-coil type loudspeaker can be increased by reducing the size of the air gap between the voice coil and the permanent magnet. However, reducing the size of this air gap increases the risk of the voice coil touching one of the metal parts of the magnetic circuit (i.e. a metal part of the permanent magnet). As discussed above, such contact is undesirable because it creates an unwanted sound, and therefore degrades the acoustic properties of the loudspeaker. Therefore, in the absence of the magnetic circuit, and particularly in the absence of the permanent magnet, there would be a considerable amount of simplification in the design of the loudspeakers, due to the reduced tolerances in constraining sideways movement of the diaphragm.

Aside from magnetism, pneumatics has been used to excite the diaphragm or to generate directly a pressure difference. These types of loudspeakers have been found to be useful in alarm systems or in systems that require high acoustic energy output, where the fidelity is not the main objective. However, this type of loudspeaker has been found to produce poor fidelity sound.

Piezoelectric materials have also been used as another way to excite the diaphragm in a loudspeaker. These types of loudspeakers have been found to be efficient in high frequency applications, where small magnitude diaphragm movements are sufficient to generate acceptable levels of sound. However, their limitations in terms of magnitude of deflection have significantly limited their application in other areas, especially in low frequency applications.

The electro-static phenomenon has also been used in panel loudspeakers to generate a wide band high fidelity sound. This involves exciting charged panels with an audio electrical signal to generate sound. However the requirement for a high external polarization voltage has considerably limited their areas of application.

Given all the alternatives and their disadvantages, up till now no practical way of efficiently exciting a diaphragm has existed other than the magnetic circuit system of the moving-coil type loudspeaker. In particular, no practical way of efficiently exciting a cone-shaped diaphragm has existed other than the magnetic circuit system.

Summary of the Invention

The present inventors have realised that electro-active polymers can be used to efficiently excite a diaphragm of a loudspeaker.

The term “diaphragm” refers to the primary (i.e. main) sound creating element of the loudspeaker, which moves in order to create the primary (i.e. main) sound output of the loudspeaker.

Electro-active polymers are polymers that exhibit a change in size or shape when they are stimulated by an electric field. At their most basic, electro-active polymers can be thought of as electro-mechanical transducers that convert electrical energy (an applied electric filed) into mechanical energy (a change in size or shape). Electro-active polymers are finding applications as actuators in some different technical fields, such as in robotics or in medical applications, because of their ability to convert electrical energy into mechanical energy relatively efficiently and controllably.

A known way of applying an electric field to a layer of an electro-active polymer is to sandwich (i.e. position or place) the layer of electro-active polymer material between two compliant electrodes, which may be directly formed on, coated on, applied on, or bonded to, opposite surfaces of the electro-active polymer material. The resulting structure can be used as an actuator (or as an electrical-mechanical transducer), and may be termed an “electro-active polymer actuator” or an “electro-active polymer transducer”.

For high-flexibility applications, the electrodes may be made of graphite, formed into a thin layer on surfaces of the electro-active polymer (or formed separately and then bonded to the surface of the electro-active polymer).

In some embodiments of the present invention, the electrodes may comprise carbon conductive grease, for example the commercial products 846-80G and/or 846-1P available from MG Chemicals. Carbon conductive grease is an electrically conductive silicone grease suitable for establishing electrical connections between irregularly shaped surfaces and parts. Alternatively, in other embodiments of the present invention the electrodes may comprise carbon black particles that are applied as a single component or as a mixture with another material. Some examples of carbon black particles that can be used in embodiments of the present invention are: Vulcan XC-72 from Cabot Corp., Ketjenblack EC300J from Akzo Nobel, Raven 7000 from Columbian Chem. Corp and Shawinigan Acetylene Black P-1250 from VSP

The exact deformation of an electro-active polymer achieved when it is stimulated by an applied electric field depends upon the initial geometry and design of the electro-active polymer.

There are a variety of different types of electro-active polymers, including, but not limited to, dielectric electro-active polymers (also commonly called “dielectric elastomers”), ferroelectric electro-active polymers, electrostrictive graft electro-active polymers, and ionic electro-active polymers. Much of the following description relates to the particular example of dielectric elastomers. However, it is to be understood that other types of electro-active polymers can be used instead of dielectric elastomers, and that the present invention is intended to cover the use of any suitable type of electro-active polymer for the purposes described below.

Electro-active polymers can be broadly grouped into high-voltage and low-voltage electro-active polymers, depending on the magnitude of the voltage across the electrodes that is required to cause a change in size or shape of the electro-active polymer. Both high and low voltage electro-active polymers may be utilised in embodiments of the present invention. High voltage electro-active polymers which are currently available and may be used in embodiments of the present invention include, but are not limited to, the VHB-4910 from 3M, the Nafion 117 from DuPont, and Elastosil P7670 from Wacker. These products require a voltage of approximately 100 to 200 Volts per micron thickness, and are currently available at thicknesses of down to 5 microns. Low voltage electro-active polymers have been reported that operate (i.e. can be deformed, or caused to change size or shape) at voltages of 5 Volts per micron or lower. Low voltage electro-active polymers may be particularly well suited to use in the loudspeakers of the present invention, as the voltage required to operate them is close to the normal voltages of operation of a loudspeaker. However, the present invention is not limited to low voltage electro-active polymers.

The basic working structure of an electro-active polymer is illustrated in FIGS. 2A and 2B. The basic working structure 25 comprises a layer 27 (or a film) of an electro-active polymer sandwiched (i.e. placed or positioned) between two compliant (e.g. flexible and/or elastic) electrodes 29. For example, in the specific example of a dielectric elastomer, the layer 27 may be a layer of a dielectric elastomer polymer.

When an electrical signal is applied to the two compliant electrodes (via a circuit – not shown in FIGS. 2A or 2B), an electric field is produced that causes a change in size and/or shape of the electro-active polymer layer 27 (and also consequently a change in size and/or shape of the compliant electrodes 29). The extent of the change in size and/or shape may be dependent on the magnitude of the applied electric field. The change in size and/or shape may also be dependent on the direction of the applied electric field.

In the specific example of a dielectric elastomer actuator/transducer, the dielectric elastomer actuator/transducer can essentially be considered to be a compliant capacitor. In more detail, when a voltage is applied to the two electrodes 29, a charge Q stored on the two electrodes 29 is increased. The increase in the stored charge causes an increase in the Coulomb forces acting between the two electrodes 29. Because the charge stored on one electrode 29 is negative and the corresponding charge on the other electrode 29 is positive, the Coulomb force is attractive.

This increase in force causes a corresponding increase in the electrostatic pressure on the dielectric elastomer polymer layer 27, which causes the dielectric elastomer polymer layer 27 to be compressed/squashed (so that it contracts) in the thickness direction (i.e. in a direction perpendicular to the two electrodes 29) and to expand in the plane of the dielectric elastomer polymer layer 27 (i.e. in directions parallel to the two electrodes 29). When the voltage is no-longer applied to the two electrodes 29, the dielectric elastomer polymer layer 27 may return back to its original size and shape (i.e. the deformation of the dielectric elastomer polymer layer 27 is elastic rather than plastic, because the polymer is an elastomer).

The changes in thickness, area or both that can occur when an electrical signal is applied to an electro-active polymer enables electro-active polymers to be designed to deform in a variety of different possible directions. Such deformation may include e.g. bending, or deflection of the electro-active polymer.

The present inventors have realised that simply replacing a diaphragm of a conventional loudspeaker with a diaphragm made of electro-active polymer material(s) has various disadvantages. Due to their mechanical properties, electro-active polymers may not be suitable materials to be used as diaphragms. For example, electro-active polymers generally have a low elastic modulus and a high density as compared to other materials conventionally used to make a diaphragm for a loudspeaker. Therefore, using electro-active polymers to form the diaphragm may lead to a diaphragm that is too heavy, or insufficiently rigid, to produce good quality (e.g. high-fidelity) sound. When a more rigid structure is attached (e.g. glued) over a part of an electro-active polymer diaphragm to improve the stiffness of the diaphragm, the total weight of the diaphragm will increase. This increase in weight causes a disadvantageous decrease in the efficiency of the loudspeaker.

Instead, the present inventors have realised that the considerable freedom in terms of the design of the configuration of electro-active polymers means that electro-active polymers can be used in a loudspeaker to efficiently excite (i.e. displace) a diaphragm, e.g. a conventional diaphragm where at least a part of the diaphragm does not comprise an electro-active polymer, or where the whole diaphragm does not comprise an electro-active polymer. In other words, an electro-active polymer(s) can be used as an actuator/transducer to displace/deflect the diaphragm.

Therefore, at its most general, the present invention provides a loudspeaker in which a diaphragm, at least a part of which does not comprise an electro-active polymer, of the loudspeaker is excited using an electro-active polymer(s).

According to an aspect of the present invention, there is provided a loudspeaker comprising: a frame, a diaphragm, at least a part of which does not comprise an electro-active polymer, and one or more connecting parts comprising an electro-active polymer connecting the diaphragm to the frame, wherein the one or more connecting parts are operable to excite the diaphragm to displace it relative to the frame.

Of course, the loudspeaker may comprise a plurality of the connecting parts.

The term “diaphragm” means the primary (i.e. main) sound creating element of the loudspeaker, which moves in order to create the primary (i.e. main) sound output of the loudspeaker.

The fact that the diaphragm is excited by the one or more connecting parts that comprise an electro-active polymer means that it is not necessary for the loudspeaker to include a magnetic circuit, for example the magnetic circuit of the conventional moving-coil type loudspeaker illustrated in FIG. 1. Therefore, some or all of the magnetic circuit of the conventional moving-coil type loudspeaker shown in FIG. 1 may be omitted in the loudspeaker according to the present invention, because its function has been replaced by the one or more connecting parts.

In particular, in the loudspeaker according to the present invention the permanent magnet 21 of the moving-coil type loudspeaker illustrated in FIG. 1 may be omitted, because excitation of the diaphragm is achieved using the electro-active polymer connecting part(s) rather than by a magnetic force. In addition, the voice coil 17 of the moving-coil type loudspeaker illustrated in FIG. 1 may also be omitted, for the same reasons. The removal of the permanent magnet 21 and the voice coil 17 may mean that the size of the voice coil former 13 of the diaphragm 7 may be significantly reduced, i.e. it may be made significantly shorter so that it protrudes from the diaphragm to a lesser extent, or it may be omitted entirely.

Therefore, the present invention provides an advantage that the physical size of the loudspeaker may be significantly reduced when compared to e.g. the conventional loudspeaker illustrated in FIG. 1. In particular, the removal of the magnetic circuit means that the loudspeaker may be made significantly flatter and/or thinner than e.g. the conventional loudspeaker illustrated in FIG. 1, i.e. the height/thickness of the loudspeaker may be significantly reduced.

The fact that the magnetic circuit (particularly the permanent magnet and the voice coil) may be omitted in the loudspeaker according to the present invention may also have an advantage of simplifying the required tolerances in the design of the loudspeaker. As discussed in more detail above, in the moving-coil type loudspeaker illustrated in FIG. 1 it is desirable to reduce the size of the air gap between the voice coil and the permanent magnet as much as possible to improve the efficiency of the magnetic circuit drive system, whilst still maintaining a sufficiently large air gap so that the voice coil does not come into contact with the permanent magnet. Maintaining this air gap requires tight/strict tolerances in the design of the size of the air gap, and in the design of the spider which acts to constrain the voice coil and diaphragm to only move along a central axis of the loudspeaker (rather than e.g. sideways into the air gap). With the loudspeaker according to the present invention, these required tolerances are significantly simplified or removed altogether, which provides an advantage of simplifying the design and manufacture of the loudspeaker.

Electro-active polymers are capable of achieving relatively large deformations in response to an applied electrical signal. Therefore, with the loudspeaker according to the present invention it may be possible to achieve relatively large deformations of the connecting part(s), and therefore to achieve relatively large displacements of the diaphragm. As such, the loudspeaker according to the present invention may be able to provide the necessary deflection of the diaphragm for low frequency sound generation. This is in contrast to many of the other proposed replacements for the magnetic circuit discussed above, such as piezoelectric materials, which cannot provide the necessary deflection of the diaphragm for low frequency sound generation.

In addition, electro-active polymers can also be controlled to achieve relatively small deformations in response to an applied electrical signal. Therefore, with the loudspeaker according to the present invention it may be possible to achieve relatively small deformations of the connecting part(s), and therefore to achieve relatively small displacements of the diaphragm. As such, the loudspeaker according to the present invention may be able to provide the necessary deflection of the diaphragm for high frequency sound generation.

Indeed, the electro-active polymer may be able to achieve both relatively small and relatively large displacements, depending on the magnitude of the applied electrical signal, so that the loudspeaker is able to produce both low and high frequency sounds.

Thus, in addition to reducing the size (i.e. thickness or height) of the loudspeaker, the loudspeaker of the present invention may also provide an advantage that the frequency range of the loudspeaker may include low frequency sounds, and/or may be a broad frequency range that covers both low and high frequency sounds. In this way, the fidelity of the sound produced by the loudspeaker may also be maintained at a high level (e.g. high-fidelity sound).

The fact that at least a part of the diaphragm does not comprise electro-active material means that the diaphragm may be made primarily from a material that has a higher elastic modulus and a lower density than an electro-active polymer, and therefore is more suited to use in a diaphragm.

The loudspeaker according to this aspect of the invention may have any one, or to the extent that they are compatible, any combination of the following optional features.

The one or more connecting parts may be operable to excite the diaphragm by applying an electric field to the one or more connecting parts to change the size or shape of the one or more connecting parts. For example, applying an electric field may cause the size of the one or more connecting parts to increase or decrease, or may cause the one or more connecting parts to bend or to otherwise deform and change shape. Therefore, it is not necessary for the loudspeaker to include a permanent magnet as with the conventional loudspeaker illustrated in FIG. 1, because displacement of the diaphragm can be achieved by applying an electric field to the one or more connecting parts.

The extent of the change in size or shape of the one or more connecting parts may depend on the magnitude of the applied electric field. For example, the extent/magnitude of the change in size or shape of the one or more connecting parts may be increased when the magnitude of the applied electric field is increased, and decreased when the magnitude of the applied electric field is decrease. Therefore, changing the applied electric field may change the extent to which the one or more connecting parts displace the diaphragm relative to the frame.

Indeed, the one or more connecting parts may be operable to excite the diaphragm to displace it relative to the frame by an amount that depends on the magnitude of the applied electric field. For example, the displacement of the diaphragm relative to the frame may be increased by increasing the magnitude of the electric field applied to the one or more connecting parts, and decreased by decreasing the magnitude of the electric field. Therefore, it may be possible to control the displacement of the diaphragm relative to the frame by controlling the magnitude of the applied electric field. In this way, the diaphragm can be controllably displaced (e.g. made to oscillate) to produce acoustic energy.

The direction in which the diaphragm is displaced relative to the frame may be reversed when the direction of the applied electric field is reversed. Thus, it may be possible to excite the diaphragm to move in more than one direction, e.g. to oscillate, by reversing the direction of the applied electric field.

The one or more connecting parts may comprise a layer of electro-active polymer sandwiched (i.e. placed, or positioned) between two compliant (i.e. flexible, and/or elastic) electrodes. Therefore, an electric field may easily and controllably be applied to the layer of an electro-active polymer in a uniform manner by connecting the two electrodes to an electrical circuit that provides an electrical signal. The strength of the applied electric field may be changed by changing the voltage of the electrical signal provided to the electrodes. The direction of the applied electric field may be switched by switching the polarity of the voltage of the electrical signal provided to the electrodes. This may provide an efficient and practical way of applying the electrical field to the electro-active polymer.

Furthermore, the fact that the electrodes are compliant means that the electrodes can deform (i.e. bend, and/or change shape, and/or change area) with the polymer. Thus, the electrodes may not significantly restrict the deformation of the electro-active polymer.

The one or more connecting parts may be operable to excite the diaphragm to displace it relative to the frame by an amount that depends on a voltage applied to the two compliant electrodes. For example, the amount by which the diaphragm is displaced relative to the frame may be increased by increasing the voltage that is applied to the two compliant electrodes (or the voltage difference), and decreased by decreasing the voltage applied to the two compliant electrodes. Therefore, the extent of displacement of the diaphragm relative to the frame may be easily controlled, enabling the generation of good quality (e.g. high-fidelity) sound.

The direction in which the diaphragm is displaced relative to the frame may be reversed when the polarity of the voltage applied to the two compliant electrodes is reversed. Therefore, the diaphragm can be made to move in more than one direction, e.g. to oscillate, by reversing the polarity of the voltage applied to the two compliant electrodes. It may therefore be possible to generate good quality (e.g. high-fidelity) sound.

The one or more connecting parts may be usable to excite the diaphragm to displace it linearly (i.e. along a straight line) relative to the frame. In other words, the one or more connecting parts may act to only displace the diaphragm along a straight line. For example, the one or more connecting parts may be arranged so that any forces applied by the one or more connecting parts to the diaphragm in any other direction cancel or balance out, so that the resulting force acting on the diaphragm is along the straight line. Thus, it may be possible to achieve linear displacement of the diaphragm, to generate sound. As discussed above, any non-linear movement of the diaphragm, e.g. rocking or side to side movement of the diaphragm, may reduce the quality of the sound produced by the loudspeaker. Therefore, displacing the diaphragm linearly (i.e. along a straight line) relative to the frame may improve the quality (e.g. fidelity) of the sound produced by the loudspeaker.

Indeed, the one or more connecting parts may be usable to excite the diaphragm to displace it linearly relative to the frame in a direction parallel to a central axis of the loudspeaker (e.g. a central symmetry axis of the loudspeaker, or an axis perpendicular to a central portion of the diaphragm). Thus, the quality (e.g. fidelity) of the sound produced by the loudspeaker may be improved.

The one or more connecting parts may be usable to excite the diaphragm to displace it in either of two opposite directions relative to the frame. For example, the one or more connecting parts may be usable to excite the diaphragm to displace it in two opposite directions along a linear direction (e.g. an ‘up’ or ‘outwards’ direction and an opposite ‘down’ or ‘inwards’ direction). Therefore, it may be possible to make the diaphragm oscillate relative to the frame (e.g. move forwards and backwards) and therefore generate sound.

The one or move connecting parts may be disposed (e.g. positioned or arranged) so that they constrain the diaphragm to move in a linear direction relative to the frame. For example, the one or more connecting parts may be disposed so that any sideways forces (i.e. not along a central axis of the loudspeaker) applied to the diaphragm may cancel out or balance out around the diaphragm, so that the resulting force on the diaphragm acts in a single, linear direction. Therefore, the one or more connecting parts may constrain (i.e. restrict or force) the diaphragm to only move in a linear fashion, e.g. along the central axis of the loudspeaker. Thus, the loudspeaker may produce good quality (e.g. high-fidelity) sound.

Indeed, the one or more connecting parts may be evenly disposed (e.g. at fixed intervals, e.g. at a fixed angular separation between connecting parts or between parts of a connecting part) around the diaphragm and may constrain the diaphragm to move in a linear fashion.

The electro-active polymer may be a dielectric polymer. In other words, the polymer may be an electrical insulator that can be polarised by an applied electric field. Thus, when an electric field is applied to the layer of dielectric polymer, e.g. using the two electrodes, the dielectric polymer may become polarized. Therefore, the actuator/transducer may effectively act as a capacitor, as it comprises a layer of dielectric material between two conductors.

The electro-active polymer may be an elastomer polymer. In other words, the polymer may be an elastic polymer which deforms elastically (rather than plastically) in response to an applied force. Thus, the electro-active polymer, and therefore an electro-active polymer actuator/transducer containing the electro-active polymer, may automatically return to its original configuration (i.e. size, shape, etc.) when the electric field is removed (e.g. when an electrical signal to the conductors is stopped). Therefore, the electro-active polymer actuator/transducer may effectively act as a compliant capacitor, where a dielectric elastomer polymer layer is increasingly squashed between the conductors as the charge on the conductors is increased (as discussed in more detail above).

In addition, the fact that the polymer is an elastomer may mean that it is capable of being deformed without any plastic deformation and/or damage occurring to the polymer. Thus, it may be possible to repeatedly deform the polymer, e.g. to make it oscillate to produce sound.

The diaphragm may have a conical-shaped (cone-shaped) geometry. As discussed above in more detail, the stiffness of a diaphragm depends not only on the stiffness of the material from which it is made, but also on the geometry of the diaphragm. It has been noted that in some cases the geometry of the diaphragm has more of an influence on the total rigidity of the diaphragm than the material properties of the material from which the diaphragm is made. When compared to the flat-panel loudspeakers, electro-static or magneto-static loudspeakers, the advantage of the increased rigidity provided by the conical-shaped (cone-shaped) geometry may play an important role in increasing the efficiency of the loudspeaker. The term cone-shaped is intended to cover frusto-conical shapes, and e.g. the shape illustrated in FIG. 1 in which the diaphragm has a voice coil former at a central region thereof.

The electro-active polymer connecting parts of the present invention may be an efficient way of driving/exciting a cone-shaped diaphragm of a loudspeaker, thereby providing a loudspeaker that benefits from the efficiency increases that arise from using a cone-shaped geometry for the diaphragm (which causes increased stiffness of the diaphragm relative to e.g. a flat diaphragm) and that also benefits from a decreased thickness due to the removal of the magnetic-circuit drive system. Thus, the combination of a cone-shaped diaphragm and the electro-active connecting parts as a driving/exciting system for the diaphragm may provide a particularly advantageous loudspeaker design, that is efficient and that has a relatively small thickness/size.

The one or more connecting parts may comprise a surround of the loudspeaker. In other words, rather than a standard/conventional surround as in e.g. the conventional moving-coil type loudspeaker illustrated in FIG. 1, the surround may instead be made of an electro-active polymer and may have the additional function (in addition to one or more of the existing functions of the conventional surround discussed above) of displacing the diaphragm relative to the frame.

Therefore, in addition to the function of exciting the diaphragm to displace it relative to the frame, the connecting part(s) comprising the surround may also have the function of constraining the diaphragm to only move linearly along a central symmetry axis of the loudspeaker. For example, the surround may be disposed so that any forces it applies to the diaphragm in a direction other than along the central symmetry axis balance out, or cancel out, around the diaphragm, so that the resulting force is parallel to the central symmetry axis. Thus, the surround may be able to excite the diaphragm to displace it in a linear direction, so as to produce sound, while constraining the displacement of the diaphragm to only be in the linear direction.

In addition, the connecting part(s) comprising the surround may also have a function of providing a restoring force to return the diaphragm to an equilibrium position when the diaphragm is not being driven (e.g. because the connecting parts are elastic). Therefore, the connecting parts may replace the conventional surround and may fulfil one or more of the functions of the conventional surround.

Indeed, the one or more connecting parts may connect the frame to an outer perimeter of the diaphragm. Therefore, the one or more connecting parts may act to displace the diaphragm by moving/displacing an outer perimeter/edge of the diaphragm. For example, the one or more connecting parts may connect an outer edge of the diaphragm to an inner edge of an aperture or opening in the frame.

Indeed, a plurality of connecting parts may connect the frame to a plurality of positions on the outer perimeter of the diaphragm. Thus, as discussed above, the plurality of connecting parts may combine to produce a linear displacement of the diaphragm, because any forces applied by the plurality of connecting parts to the diaphragm in a direction other than the linear direction may cancel out around the diaphragm, because they are applied at different positions around the diaphragm.

Indeed, the one or more connecting parts may form a continuous band around an outer perimeter of the diaphragm, which may help to balance out, or cancel out, any sideways movement of the diaphragm. Therefore, the one or more connecting parts may equally displace all positions on the perimeter of the diaphragm. In addition, the one or more connecting parts may effectively provide a flexible edge/perimeter to the diaphragm, connecting the diaphragm to the frame, which may prevent air from passing around the sides of the diaphragm during movement of the diaphragm relative to the frame.

The one or more connecting parts comprise a spider of the loudspeaker. In other words, rather than a standard/conventional spider as in e.g. the conventional moving-coil type loudspeaker illustrated in FIG. 1, the spider may instead be made of an electro-active polymer and may have the additional function (in addition to one or more of the existing functions discussed above) of displacing the diaphragm relative to the frame.

Therefore, in addition to the function of exciting the diaphragm to displace it relative to the frame, the connecting part(s) comprising the spider may also have the function of constraining the diaphragm to only move linearly along a central axis of symmetry of the loudspeaker. For example, the spider may be disposed so that any forces it applies to the diaphragm in a direction other than along the central symmetry axis balance out, or cancel out, around the diaphragm, so that the resulting force is parallel to the central symmetry axis. Thus, the spider may be able to excite the diaphragm to displace it in a linear direction, so as to produce sound, while constraining the displacement of the diaphragm to only be in the linear direction.

In addition, the connecting part(s) comprising the spider may also have a function of providing a restoring force to return the diaphragm to an equilibrium position when the diaphragm is not being driven (e.g. because the connecting parts are elastic). Therefore, the connecting parts may replace the conventional spider and fulfil one or more of the functions of the conventional spider.

Indeed, the one or more connecting parts may connect the frame to one or more positions on a central part (or central region) of the diaphragm. Therefore, the one or more connecting parts may act to displace the diaphragm by moving/displacing the central part of the diaphragm directly. Thus, the one or more connecting parts may be able to efficiently displace the diaphragm relative to the frame.

Indeed, a plurality of connecting parts may connect the frame to a plurality of positions on a central part of the diaphragm. Thus, as discussed above, the plurality of connecting parts may combine to produce a linear displacement of the diaphragm, because any forces applied by the plurality of connecting parts to the diaphragm in a direction other than the linear direction may cancel out around the diaphragm, because they are applied at different positions around the diaphragm.

Indeed, the one or more connecting parts may form a continuous band (i.e. extend continuously) around a central part of the diaphragm. Therefore, the one or more connecting parts may equally displace all positions around the central part of the diaphragm, which may help to balance out, or cancel, any sideways movement of the diaphragm.

The diaphragm may not comprise an electro-active polymer. In other words, rather than simply at least a part of the diaphragm not comprising an electro-active polymer, the whole of the diaphragm may not comprise an electro-active polymer. That is, the diaphragm as a whole (i.e. the primary sound creating element that moves to create the primary sound of the loudspeaker) may not contain any electro-active polymer.

Of course, the loudspeaker may have various combinations of the above described connecting parts.

For example, the surround may comprise an electro-active polymer, while the spider does not comprise an electro-active polymer. Alternatively, the spider may comprise an electro-active polymer, while the surround does not comprise an electro-active polymer. Alternatively, both the spider and the surround may comprise an electro-active polymer.

Also, for example, neither the surround nor the spider may comprise an electro-active polymer, and instead one or more separate connecting parts that comprise an electro-active polymer and that connect the frame to the diaphragm may be provided. These connecting parts may connect any part of the diaphragm to the frame, and are not limited to the specific examples discussed above. Alternatively, where the connecting parts do not comprise the surround and/or the spider, the loudspeaker may omit one or both of the conventional surround and/or spider.

Where the connecting parts do not comprise the surround and/or the spider, the loudspeaker may comprise a conventional (i.e. not comprising electro-active material) surround and/or spider in addition to the connecting parts, i.e. the connecting parts may not also replace or fulfil the functions of the surround and/or spider.

Where the spider and/or the surround comprises an electro-active polymer, it is not essential that the whole of the spider and/or the surround comprises an electro-active polymer. Instead, only a part of the spider and/or the surround may comprise an electro-active polymer. For example, the surround and/or the spider may comprise one or more strips or portions of an electro-active polymer that is merged/bonded/integrated with, or that covers or is attached to or over, surrounding material of the surround and/or spider that is not an electro-active material. The electrodes may cover only the electro-active polymer, or both the electro-active polymer and the surrounding non-electro-active polymer material. Thus, it may be possible to change the size and/or shape of the surround and/or spider, and therefore displace the diaphragm, by applying an electric field to change the size and/or shape of the strips or portions of electro-active material merged/bonded/integrated into the surround and/or spider.

Alternatively, strips or portions of electro-active polymer material may be attached/bonded onto one or more surfaces of an existing surround and/or spider that does not comprise an electro-active polymer material.

Furthermore, in some embodiments part of the spider (but not all of it) and some or the entire surround may comprise an electro-active polymer. Alternatively, in some embodiments part of the surround (but not all of it) and some or the entire spider may comprise an electro-active polymer.

When the loudspeaker has one or more connecting parts that connect to a central part of the diaphragm, or a spider, the diaphragm may comprise a protruding part that protrudes from the central part of the diaphragm, and the one or more connecting parts or the spider may connect to the protruding part of the diaphragm. The protruding part may be similar in structure and form to the voice coil former 17 of the conventional loudspeaker 1 illustrated in FIG. 1. In particular, the protruding part may comprise a thin and light-weight sheet of material (e.g. paper, or very thin aluminium) formed into a hollow cylindrical tube, and the rest of the diaphragm (i.e. a thin sheet/layer part of the diaphragm) may cover the top of the protruding part and may be secured to the top of the protruding part, e.g. by glue. However, in other embodiments of the invention other types of protruding part may be used, for example other shapes of tube, or solid rods of material. The reason for including a protruding part at the central part of the diaphragm is to increase the distance between the one or more connecting parts that connect to the central part of the diaphragm, or the spider, and the outer perimeter or edge of the diaphragm. Increasing this distance may help in restraining the diaphragm to only move in a linear direction along a central axis of the diaphragm, especially when the diaphragm is also connected to the frame around its outer perimeter or edge.

In other embodiments, the diaphragm may be deep enough that connecting one or more connecting parts or a spider to the central part of the diaphragm without a protruding part being present at the central part of the diaphragm is sufficient to constrain the diaphragm to only move in a linear direction. Therefore, in some embodiments of the invention it may not be necessary for the diaphragm to have a protruding part.

The performance of the loudspeaker may be improved by using more electro-active polymer connecting parts, as this may provide more control over the displacement of the diaphragm.

The one or more connecting parts may comprise a plurality of layers of electro-active polymer. In other words, a connecting part may be formed from a number of stacked (i.e. arranged one on top of the other, possibly with intermediate layers such as electrodes) layers of electro-active polymer. Forming a connecting part out of multiple layers of electro-active polymer may mean that the layers can be arranged in such a way that when they are excited by an electrical signal, the mechanical forces that they generate cause them to move or to deform in a particular way, for example to bend or to twist.

In one example, a multi-layer electro-active polymer connecting part may be formed from a plurality of layers of thickness-mode electro-active polymer (e.g. a plurality of layers of thickness-mode dielectric elastomer(s)). Thickness-mode electro-active polymers are configured to change their thickness when subjected to an applied electric field. Through a suitable layering (i.e. arrangement of the layers) of thickness-mode electro-active polymers the multi-layer electro-active polymer connecting part can be made to bend, for example in either of two directions, by applying electrical signals of appropriate voltage and polarity to the layers of electro-active polymer.

In other embodiments, the one or more connecting parts may instead comprise a single layer of electro-active polymer. In this case, the connecting part can be configured or arranged so that the electro-active polymer deforms in a particular way, e.g. by bending or twisting, when an electric field is applied to the electro-active polymer layer.

In one example, the layer of electro-active polymer may be a bending-mode electro-active polymer, for example a bending mode dielectric elastomer. Connecting parts comprising a bending-mode electro-active polymer may have the ability to bend in either of two directions depending on the polarity of the voltage that is applied to them. As an example, the chemical configuration of the electro-active polymer layer may be designed in such a way that a certain polarity of applied electrical signal causes movement of charge inside the material from one electrode (i.e. on one surface) to another electrode (i.e. on an opposite surface), and this movement of charges within the material may cause the material, and therefore the connecting part, to bend.

In other embodiments, a connecting part may include more than one layer of bending-mode electro-active polymer, for example two layers of bending mode electro-active polymer (which may be called a bi-morph design). For example, two layers of electro-active polymer material (e.g. a dielectric elastomer) may be positioned one on top of the other so that they share one electrode in the middle between them and have one electrode free each. This arrangement of electro-active polymers may mimic the deformation that can be achieved with piezoelectric-actuators, and may allow for bending or twisting of the connecting part.

Brief description of the Figures

Exemplary embodiments of the invention will now be described with reference to the accompanying drawings, in which:

FIG. 1 shows a perspective view of a prior art moving-coil type loudspeaker;

FIG. 2A shows a perspective view and a cross-sectional view of a basic working structure of an electro-active polymer in a first configuration;

FIG. 2B shows a perspective view and a cross-sectional view of the basic working structure shown in FIG. 2A in a second configuration;

FIG. 3 shows a schematic cross-sectional view of the prior art moving-coil type loudspeaker shown in FIG 1;

FIG. 4 shows a schematic cross-sectional view of a loudspeaker according to an embodiment of the present invention, with the diaphragm in a first position;

FIG. 5 shows a schematic cross-sectional view of the loudspeaker of FIG. 4 with the diaphragm in a second, displaced position;

FIG. 6 shows a partial schematic cross-sectional view of a loudspeaker according to an embodiment of the present invention, with the diaphragm in a first position;

FIG. 7 shows a partial schematic cross-sectional view of the loudspeaker of FIG. 6 with the diaphragm in a second position.

FIG. 8 shows a cross-sectional view of a loudspeaker according to an embodiment of the present invention.

FIG. 9 shows a cross-sectional view of a loudspeaker according to an embodiment of the present invention.

Detailed Description

With reference to FIG. 4, a loudspeaker 31 according to an embodiment of the present invention may comprise a frame 33 (also called a basket) having an aperture 35 (or opening). The frame 33 may be substantially the same as the upper part (i.e. above the magnetic drive system 17, 21) of the frame 3 of the conventional loudspeaker 1 illustrated in FIG. 1. Alternatively, the frame 33 may be different, e.g. a different shape and/or configuration.

A diaphragm 37 may extend across the aperture 35 of the frame 33. The diaphragm 37 is defined as being the primary (main) sound creating element of the loudspeaker 31, which creates the primary (main) sound produced by the loudspeaker 31.

The diaphragm 37 may be connected to the frame 33 by a surround 39 that may be connected (i.e. extends) around an outer perimeter of the diaphragm 37 and that may also be connected (i.e. extends) around a corresponding inner perimeter of the aperture 35. The shape and/or appearance of the surround 39 may be substantially the same as the shape and/or appearance of the surround 7 of the conventional loudspeaker 1 illustrated in FIG. 1. Alternatively, the shape and/or appearance of the surround 39 may be different.

Essentially, in this embodiment the surround 39 provides a flexible border or boundary around the outside of the diaphragm 37, and may act to prevent air from passing around the side of the diaphragm 37 when the diaphragm 37 moves relative to the frame 33. In other embodiments, the surround 39 may connect the frame to one or more positions on the outer perimeter of the diaphragm 37.

The surround 39 may comprise an electro-active polymer. In other words, the surround 39 may comprise a polymer material that exhibits a change of size and/or shape when it is stimulated by an electric field. The surround 39 can be termed a “connecting part” that connects the diaphragm 37 to the frame 33, and that can be used to excite the diaphragm 37 to displace it relative to the frame 33.

The extent of the change in size or shape of the surround 39 when stimulated by an electric field may depend on the magnitude of the applied electric field, i.e. the surround 39 may be deformed to a greater extent by a larger magnitude electric field. Because changes in size and/or shape of the surround act to move the diaphragm 37, the amount by which the diaphragm 37 is displaced relative to the frame 33 may also depend on the magnitude of the applied electric field.

As shown in more detail in FIG. 6, the surround 39 may comprise a layer of electro-active polymer 41 (i.e. a sheet or film of electro-active polymer material) sandwiched (i.e. placed, located, positioned) between first 43 and second 45 compliant (i.e. flexible and/or elastic) electrodes on opposite sides of the layer of electro-active polymer 41, to form an electro-active polymer transducer/actuator. In particular the first compliant electrode 43 may be positioned on an upper side of the layer of electro-active polymer 41, i.e. a side facing out of the loudspeaker 31. The second compliant electrode 45 may be positioned on an opposite, lower side of the layer of electro-active polymer 41, i.e. a side facing into the loudspeaker 31.

As illustrated in FIG. 6, each of the compliant electrodes 43, 45 may be connectable to an electrical circuit (not shown) via terminals 47, for applying an electrical signal to the compliant electrodes 43, 45, to thereby generate an electric field across the layer or electro-active polymer 41. In this embodiment, the compliant electrodes 43, 45 may be made of graphite.

The magnitude of the applied electric field, and therefore the extent of the change in size and/or shape of the electro-active polymer may be determined by the voltage applied to the compliant electrodes 43, 45. Therefore, the displacement of the diaphragm 37 relative to the frame 33 may be increased by increasing the voltage applied to the compliant electrodes 43, 45. Reversing the polarity of the applied voltage may cause the electro-active material to change size and/or shape in an opposite sense (i.e. to become smaller rather than larger), and may therefore cause the direction in which the diaphragm is displaced relative to the frame to be reversed.

As discussed in more detail below, the surround 39 may be usable to excite the diaphragm 37 to displace it linearly (i.e. in a straight line) relative to the frame 33. In particular the surround 39 may be usable to displace the diaphragm 37 relative to the frame 33 in a direction parallel to a central axis of the loudspeaker (e.g. a vertical in FIG. 4). In particular, the surround 39 may be disposed so that any forces applied to the diaphragm 37 that would act to move it in a direction other than along the linear direction balance out, or cancel out, around the diaphragm 37, so that the resulting force on the diaphragm 37 acts solely along the linear direction. This may be achieved e.g. by the surround 39 being uniformly disposed, for example symmetrically disposed, around the diaphragm 37.

In this embodiment, the diaphragm 37 may have a substantially conical-shaped (i.e. substantially cone-shaped) geometry, which extends from an outer perimeter of the diaphragm 37 to a protruding part 49 that protrudes from a central region of the diaphragm 37. Thus, the diaphragm 37 may comprise a thin sheet/layer part and a protruding part 49. The protruding part 49 may be similar in structure and form to the voice coil former 17 of the conventional loudspeaker 1 illustrated in FIG. 1. In particular, the protruding part 49 may comprise a thin and light-weight sheet of material (e.g. paper, or very thin aluminium) formed into a hollow cylindrical tube, and the rest of the diaphragm (i.e. the thin sheet/layer part of the diaphragm) may cover the top of the protruding part 49 and may be secured to the top of the protruding part 49, e.g. by glue. However, in other embodiments of the invention other types of protruding part 49 may be used, for example other shapes of tube, or solid rods of material.

The reason for including a protruding part 49 in the present embodiment is to increase the distance (i.e. along the central axis of the loudspeaker) between the spider 51 (discussed in more detail below) and the surround 37 around the outer perimeter of the diaphragm 37. Increasing this distance may increase the ability of the spider 51 and the surround 39 to constrain the diaphragm 37 to only move along a linear direction, i.e. along a central axis of the loudspeaker (as discussed in more detail below). In some other embodiments, the depth of the diaphragm 37 may be sufficient that it can be suitably constrained by connecting the spider 51 directly to the sheet part of the diaphragm 37, without requiring a protruding part 49 to increase the distance (i.e. spacing) between the spider 51 and the surround 39. Thus, in other embodiments of the present invention the protruding part 49 may be omitted.

As discussed above, a cone-shaped geometry of the diaphragm 37 may significantly increase the stiffness of the diaphragm 37, relative to the inherent stiffness of the material making up the diaphragm 37. Increasing the stiffness can provide an increased efficiency of the loudspeaker 31. As discussed in more detail below, the present embodiment may provide an efficient way of exciting a cone-shaped diaphragm that retains the efficiency advantages of the cone-shaped diagram (caused by the increased stiffness) and that results in a significantly thinner and flatter loudspeaker than the convention moving-coil type loudspeaker illustrated in FIG. 1 that includes the magnetic circuit drive system.

At least a part of the diaphragm 37 is not made of an electro-active polymer. Indeed, the whole diaphragm may not include any electro-active polymer material. The diaphragm 37 may be substantially the same as the diaphragm 7 of the conventional loudspeaker 1 illustrated in FIG. 1. Alternatively, the diaphragm 37 may be different, e.g. a different shape, size and/or made of a different material.

The diaphragm 37 is preferably made from a material that is light-weight and rigid. Where the geometry of the diaphragm 37 increases the rigidity of the diaphragm 37, for example with a cone shaped diaphragm 37 as in the present embodiment, paper material may be a suitable material for forming the diaphragm 37. Paper is light weight and can be manufactured to have increased rigidity, for example by pressing the paper or by adding some chemicals to the paper. Alternatively, some polypropylene materials may be suitable for forming the diaphragm 37, and have been used for this purpose in the industry. Very thin sheets of magnesium or aluminium may also be suitable materials for forming the diaphragm 37.

A spider 51, which is a flexible suspension, may connect the frame 33 to a central part of the diaphragm 37, for example the protruding part 49 of the diaphragm 37. The spider 51 may connect the frame 33 to one or more position on the central part of the diaphragm 37. Indeed, the spider 51 may extend continuously around a central part of the diaphragm 37, e.g. as a continuous band or ring. For example, as with the spider 23 of the conventional loudspeaker 1 illustrated in FIG. 1, the spider 51 may extend around substantially the whole of an outer perimeter of the protruding part 49, and around substantially the whole of an inner perimeter of the frame 33. As shown in FIG. 4, the spider 51 may have a wavy and/or corrugated appearance (or configuration).

However, as discussed above, in other embodiments of the present invention the protruding part 49 may be omitted. In these cases, the spider 51 may connect the frame 33 to a central part of the sheet part of the diaphragm 37 (i.e. to the underside of a lower part of the sheet part of the diaphragm 37).

The spider 51 may comprise an electro-active polymer. In other words, the spider 51 may comprise a polymer material that exhibits a change of size and/or shape when it is stimulated by an electric field. The spider 51 can be termed a “connecting part” that connects the diaphragm 37 to the frame 33, and that can be used to excite the diaphragm 37 to displace it relative to the frame 33.

As shown in more detail in FIG. 6, the spider 51 may comprise a layer of electro-active polymer 53 (i.e. a sheet or film of electro-active polymer material) sandwiched (i.e. placed, located, positioned) between first 55 and second 57 compliant electrodes on opposite sides of the layer of electro-active polymer 53, to form an electro-active polymer transducer/actuator. In particular the first compliant electrode 55 may be positioned on an upper side of the layer of electro-active polymer 53, i.e. a side facing out of the loudspeaker 31. The second compliant electrode 57 may be positioned on an opposite, lower side of the layer of electro-active polymer 53, i.e. a side facing into the loudspeaker 31.

As illustrated in FIG. 6, each of the compliant electrodes 55, 57 may be connectable to an electrical circuit (not shown) via terminals 47, for applying an electrical signal to the compliant electrodes 55, 57, to thereby generate an electric field across the layer or electro-active polymer 53. In this embodiment, the compliant electrodes 55, 57 may be made of graphite.

The magnitude of the applied electric field, and therefore the extent of the change in size and/or shape of the electro-active polymer may be determined by the voltage applied to the compliant electrodes 55, 57. Therefore, the displacement of the diaphragm 37 relative to the frame 33 may be increased by increasing the voltage applied to the compliant electrodes 55, 57. Reversing the polarity of the applied voltage may cause the electro-active material to change size and/or shape in an opposite sense (i.e. to become smaller rather than larger), and may therefore cause the direction in which the diaphragm 37 is displaced relative to the frame 33 to be reversed.

As discussed in more detail below, the spider 51 may be usable to excite the diaphragm 37 to displace it linearly relative to the frame 33. In particular the spider 51 may be usable to displace the diaphragm 37 relative to the frame 33 in a direction parallel to a central axis of the loudspeaker (e.g. a vertical in FIG. 4). In particular, the spider 51 may be disposed so that any forces applied to the diaphragm 37 that would act to move it in a direction other than along the linear direction balance out, or cancel out, around the diaphragm 37, so that the resulting force on the diaphragm 37 acts solely along the linear direction. This may be achieved e.g. by the spider 39 being uniformly disposed, for example symmetrically disposed, around the diaphragm 37.

As illustrated in FIG. 4, the loudspeaker 31 of this embodiment of the present invention does not have a magnetic circuit drive system for exciting the diaphragm 37. In particular, the loudspeaker 31 does not have a voice coil (17 in FIGS. 1 and 3). Furthermore, the loudspeaker 31 does not have a permanent magnet (21 in FIG. 1). The removal of the magnetic circuit (i.e. the voice coil and the permanent magnet) significantly reduces the thickness of the loudspeaker 31. For example, comparing the loudspeaker 31 according to the present embodiment illustrated in FIG. 4 and the conventional loudspeaker 1 illustrated in FIGS. 1 and 3, illustrates that the length/size of the protruding part 49 is significantly reduced in the loudspeaker 31 according to the present invention.

Therefore, the loudspeaker 31 according to this embodiment may provide an advantage of having a significantly thinner and or/flatter shape and/or configuration when compared to e.g. the conventional loudspeaker illustrated in FIG. 1.

As discussed in more detail above, the fact that the magnetic circuit (particularly the permanent magnet and the voice coil) may be omitted in the loudspeaker 31 according to the present invention also has an advantage of simplifying the required tolerances in the design of the loudspeaker 31. This is because it is not necessary to precisely control a small air-gap between a voice coil and a permanent magnet as in the conventional loudspeaker 1 illustrated in FIG. 1. With the loudspeaker 31 according to the present invention, these required tolerances are significantly simplified or removed altogether, which provides an advantage of simplifying the design and manufacture of the loudspeaker 31.

In use, displacement (or deflection) of the diaphragm 37 relative to the frame 33, in order to generate sound, may be achieved by applying electrical signals to the compliant electrodes 43, 45, 55, 57 of the surround 39 and the spider 51. The extent of the displacement of the diaphragm 37 may be dependent on the voltage of the electrical signals applied to the compliant electrodes 43, 45, 44, 57.

The following description assumes that both the surround 39 and spider 51 comprise an electro-active polymer and are used to excite the diaphragm 37 to displace it relative to the frame. However, the present invention also covers arrangements where only the surround 39 or the spider 51 comprises an electro-active polymer, in addition to an arrangement in which neither the spider 51 nor the surround 39 comprise an electro-active polymer and instead additional connecting parts comprising an electro-active polymer are provided.

As discussed above, other examples are also possible, for example only a part of the spider 51 and/or the surround 39 comprise an electro-active polymer.

With reference to FIGS. 5 and 6, to displace the diaphragm 37 in a first direction relative to the frame (i.e. upwards in FIGS. 5 and 6) a positive voltage is applied to the first electrodes 43, 55 of the surround 39 and the spider 51. A corresponding negative voltage is applied to the second electrodes 45, 57 of the surround 39 and the spider 51 (these polarities are intended only as examples and in other embodiments this displacement may be achieved with opposite polarities).

These applied voltages cause electric fields to be generated across the respective layers of electro-active material 41, 53 of the surround 39 and spider 53. These electric fields stimulate the respective layers of electro-active polymer 41, 53 to change size and or shape, for example to bend or deform. Because the diaphragm 37 is connected to the frame 33 through the surround 39 and spider 51, changes in the size and/or shape of the surround 39 and spider 51 will cause the diaphragm 37 to be displaced relative to the frame 33.

The surround 43 and spider 51 are configured so that applying a voltage with a first polarity (e.g. as illustrated in FIG. 5) means that the corresponding size and/or shape changes of the surround 39 and spider 51 displace the diaphragm 37 in a first linear direction along a symmetry axis of the loudspeaker 31. For example, as illustrated in FIGS. 4 and 5, applying a positive voltage to the first electrodes 43, 55 of the surround 39 and the spider 51 and a corresponding negative voltage to the second electrodes 45, 57 of the surround 39 and the spider 51 causes the surround 39 and spider 51 to deform so as to displace the diaphragm upwards relative to the frame. This upward displacement may be achieved by e.g. the surround 39 and spider 51 being deformed by bending or deflecting, or by a change in length of the surround 39 and spider 51 (i.e. the distance along the surround 39 or spider 51 from the frame 33 to the diaphragm 37).

As discussed above, there are a number of ways in which bending of the whole or part of the surround 39 or spider 51 can be achieved, in order to displace the diaphragm 37 relative to the frame 33.

The spider 51 and /or the surround 39 may comprise a plurality of layers of electro-active polymer. In other words, the spider 51 and /or the surround 39 may be formed from a number of stacked (i.e. arranged one on top of the other, possibly with intermediate layers such as electrodes) layers of electro-active polymer. Forming the spider 51 and /or the surround 39 out of multiple layers of electro-active polymer may mean that the layers can be arranged in such a way that when they are excited by an electrical signal, the mechanical forces that they generate cause them to move or to deform in a particular way, for example to bend or to twist. Therefore, the spider 51 and /or the surround 39 can be caused to bend in a particular direction in response to an applied electrical signal or a particular polarity.

For example, a multi-layer electro-active polymer spider 51 and /or surround 39 may be formed from a plurality of layers of thickness-mode electro-active polymer (e.g. a plurality of layers of thickness-mode dielectric elastomer(s)). Thickness-mode electro-active polymers are configured to change their thickness when subjected to an applied electric field. Through a suitable layering of thickness-mode electro-active polymers the multi-layer electro-active polymer spider 51 and /or surround 39 can be made to bend, for example in either of two directions, by applying electrical signals of appropriate voltage and polarity

In other embodiments, the spider 51 and /or the surround 39 may instead comprise a single layer of electro-active polymer. In this case, the spider 51 and /or the surround 39 can be configured or arranged so that the electro-active polymer deforms in a particular way, e.g. by bending or twisting, when an electric field is applied to the electro-active polymer layer.

This single layer of electro-active polymer may be a bending-mode electro-active polymer, for example a bending mode dielectric elastomer. Thus, the spider 51 and /or the surround 39 may have the ability to bend in either of two directions depending on the polarity of the voltage that is applied to them. As an example, the chemical configuration of the electro-active polymer layer may be designed in such a way that a certain polarity of applied electrical signal causes movement of charge inside the material from one electrode (i.e. on one surface) to another electrode (i.e. on an opposite surface), and this movement of charges within the material may cause the material, and therefore the spider 51 and /or the surround 39, to bend.

In other embodiments, the spider 51 and /or the surround 39 may include more than one layer of bending-mode electro-active polymer, for example two layers of bending mode electro-active polymer (which may be called a bi-morph design). For example, two layers of electro-active polymer material, for example two layers of dielectric elastomer, may be positioned one on top of the other so that they share one electrode in the middle between them and have one electrode free each. This arrangement of electro-active polymers may mimic the deformation that can be achieved with piezoelectric-actuators, and may allow for bending of the spider 51 and /or the surround 39.

As shown in FIG. 7, applying the opposite voltages to the electrodes, i.e. a negative voltage to the first electrodes 43, 55 of the surround 39 and spider 51 and a positive voltage to the second electrodes 45, 57 of the surround 39 and spider 51 means that the corresponding size and/or shape changes of the surround 43 and spider 51 displace the diaphragm 37 in the opposite linear direction along the symmetry axis of the loudspeaker 31, i.e. downwards relative to the frame 33. Again, this downward displacement may be achieved by e.g. the surround 39 and spider 51 being deformed by bending or deflecting, or by a change in length of the surround 39 and spider 51.

Therefore, by applying voltages with varying polarities (e.g. positive or negative) to the electrodes 43, 45, 55, 57, the diaphragm 37 can controllably be displaced upwards and downwards relative to the frame (i.e. inwards and outwards relative to the loudspeaker 31, along a central axis of symmetry of the loudspeaker 31). Thus, the required linear movement/oscillation of the diaphragm 37 required to generate acoustic energy can be achieved by applying electrical signals to the electrodes 43, 45, 55, 57 of the surround 39 and spider 51.

Linear motion of the diaphragm 37 relative to the frame 33 can be achieved by the surround 37 and/or the spider 51 constraining the diaphragm to only move in the linear direction. For example, the surround 39 and/or spider 51 may be disposed so that the resulting forces that they apply to the diaphragm 37 to displace the diaphragm 37 only act along this linear direction. This may be achieved by the surround 39 and/or spider 51 being disposed around the diaphragm 37 so that forces applied to the diaphragm 37 in any direction other than in this linear direction cancel out, or balance out, around the diaphragm 37, so that the resulting force and subsequent displacement is along the linear direction. For example, the surround 39 and/or spider 51 may be disposed uniformly or symmetrically around the diaphragm 37.

Essentially, the surround 39 and spider 51 are used as electro-active polymer actuators/transducers to controllably displace the diaphragm 37 relative to the frame.

The surround 39 and spider 51 may extend symmetrically around the loudspeaker 31. In particular, the surround 39 may extend symmetrically around the outer perimeter of the diaphragm 37, and/or the spider 51 may extend symmetrically around the central part (e.g. the protruding part 49) of diaphragm 37. Therefore, the changes in shape and/or area of the surround 39 and/or spider 51 may balance out around the symmetry axis of the loudspeaker 33 to only result in linear displacement of the diaphragm 37 along a central symmetry axis of the loudspeaker 31. In this way, the acoustic properties of the loudspeaker 31 may be maintained at a high level.

Therefore, in addition to being used to excite the diaphragm 37 to displace it relative to the frame 33, the surround 39 and/or spider 51 may also retain their original functions of constraining the diaphragm 37 to only move linearly along a central symmetry axis of the loudspeaker 31.

As discussed above, when the magnetic drive system (i.e. the voice coil and the permanent magnet) are replaced, the tolerances with which the diaphragm 37 must be constrained to only move in a linear direction along the central symmetry axis are relaxed/reduced, because it is no longer necessary to precisely maintain a small air gap between the voice coil and the permanent magnet. This reduction in the necessary tolerances means that with the present invention it may not be necessary for the loudspeaker 31 to have a spider 51 (because the surround 39 alone may sufficiently limit any sideways movement of the diaphragm 37), and therefore in other embodiments of the present invention the spider 51 may be omitted, and therefore the protruding part 49 may also be omitted.

In this embodiment, both the surround 39 and spider 51 have been described as comprising electro-active polymer material, and being used to excite the diaphragm. However, it is not essential that both the surround 39 and spider 51 comprise an electro-active polymer, and only one of these parts may comprise an electro-active polymer. For example, the surround 39 may comprise an electro-active polymer and be used to excite the diaphragm 37, while the spider 51 may be a conventional spider that does not comprise an electro-active polymer and is not used to excite the diaphragm. In this case, as discussed above, the spider 51 may even be omitted altogether. Alternatively, the surround 39 may be a conventional surround that does not comprise an electro-active polymer and the spider 51 may comprise an electro-active polymer and be used to excite the diaphragm 37.

In other embodiments, both the spider 51 and the surround 39 may be conventional and not comprise an electro-active polymer. In this case, additional connecting members that comprise an electro-active polymer and which connect the diaphragm 37 to the frame 33 may be present and used to excite the diaphragm 37 to displace it relative to the frame 33. Again, as mentioned above, in this case the spider 51 may even be omitted altogether.

Where the spider 51 and/or the surround 39 comprise an electro-active material, it is not necessary for the whole of the spider 51 and/or the surround 39 to comprise an electro-active material. Instead, the spider 51 and/or the surround 39 may include parts or portions, for example elongate strips, of electro-active material, embedded/merged with surrounding material that is not an electro-active polymer. In this case, the electrodes may only cover the electro-active polymer, or may cover both the electro-active polymer and the surrounding material.

Alternatively, electro-active material may be disposed, e.g. attached or bonded, on to a surface of a conventional surround 39 and/or spider 51.

In this embodiment, the electro-active polymer is a dielectric polymer. Therefore, the electro-active polymer transducer/actuator formed by the layer of dielectric polymer and the two compliant electrodes may effectively form a compliant capacitor, in which changes in the charges stored on the two compliant electrodes cause changes in the extent of compression/compaction of the layer of dielectric material. In other embodiments, other types of electro-active material may be used in place of a dielectric polymer, such as ferroelectric electro-active polymers, electrostrictive graft electro-active polymers, and ionic electro-active polymers.

In particular, in other embodiments the electro-active polymers may be thickness-mode electro-active polymers and/or bending mode electro-active polymers.

In this embodiment, the dielectric polymer is an elastomer polymer, i.e. a polymer that deforms in an elastic manner. Therefore, when the surround 39 and/or spider 51 are deformed to displace the diaphragm 37 away from an equilibrium position, when the electrical signal to the electrodes 43, 45, 55, 57 is stopped the surround 39 and/or spider 51 may automatically return to their initial configurations, due to the elastic recovery of the dielectric polymer. Furthermore, because the dielectric polymer is an elastomer polymer, the changes in shape and/or area of the dielectric polymer may be reversible, and may not cause plastic deformation or damage to the dielectric polymer. Therefore, the dielectric polymer may be deformed many times to displace the diaphragm 37 without the dielectric polymer degrading significantly or being damaged significantly.

In this embodiment, the electrodes of the electro-active polymer actuators/transducers may comprise carbon conductive grease.

With reference to FIG. 8, in a second embodiment of the present invention a loudspeaker 61 comprises a frame 63, which may be substantially flat, having an aperture 65 (or opening). A substantially flat (or planar) diaphragm 67 (i.e. a thin sheet of material forming a partition) may extend across the aperture 65 of the frame 63. The diaphragm 67 may be connected to the frame 63 by a surround 69 that may be connected (i.e. extends) around an outer perimeter of the diaphragm 67 and that may also be connected (i.e. extends) around a corresponding inner perimeter of the aperture 65. The surround 69 effectively provides a flexible border, edge or boundary around the outer perimeter of the diaphragm 67, and may prevent air from passing around the sides of the diaphragm 67 when it moves relative to the frame 63.

The surround 69 may comprise an electro-active polymer. In other words, the surround 69 may comprise a polymer material that exhibits a change of size and/or shape when it is stimulated by an electric field. The surround 69 can be termed a “connecting part” that connects the diaphragm 67 to the frame 63, and that can be used to excite the diaphragm 67 to displace it relative to the frame 63.

In this embodiment, the surround 69 connects an upper edge of the diaphragm 67 to an upper edge of the frame 63.

Similarly to the previously described embodiment, the surround 69 may comprise a layer of electro-active polymer material sandwiched between two compliant electrodes, to form an electro-active polymer actuator/transducer. The overall structure may be substantially the same as that illustrated in e.g. FIGS. 2 and 6 and described above.

Similarly to the previous embodiment, in use the diaphragm 67 can be excited to displace it relative to the frame 63 by applying an electrical signal to the electrodes of the surround 69, to cause the surround 69 to change size and/or shape (e.g. to bend or to change in length), so that it displaced the diaphragm 67 relative to the frame 63.

Other features and/or advantages of this embodiment may be the same or similar to features and/or advantages of the previously described embodiments.

In a third embodiment of the present invention, as illustrated in FIG. 9, the diaphragm 67 may have a second surround 71 on an opposite side of the diaphragm 67 to the first surround 69. The second surround 71 may be essentially the same as the first surround 69, e.g. it may comprise an electro-active polymer and may be used to excite the diaphragm.

Having two such surrounds 69, 71 on opposite sides of the diaphragm 67 may better prevent any sideways (i.e. parallel to the plane of the diaphragm 67) movement of the diaphragm 67 relative to the frame 63. Thus, ‘rocking’ of the diaphragm 67 relative to the frame 63 may be minimised, therefore improving the acoustic properties of the loudspeaker 61 (i.e. the fidelity of the produced sound).

Claims

1. A loudspeaker comprising:

a frame;

a diaphragm, at least a part of which does not comprise an electro-active polymer; and

one or more connecting parts, comprising an electro-active polymer, connecting the diaphragm to the frame;

wherein the one or more connecting parts are operable to excite the diaphragm to displace it relative to the frame.

2. A loudspeaker according to claim 1, wherein the one or more connecting parts are operable to excite the diaphragm by applying an electric field to the one or more connecting parts to change the size or shape of the one or more connecting parts.

3. A loudspeaker according to claim 2, wherein the extent of the change in size or shape of the one or more connecting parts depends on the magnitude of the applied electric field.

4. A loudspeaker according to claim 2 or claim 3, wherein the one or more connecting parts are operable to excite the diaphragm to displace it relative to the frame by an amount that depends on the magnitude of the applied electric field.

5. The loudspeaker according to any one of the previous claims, wherein the one or more connecting parts comprise a layer of electro-active polymer sandwiched between two compliant electrodes.

6. The loudspeaker according to claim 5, wherein the one or more connecting parts are operable to excite the diaphragm to displace it relative to the frame by an amount that depends on a voltage applied to the two compliant electrodes.

7. The loudspeaker according to claim 5 or claim 6, wherein the direction in which the diaphragm is displaced relative to the frame is reversed when the polarity of the voltage applied to the two compliant electrodes is reversed.

8. The loudspeaker according to any one of the previous claims, wherein the one or more connecting parts are usable to excite the diaphragm to displace it linearly relative to the frame.

9. The loudspeaker according to claim 8, wherein the one or more connecting parts are usable to excite the diaphragm to displace it linearly relative to the frame in a direction parallel to a central axis of the loudspeaker.

10. The loudspeaker according to any one of the previous claims, wherein the one or more connecting parts are usable to excite the diaphragm to displace it in either of two opposite directions relative to the frame.

11. The loudspeaker according to any one of the previous claims, wherein the one or move connecting parts are disposed so that they constrain the diaphragm to move in a linear direction relative to the frame

12. The loudspeaker according to any one of the previous claims, wherein the one or more connecting parts are evenly disposed around the diaphragm and constrain the diaphragm to move in a linear direction relative to the frame.

13. The loudspeaker according to any one of the previous claims, wherein the electro-active polymer is a dielectric polymer.

14. The loudspeaker according to any one of the previous claims, wherein the electro-active polymer is an elastomer polymer.

15. The loudspeaker according to any one of the previous claims, wherein the diaphragm has a conical-shaped geometry.

16. The loudspeaker according to any one of the previous claims, wherein the one or more connecting parts comprise a surround of the loudspeaker.

17. The loudspeaker according to any one of the previous claims, wherein the one or more connecting parts connect the frame to one or more positions on an outer perimeter of the diaphragm.

18. The loudspeaker according to any one of the previous clams, wherein a plurality of connecting parts connect the frame to a plurality of positions on an outer perimeter of the diaphragm.

19. The loudspeaker according to any one of the previous claims, wherein the one or more connecting parts form a continuous band around an outer perimeter of the diaphragm.

20. The loudspeaker according to any one of the previous claims, wherein the one or more connecting parts comprise a spider of the loudspeaker.

21. The loudspeaker according to any one of the previous claims, wherein the one or more connecting parts connect the frame to one or more positions on a central part of the diaphragm.

22. The loudspeaker according to any one of the previous claims, wherein a plurality of connecting parts connect the frame to a plurality of positions on a central part of the diaphragm.

23. The loudspeaker according to claim 21, wherein the one or more connecting parts form a continuous band around a central part of the diaphragm.

24. The loudspeaker according to any one of the previous claims, wherein the diaphragm does not comprise an electro-active polymer.

25. The loudspeaker according to any one of the previous claims, wherein the one or more connecting parts comprise a plurality of layers of electro-active polymer.

26. The loudspeaker according to any one of the previous claims, wherein the one or more connecting parts comprise a thickness-mode electro-active polymer.

27. The loudspeaker according to any one of the previous claims, wherein the one or more connecting parts comprise a bending-mode electro-active polymer.

28. A loudspeaker substantially according to any one embodiment herein described with reference to, and as illustrated in, Figures 2A, 2B and 4 to 9.

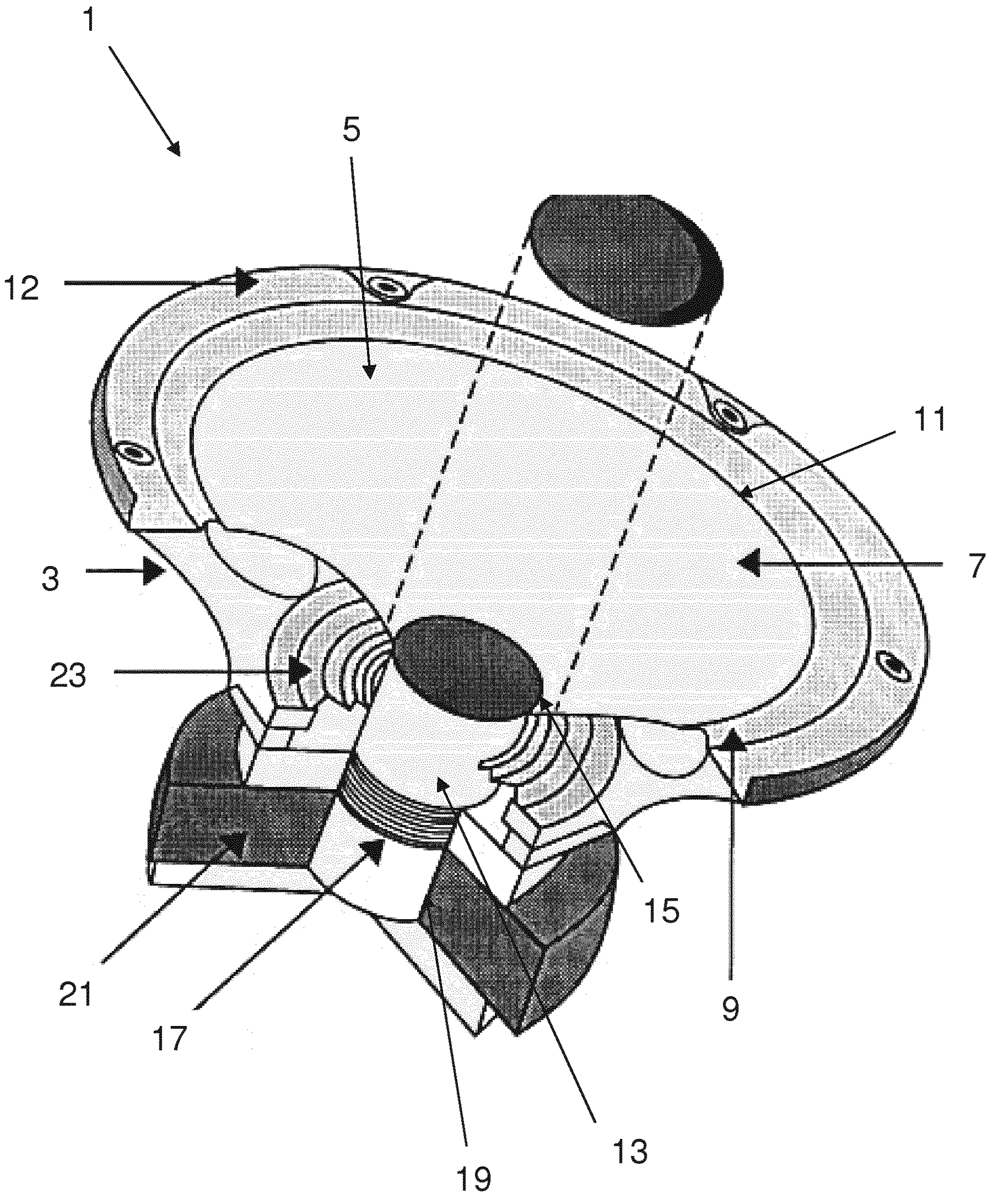

FIG. 1

PRIOR ART

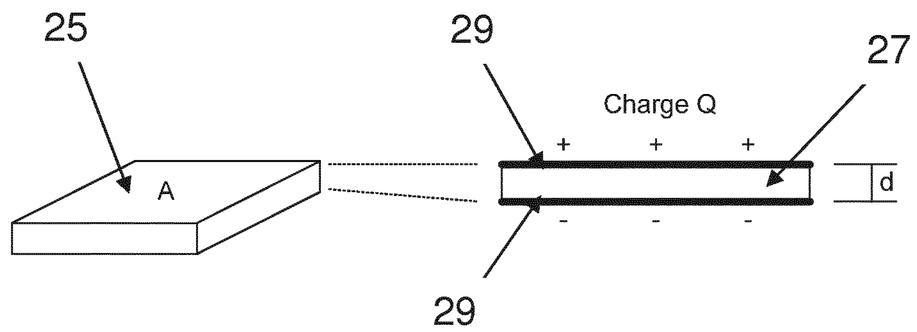

FIG. 2A

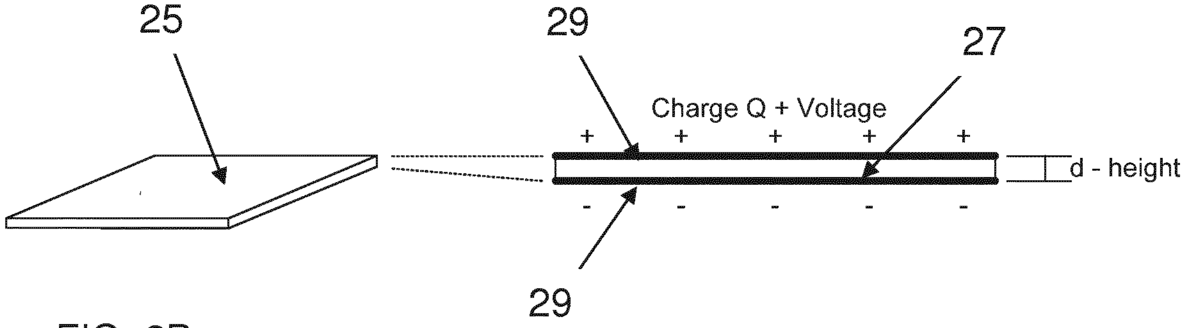

FIG. 2B

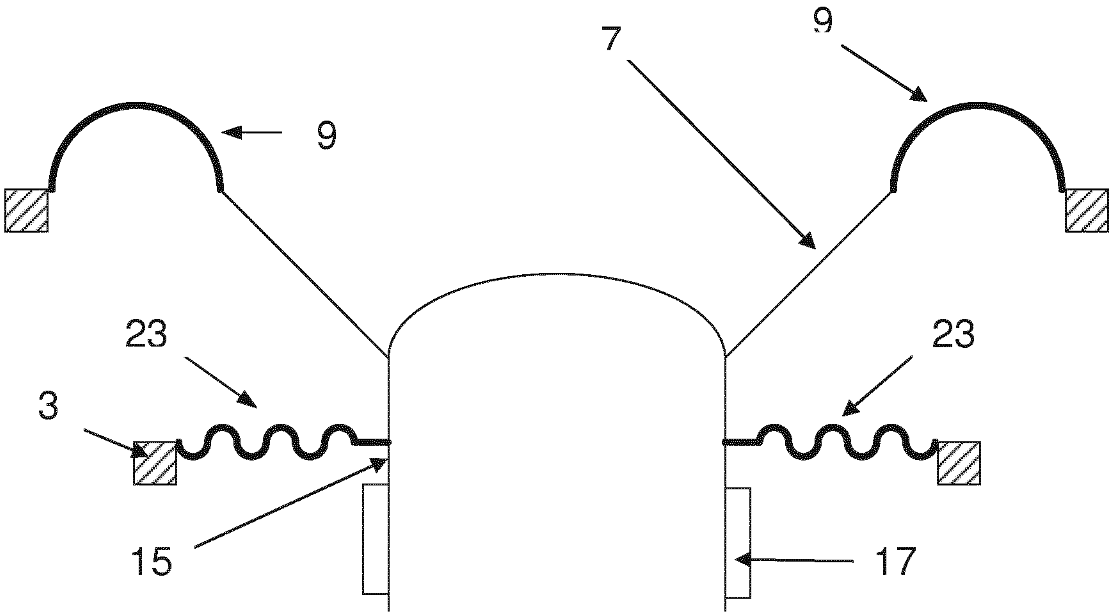

FIG. 3

PRIOR ART

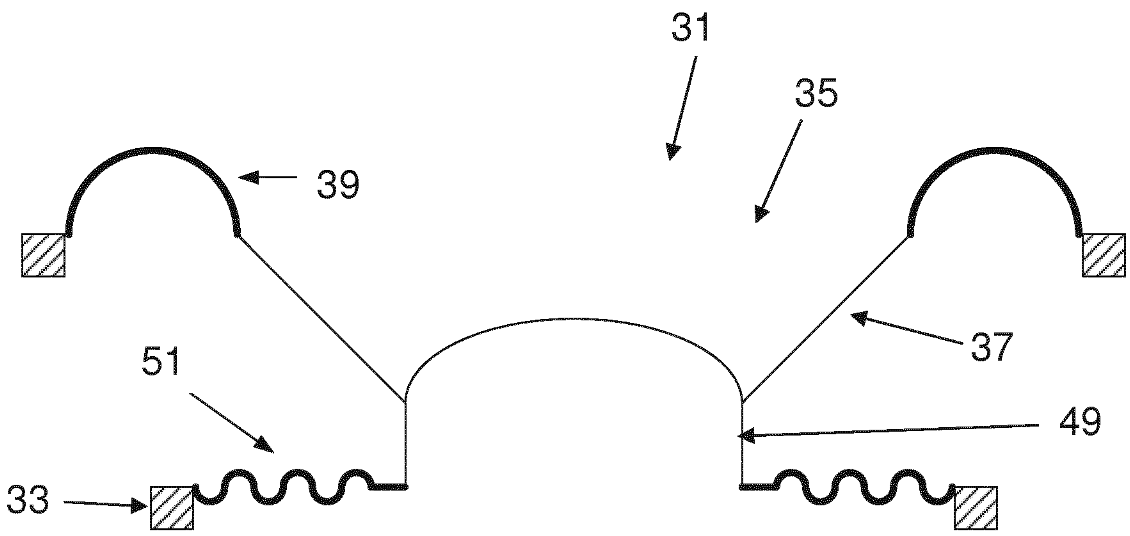

FIG. 4

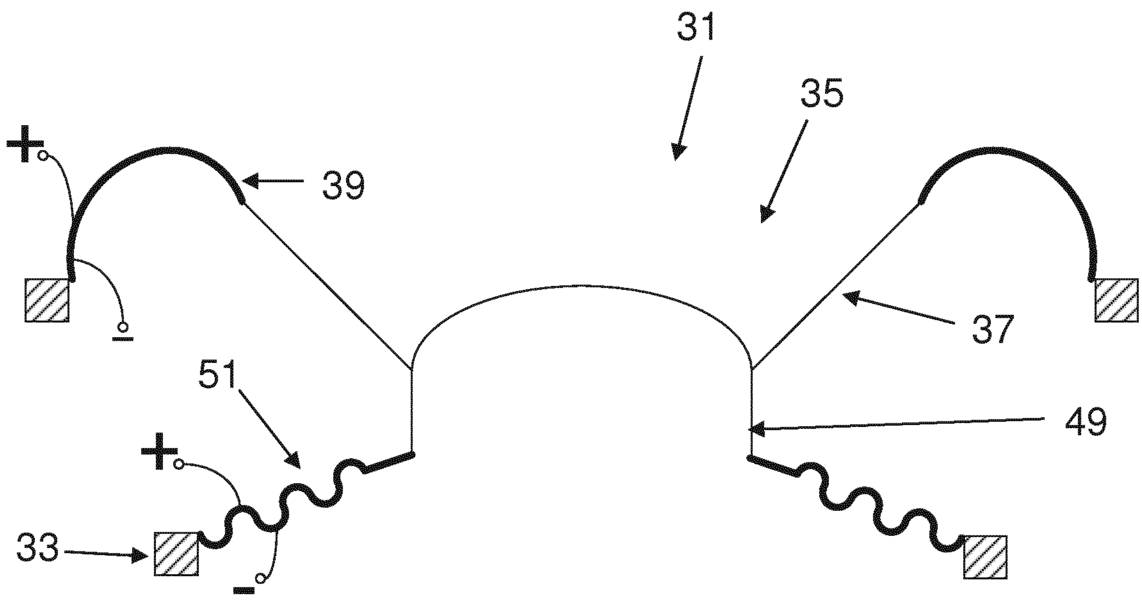

FIG. 5

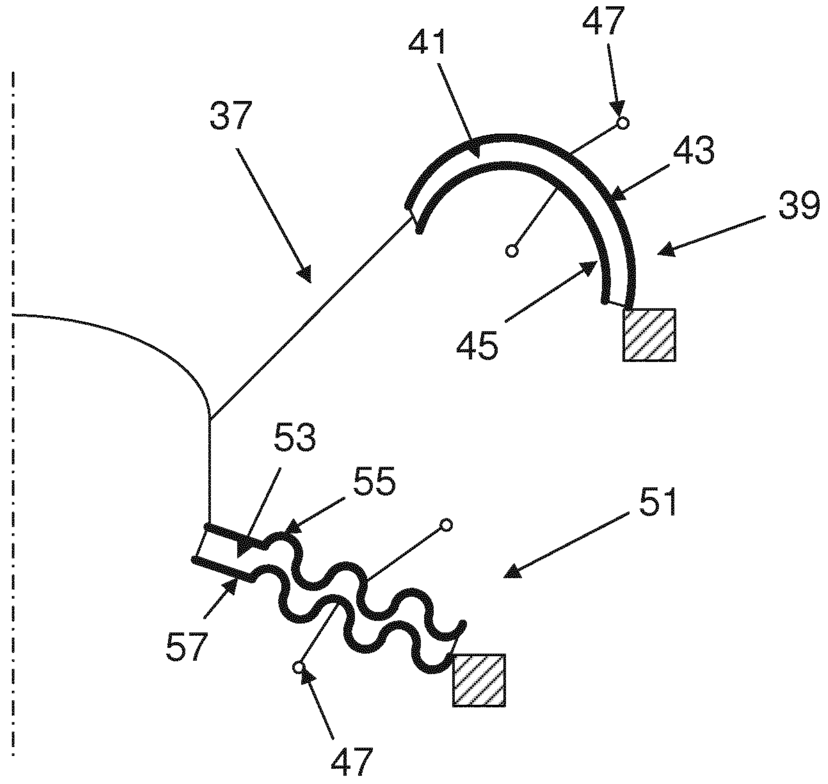

FIG. 6

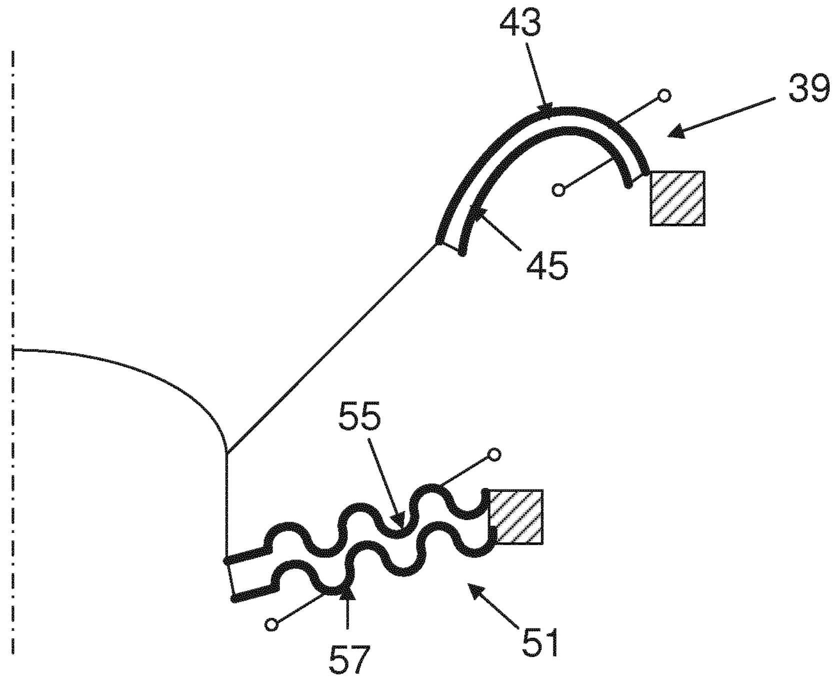

FIG. 7

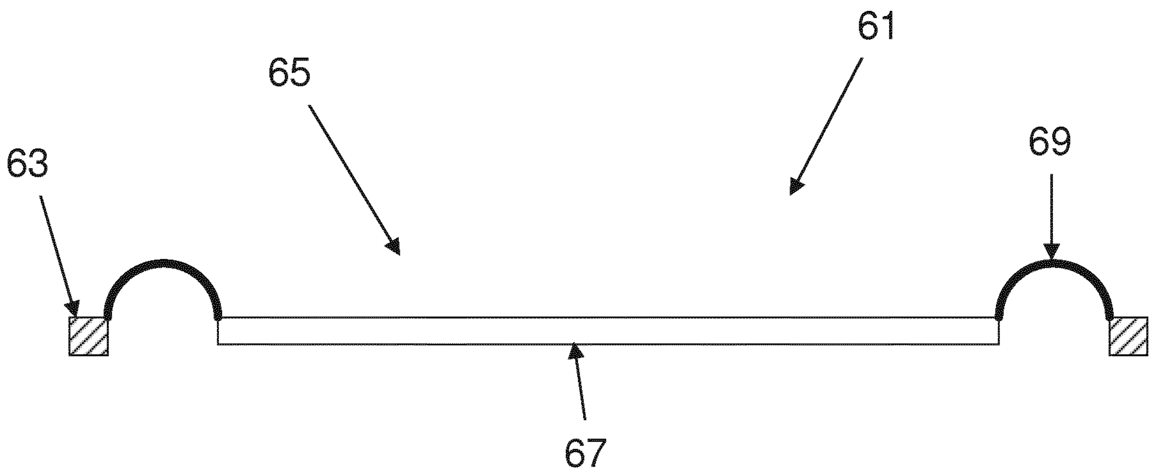

FIG. 8

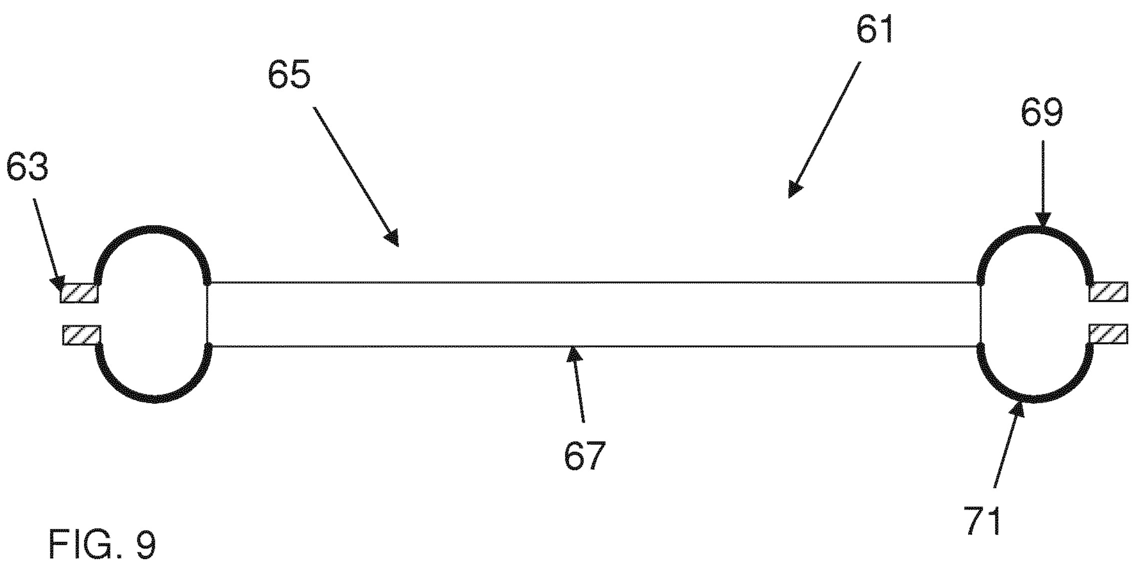

FIG. 9

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2013/075847

A. CLASSIFICATION OF SUBJECT MATTER
INV. H04R7/20 H04R7/16 H04R19/02
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H04R

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

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

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	WO 01/47318 A2 (1 IPR LIMTED [GB]; HOOLEY ANTHONY [GB]; PEARCE DAVID HENRY [GB]; LENEL) 28 June 2001 (2001-06-28) page 11, line 15 - line 23; claim 1; figure 49 page 10, line 32 - page 11, line 16 page 4, line 21 - line 22 page 32, line 8 - line 21 -----	1-9,11, 15,24, 25,27,28 10, 12-14, 16-23,26
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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

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

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

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

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

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
6 May 2014	15/05/2014

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Gastaldi, Giuseppe

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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Y	US 2012/126959 A1 (ZARRABI ALIREZA [US] ET AL) 24 May 2012 (2012-05-24) paragraph [0110]; figure 20A -----	26
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International application No
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