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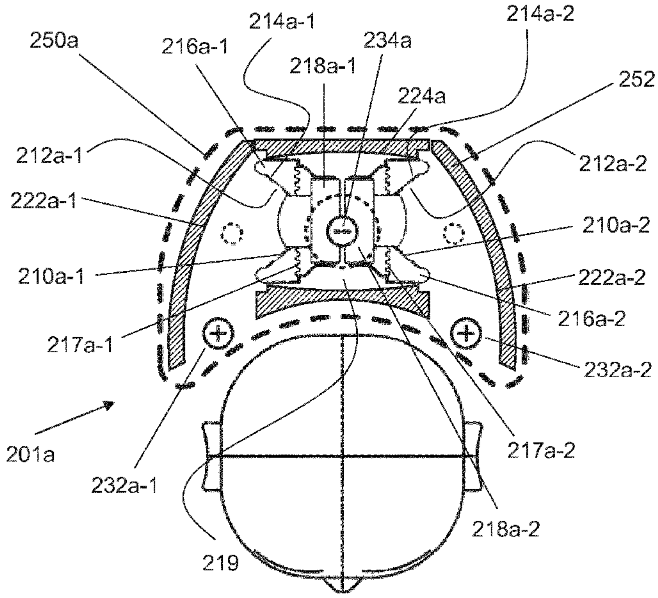

FIG. 3(b)

(57) Abstract: A loudspeaker unit for producing sound at bass frequencies. The loudspeaker unit includes: a diaphragm having a first radiating surface and a second radiating surface, wherein the first radiating and second radiating surfaces are located on opposite faces of the diaphragm, and wherein the loudspeaker unit is configured to allow sound produced by the first and second radiating surfaces to propagate out from the loudspeaker unit; a drive unit configured to move the diaphragm based on an electrical signal; a frame from which the diaphragm is suspended via one or more suspension elements; drive circuitry configured to provide the drive unit with an electrical signal derived from an audio source; a sound guide configured to guide sound produced by the first or second radiating surface to at least one outlet such that the sound propagates out of the loudspeaker unit from the at least one outlet, the/each outlet being remote from said first or second radiating surface. The loudspeaker unit is preferably configured so that, at the locations at which sound

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propagates out from the loudspeaker, and preferably in the operational bandwidth of the loudspeaker unit, the sound produced by the/each first radiating surface is substantially out of phase with the sound produced by the/each second radiating surface.

LOUDSPEAKER UNIT

This application claims priority from GB1805523.6 filed 4 April 2018, from GB1811828.1 filed 19 July 2018, and from PCT/EP2019/056109 filed 12 March 2019, the contents and elements of which are herein incorporated by reference for all purposes.

Field of the Invention

The present invention relates to a loudspeaker unit, a seat assembly that includes the loudspeaker unit, and a vehicle having a plurality of the seat assemblies.

Background

Among the frequencies in the audible spectrum, lower frequencies are the ones that tend to carry most well over larger distances and are the ones difficult to keep inside a room. For example, nuisance from neighboring loud music has mostly a low frequency spectrum. “Low” frequencies can also be referred to as “bass” frequencies and these terms may be used interchangeably throughout this document.

Many cars today are equipped with a main audio system, which typically consists of a central user interface console with internal or external audio amplifiers, and one or more loudspeakers placed in the doors. This type of audio system is used to ensure enough loudness of the same content (e.g. radio or cd-playback) for all passengers.

Some cars include personal entertainment systems (music, games & television) which are typically equipped with headphones to ensure individual passengers receive personalized sound, without disturbing (or being disturbed by) other passengers who are enjoining a different audio-visual content.

Some cars include loudspeakers placed very close to an individual passenger, so that sound having an adequately high sound pressure level (“SPL”) can be obtained at the ears of that individual passenger, whilst having a much lower SPL at the positions of other passengers.

The present inventor has observed that the concept of a personal sound cocoon is a useful way to understand the approach of having a loudspeaker placed close to a user, wherein the personal sound cocoon is a region in which a user is able to experience sound having an SPL deemed to be acceptably high for their enjoyment, whereas outside the personal sound cocoon the sound is deemed to have an SPL which is lower than it is within the personal sound cocoon.

The present inventor has also observed that creating a personal sound cocoon that can be enjoyed by the user with little sound leakage into his/her surroundings is a big challenge that if overcome could bring a huge change in how users experience our individual multimedia content in all kinds of settings/surroundings such as (but not limited) to automotive, home, gaming, and aviation settings.

The present inventor has also observed that creating an effective personal sound cocoon may involve sound reduction or cancellation of sound outside of the cocoon.

A main audio system as used in most cars today (with one or more loudspeakers placed in the doors) is unable to provide an effective personal sound cocoon for each individual passenger.

Although the usage of headphones ensures a good sound quality and a very effective personal sound cocoon (little sound leakage), the use of headphones has safety, ergonomic and comfort problems. Similar considerations apply for standalone applications in other environments such as home, studio, public areas where individual entertainment is needed without disturbing neighbors.

The use of highly directive loudspeakers positioned close to an individual passenger / user brings an effective solution for medium and high frequencies. However, it is generally impractical in most situations to make a loudspeaker directive at bass frequencies, since in order to provide a highly directive loudspeaker for bass frequencies, the dimensions of the radiating surface must be of the same order as the wavelength, and wavelengths are typically very long for bass frequency content (e.g. λ = 3.4m for f = 100Hz). Loudspeakers with radiating surfaces of this scale for producing bass frequency content are impractical in many situations, such as in a car. Nonetheless, bass frequency content is a very important part of the audio spectrum and in most music this spectrum represents half or more of the total sound power.

As shown by the well-known equal-loudness contours [1] e.g. as standardized as ISO 226:2003, our ears have a low sensitivity to bass frequencies under 150Hz. Therefore, in general, sound at bass frequencies needs to be boosted in order to balance the spectral loudness. Also, road noise or environmental noise will have a bigger masking effect on this part of the spectrum. However, the present inventor has found that the use of traditional monopole loudspeakers (typically a cone monopole loudspeaker) for the purpose of creating a personal sound cocoon for an individual user at bass frequency sound will in general not produce satisfactory results, since a relatively high SPL at bass frequencies is needed in order to create a personal sound cocoon to overcome the limited sensitivity of our ears in this region of the frequency spectrum, yet a traditional monopole loudspeaker will have a spherical radiation pattern at bass frequencies (same sound pressure in all directions), with its sound pressure dropping only with 6dB for every double distance from the loudspeaker under free field conditions. Further, a car environment behaves not as a free field, making the use of monopole loudspeakers for bass frequency cocooning even more cumbersome: a small room will show a pressure chamber effect whereby it will boost the bass frequency energy provided by a monopole (overall pressure increases in the chamber of 12dB/octave below 70Hz for a typical car).

The present inventor is aware of several patent documents which describe using a variety of loudspeaker arrangements for the purpose of producing personal sound in vehicles:

EP0988771A1
EP1460879A1
US8130987B2
US7688992B2
US9327628B2
US9440566B2
US9428090B2

The present inventor is also aware of other loudspeaker arrangements for producing personal sound in other contexts:

WO2014143927A2
US7692363B2

Dipole loudspeakers and their directional characteristics are well described in the literature and some of the patent documents referenced above use dipole loudspeakers, mostly for the purpose of using the directional characteristics of a dipole loudspeaker to generate spatial effects in the mid and high frequency region, or to use a dipole loudspeaker for low frequency reproduction at large distances, e.g. normal stereo setup, see e.g. [2] for useful background information on this.

In PCT/EP2018/084636, GB1721127.7 and GB1805525.1, filed by the present applicant, there was proposed a dipole loudspeaker for producing sound at bass frequencies, the dipole loudspeaker including: a diaphragm having a first radiating surface and a second radiating surface, wherein the first radiating surface and the second radiating surface are located on opposite faces of the diaphragm, and wherein the first and second radiating surfaces each have a surface area of at least 100 cm^2; a drive unit configured to move the diaphragm at bass frequencies such that the first and second radiating surfaces produce sound at bass frequencies, wherein the sound produced by the first radiating surface is in antiphase with sound produced by the second radiating surface; a frame, wherein the diaphragm is suspended from the frame via one or more suspension elements, wherein the frame is configured to allow sound produced by the first radiating surface to propagate out from a first side of the dipole loudspeaker and to allow sound produced by the second radiating surface to propagate out from a second side of the dipole loudspeaker; wherein preferably the loudspeaker is for use with an ear of a user being located at a listening position that is in front of the first radiating surface and is 40cm or less from the first radiating surface. PCT/EP2018/084636, GB1721127.7 and GB1805525.1 also disclosed a dipole loudspeaker having multiple diaphragms having a combined surface area of 100 cm^2.

The inventions described in PCT/EP2018/084636, GB1721127.7 and GB1805525.1, devised by the present inventor, were based on an insight that for a suitably large diaphragm (or array of diaphragms), from a listening position that is close to (e.g. 40cm or less from) the first radiating surface(s) of such a loudspeaker, a user can experience bass sound (typically up to 100Hz) that is highly localized, in the sense that the sound pressure level (SPL) experienced by a user will quickly decrease with increasing distance from the loudspeaker due to, it is believed, interference between sound produced by the first radiating surface(s) and the second radiating surface(s).

The inventions described in PCT/EP2019/056109 and GB1805523.6, also devised by the present inventor, provide various “multipole” arrangements for providing even more effectively localization of bass sounds, through having at least two in-phase poles and at least two out-of-phase poles arranged e.g. in quadrupole or octopole arrangements.

The present inventor has observed that it may be a design challenge to implement loudspeaker units such as those described in PCT/EP2018/084636, GB1721127.7, GB 1805525.1, and also those described in PCT/EP2019/056109 and GB1805523.6, in certain environments, such as in a car, and that it would be desirable to provide a loudspeaker unit that is able to provide effective localization of bass sounds yet be incorporated into an apparatus in a manner that provides the designer of that apparatus with more flexibility.

The present invention has been devised in light of the above considerations.

Summary of the Invention

In a first aspect (which may be referred to herein as a “dipole type” aspect of the present invention), the present invention may provide:

A loudspeaker unit for producing sound at bass frequencies, including:

a diaphragm having a first radiating surface and a second radiating surface, wherein the first radiating and second radiating surfaces are located on opposite faces of the diaphragm, and wherein the loudspeaker unit is configured to allow sound produced by the first and second radiating surfaces to propagate out from the loudspeaker unit;

a drive unit configured to move the diaphragm based on an electrical signal;

a frame from which the diaphragm is suspended via one or more suspension elements;

drive circuitry configured to provide the drive unit with an electrical signal derived from an audio source;

a sound guide configured to guide sound produced by the first or second radiating surface to at least one outlet such that the sound propagates out of the loudspeaker unit from the at least one outlet, the/each outlet being remote from said first or second radiating surface.

In this way a person seeking to implement the loudspeaker unit is able to provide an effective personal sound cocoon whilst having much greater freedom in locating the diaphragm of the loudspeaker unit, since the radiating surfaces of the diaphragm do not need to be located at the locations at which sound propagates out from the loudspeaker unit.

A skilled person will appreciate from the disclosure herein that a loudspeaker unit according to the first aspect of the invention may be able to provide an effective personal sound cocoon by configuring the loudspeaker unit so that, at the locations (or "poles") at which sound propagates out from the loudspeaker unit (as guided by a sound guide or not as the case may be), and preferably in the operational bandwidth of the loudspeaker unit, the sound produced by the(/each) first radiating surface is substantially out of phase with the sound produced by the(/each) second radiating surface.

Configuring the loudspeaker unit to meet the substantially out-of-phase criterion as described above may help to differentiate the loudspeaker unit according to the first aspect of the invention from a classic bandpass subwoofer, since the poles of a classic bandpass subwoofer are designed to be substantially in phase in its operational bandwidth rather than substantially out of phase in its operational bandwidth.

A skilled person would appreciate in view of the present disclosure that configuring the loudspeaker unit to meet the substantially out-of-phase criterion as described above may be achieved in various ways, and would be well within the abilities of a skilled person in view of the disclosure herein. For example, configuring the loudspeaker unit in this way could be achieved by appropriately modeling the loudspeaker unit (including the/each sound guide), and then configuring the/each sound/guide to ensure that the substantially out-of-phase criterion is met. Alternatively, configuring the loudspeaker unit in this way could be achieved by using functionally equivalent (e.g. identical) sound guides with each radiating surface of the/each diaphragm (thereby potentially avoiding the need to model). Various considerations associated with meeting the substantially out-of-phase criterion as described above and modelling a loudspeaker unit to assess whether poles are substantially out-of-phase are discussed below with reference to experimental data 3.

Reasons why an effective personal sound cocoon can be created by substantially out-of-phase poles are explained e.g. in PCT/EP2018/084636, GB1721127.7 and GB1805525.1.

In the context of this disclosure, the term "remote" in connection with a first element relative to a second element may be understood as requiring that the first element is remotely located with respect to, i.e. separated from, the second element.

The loudspeaker unit may include multiple sound guides. For example, the loudspeaker unit may include:

a sound guide configured to guide sound produced by the first radiating surface to at least one outlet such that the sound propagates out of the loudspeaker unit from the at least one outlet, the/each outlet being remote from the first radiating surface;

a further sound guide configured to guide sound produced by the second radiating surface to at least one further outlet such that the sound propagates out of the loudspeaker unit from the at least one further outlet, the/each further outlet being remote from the second radiating surface.

The loudspeaker unit may include:

a plurality of diaphragms, each diaphragm having a first radiating surface and a second radiating surface, wherein the first radiating and second radiating surfaces of each diaphragm are located on opposite faces of the diaphragm, wherein each diaphragm is suspended from the frame via one or more suspension elements;

a plurality of drive units, wherein each drive unit is configured to move a respective diaphragm based on a respective electrical signal;

drive circuitry is configured to provide each drive unit with a respective electrical signal derived from the same audio source, preferably such that the electrical signals provided to the drive units are configured to move the first radiating surfaces of the diaphragm substantially in phase with each other.

If the loudspeaker includes a plurality of diaphragms, a plurality of drive units, and drive circuitry, the drive circuitry may be configured to apply a predetermined delay to one or more of the electrical signals provided to the drive units. A delay may be used to cause vibrations, e.g. to provide feedback to a user sat in a car seat in which the loudspeaker unit is implemented.

The loudspeaker unit may include a plurality of sound guides configured as described above.

If the loudspeaker unit includes a plurality of diaphragms, the loudspeaker unit may include:

one or more sound guides each respectively configured to guide sound produced by one or more of the first radiating surfaces to at least one outlet such that the sound propagates out of the loudspeaker unit from the at least one outlet, the/each outlet being remote from said one or more first radiating surfaces; and/or

one or more sound guides each respectively configured to guide sound produced by one or more of the second radiating surfaces to at least one outlet such that the sound propagates out of the loudspeaker unit from the at least one outlet, the/each outlet being remote from said one or more second radiating surfaces.

For avoidance of any doubt, one or more radiating surfaces of the loudspeaker unit may produce sound that is radiated directly out from the loudspeaker unit, i.e. without being guided by a sound guide.

If the loudspeaker unit includes a plurality of diaphragms, the loudspeaker unit preferably includes one or more pairs of diaphragms. The two diaphragms in the/each pair of diaphragms are preferably oriented back to back, i.e. with the second radiating surface of one diaphragm of the pair facing the second radiating surface of the other diaphragm of the pair (preferably with the two radiating surfaces radiating into a shared space, which shared space may be partially enclosed), since this helps with force cancellation (see e.g. Fig. 4(a)).

Preferably, the loudspeaker unit includes:

a sound guide configured to guide sound produced by a first radiating surface of a diaphragm in the loudspeaker unit to an outlet such that the sound propagates out of the loudspeaker unit from the outlet, wherein the loudspeaker unit is configured for use with an ear of a user located at a listening position that is 50cm or less (more preferably 40cm or less, more preferably 30cm or less, more preferably 25cm or less, more preferably 20cm or less, more preferably 15cm or less) from the outlet.

More preferably, the loudspeaker unit includes:

a first sound guide configured to guide sound produced by a first radiating surface of a diaphragm in the loudspeaker unit to a first outlet such that the sound propagates out of the loudspeaker unit from the first outlet, wherein the loudspeaker unit is configured for use with a first ear of a user located at a first listening position that is 50cm or less (more preferably 40cm or less, more preferably 30cm or less, more preferably 25cm or less, more preferably 20cm or less, more preferably 15cm or less) from the first outlet;

a second sound guide configured to guide sound produced by a first radiating surface of a diaphragm in the loudspeaker unit to a second outlet such that the sound propagates out of the loudspeaker unit from the second outlet, wherein the loudspeaker unit is configured for use with a second ear of a user located at a second listening position that is 50cm or less (more preferably 40cm or less, more preferably 30cm or less, more preferably 25cm or less, more preferably 20cm or less, more preferably 15cm or less) from the second outlet, whilst the first ear of the user is located at the first listening position.

In this way, sound from a first radiating surface is guided to an outlet that is close to an ear of a user so that a user can clearly hear the sound produced by that first radiating surface, whilst a person who is further away from the outlet than the user will preferably hear sound with a significantly reduced SPL level (compared with an ordinary monopole loudspeaker unit producing the same SPL level at the ear of the user) it is believed due to interference from out of phase sound produced by the/each second radiating surface.

For avoidance of any doubt, the first sound guide and second sound guide may be configured to guide sound from the first radiating surface of the same diaphragm, or from the first radiating surfaces of different diaphragms in the loudspeaker unit.

Also for avoidance of any doubt, in connection with the first aspect of the invention, the term "first radiating surface" is typically allocated to the radiating surface(s) of the diaphragm(s) configured to produce sound which is guided to an ear of a user, but this is just a naming convention and is not intended to infer that the "first radiating surface" must necessarily have a particular set of features that is lacked by the "second radiating surface".

Also for avoidance of any doubt, whilst it is preferable for sound to be guided by a sound guide from a radiating surface to at least one ear of a user, it would also be possible for an ear of a user to be located at a listening position that is in front of and 50cm or less (more preferably 40cm or less, more preferably 30cm or less, more preferably 25cm or less, more preferably 20cm or less, more preferably 15cm or less) from a radiating surface of the loudspeaker unit. That is, it is not a requirement of the invention that one or more sound guides are used to guide sound to an ear of a user (though this is generally preferred, since locating the ears of a user in front of and close to a diaphragm causes certain design limitations).

For completeness, we note that it is generally preferable for substantially in-phase sound to be directed towards the two ears of a user (i.e. sound produced by one or more first radiating surfaces), though in some cases it may be possible for out-of-phase sound to be directed towards the two ears of a user (i.e. with sound produced by a first radiating surface being directed to one ear of a user and with sound produced by a second radiating surface being directed to the other ear of the user), though the present inventor has found that this is only workable at very low frequencies (100Hz or less, more preferably 80 Hz or less) before a user starts to feel fatigue/discomfort, as described in PCT/EP2019/056109 and GB1805523.6.

The terms “user” and “listener” (and “passenger”, if the loudspeaker unit is located in a car) may be used interchangeably in this disclosure.

In a second aspect (which may be referred to herein as a “monopole type” aspect of the present invention), the present invention may provide:

A loudspeaker unit for producing sound at bass frequencies, including:

an array of two or more diaphragms, each diaphragm in the array having a first radiating surface and a second radiating surface, wherein the first radiating surface and the second radiating surface are located on opposite faces of the diaphragm, and wherein one or more of the diaphragms are included in a first subset of the diaphragms and one or more of the diaphragms are included in a second subset of the diaphragms;

a plurality of drive units, wherein each drive unit is configured to move a respective one of the diaphragms in the array based on a respective electrical signal;

a frame, wherein each diaphragm in the array is suspended from the frame via one or more suspension elements;

at least one enclosure configured to receive sound produced by the second radiating surfaces;

drive circuitry configured to provide each drive unit with a respective electrical signal derived from the same audio source such that the electrical signal(s) provided to the one or more drive units configured to move the first subset of diaphragms is/are out of phase with respect to the electrical signal(s) provided to the one or more drive units configured to move the second subset of diaphragms;

a sound guide configured to guide sound produced by the first radiating surface of a diaphragm in the first or second subset to at least one outlet such that the sound propagates out of the loudspeaker unit from the at least one outlet, the/each outlet being remote from said first radiating surface.

In this way a person seeking to implement the loudspeaker unit is able to provide an effective personal sound cocoon whilst having much greater freedom in locating the diaphragms of the loudspeaker unit, since the radiating surfaces of the diaphragms do not need to be located at the locations at which sound propagates out from the loudspeaker unit.

A skilled person will appreciate from the disclosure herein that a loudspeaker unit according to the second aspect of the invention is able to provide an effective personal sound cocoon by configuring the loudspeaker unit so that, at the locations at which sound propagates out from the loudspeaker unit (as guided by a sound guide or not as the case may be), and preferably in the operational bandwidth of the loudspeaker unit, the sound produced by the first radiating surface of the(/each) diaphragm in the first subset is substantially out of phase with the sound produced by the first radiating surface of the(/each) diaphragm in the second subset.

A skilled person would appreciate in view of the present disclosure that configuring the loudspeaker unit to meet the substantially out-of-phase criterion as described above may be achieved in various ways, and would be well within the abilities of a skilled person in view of the disclosure herein. For example, configuring the loudspeaker unit in this way could be achieved by appropriately modeling the loudspeaker unit (including the/each sound guide), and then configuring the/each sound/guide to ensure that the substantially out-of-phase criterion is met. Alternatively, configuring the loudspeaker unit in this way could be achieved by using functionally equivalent (e.g. identical) sound guides with each first radiating surface of the/each diaphragm (thereby potentially avoiding the need to model). Various considerations associated with meeting the substantially out-of-phase criterion and modelling a loudspeaker unit to assess whether poles are substantially out-of-phase are discussed below with reference to experimental data 3 (although the discussion in experimental data 3a relates to a loudspeaker unit according to the first aspect of the invention, the same principles could readily be applied by a skilled person to a loudspeaker unit according to the second aspect of the invention).

Reasons why an effective personal sound cocoon can be created by substantially out-of-phase poles are explained e.g. in PCT/EP2018/084636, GB1721127.7 and GB1805525.1.

The loudspeaker unit may include:

a sound guide configured to guide sound produced by the first radiating surface of a diaphragm in the first subset to at least one outlet such that the sound propagates out of the loudspeaker unit from the at least one outlet, the/each outlet being remote from the first radiating surface of the diaphragm in the first subset;

a further sound guide configured to guide sound produced by the first radiating surface of a diaphragm in the second subset to at least one further outlet such that the sound propagates out of the loudspeaker unit from the at least one further outlet, the/each further outlet being remote from the first radiating surface of the diaphragm in the second subset.

The loudspeaker unit may include a plurality of sound guides configured as described above.

The loudspeaker unit may include:

one or more sound guides each respectively configured to guide sound produced by one or more first radiating surfaces of one or more diaphragms in the first subset to at least one outlet such that the sound propagates out of the loudspeaker unit from the at least one outlet, the/each outlet being remote from said one or more first radiating surfaces of the one or more diaphragms in the first subset; and/or

one or more sound guides each respectively configured to guide sound produced by one or more first radiating surfaces of one or more diaphragms in the second subset to at least one outlet such that the sound propagates out of the loudspeaker unit from the at least one outlet, the/each outlet being remote from said one or more first radiating surfaces of the one or more diaphragms in the second subset.

For avoidance of any doubt, one or more first radiating surfaces of the loudspeaker unit (of diaphragms in the first and/or second subset) may produce sound that is radiated directly out from the loudspeaker unit, i.e. without being guided by a sound guide.

Preferably, the loudspeaker unit includes:

a sound guide configured to guide sound produced by a first radiating surface of a diaphragm in the first subset to an outlet such that the sound propagates out of the loudspeaker unit from the outlet, wherein the loudspeaker unit is configured for use with an ear of a user located at a listening position that is 50cm or less (more preferably 40cm or less, more preferably 30cm or less, more preferably 25cm or less, more preferably 20cm or less, more preferably 15cm or less) from the outlet.

More preferably, the loudspeaker unit includes:

a first sound guide configured to guide sound produced by a first radiating surface of a diaphragm in the first subset to a first outlet such that the sound propagates out of the loudspeaker unit from the first outlet, wherein the loudspeaker unit is configured for use with a first ear of a user located at a first listening position that is 50cm or less (more preferably 40cm or less, more preferably 30cm or less, more preferably 25cm or less, more preferably 20cm or less, more preferably 15cm or less) from the first outlet;

a second sound guide configured to guide sound produced by a first radiating surface of a diaphragm in the first subset to a second outlet such that the sound propagates out of the loudspeaker unit from the second outlet, wherein the loudspeaker unit is configured for use with a second ear of a user located at a second listening position that is 50cm or less (more preferably 40cm or less, more preferably 30cm or less, more preferably 25cm or less, more preferably 20cm or less, more preferably 15cm or less) from the second outlet, whilst the first ear of the user is located at the first listening position.

In this way, sound from the first radiating surface of a diaphragm in the first subset is guided to an outlet that is close to an ear of a user so that a user can clearly hear the sound produced by that first radiating surface of the diaphragm in the first subset, whilst a person who is further away from the outlet than the user will preferably hear sound with a significantly reduced SPL level (compared with an ordinary monopole loudspeaker unit producing the same SPL level at the ear of the user) it is believed due to interference from out of phase sound produced by the/each first radiating surface of diaphragms in the second subset.

For avoidance of any doubt, the first sound guide and second sound guide may be configured to guide sound from the first radiating surface of the same diaphragm in the first subset, or from the first radiating surfaces of different diaphragms in the first subset.

Also for avoidance of any doubt, in this disclosure the term "first subset" is typically allocated to the subset of diaphragm(s) whose first radiating surface(s) are configured to produce sound which is guided to an ear of a user, but this is just a naming convention and is not intended to infer that the "first subset" of diaphragms has a particular set of features.

Also for avoidance of any doubt, whilst it is preferable for sound to be guided by a sound guide from a radiating surface to at least one ear of a user, it would also be possible for an ear of a user to be located at a listening position that is in front of and 50cm or less (more preferably 40cm or less, more preferably 30cm or less, more preferably 25cm or less, more preferably 20cm or less, more preferably 15cm or less) from a first radiating surface of the loudspeaker unit. That is, it is not a requirement of the invention that one or more sound guides are used to guide sound to an ear of a user (though this is generally preferred, since locating the ears of a user in front of and close to a diaphragm causes certain design limitations).

For completeness, we note that it is generally preferable for in-phase sound to be directed towards the two ears of a user (i.e. sound produced by one or more first radiating surfaces in the first subset of diaphragms), though in some cases it may be possible for out-of-phase sound to be directed towards the two ears of a user (i.e. with sound produced by the first radiating surface of a diaphragm in the first subset being directed to one ear of a user and with sound produced by the first radiating surface of a diaphragm in the second subset being directed to the other ear of the user), though the present inventor has found that this is only workable at very low frequencies (100Hz or less, more preferably 80 Hz or less) before a user starts to feel fatigue/discomfort, as described in PCT/EP2019/056109 and GB1805523.6.

The loudspeaker unit according to the second aspect of the invention may have multiple operational modes, wherein:

in a first operational mode, the drive circuitry is configured to provide the drive unit(s) configured to move the first subset of diaphragms with an electrical signal that is out of phase with respect to an electrical signal that is provided to the drive unit(s) configured to move the second subset of diaphragms; and

in a second operational mode, the drive circuitry is configured to provide the drive unit(s) configured to move the first subset of diaphragms with an electrical signal that is in phase with respect to an electrical signal that is provided to the second subset of the diaphragms.

In this way, the loudspeaker unit can have an operational mode (the second operational mode) in which in-phase sound is produced by all first radiating surfaces. This may be useful e.g. to allow the loudspeaker unit to produce higher sound pressure levels in situations in which creating a personal sound cocoon is not needed or not as important (e.g. where all passengers in a car are listening to the same audio).

The second operational mode may be deliberately used to cause vibrations, e.g. to provide feedback to a user sat in a car seat in which the loudspeaker unit is implemented, since all the diaphragms moving in phase with each other will in general increase the forces caused by movement of the diaphragms on the frame.

In a loudspeaker unit according to the second aspect of the invention, the drive circuitry may be configured to apply a predetermined delay to one or more of the electrical signals provided to the drive units. Applying a predetermined delay to one or more of the electrical signals provided to the drive unit may be useful to virtually "move" the location of those one or more drive units. For avoidance of any doubt, if a predetermined delay is applied to more than one of the electrical signals provided to the drive units, the predetermined delay respectively applied to each of the electrical signals could be different.

A delay may also/alternatively be used to cause vibrations, e.g. to provide feedback to a user sat in a car seat in which the loudspeaker unit is implemented.

A skilled person would appreciate that the at least one enclosure should be adequately enclosed so as to significantly inhibit sound produced by the second radiating surfaces from propagating out from the loudspeaker unit. This may be achieved e.g. by sealing the enclosure, by making the enclosure adequately large, and/or by including appropriate sound absorption materials in the enclosure.

In other words, the at least one enclosure should adequately contain sound produced by the second radiating surfaces so that each diaphragm can, optionally in combination with the drive unit configured to move the diaphragm, be viewed as providing a respective monopole loudspeaker within the loudspeaker unit.

Accordingly, for this second aspect of the invention, each diaphragm, optionally in combination with the drive unit configured to move the diaphragm, may be referred to as a (respective) monopole loudspeaker.

Since in this aspect of the invention each diaphragm is in effect providing a respective monopole loudspeaker, the polar response of each monopole loudspeaker at bass frequencies can be approximated to be spherical, meaning that the orientation of each diaphragm can be varied without significantly affecting the personal sound cocoon achieved by the loudspeaker unit. This means the orientation of each diaphragm can be chosen according to design choices.

Preferably, the loudspeaker unit includes a single enclosure configured to receive sound produced by the second radiating surfaces of the diaphragms. This may help with pressure equalisation.

Preferably, the loudspeaker unit includes an even number of diaphragms such that the loudspeaker unit can be viewed as including one or more pairs of diaphragms. If the two diaphragms of a pair of diaphragms are included in the same subset, then the two diaphragms of that pair of diaphragms are preferably oriented back to back, i.e. with the second radiating surface of one diaphragm of the pair facing the second radiating surface of the other diaphragm of the pair (preferably with the two radiating surfaces radiating into a shared space enclosed by the at least one enclosure), since this helps with force cancellation. If the two diaphragms of a pair of diaphragms are included in different subsets, then the two diaphragms of that pair of diaphragms are preferably oriented front to back, i.e. with the first radiating surface of one loudspeaker of the pair facing the second radiating surface of the other loudspeaker of the pair, since this helps with force cancellation.

The drive circuitry may take various forms in order that the electrical signal(s) provided to the one or more drive units configured to move the first subset of diaphragms is/are out of phase with respect to the electrical signal(s) provided to the one or more drive units configured to move the second subset of diaphragms, as would be appreciated by a skilled person.

For example, the drive circuitry could simply include wiring configured to reverse the polarity of the electrical signal provided to the/each drive unit configured to move a diaphragm in the second subset of diaphragms compared to the electrical signal provided to the/each drive unit configured to move a diaphragm in the first subset of diaphragms.

Preferably, the drive circuitry includes a signal processing unit (preferably a digital signal processor or "DSP") configured to provide each drive unit with a respective electrical signal derived from an audio signal provided by the audio source. An advantage provided by such a signal processing unit is that the signal processing unit can be used not only to provide each drive unit with a respective electrical signal derived from the same audio source such that the electrical signal(s) provided to the one or more drive units configured to move the first subset of diaphragms is/are out of phase with respect to the electrical signal(s) provided to the one or more drive units configured to move the second subset of diaphragms (as is required by a loudspeaker according to the second aspect of the invention), but can also be used to manipulate the electrical signal respectively provided to each drive unit, e.g. to modify the phase, delay or amplitude of the electrical signal respectively provided to each drive unit, e.g. so as to optimize the sound provided to a user (as might be useful e.g. for changing an operational mode of the loudspeaker unit, for changing a path length and/or for noise cancelling, e.g. in a manner described herein).

The electrical signal(s) provided to the one or more drive units configured to move the first subset of diaphragms should be out of phase with respect to the electrical signal(s) provided to the one or more drive units configured to move the second subset of diaphragms, such that sound produced by the first radiating surface(s) of the first subset of loudspeakers cancels in the far field with sound produced by the second radiating surface(s) of the first subset of loudspeakers. In general, this will mean that the electrical signals provided to the first subset of diaphragms should be 180° or close to 180° (e.g. between 90° and 270°, or between 160° and 200°) out of phase with respect to the electrical signal(s) provided to the one or more drive units configured to move the second subset of diaphragms.

A skilled person will appreciate that because the signals provided to each drive unit can be individually manipulated (e.g. to modify phase, delay or amplitude), and since different drive units in the loudspeaker unit may be provided with a respective electrical signal derived from a different channel of an audio signal provided by the audio source (e.g. so as to provide a stereo effect), the electrical signal(s) provided to the one or more drive units configured to move the first subset of diaphragms need not be identical to each other, the electrical signal(s) provided to the one or more drive units configured to move the second subset of diaphragms need not be identical to each other, and the electrical signal(s) provided to the one or more drive units configured to move the first subset of diaphragms need not be the exact opposite (i.e. same waveform, with the same amplitude whilst being exactly 180° out of phase with respect to) the electrical signal(s) provided to the one or more drive units configured to move the second subset of diaphragms. However, the electrical signal(s) provided to each drive unit configured to move a diaphragm in the first subset of diaphragms should be adequately out of phase (i.e. close enough to being the exact opposite) with respect to the electrical signal(s) provided to each drive unit configured to move a diaphragm in the second subset of diaphragms so as to provide a desired degree of cocooning effect, since without wishing to be bound by theory the present inventor believes that deviations from such signals being exactly out of phase will in general worsen the cocooning effect. However, the present inventors believe that an optimum cocooning effect would usually be achieved by a phase difference of 180°.

In view of the disclosure below, a skilled person would appreciate that the/each sound guide in a loudspeaker unit according to the first or second aspect of the invention may take various forms and may be configured in various ways, as will now be discussed.

One or more sound guides (optionally the/each sound guide) in a loudspeaker unit according to the first or second aspect of the invention may be configured to guide sound produced by a radiating surface to multiple outlets (rather than to a single outlet).

One or more sound guides (optionally the/each sound guide) in a loudspeaker unit according to the first or second aspect of the invention may form at least one passage which extends from a radiating surface to at least one outlet.

One or more sound guides (optionally the/each sound guide) in a loudspeaker unit according to the first or second aspect of the invention may form multiple passages which extend from a radiating surface to multiple outlets. Each of the multiple passages may extend from a shared space in front of the radiating surface to a respective outlet. Alternatively, one or more of the multiple passages may branch off from one or more other of the multiple passages.

One or more passages (optionally the/each passage) may be formed by a respective tube.

One or more passages (optionally the/each passage) formed by a sound guide in a loudspeaker unit according to the first or second aspect of the invention may include a curved region configured to gradually change the direction in which sound produced by the radiating surface propagates.

One or more passages (optionally the/each passage) formed by a sound guide in a loudspeaker unit according to the first or second aspect of the invention may be formed from one or more walls of the loudspeaker unit.

The one or more walls are preferably rigid. The one or more walls preferably have a fixed position with respect to the frame. In this way the position(s) of the outlets and lengths of passage(s) formed by the sound guide(s) can be configured by a manufacturer of the loudspeaker unit, e.g. to provide a personal sound cocoon having desired properties. The one or more walls could be rigid elements which are part of the frame, or rigid elements which are fixedly attached to the frame, for example.

One or more sound guides (optionally the/each sound guide) in a loudspeaker unit according to the first or second aspect of the invention may be configured to change the direction in which sound produced by a (respective) radiating surface propagates at least once (optionally at least twice). The/each change in direction could be continuous (i.e. smoothly varying) or discontinuous (i.e. abrupt).

One or more passages (optionally the/each passage) formed by a sound guide in a loudspeaker unit according to the first or second aspect of the invention may (respectively) have a cross-sectional area that is less than (more preferably 50% or less than) the effective radiating surface area of the radiating surface from which the passage extends (to an outlet). In other embodiments, said one or more passages may (respectively) have a cross-sectional area that is more than the effective radiating surface area of the radiating surface from which the passage extends (to an outlet)

If there are multiple passages formed by a sound guide, then a cumulative cross-sectional area of said passages may be less than (more preferably 50% or less than) the effective radiating surface area of the radiating surface from which the passages extend. In other embodiments, said cumulative cross-sectional area of said passages may be more than the effective radiating surface area of the radiating surface from which the passages extend.

Effective radiating surface area is a well understood concept and may be calculated according to a technique described in [8], for example (where this parameter is referred to as "effective radiation area").

A passage whose cross-sectional area is reduced compared with the effective radiating surface area has been found to slightly improve the performance of the personal sound cocoon produced by the loudspeaker unit in experimental conditions, as discussed below with reference to experimental data 1.

In a loudspeaker unit according to the first or second aspect of the invention, the tuning frequency of a Helmholtz resonator formed by one or more sound guides (preferably the/each sound guide in the loudspeaker unit) is preferably outside an operational bandwidth of the loudspeaker unit, more preferably above an operational bandwidth of the loudspeaker unit.

The operational bandwidth of the loudspeaker unit may be defined as the range of frequencies over which the loudspeaker unit is configured to produce sound. For example, the/each drive unit of the loudspeaker may be configured so that the/each diaphragm does not produce sound at a frequency which exceeds an upper limit of the operational bandwidth.

If the loudspeaker unit is a subwoofer, an upper limit of the operational bandwidth of the loudspeaker unit may be 200 Hz or lower, more preferably 160Hz or lower, and could be 100Hz or lower.

In a loudspeaker unit according to the first or second aspect of the invention, the tuning frequency of a Helmholtz resonator formed by one or more sound guides (preferably the/each sound guide in the loudspeaker unit) is preferably 100Hz or higher, and in some examples may be 160Hz or higher, or 200Hz or higher.

In a loudspeaker unit according to the first aspect of the invention in which there is a sound guide configured to guide sound produced by a first radiating surface of a diaphragm and a further sound guide configured to guide sound produced by the second radiating surface of that diaphragm, the sound guide and further sound guide preferably both have a (respective) tuning frequency above an operational bandwidth of the loudspeaker unit.

In a loudspeaker unit according to the first aspect of the invention in which there is a sound guide configured to guide sound produced by a first radiating surface of a diaphragm and a further sound guide configured to guide sound produced by the second radiating surface of that diaphragm, the sound guide and further sound guide preferably both have a (respective) tuning frequency that is 100Hz or higher, or in some examples 160Hz or higher.

In a loudspeaker unit according to the first aspect of the invention in which there is a sound guide configured to guide sound produced by a first radiating surface of a diaphragm and a further sound guide configured to guide sound produced by the second radiating surface of that diaphragm, the sound guide preferably has a tuning frequency that is similar (e.g. with 10% of) or the same as the tuning frequency of the further sound guide, since (for reasons discussed below in relation to experimental data 3) this helps to avoid a bandpass region in which the sound at the outlets of the sound guides is substantially in phase.

For the avoidance of any doubt, for the purposes of this disclosure, a loudspeaker unit according the invention could form part of a composite loudspeaker system including the loudspeaker unit according to the invention and one or more additional loudspeaker units. The loudspeaker unit according to the invention could share structure (e.g. a frame, an enclosure) and/or electronics with those one or more additional loudspeaker units. For example, a composite loudspeaker system could include a loudspeaker unit according to the present invention having operational bandwidth with an upper frequency limit of 200Hz or lower, as well as one of more additional loudspeaker units having an operational bandwidth extending above that of the loudspeaker unit, preferably into medium frequencies (e.g. 200Hz or higher), and high range frequencies (e.g. 4kHz or higher). An example of a composite loudspeaker system including multiple loudspeaker units sharing some structure is described with reference to Fig. 8.

In a loudspeaker unit according to the first or second aspect of the invention, where the loudspeaker unit includes a plurality of diaphragms, a plurality of drive units, and drive circuitry configured to provide each drive unit with a respective electrical signal derived from the same audio source, each respective electrical signal may be derived from an audio signal provided by the audio source. The audio source could be any source capable of providing an audio signal. Herein, an audio signal can be understood as a signal containing information representative of sound. An audio signal produced by an audio source may typically be an electrical signal (which could be digital or analogue), but could also take another form, such as an optical signal, for example. For avoidance of any doubt, the audio signal provided by the audio source could include a single channel or multiple channels. For example, the audio signal provided by the audio source could be a stereo audio signal including two channels, with each channel being a respective component of the stereo audio signal (though it is thought the respective stereo channels would need to be similar to get adequate cancellation). Different drive units in the loudspeaker unit may be provided with a respective electrical signal derived from a different channel of an audio signal provided by the audio source, e.g. so as to provide a stereo effect.

In a loudspeaker unit according to the first or second aspect of the invention where the loudspeaker unit includes a plurality of diaphragms, a plurality of drive units, and drive circuitry configured to provide each drive unit with a respective electrical signal derived from the same audio source, the drive circuitry preferably includes a signal processing unit (preferably a digital signal processor or “DSP”) configured to provide each drive unit with a respective electrical signal derived from an audio signal provided by the audio source. In this way, the signal processing unit can be used to manipulate the electrical signal respectively provided to each drive unit, e.g. to modify the phase, delay or amplitude of the electrical signal respectively provided to each drive unit, e.g. so as to optimize the sound provided to a user (as might be useful e.g. for changing an operational mode of the loudspeaker unit, for changing a path length and/or for noise cancelling, e.g. in a manner described herein).

In a loudspeaker unit according to the first or second aspect of the invention, the loudspeaker unit may be configured to produce sound over an operational bandwidth that includes bass frequencies, wherein the bass frequencies preferably include frequencies across the range 60-80Hz, more preferably frequencies across the range 50-100Hz, more preferably frequencies across the range 40-100Hz, and may include frequencies across the range 40-160Hz. At these frequencies, the present inventor has found that a loudspeaker unit according to the first and/or second aspect of the present invention is able to produce a particularly useful personal sound cocoon.

Accordingly, in a loudspeaker unit according to the first or second aspect of the invention, the drive circuitry may be configured to provide each drive unit with a respective electrical signal that includes frequencies across the range 60-80Hz, more preferably frequencies across the range 50-100Hz, more preferably frequencies across the range 40-100Hz, and may include frequencies across the range 40-160Hz.

Moving the diaphragm at frequencies below 40Hz may be useful for some applications, but not for others (such as in a car, where below 40Hz background noise tends to be too loud).

Above 160Hz, the present inventor has found that the “cocooning” effect worsens considerably, though with an adequate number of diaphragms it has been found that a useful cocooning effect can be obtained up to 200Hz or even 400Hz.

Accordingly, in some applications, in a loudspeaker unit according to the first or second aspect of the invention, the drive circuitry may be configured to provide each drive unit with a respective electrical signal that includes frequencies that do not exceed 400Hz, 200Hz, or 160Hz. This may help to ensure the loudspeaker achieves a desired level of “cocooning”.

In other applications (e.g. where cocooning is not required), in a loudspeaker unit according to the first or second aspect of the invention, the drive circuitry may be configured to provide each drive unit with a respective electrical signal that includes frequencies that exceed 400Hz, and could provide a full range of frequencies e.g. up to 20kHz or higher.

A loudspeaker unit according to the first or second aspect of the invention is preferably (configured as) a subwoofer. A subwoofer can be understood as a loudspeaker unit dedicated to (rather than suitable for) producing sound at bass frequencies.

In a loudspeaker unit according to the first or second aspect of the invention, the/each diaphragm may take various forms.

In some examples of a loudspeaker unit according to the first or second aspect of the invention, one or more diaphragms (optionally the/each diaphragm) may include a cone. For the/each diaphragm that includes a cone, the first radiating surface of the diaphragm may be provided by a concave surface of the cone and the second radiating surface of the diaphragm may be provided by a convex surface of the cone.

In some examples of a loudspeaker unit according to the first or second aspect of the invention, one or more diaphragms (optionally the/each diaphragm) may have a non-circular shape, e.g. a rectangular or square shape. This may help to maximize the surface area of the first and second radiating surfaces within other design constraints (e.g. incorporating the loudspeaker unit into a car headrest).

In some examples of a loudspeaker unit according to the first or second aspect of the invention, one or more diaphragms (optionally the/each diaphragm) may be a single (monolithic) piece of material. The material may be lightweight, e.g. having a density of 0.1 g/cm^3 or less. The material may be extruded polystyrene, extruded polypropylene or similar.

In some examples of a loudspeaker unit according to the first or second aspect of the invention, one or more diaphragms (optionally the/each diaphragm) be covered by a skin, e.g. to protect the diaphragm. The skin could e.g. be of paper, carbon fiber, plastic foil, for example.

In some examples of a loudspeaker unit according to the first or second aspect of the invention, one or more diaphragms (optionally the/each diaphragm) may include several pieces of material attached together, e.g. by glue. For example, one or more diaphragms may include a first cone and a second cone, wherein the first and second cones are glued back to back. For the/each diaphragm that includes a first cone and a second cone, wherein the first and second cones are glued back to back, the first radiating surface of the diaphragm may be provided by a concave surface of the first cone and the second radiating surface of the diaphragm may be provided by a concave surface of the second cone. The/each cone may e.g. be made of paper.

In some examples of a loudspeaker unit according to the first or second aspect of the invention, the first and second radiating surfaces of the/each diaphragm could be circular, rectangular, rectangular with rounded corners, or indeed have a more freeform shape.

In some examples of a loudspeaker unit according to the first or second aspect of the invention, the one or more suspension elements via which the/each diaphragm is suspended from the frame may take a variety of forms.

Suspension elements for loudspeakers are well known, and a variety of different types of suspension elements may be used in each case where one or more suspension elements are recited in the present disclosure. For example, a suspension element referred to herein may be a roll suspension, a metal spring, a rubber band etc.

In some examples of a loudspeaker unit according to the first or second aspect of the invention, for one or more diaphragms included in the loudspeaker unit, the one or more suspension elements via which the diaphragm is suspended from the frame may include one or more suspension elements (e.g. one or more roll suspensions) attached between the first radiating surface of the diaphragm and the frame, and one more suspension elements (e.g. one or more roll suspensions) attached between the second radiating surface of the diaphragm and the frame. This may be useful if the diaphragm has a significant thickness, e.g. of 1 cm or more, for example as might be the case if the diaphragm is of extruded polystyrene or similar. Preferably, the one or more suspension elements (e.g. one or more roll suspensions) attached between the first radiating surface of the diaphragm and the frame correspond to (e.g. match, e.g. match in position, number and length) the one or more suspension elements (e.g. one or more roll suspensions) attached between the second radiating surface of the diaphragm and the frame. This matching of suspension elements is particularly useful if the diaphragm is non-circular, since it may help to eliminate any asymmetries in the performance of the suspension elements attached to one radiating surface of the diaphragm.

In some examples of a loudspeaker unit according to the first or second aspect of the invention, the one or more suspension elements via which the/each diaphragm is suspended from the frame may be tuned to have a resonance frequency that is below the operational bandwidth of the loudspeaker unit, e.g. to maximize the efficiency of the loudspeaker unit in the frequency spectrum of interest.

In some examples of a loudspeaker unit according to the first or second aspect of the invention, the/each drive unit may be an electromagnetic drive unit that includes a magnet unit configured to produce a magnetic field, and a voice coil attached to the diaphragm (that the drive unit is configured to move). In use, the voice coil may be energized (have a current passed through it) to produce a magnetic field which interacts with the magnetic field produced by the magnet unit and which causes the voice coil (and therefore the diaphragm) to move relative to the magnet unit. The magnet unit may include a permanent magnet. The magnet unit may be configured to provide an air gap, and may be configured to provide a magnetic field in the air gap. The voice coil may be configured to sit in the air gap when the diaphragm is at rest. Such drive units are well known.

In some examples of a loudspeaker unit according to the first or second aspect of the invention, the magnet unit of the/each drive unit may be located in front of the second radiating surface of the diaphragm (that the drive unit is configured to move). The loudspeaker unit may include a respective safety element which is located between the magnet unit and the second radiating surface of each diaphragm. The safety element may be configured to prevent the magnet unit from passing through the diaphragm, e.g. in a crash event or another event that involves a sudden deceleration of the loudspeaker (e.g. where the loudspeaker has been moving in the direction of the principal radiating axis of the first radiating surface). The safety element is preferably rigid. The safety element may be a voice coil coupler configured to attach the voice coil to the diaphragm.

In some examples of a loudspeaker unit according to the first or second aspect of the invention, a safety element as described above may be particularly useful if the loudspeaker is mounted in a headrest of a vehicle seat, since it may help to provide protection for a person sat in such a seat in the event of a vehicle crash.

In some examples of a loudspeaker unit according to the first or second aspect of the invention, the voice coil of the/each drive unit may be attached to the diaphragm (that the drive unit is configured to move), e.g. to the second radiating surface of that diaphragm. The/each voice coil may be attached to (e.g. the second radiating surface of) the diaphragm (that the drive unit is configured to move) either directly, or via a voice coil coupler. The voice coil coupler may also be a safety element, as described above.

In the context of this disclosure, the term frame is intended to encompass any substantially rigid structure from which one or more diaphragms can be suspended. The frame may include metal and/or plastic, for example.

In a loudspeaker unit according to the first or second aspect of the invention, the frame may respectively include one or more rigid supporting elements (e.g. arms) configured to hold a magnet unit of the/each drive unit in front of the first and/or second radiating surface of the diaphragm (that the drive unit is configured to move), preferably in front of the second radiating surface of that diaphragm.

In a loudspeaker unit according to the first or second aspect of the invention, the frame from which the/each diaphragm is suspended may include one or more mounting legs which extend into one or more (respective) cavities in the/each diaphragm, wherein the/each diaphragm is suspended from the one or more mounting legs via one or more suspension elements.

In a loudspeaker unit according to the first or second aspect of the invention, the/each diaphragm may include one or more cavities in one of the radiating surfaces (preferably the second radiating surface), wherein the/each cavity is configured to have a respective rigid supporting element extend through it when the loudspeaker unit is in use. This may allow the loudspeaker unit to have a lower profile in the thickness direction of the diaphragms.

Alternatively, in a loudspeaker unit according to the first or second aspect of the invention, the magnet unit of the/each drive unit may be suspended from the diaphragm (that the drive unit is configured to move) via one or more suspension elements.

In some examples of a loudspeaker unit according to the first or second aspect of the invention wherein the loudspeaker unit includes more than one diaphragm (which may be referred to herein for brevity as a "dual frame configuration"), the frame from which each diaphragm is suspended is a secondary frame, wherein the diaphragms are suspended from one or more primary frames (optionally one primary frame) via one or more primary suspension elements, wherein the/each primary frame is suspended from the secondary frame via one or more secondary suspension elements. Note that in this case all of the diaphragms can be viewed as being suspended from the secondary frame via the secondary suspension element(s), primary frame(s) and primary suspension element(s).

In a dual frame configuration, the use of one or more primary frames suspended from a secondary frame may be useful to reduce vibrations passing from the loudspeaker into the environment. However, vibrations passing from the loudspeaker into the environment can also be avoided by appropriately configuring the two or more diaphragms in a loudspeaker unit according to the first and/or second aspect of the invention to provide force cancellation.

In a dual frame configuration, the/each primary frame may include a rigid body which extends around a respective diaphragm axis along which a respective drive unit is configured to move a respective diaphragm. The primary frame is preferably located radially outwards from the diaphragm, relative to the diaphragm axis.

In a dual frame configuration, the/each primary frame may include one or more rigid supporting elements (e.g. arms) configured to hold a magnet unit of a respective drive unit in front of the first and/or second radiating surface of a respective diaphragm (preferably in front of the second radiating surface of the diaphragm).

In a dual frame configuration, the/each diaphragm may include one or more cavities in one of its radiating surfaces (preferably the second radiating surface), wherein each cavity is configured to have a respective rigid supporting element extend through it when the loudspeaker is in use. This may allow the loudspeaker unit to have a lower profile in the thickness direction of the diaphragm.

In a dual frame configuration, the secondary frame may be part of, or may be configured to fixedly attach to, a rigid supporting structure, such as a car seat frame.

In some examples of a loudspeaker unit according to the first or second aspect of the invention wherein the loudspeaker unit includes more than one diaphragm (which may be referred to herein for brevity as a "single frame configuration"), the frame from which each diaphragm is suspended is part of or configured to fixedly attach to, a rigid supporting structure, such as a car seat frame.

In a single frame configuration, the magnet unit of each drive unit may be suspended from a respective diaphragm via one or more magnet unit suspension elements.

In a single frame configuration, the one or more magnet unit suspension elements via which each magnet unit is suspended may include one or more (preferably two or more) spiders for example, wherein a spider may be understood as a textile ring having circumferentially extending corrugations (which may facilitate movement along the longitudinal axis whilst movement perpendicular to this axis), as is known in the art. Other suspension element forms may be considered by a skilled person, e.g. springs such as metal springs.

In a loudspeaker unit according to the first or second aspect of the invention, the loudspeaker unit may be configured for use in performing noise cancelation, e.g. at bass frequencies.

For example, in the first, aspect of the invention, the drive circuitry may be configured to provide at least one diaphragm with an electrical signal configured to move the at least one diaphragm (e.g. at bass frequencies) so that the first radiating surface of that at least one diaphragm produces sound configured to cancel environmental sound at a listening position, wherein one or more microphones are configured to detect the environmental sound. For example, in the second aspect of the invention, the drive circuitry may be configured to provide the first subset of diaphragms with an electrical signal configured to move at least one diaphragm in the first subset of diaphragms (e.g. at bass frequencies) so that the first radiating surface of that at least one diaphragm produces sound configured to cancel environmental sound at a listening position, wherein one or more microphones are configured to detect the environmental sound. The listening position may be as defined above. Preferably the diaphragm being moved to cancel environmental sound at the listening positions is the same diaphragm that the listening position is defined with respect to. This may be of use in a noisy environment, such as in a car or aeroplane, e.g. where the loudspeaker is part of a seat assembly including a vehicle seat. Noise cancellation techniques are well-known.

A loudspeaker unit according to the first or second aspect of the invention may find utility in any application where it might be desirable to provide a personal sound cocoon.

In a third aspect, the present invention may provide a seat assembly including a seat and a loudspeaker unit according to the first or second aspect of the present invention.

Preferably, the seat is configured to position a user who is sat down in the seat such that an ear of the user is located at a listening position as described above.

Preferably, the seat is configured to position a user who is sat down in the seat such that a first ear of the user is located at a first listening position as described above whilst a second ear of the same user is located at a second listening position as described above.

The loudspeaker unit and/or one or more outlets of the loudspeaker unit may be mounted within a headrest of the seat ("seat headrest"). Since a typical headrest is configured to be a small distance (e.g. 30cm or less) from the ears of a user who is sat down in a seat, this is a particularly convenient way of configuring the seat to position a user who is sat down in the seat such that an ear of the user is located at a listening position as described above.

In some cases, the loudspeaker unit may be mounted in a body of the seat, with one or more outlets located in a headrest of the seat.

In some embodiments, one or more diaphragms of the loudspeaker unit configured to produce sound guided to one or more outlets mounted within a headrest of the seat are located outside of the headrest. This arrangement is made possible by the use of one or more sound guides as disclosed herein.

A seat headrest typically has a front surface configured to face towards the head of a user sat in the seat, and a back surface configured to face away from the head of a user sat in the seat.

Preferably, the seat assembly includes a head tracking unit configured to track head movement of a user sat in the seat. Head tracking and face recognition technology based on video monitoring/processing is a known technology that is finding its way into cars for various purposes such as safety (to detect and then prevent a driver from falling asleep) and gesture control, see e.g. [3]-[7]. Head tracking based on one or more ultrasonic sensors may also be possible.

If the loudspeaker unit includes a plurality of diaphragms and a plurality of drive units, the drive circuitry is configured to modify the electrical signals provided to the drive units based on head movement as tracked by the head tracking unit, e.g. to compensate for movement of the head of a user sat in the seat. For example, the drive circuitry may be configured to increase the amplitude of sound produced by one of the diaphragms if it is determined based on head movement as tracked by the head tracking unit that an ear of the user has moved further away from an outlet of a sound guide configured to guide sound produced by that diaphragm to an ear of a user. Similarly, the drive circuitry may be configured to decrease the amplitude of sound produced by one of the diaphragms if it is determined based on head movement as tracked by the head tracking unit that an ear of the user has moved closer to an outlet of a sound guide configured to guide sound produced by that diaphragm to an ear of a user. It would be straightforward for a skilled person to adapt existing head tracking technologies e.g. as discussed in [3]-[7] to this purpose.

The seat may have a rigid seat frame. The frame of the loudspeaker unit may be part of or fixedly attached to the rigid seat frame. For example, in a dual frame configuration as discussed above, the secondary frame of the loudspeaker may be part of or fixedly attached to the rigid seat frame. For example, in a single frame configuration as discussed above, the frame of the loudspeaker unit may be part of or fixedly attached to the rigid seat frame.

The seat assembly may include additional loudspeaker units (which may be monopole loudspeaker units). The additional loudspeaker units preferably have an operational bandwidth extending above that of the loudspeaker unit, preferably into medium frequencies (e.g. 200Hz or higher), and high range frequencies (e.g. 4kHz or higher). The additional loudspeaker units may be highly directional, e.g. to provide an effective personal sound cocoon.

The additional loudspeaker units may therefore have an operational bandwidth which extends above 200Hz, more preferably above 1kHz, more preferably above 4kHz.

The seat may be a vehicle seat, for use in a vehicle such as a car ("car seat") or an aeroplane ("plane seat").

The seat could be a seat for use outside of a vehicle. For example, the seat could be a seat for a computer game player, a seat for use in studio monitoring or home entertainment.

In a fourth aspect, the present invention may provide a vehicle (e.g. a car or an aeroplane) having a plurality of seat assemblies according to the fourth aspect of the invention.

The invention includes the combination of the aspects and preferred features described except where such a combination is clearly impermissible or expressly avoided.

Herein, a principal radiating axis of a radiating surface may be understood as an axis along which the radiating surface produces direct sound at maximum amplitude (sound pressure level). Typically, the principal radiating axis will extend outwardly from a central location on the radiating surface. The principal radiating axes of the first and second radiating surfaces will in general extend in opposite directions, since they are located on opposite faces of the diaphragm.

Summary of the Figures

Embodiments and experiments illustrating the principles of the invention will now be discussed with reference to the accompanying figures in which:

Figs. 1(a)-(h) are schematic views of various loudspeaker units 101a-h which implement the first aspect of the invention.

Figs. 2(a)-(f) show various multipole (including higher order multipole) configurations that may be achieved according to the positioning of remote poles.

Figs. 3(a)-(b) show a headrest for a car that includes a loudspeaker unit 201a according to the first aspect of the invention.

Fig. 4 shows a headrest for a car that includes a loudspeaker unit 201b according to the first aspect of the invention.

Figs. 5(a)-(b) show a car seat including an integral headrest, wherein the car seat includes a loudspeaker unit 201c according to the first aspect of the invention.

Figs. 6(a)-(b) show a car seat including an integral headrest, wherein the car seat includes a loudspeaker unit 201d according to the first aspect of the invention.

Figs. 7(a)-(c) are schematic views of various loudspeaker units which implement the second aspect of the invention.

Figs. 8(a)-(b) show a headrest 450a for a car that includes a loudspeaker unit 401a according to the second aspect of the invention.

Figs. 9(a)-(d) illustrate an experimental set up used to obtain experimental data 1, and the results of said experiment.

Figs. 10(a)-(c) illustrate an experimental set up used to obtain experimental data 2, and the results of said experiment.

Figs. 11(a)-(b) show the parameters necessary to model a Helmholtz resonator such as the sound guides detailed in the present invention, and the lumped element model and relevant parameters used to obtain experimental data 3a and 3b.

Figs. 12(a)-(e) show experimental data obtained from the model depicted in Fig. 11(b), intended to model loudspeaker units according to the first aspect of the invention.

Fig. 13 shows experimental data obtained from the model depicted in Fig. 11(b), intended to model a classic bandpass subwoofer.

Detailed Description of the Invention

Aspects and embodiments of the present invention will now be discussed with reference to the accompanying figures. Further aspects and embodiments will be apparent to those skilled in the art. All documents mentioned in this text are incorporated herein by reference.

<u>Examples implementing first aspect of the invention</u>

Various loudspeaker units implementing the first aspect of the invention will now be described. Where possible, alike features have been given corresponding reference numerals, such that such features may not need to be described in further detail.

Figs. 1(a)-(h) are schematic views of various loudspeaker units 101a-h which implement the first aspect of the invention.

In each case, the loudspeaker unit 101a-h has one or more diaphragms 110a-h and a respective drive unit (not shown) configured to move the/each diaphragm 110a-h based on an electrical signal derived from the same audio source such that the electrical signals provided to the drive units are configured to move the first radiating surfaces of the diaphragm substantially in phase with each other.

Each diaphragm 110a-h has a first radiating surface 112a-h and a second radiating surface 114a-h.

Each diaphragm 110a-h may be incorporated in a wall, but in any case the/each diaphragm 110a-h (and if present the wall) is configured to block air moved by the diaphragm from getting from one radiating surface 112a-h to the other radiating surface 114a-h of that diaphragm.

Each loudspeaker unit 101a-h also includes:

one or more sound guides 122a-h each respectively configured to guide sound produced by one or more of the first radiating surfaces 112a-h to at least one outlet 132a-h such that the sound propagates out of the loudspeaker unit 101a-h from the at least one outlet 132a-h, the/each outlet 132a-h being remote from said one or more first radiating surfaces 112a-h; and

one or more sound guides 124a-h each respectively configured to guide sound produced by one or more of the second radiating surfaces 114a-h to at least one outlet 134a-h such that the sound propagates out of the loudspeaker unit 101a-h from the at least one outlet 134a-h, the/each outlet 134a-h being remote from said one or more second radiating surfaces 114a-h.

Although many of Figs. 1(a)-(h) show the sound guides 122a-h, 124a-h as including tubes having a wavy shape, this is just schematic and is intended to illustrate that a designer seeking to implement the loudspeaker units 101a-h would have many degrees of design freedom available to them in implementing the sound guides 122a-h, 124a-h.

In this description, "poles" can be understood as locations at which sound propagates out from a loudspeaker unit. A "pole" may therefore be an outlet to which sound is guided by a sound guide, or a radiating surface of a diaphragm from which sound is able to propagate out from the loudspeaker unit substantially uninhibited (i.e. without being guided to an outlet). The poles 132a-h to which sound is guided from one or more first radiating surfaces 112a-h are labelled as '+', whereas poles 134a-h to which sound is guided from one or more second radiating surfaces 114a-h are labelled as '-', to indicate that sound emitted at poles 132a-h is out of phase from sound emitted at poles 134a-h. Similarly, first radiating surfaces 112a-h from which sound is able to propagate out from the loudspeaker unit substantially uninhibited are labelled '+' whereas second radiating surfaces 114a-h from which sound is able to propagate out from the loudspeaker unit substantially uninhibited are labelled '-'. A skilled reader will appreciate this labelling is just a labelling convention that has been adopted to indicate phase difference, and such labels could easily be reversed.

A skilled person will also understand from the discussion below that where sound guides 122a-h, 124a-h are used, the loudspeaker unit 101a-h is preferably configured so that, at the poles 132a-h, 134a-h (i.e. the locations at which sound propagates out from the loudspeaker unit, as guided by a sound guide or not as the case may be), and preferably in the operational bandwidth of the loudspeaker unit, the sound produced by the(/each) first radiating surface 112a-h is substantially out of phase with the sound produced by the(/each) second radiating surface 114a-h, since this helps to achieve an effective personal sound cocoon. Reasons why an effective personal sound cocoon can be created by substantially out-of-phase poles are explained e.g. in PCT/EP2018/084636, GB1721127.7 and GB1805525.1 .

In the example of Fig. 1(a), the loudspeaker unit 101a includes one diaphragm 110a, one sound guide 122a configured to guide sound produced by the first radiating surface 112a of the diaphragm 110a to two outlets 132a, 132a' and one sound guide 124a configured to guide sound produced by the second radiating surface 114a of the diaphragm 110a to two outlets 134a, 134a'.

In this particular example, each sound guide 122a, 124a is shown respectively as including a pair of tubes, each of which form a passage which extends from a respective shared space in front of one of the radiating surfaces 112a, 114a of the diaphragm 110a.

In the example of Fig. 1(b), the loudspeaker unit 101b includes one diaphragm 110b, one sound guide 122b configured to guide sound produced by the first radiating surface 112b of the diaphragm 110b to four outlets 132b, 132b', 132b'', 132b''' and one sound guide 124b configured to guide sound produced by the second radiating surface 114b of the diaphragm 110b to four outlets 134b, 134b', 134b'', 134b'''.

The tubes of the loudspeaker units 101a, 101b shown in Figs. 1(a)-(b) clearly have a cross sectional area that is smaller than the surface area of the corresponding radiating surface.

In the example of Fig. 1(c), the loudspeaker unit 101c includes one diaphragm 110c, one sound guide 122c configured to guide sound produced by the first radiating surface 112c of the diaphragm 110c to one outlet 132c and one sound guide 124c configured to guide sound produced by the second radiating surface 114c of the diaphragm 110c to one outlet 134c.

The sound guides 122c, 124c of this loudspeaker unit 101c include a tapering portion such that the cross sectional area of the passage formed by each sound guide is smaller than the surface area of the corresponding radiating surface.

In the example of Fig. 1(d), the loudspeaker unit 101d includes one diaphragm 110d, one sound guide 122d configured to guide sound produced by the first radiating surface 112d of the diaphragm 110d to two outlets 132d, 132d' and one sound guide 124d configured to guide sound produced by the second radiating surface 114d of the diaphragm 110d to one outlet 134d.

In the example of Fig. 1(e), the loudspeaker unit 101e includes one diaphragm 110e, one sound guide 124e configured to guide sound produced by the second radiating surface 114e of the diaphragm 110e to an outlet 134e. In this example, the first radiating surface 112e of the diaphragm 110e is configured to produce sound that is radiated directly out from the loudspeaker unit 101e to form pole 132e, i.e. without being guided by a sound guide.

The flared tube provided by the sound guides 124d, 124e of the loudspeaker units 101d, 101e shown in Figs. 3(d)-(e) can reduce “blowing” noise by reducing the particle velocity at the remote pole. These loudspeaker units 101d, 101e also have non-symmetrically arranged sound guides.

In the example of Fig. 1(f), the loudspeaker unit 101f includes two diaphragms 110f-1, 110f-2, one sound guide 122f-1 is configured to guide sound produced by the first radiating surface 112f-1 of a first one of the diaphragms 110f-1 to two outlets 132f-1, 132f'-1, one sound guide 122f-2 is configured to guide sound produced by the first radiating surface 112f-2 of a second one of the diaphragms 110f-2 to two outlets 132f-2, 132f'-2, and one sound guide 124f is configured to guide sound produced by the second radiating surfaces 114f-1, 114f-2 of both diaphragm 110f-1, 110f-2 to four outlets 134f, 134f', 134f'', 134f'''.

In the example of Fig. 1(g), the loudspeaker unit 101g includes two diaphragms 110g-1, 110g-2, one sound guide 122g-1 is configured to guide sound produced by the first radiating surface 112g-1 of a first one of the diaphragms 110g-1 to one outlet 132g-1, one sound guide 122g-2 is configured to guide sound produced by the first radiating surface 112g-2 of a second one of the diaphragms 110g-2 to one outlet 132g-2, and one sound guide 124g is configured to guide sound produced by the second radiating surfaces 114g-1, 114g-2 of both diaphragm 110g-1, 110g-2 to two outlets 134g, 134g'.

The loudspeaker units 101f, 101g shown in Figs. 1(f)-(g) have their diaphragms 110f, 110g mounted with their second radiating surfaces 114f, 114g back to back, which is advantageous to produce little vibration aside from the volume velocity due to force cancelling between the two diaphragms 110f, 110g.

In the example of Fig. 1(h), the loudspeaker unit 101h includes two diaphragms 110h-1, 110h-2, one sound guide 122h-1 is configured to guide sound produced by the first radiating surface 112h-1 of a first one of the diaphragms 110h-1 to two outlets 132h-1, 132h'-1, one sound guide 122h-2 is configured to guide sound produced by the first radiating surface 112h-2 of a second one of the diaphragms 110h-2 to two outlets 132h-2, 132h'-2, one sound guide 124h-1 is configured to guide sound produced by the second radiating surface 114h-1 of the first one of the diaphragms 110h-1 to one outlet 134h-1, and one sound guide is configured to guide sound produced by the second radiating surface 114h-2 of the second one of the diaphragms 110h-2 to one outlet 134h-2.

The loudspeaker unit 101h shown in Fig. 1(h) may, for example, facilitate the provision of stereo sound to a listener, e.g. since the two diaphragms 110h-1, 110h-2 can be driven by different stereo channels of an audio signal.

Fig. 2 shows some of the various multipole (including higher order multipole) configurations that may be achieved according to the positioning of remote poles.

The examples shown in Figs. 2(a)-(c) are a dipole (Fig. 2(a)), a quadrupole (Fig. 2(b)), and an octopole (Fig. 2(c)).

The eight poles as shown in Figs. 2(a)-(c) could be produced by the loudspeaker 101b as shown in Fig. 1(b) for example, but could also be produced from the two radiating surfaces of a single diaphragm.

As explained in PCT/EP2019/056109 and GB1805523.6, higher order multipole configurations (e.g. quadrupole; Fig. 2(b), octopole; Fig. 2(c)) can allow improved cocooning compared to dipole arrangements.

The improvement in cocooning for higher order multipole configurations may be understood from a theoretical consideration of path length. A dipole can be regarded as equivalent to two monopoles spaced by a distance D, see Fig. 2(a). The SPL p at bass frequencies in the far field, k and D can be theoretically represented by the following relation:

$$p \propto k \cdot D \qquad (1)$$

where $k = 2\pi/\lambda$, and λ is the wavelength of sound.

Similarly, a quadrupole loudspeaker can be represented by four monopoles separated by a distance D along the *x* axis, and d along the *y* axis; Fig. 2(b). In this case, the SPL at bass frequencies in the far field, k and D can be theoretically represented by the following relation:

$$p \propto k^2 \cdot D \cdot d \qquad (2)$$

An octopole loudspeaker can be represented by eight monopoles separated by a distance D along the *x* axis, d along the *y* axis and d' along the *z* axis. The SPL at bass frequencies in the far field can be represented by:

$$p \propto k^3 \cdot D \cdot d \cdot d' \qquad (3)$$

From relations (1), (2) and (3) above, it can be seen that:

- Reducing D. d. or d' will reduce the far field SPL of the loudspeaker, improving the cocooning effect.
- The k, k^2, and k^3 terms mean that the farfield SPL drops off more rapidly with frequency for higher order multipoles, improving the cocooning effect for lower frequencies.

Therefore, the use of remote poles to create reduced path lengths or higher order multipolar loudspeakers can allow improvements of the loudspeaker cocooning effect, even with a single diaphragm.

Figs. 2(d)-(f) show alternative arrangements that are also possible through the use of remote poles, even from a single diaphragm, such as arrangements which place remote poles close to each ear of the listener for improved volume velocity transmission.

Some example loudspeaker units according to the first aspect of the invention that are implemented in a car headrest or car seat will now be described.

Figs. 3(a)-(b) show a headrest 250a for a car that includes a loudspeaker unit 201a according to the first aspect of the invention, as viewed from the front (Fig. 3(a)), and top (Fig. 3(b)).

The headrest 250a has a frame 252 and mounting pins 254 configured to rigidly connect the headrest to a rigid seat frame (not shown).

In this example, the loudspeaker unit 201a includes two diaphragms 210a-1, 210a-2, one sound guide 222a-1 is configured to guide sound produced by the first radiating surface 212a-1 of a first one of the diaphragms 210a-1 to one outlet 232a-1, one sound guide 222a-2 is configured to guide sound produced by the first radiating surface 212a-2 of a second one of the diaphragms 210a-2 to one outlet 232a-2, and one sound guide 224a is configured to guide sound produced by the second radiating surfaces 214a-1, 214a-2 of both diaphragms 210a-1, 210a-2 to two outlets 234a, 234a'.

In this example, the sound guides 222a-1, 222a-2, 224a are passages formed by walls of a frame 252 of the headrest 250a.

In this example, each diaphragm 210a-1, 210a-2 is a paper cone, suspended from the frame 252 by a roll suspension 216a-1, 216a-2 and a spider 217a-1, 217a-2. An electromagnetic drive unit 218a-1, 218a-2 is provided for each diaphragm 210a-1, 210a-2.

The two diaphragms 210a-1, 210a-2 are oriented back to back, i.e. with the second radiating surface 214a-1 of one diaphragm 210a-1 facing the second radiating surface 214a-2 of the other diaphragm 210a-2, with the two radiating surfaces 214a-1, 214a-2 radiating into a shared space 219a, since this helps with force cancellation. The shared space 219a is only partially enclosed.

As shown in Fig. 3(b), the loudspeaker unit 201a is configured for use with a first (right) ear of a user located at a first listening position that is close to (e.g. 20cm or less) from the outlet 232a-1, whilst a second (left) each of the user is located at a second listening position that is close to (e.g. 20cm or less) from the outlet 232a-2.

The car seat incorporating the headrest 250a preferably is configured to position a user who is sat down in the seat such that their first and second ears are located in the first and second listening positions as described above.

In this way, sound from the first radiating surfaces 212a-1, 212a-2 is guided to outlets 232a-1, 232a-2 close to the ears of a user so that the user can clearly hear in-phase sound produced by the first radiating surfaces 212a-1, 212a-2, whilst a person who is further away from the outlets 232a-1, 232a-2 than the user will preferably hear sound with a significantly reduced SPL level (compared with ordinary monopole loudspeakers producing the same SPL level at the ears of the user) it is believed due to interference from out of phase sound produced by the second radiating surfaces 214a-1, 214a-2.

Fig. 4 shows a headrest 250b for a car that includes a loudspeaker unit 201b according to the first aspect of the invention, as viewed from the top.

In this example, the loudspeaker unit 201b includes one diaphragm 210b, one sound guide 222b is configured to guide sound produced by the first radiating surface 212b of the diaphragms 210b to two outlets 232b, 232b', and one sound guide 224b configured to guide sound produced by the second radiating surface 214b of the diaphragms 210b to two outlets 234b, 234b'.

In this case, the sound guides 222a, 222b take the form of plates located in front of the radiating surfaces 212a, 212b which are configured to guide sound to the outlets 232b, 232b', 234b, 234b'.

In this example, the diaphragm 210b is a single (monolithic) piece of lightweight material such as extruded polystyrene having a density of 0.1 g/cm^3 or less.

In this example, the loudspeaker unit has a dual frame configuration in which the diaphragm 210b is suspended from a primary frame 251b via primary suspension elements which in this example are roll suspensions 216b. The primary frame 251b is suspended from a secondary frame 252b via secondary suspension elements which in this example are spiders 217b.

As shown in Fig. 4, the primary frame 251b includes arms 253b configured to hold a magnet unit 255b of a drive unit in front of the secondary radiating surface 214b of the diaphragm 210.

The diaphragm includes cavities (now shown) in the secondary radiating surface 214b, wherein each cavity is configured to have a respective arm 253b extend through it when the loudspeaker is in use. This allows the loudspeaker unit to have a lower profile in the thickness direction of the diaphragm 210b.

The secondary frame 250b may be part of, or may be configured to fixedly attach to, a rigid supporting structure, such as a car seat frame, e.g. via mounting pins (not shown).

The loudspeaker unit 201b includes a safety element 257b which is located between the magnet unit 255b and the second radiating surface 214b of the diaphragm. The safety element 257b is configured to prevent the magnet unit 255b from passing through the diaphragm 210b, e.g. in a crash event or another event that involves a sudden deceleration of the loudspeaker unit 201b (e.g. where the loudspeaker unit 201b has been moving in the direction of the principal radiating axis of the first radiating surface 212b). The safety element 257b is preferably rigid. The safety element 257b may be a voice coil coupler configured to attach the voice coil to the diaphragm 210b.

Again, the loudspeaker unit 201b is configured for use with a first (right) ear of a user located at a first listening position that is close to (e.g. 20cm or less) from the outlet 232b, whilst a second (left) each of the user is located at a second listening position that is close to (e.g. 20cm or less) from the outlet 232b'.

The loudspeaker unit 201b has an additional benefit of reducing the path-length D compared to an equivalent loudspeaker unit 201b lacking the guiding plates 222a, 222b, thereby improving the cocooning effect, as can be seen from relation (2) above.

Figs. 5(a)-(b) show a car seat 240c including an integral headrest 250c, wherein the car seat includes a loudspeaker unit 201c according to the first aspect of the invention, as viewed from the front (Fig. 5(a)) and side (Fig. 5(b)).

In this example, the loudspeaker unit 201c is similar the same as the loudspeaker unit 201a shown in Figs. 3(a)-(b), except that here the loudspeaker unit 201c is mounted in a body of the car seat 240c, with sound guides 222c-1, 222c-2 being configured to respectively guide sound from the first radiating surfaces 212c-1, 212c-2 of diaphragms 210c-1, 210c-2 to outlets 232a-1, 232a-2 which are located such that, in use, a first (right) ear of a user located at a first listening position that is close to (e.g. 20cm or less) from the outlet 232a-1, whilst a second (left) each of the user is located at a second listening position that is close to (e.g. 20cm or less) from the outlet 232a-2.

A sound guide 224c is configured to guide sound produced by the second radiating surfaces 214c-1, 214c-2 of both diaphragms 210c-1, 210c-2 to an outlet 234c at the rear of the seat.

In this case, the sound guides 222c-1, 222c-2, 224c are passages formed by internal walls of the car seat 240c.

In this example, the sound guide 224c includes a tapering portion such that the cross sectional area of the passage formed by each sound guide is smaller than the surface area of the corresponding radiating surface.

An arrangement as shown in Figs. 5(a)-(b) allows use of speakers/diaphragms that are impractical for locating in a car headrest.

Figs. 6(a)-(b) show a car seat 240d including an integral headrest 250d, wherein the car seat includes a loudspeaker unit 201d according to the first aspect of the invention, as viewed from the front (Fig. 6(a)) and side (Fig. 6(b)).

The car seat 240d shown in Figs. 6(a)-(b) is the same as the car seat 240c shown in Figs. 5(a)-(b) except that in this example, the sound guide 224d omits the tapering portion that was included in the sound guide 224c of Figs. 5(a)-(b), so there is no deliberate guiding of sound here (though the internal walls of the car seat may to some extent guide sound out from the back of the car seat).

<u>Examples implementing second aspect of the invention</u>

Various loudspeaker units implementing the second aspect of the invention will now be described. Where possible, alike features previously described have been given corresponding reference numerals, such that such features may not need to be described in further detail.

Figs. 7(a)-(c) are schematic views of various loudspeaker units 301a-c which implement the second aspect of the invention.

In each case, the loudspeaker unit 301a-c has an array of two or more diaphragms 310a-c, 311a-c each diaphragm 310a-c, 311a-c in the array having a first radiating surface 312a-c, 314a-c and a second radiating surface 313a-c, 315a-c, wherein the first radiating surface 312a-c, 314a-c and the second radiating surface 313a-c, 315a-c are located on opposite faces of the diaphragm 310a-c, 311a-c, and wherein one or more of the diaphragms 310a-c are included in a first subset of the diaphragms and one or more of the diaphragms 311a-c are included in a second subset of the diaphragms.

Each loudspeaker unit 301a-c also includes a plurality of drive units (not shown), wherein each drive unit is configured to move a respective one of the diaphragms 310a-c, 311a-c in the array based on a respective electrical signal.

Each loudspeaker unit 301a-c also includes drive circuitry (not shown) configured to provide each drive unit with a respective electrical signal derived from the same audio source such that the electrical signal(s) provided to the one or more drive units configured to move the first subset of diaphragms 310a-c is/are out of phase with respect to the electrical signal(s) provided to the one or more drive units configured to move the second subset of diaphragms 311a-c.

Each loudspeaker unit 301a-c also includes:

one or more sound guides 322a-c each respectively configured to guide sound produced by one or more first radiating surfaces 312a-c of one or more diaphragms 310a-c in the first subset to at least one outlet 332a-c such that the sound propagates out of the loudspeaker unit from the at least one outlet 332a-c, the/each outlet 332a-c being remote from one or more first radiating surfaces 312a-c of the one or more diaphragms 310a-c in the first subset; and/or

one or more sound guides 323a-c each respectively configured to guide sound produced by one or more first radiating surfaces 314a-c of one or more diaphragms 311a-c in the second subset to at least one outlet 334a-c such that the sound propagates out of the loudspeaker unit from the at least one outlet 334a-c, the/each outlet 334a-c being remote from said one or more first radiating surfaces 314a-c of the one or more diaphragms 311a-c in the second subset.

Each loudspeaker unit 301a-c also includes at least one enclosure 306 defining an enclosed space 307 configured to receive sound produced by the second radiating surfaces 313a-c, 315a-c. The at least one enclosure 306 is configured to significantly inhibit sound produced by the second radiating surfaces 313a-c, 315a-c from propagating out from the loudspeaker unit 301a-c, i.e. such that each diaphragm can be viewed as providing a respective monopole loudspeaker.

In the following drawings, the poles 332a-c to which sound is guided from one or more first radiating surfaces 312a-c of diaphragms 310a-c in the first subset are labelled as '+', whereas poles 334a-c to which sound is guided from one or more first radiating surfaces 314a-c of diaphragms in the second subset are labelled as '-', to indicate that sound emitted at poles 332a-c is out of phase from sound emitted at poles 334a-c. Similarly, first radiating surfaces 312a-c of diaphragms 310a-c in the first subset from which sound is able to propagate out from the loudspeaker unit substantially uninhibited are labelled '+' whereas first radiating surfaces 314a-c of diaphragms 311a-c in the second subset from which sound is able to propagate out from the loudspeaker unit substantially uninhibited are labelled '-'. A skilled reader will appreciate this labelling is just a labelling convention that has been adopted to indicate phase difference, and such labels could easily be reversed.

A skilled person will also understand from the discussion below that where sound guides 322a-c, 323a-c are used, the loudspeaker unit 301a-c is preferably configured so that, at the poles 332a-c, 334a-c (i.e.

the locations at which sound propagates out from the loudspeaker unit, as guided by a sound guide or not as the case may be), and preferably in the operational bandwidth of the loudspeaker unit, the sound produced by the first radiating surface 312a-c of the(/each) diaphragm 310a-c in the first subset is substantially out of phase with the sound produced by the first radiating surface 314a-c of the(/each) diaphragm 311a-c in the second subset, since this helps to achieve an effective personal sound cocoon. Reasons why an effective personal sound cocoon can be created by substantially out-of-phase poles are explained e.g. in PCT/EP2018/084636, GB1721127.7 and GB1805525.1.

In the example of Fig. 7(a), the loudspeaker unit 301a includes one diaphragm 310a in the first subset, one diaphragm 311a in the second subset, and one sound guide 322a configured to guide sound produced by the first radiating surface 312a of the diaphragm 310a in the first subset to one outlet 332a.

In the example of Fig. 7(b), the loudspeaker unit 301b includes one diaphragm 310b in the first subset, one diaphragm 311b in the second subset, one sound guide 322b configured to guide sound produced by the first radiating surface 312b of the diaphragm 310b in the first subset to one outlet 332b, one sound guide 324b configured to guide sound produced by the first radiating surface 314b of the diaphragm 311b in the second subset to one outlet 334b.

The loudspeaker unit 301b shown in Fig. 7(b) has its diaphragms 310b, 311b mounted with the second radiating surface 313b of the diaphragm 310b in the first subset facing the first radiating surface 314b of the diaphragm 311b in the second subset, which is advantageous to produce little vibration aside from the volume velocity due to force cancelling between the two diaphragms 310b, 311b.

In the example of Fig. 7(c), the loudspeaker unit 301c includes two diaphragms 310c-1, 310c-2 in the first subset, two diaphragms 311c-1, 311c-2 in the second subset, one sound guide 322c-1 configured to guide sound produced by the first radiating surface 312c-1 of a first diaphragm 310c-1 in the first subset to two outlets 332c-1, 332c-1', one sound guide 322c-2 configured to guide sound produced by the first radiating surface 312c-2 of a second diaphragm 310c-2 in the first subset to two outlets 332c-2, 332c-2', one sound guide 324c-1 configured to guide sound produced by the first radiating surface 314c-1 of a first diaphragm 311c-1 in the second subset to one outlet 334c-1, one sound guide 324c-2 configured to guide sound produced by the first radiating surface 314c-2 of a first diaphragm 311c-2 in the second subset to one outlet 334c-2.

In this example, the loudspeaker unit 301c includes two pairs of diaphragms, a first pair of diaphragms including the two diaphragms 310c-1, 310c-2 in the first subset and a second pair of diaphragms including the two diaphragms 311c-1, 311c-2 in the second subset. The two diaphragms of each pair of diaphragms are oriented back to back, i.e. with the second radiating surface of one diaphragm of the pair facing the second radiating surface of the other diaphragm of the pair, with the two radiating surfaces radiating into a shared space 307c enclosed by a single enclosure 306c, since this helps with force cancellation.

An example loudspeaker unit according to the second aspect of the invention that is implemented in a car headrest will now be described.

Figs. 8(a)-(b) show a headrest 450a for a car that includes a loudspeaker unit 401a according to the second aspect of the invention, as viewed from the front (Fig. 8(a)), and top (Fig. 8(b)).

In this example, the loudspeaker unit 401a includes one diaphragm 410a in the first subset, one diaphragm 411a in the second subset, one sound guide 422a configured to guide sound produced by the first radiating surface 412a of the diaphragm 410a in the first subset to two outlets 432-a, 432a', one sound guide 424a configured to guide sound produced by the first radiating surface 414a of the diaphragm 411a in the second subset to one outlet 434a.

In this example, the sound guides 422a, 424a are passages formed by internal walls of the car seat 240c, the outlets 432a, 432a' are configured to be located close to the ears of a user whereas the outlet 434a is located at the top of the headrest 450a.

In this example, the diaphragms 410a, 411b and their corresponding drive units have an operating bandwidth of up to 150Hz. Therefore, to provide the user with full range stereo audio, the headrest 450 includes two additional, smaller, monopole, loudspeakers 460, integrated into the tubing to produce sound having medium and high frequencies. The additional loudspeakers 460 are highly directional, and configured to direct sound only towards the depicted user, thereby providing said user with a full range personal sound cocoon.

The features disclosed in the present description, or in the following claims, or in the accompanying drawings, expressed in their specific forms or in terms of a means for performing the disclosed function, or a method or process for obtaining the disclosed results, as appropriate, may, separately, or in any combination of such features, be utilised for realising the invention in diverse forms thereof.

While the invention has been described in conjunction with the exemplary embodiments described above, many equivalent modifications and variations will be apparent to those skilled in the art when given this disclosure. Accordingly, the exemplary embodiments of the invention set forth above are considered to be illustrative and not limiting. Various changes to the described embodiments may be made without departing from the spirit and scope of the invention.

For the avoidance of any doubt, any theoretical explanations provided herein are provided for the purposes of improving the understanding of a reader. The inventor does not wish to be bound by any of these theoretical explanations.

Any section headings used herein are for organizational purposes only and are not to be construed as limiting the subject matter described.

Throughout this specification, including the claims which follow, unless the context requires otherwise, the word “comprise” and “include”, and variations such as “comprises”, “comprising”, and “including” will be understood to imply the inclusion of a stated integer or step or group of integers or steps but not the exclusion of any other integer or step or group of integers or steps.

It must be noted that, as used in the specification and the appended claims, the singular forms “a,” “an,” and “the” include plural referents unless the context clearly dictates otherwise. Ranges may be expressed herein as from “about” one particular value, and/or to “about” another particular value. When such a range is expressed, another embodiment includes from the one particular value and/or to the other particular value. Similarly, when values are expressed as approximations, by the use of the antecedent “about,” it will be understood that the particular value forms another embodiment. The term “about” in relation to a numerical value is optional and means for example +/- 10%.

Experimental data

Experimental data 1

Figs. 9(a)-(b) illustrate an experimental set up used to obtain experimental data 1.

Figs. 9(c)-(d) illustrate experimental data 1 obtained using the experimental set up of Figs. 9(a)-(b).

Experiments were performed to determine the influence of the sound guide width on the SPL at a distance r from the guide outlet.

These experiments were performed using a loudspeaker mounted in a tube as shown in Figs. 9(a)-(b). The length of the tube (D) is 17 cm, loudspeaker effective area is 95 cm^2, and the applied voltage is 2 V. The frequency used for evaluation was 100 Hz.

For one measurement, the diameter of the opening was 9cm (A) at both ends of the tube; Fig. 9(a), while in the second, the diameter was 5cm (B) on the measurement (+) end of the tube, but remained 9cm on the other (-) end of the tube; Fig. 9(b). The tube length (D) in both cases was 17cm. The area of the speaker was 95cm^2, operating frequency was 100Hz, and applied voltage was 2V.

In both cases, the SPL was measured at different distances from the + opening of the tube, and the results of these measurements are shown in Fig. 9(c). Fig. 9(d) shows the data normalised to the SPL at r=0 for the 9cm opening. In both Fig. 9(c) and Fig. 9(d), the measurements for the 5cm opening are indicated with a dashed line, and those for the 9cm opening are indicated with a solid line

At large distances, the SPL from both measurements is equal, but at shorter distances, the SPL is significantly higher for the smaller opening (~10dB higher) than the larger. The results from the experiment may be understood as follows. The SPL (p) at a point is determined by the particle velocity (v) and the specific acoustic impedance (Zs) of the acoustic medium (i.e. air): $Zs = \frac{p}{v}$. Zs has a fixed value, meaning that an increase in v leads to an increase in p and vice versa. The loudspeaker generates a fixed volume velocity ($v.S$), where S is the surface area of the opening. Reducing S therefore leads to an increase in v, and hence p close to the opening of the tube. The expected increase, $20\log\left(\frac{S1}{S2}\right) \approx 10\ dB$, where $S1$ and $S2$ are the surface areas of the two tubes, corresponds with the measured result, as shown in Fig. 9(d). This effect is marginally beneficial for the proximity effect, since there is an increased contrast between the SPL between near and far listening positions.

Experimental data 2

Fig. 10(a) illustrates an experimental set up used to obtain experimental data 2.

Figs 10(b)-(c) illustrate experimental data 2 obtained using the experimental setup of Fig 10(a).

Experiments were performed to confirm that the proximity effect was still obtainable when remote poles are used, as well as the effect of passage positioning (in terms of opening separation) on this.

The experiments were performed using a loudspeaker mounted in a tube, with a flexible tube attached to each end of the loudspeaker tube; Fig. 10(a). The flexible sound passages had a length of 50 cm, and diameter 4 cm. The evaluation frequency was 60 Hz.

The sound passage outlets were positioned 10 cm, 20 cm, and 40 cm apart (D), and the SPL at distance r from the sound passage outlet connected to the front (+) side of the loudspeaker was measured. The measured and normalised SPL are shown in Figs. 10(b)-(c) respectively.

As explained above with reference to Fig. 2(a), and is can be seen from the teaching of PCT/EP2019/056109 and GB1805523.6, the relationship between the SPL p, k, and D produced by a dipole loudspeaker unit in the farfield can theoretically be represented by relationship (1): $p \propto k \cdot D$. From this, it can be calculated that the SPL in the farfield is expected to increase by 6dB for every doubling of D, $\left(20\log\left(\frac{D1}{D2}\right) \approx 6\ dB\right)$, which is confirmed by the data; Figs. 10(b)-(c). This result therefore confirms that the remote poles enabled by the sound guides behave equivalently to monopole sources positioned at their outlets. This confirms that the use of sound guides allows the loudspeaker output to be moved to arbitrary positions with no detrimental impact on the cocooning effect. Meanwhile, by varying the distance between the poles, the contrast in SPL between near and far listening positions can be adjusted to control the level of cocooning.

Experimental data 3

Fig. 11(a) shows the parameters necessary to model a Helmholtz resonator such as the sound guides detailed in the present invention.

Fig. 11(b) shows the lumped element model and relevant parameters used to obtain experimental data 3a and 3b.

Experimental data 3a

Figs. 12(a)-(f) show experimental data obtained from the model depicted in Fig. 11(b) intended to model loudspeaker units according to the first aspect of the invention.

The loudspeaker parameters used were: Sd = 95cm², Mms = 14.8 g, Cms = 0.536×10⁻³ m/N, Qms = 5.4, Bl = 8.33 Tm, Re = 4.53 Ω, Le = 0.1 mH. It is known in acoustics that a chamber with volume V when combined with a tube L, such as the sound passages described in the present invention forms a Helmholtz resonator with a tuning frequency f_t, since the volume of air in the chamber provides a compliance (C) for the mass of air inside the tube, M. This is depicted in Fig. 11(a). f_t may be determined from $f_t = \frac{1}{2\cdot\pi\cdot\sqrt{M\cdot C}}$ where $M = \rho_0 \cdot S \cdot L$, and $C = \frac{V}{\rho_0\cdot c^2\cdot S^2}$. S is the cross-sectional area of the tube, c is the speed of sound in the medium, and ρ_0 is the medium density. Helmholtz resonators are well known for use with bass loudspeakers. For a conventional bass loudspeaker, the aim is to keep f_t of the Helmholtz resonator at a value that corresponds to the range of frequencies being produced (typically 20Hz to 100Hz) in order to maximise bass performance at the tuned frequency. However, in the present invention, for the reasons described below, it is preferable for f_t to fall outside the operational bandwidth of the loudspeaker, more preferably above the operating range of the loudspeaker. f_t can be tuned by varying either the dimensions (L, S) of the passage, or the volume (V) of the loudspeaker chamber. Care is important, however, as overly long/narrow passages may introduce additional effects on the sound propagation (such as influence from frictional losses along the passage). Additionally, overly narrow passages may have high particle velocity within the tubing, which can case audible blowing noise. Design features such as flaring of the tube at the pole exit and/or adding porous material to reduce the blowing noise may therefore be considered.

The effect of design considerations such as sound passage width and length, including situations where these are not equal for both/all the passages, was modelled using a lumped element model, with parameters as depicted in Fig. 11(b). All terms are as defined above, with primed terms (L', V', M', S, C'). In particular, the system was studied for the phase response of the two poles, noting that antiphase ($\sim 180°$ phase difference) is required for adequate cocooning.

Five setups are considered through the model:

A system (system 1) with identical sound passage parameters for both sides of the loudspeaker; Fig. 12(a):

$L = L' =$ 25cm

$V = V' =$ 0.5L

$S = S' =$ 20cm²

A system (system 2) with a small difference in length between the sound passages on each side of the loudspeaker; Fig. 12(b):

$L =$ 50cm, $L' =$ 45cm

$V = V' =$ 0.5L

$S = S' =$ 20cm²

A system (system 3) with a large length and width difference between the sound passages on each side of the loudspeaker; Fig. 12(c):

$L = 50\text{cm}$, $L' = 5\text{cm}$

$V = V' = 0.5\text{L}$

$S = 20\text{cm}^2$, $S' = 60\text{cm}^2$

A system (system 4) with identical (but long) sound passages for both sides of the loudspeaker; Fig. 12(d):

$L = L' = 150\text{cm}$

$V = V' = 0.5\text{L}$

$S = S' = 12.6\text{cm}^2$

A system (system 5) with identical (but short) sound passages for both sides of the loudspeaker; Fig. 12(e).

$L = L' = 10\text{cm}$

$V = V' = 0.5\text{L}$

$S = S' = 20\text{cm}^2$

The figures chart the phase response of the volume velocity immediately in front of the first (+) radiating surface of the loudspeaker ("loudspeaker" – thin line), and at the outlets of each of the tubes ("LVS" – front side – thick dark line, "L'V'S'" – reverse side – thick light line). It is the phase response at the outlets of each of the tubes ("LVS" and "L'V'S'") that represents the sound propagating out from the loudspeaker unit at the outlets (or "poles").

Figs. 12(a)-(e) reveal a number of outcomes which can inform design of systems based on the present invention. Note that in all graphs, where "LVS", "L'V'S'" or "loudspeaker" appear to "jump" across zero (e.g. ~30 Hz, ~180 Hz, ~300 Hz in Fig. 12(a)) is due to 180° and -180° phase difference being equivalent (i.e. the graph continues from the bottom of the *y*-axis to the top of the *y*-axis).

In all cases, the "loudspeaker" line is in phase with the "L V S" line while operating below f_t, and is out of phase with the "L V S" line while operating above f_t, where f_t is the lowest tuned system of both Helmholtz resonators. This "phase reversal" is a well-known phenomenon in bass loudspeaker design.

Systems 1, 4, 5; Figs. 12(a), 12(d), 12(e), show that any system with identical tubing/passage parameters on both sides of the loudspeaker will remain in antiphase for all operating frequencies, even if the tuning frequency falls within the operating range. This is to be expected from above, as $f_t = f_t'$, and the phase reversal to "loudspeaker" will occur at the same frequency for both "LVS" and "L'V'S'". For the three systems, $f_t = 180\text{Hz}$ (system 1), 45Hz (system 4) and 292Hz (system 5) respectively. This is true even for long/narrow tubing (system 4; Fig. 12(d)), although other issues, such as the formation of standing waves within the passage may prevent long/narrow tubing from being used in practice. Short/wide tubing (system 5; Fig. 12(e)), meanwhile, leads to a higher f_t, and can therefore allow for wider operational bandwidths (since as discussed herein it is generally preferably to have tuning frequencies f_t, f_t' which lie above the operational bandwidth of the loudspeaker unit.

System 2; Fig. 12(b), shows that a small difference between the two sound passage dimensions leads to a deviation from the out of phase behaviour of the poles at and around f_t. For system 2, f_t ≈120Hz. Again, this is to be expected from above, since $f_t \approx f_t'$, and the phase reversal compared to "loudspeaker" will therefore occur for similar but not identical frequencies for "LVS" and "L'V'S'". This indicates that any differences between the sound passages are preferably kept to a minimum, or the system is designed such that the operational bandwidth of the loudspeaker does not include f_t, and preferably falls below f_t.

System 3; Fig. 12(c), shows the effect of having minimal or no tubing on one side (the reverse in this example) of the loudspeaker. In this case, "LVS" and "L'V'S'" are in phase for frequencies above f_t (≈120Hz), meaning that the cocooning effect will no longer work. In this case, the lack of tubing for the reverse side means that this side will have a high tuning frequency or no measurable tuning frequency at all in practice. This indicates that the system is possible with minimal/no tubing on one side of the loudspeaker, but that it is preferably designed such that the operating frequency range is below f_t.

Experimental data 3b

Fig. 13 shows experimental data obtained from the model depicted in Fig. 11(b), intended to model a classic bandpass subwoofer.

The loudspeaker parameters used here were: Sd = 95cm², Mms=14.8g, Cms=0.536e-3m/N, Qms=5.4, Bl=8.33Tm, Re=4.53ohm, Le=0.1mH, with sound passage parameters as follows:

L = 20cm, L' =10cm

V = 15L, V' =2L

$S = S'$ = 20cm^2

These parameters lead to the Helmholtz resonators respectively formed by the sound guides on either side of the diaphragm having different tuning frequencies, f_t ≈50Hz and f_t' ≈160Hz.

As is known in the art, between these two tuning frequencies (i.e. in the bandpass region between 50Hz and 160Hz), "LVS" and "L'V'S'" are substantially in phase, resulting in an enhanced bass performance between these two frequencies, which corresponds to the operational frequency of a typical classic bandpass subwoofer.

Contrast this with examples of the invention (such as those discussed in experimental data 3a), for which it is preferred that the tuning frequencies f_t, f_t' are equal, or that both tuning frequencies f_t, f_t''s are higher than the upper frequency of the operational bandwidth of the loudspeaker unit, such that both poles of the loudspeaker unit can be substantially out of phase in the operational bandwidth of the loudspeaker unit, i.e. with no bandwidth in which the poles are substantially in phase falling within the operational bandwidth of the loudspeaker unit.

References

A number of publications are cited above in order to more fully describe and disclose the invention and the state of the art to which the invention pertains. Full citations for these references are provided below. The entirety of each of these references is incorporated herein.

[1] https://en.wikipedia.org/wiki/Equal-loudness_contour

[2] http://www.linkwitzlab.com

[3] https://www.techopedia.com/definition/31557/head-tracking

[4] http://www.autoguide.com/auto-news/2017/08/two-companies-are-working-on-bringing-in-car-sensing-tech-to-new-cars.html

[5] https://sharpbrains.com/blog/2014/09/02/general-motors-to-adopt-eye-head-tracking-technology-to-reduce-distracted-driving/

[6] http://www.patentlyapple.com/patently-apple/2016/08/apple-wins-patent-for-advanced-3d-eyehead-tracking-system-supporting-apples-3d-camera.html

[7] "Face Recognition and Head Tracking in Embedded Systems", Lenka Ivantysynova and Tobias Scheffer, Optik&Photonik, January 2015, pages 42-45.

[8] "Dynamical Measurement of the Effective Radiation Area S_D", 128th Audio Engineering Society Convention 2010, 1, 568-577.

Claims:

1. A loudspeaker unit for producing sound at bass frequencies, including:

a diaphragm having a first radiating surface and a second radiating surface, wherein the first radiating and second radiating surfaces are located on opposite faces of the diaphragm, and wherein the loudspeaker unit is configured to allow sound produced by the first and second radiating surfaces to propagate out from the loudspeaker unit;

a drive unit configured to move the diaphragm based on an electrical signal;

a frame from which the diaphragm is suspended via one or more suspension elements;

drive circuitry configured to provide the drive unit with an electrical signal derived from an audio source;

a sound guide configured to guide sound produced by the first or second radiating surface to at least one outlet such that the sound propagates out of the loudspeaker unit from the at least one outlet, the/each outlet being remote from said first or second radiating surface;

wherein the loudspeaker unit is preferably configured so that, at the locations at which sound propagates out from the loudspeaker, and preferably in the operational bandwidth of the loudspeaker unit, the sound produced by the/each first radiating surface is substantially out of phase with the sound produced by the/each second radiating surface.

2. A loudspeaker unit according to claim 1, wherein the loudspeaker unit includes:

a plurality of diaphragms, each diaphragm having a first radiating surface and a second radiating surface, wherein the first radiating and second radiating surfaces of each diaphragm are located on opposite faces of the diaphragm, wherein each diaphragm is suspended from the frame via one or more suspension elements;

a plurality of drive units, wherein each drive unit is configured to move a respective diaphragm based on a respective electrical signal;

drive circuitry is configured to provide each drive unit with a respective electrical signal derived from the same audio source such that the electrical signals provided to the drive units are configured to move the first radiating surfaces of the diaphragm substantially in phase with each other.

3. A loudspeaker unit according to any previous claim, wherein the loudspeaker unit includes a plurality of diaphragms, and the loudspeaker unit further includes:

one or more sound guides each respectively configured to guide sound produced by one or more of the first radiating surfaces to at least one outlet such that the sound propagates out of the loudspeaker unit from the at least one outlet, the/each outlet being remote from said one or more first radiating surfaces; and/or

one or more sound guides each respectively configured to guide sound produced by one or more of the second radiating surfaces to at least one outlet such that the sound propagates out of the loudspeaker unit from the at least one outlet, the/each outlet being remote from said one or more second radiating surfaces.

4. A loudspeaker unit according to any previous claim, wherein the loudspeaker unit includes:

a sound guide configured to guide sound produced by a first radiating surface of a diaphragm in the loudspeaker unit to an outlet such that the sound propagates out of the loudspeaker unit from the outlet, wherein the loudspeaker unit is configured for use with an ear of a user located at a listening position that is 25cm or less from the outlet.

5. A loudspeaker unit according to any previous claim, wherein the loudspeaker unit includes:

a first sound guide configured to guide sound produced by a first radiating surface of a diaphragm in the loudspeaker unit to a first outlet such that the sound propagates out of the loudspeaker unit from the first outlet, wherein the loudspeaker unit is configured for use with a first ear of a user located at a first listening position that 25cm or less from the first outlet;

a second sound guide configured to guide sound produced by a first radiating surface of a diaphragm in the loudspeaker unit to a second outlet such that the sound propagates out of the loudspeaker unit from the second outlet, wherein the loudspeaker unit is configured for use with a second ear of a user located at a second listening position that is 25cm or less from the second outlet, whilst the first ear of the user is located at the first listening position.

6. A loudspeaker unit for producing sound at bass frequencies, including:

an array of two or more diaphragms, each diaphragm in the array having a first radiating surface and a second radiating surface, wherein the first radiating surface and the second radiating surface are located on opposite faces of the diaphragm, and wherein one or more of the diaphragms are included in a first subset of the diaphragms and one or more of the diaphragms are included in a second subset of the diaphragms;

a plurality of drive units, wherein each drive unit is configured to move a respective one of the diaphragms in the array based on a respective electrical signal;

a frame, wherein each diaphragm in the array is suspended from the frame via one or more suspension elements;

at least one enclosure configured to receive sound produced by the second radiating surfaces;

drive circuitry configured to provide each drive unit with a respective electrical signal derived from the same audio source such that the electrical signal(s) provided to the one or more drive units configured to move the first subset of diaphragms is/are out of phase with respect to the electrical signal(s) provided to the one or more drive units configured to move the second subset of diaphragms;

a sound guide configured to guide sound produced by the first radiating surface of a diaphragm in the first or second subset to at least one outlet such that the sound propagates out of the loudspeaker unit from the at least one outlet, the/each outlet being remote from said first radiating surface;

wherein the loudspeaker unit is preferably configured so that, at the locations at which sound propagates out from the loudspeaker unit, and preferably in the operational bandwidth of the loudspeaker unit, the sound produced by the first radiating surface of the/each diaphragm in the first subset is substantially out of phase with the sound produced by the first radiating surface of the/each diaphragm in the second subset.

7. A loudspeaker unit according to claim 6, wherein the loudspeaker unit includes:

one or more sound guides each respectively configured to guide sound produced by one or more first radiating surfaces of one or more diaphragms in the first subset to at least one outlet such that the sound propagates out of the loudspeaker unit from the at least one outlet, the/each outlet being remote from said one or more first radiating surfaces of the one or more diaphragms in the first subset; and/or

one or more sound guides each respectively configured to guide sound produced by one or more first radiating surfaces of one or more diaphragms in the second subset to at least one outlet such that the sound propagates out of the loudspeaker unit from the at least one outlet, the/each outlet being remote from said one or more first radiating surfaces of the one or more diaphragms in the second subset.

8. A loudspeaker unit according to claim 6 or 7, wherein the loudspeaker unit includes:

a sound guide configured to guide sound produced by a first radiating surface of a diaphragm in the first subset to an outlet such that the sound propagates out of the loudspeaker unit from the outlet, wherein the loudspeaker unit is configured for use with an ear of a user located at a listening position that is 25cm or less from the outlet.

9. A loudspeaker unit according to any of claims 6 to 8, wherein the loudspeaker unit includes:

a first sound guide configured to guide sound produced by a first radiating surface of a diaphragm in the first subset to a first outlet such that the sound propagates out of the loudspeaker unit from the first outlet, wherein the loudspeaker unit is configured for use with a first ear of a user located at a first listening position that is 25cm or less from the first outlet;

a second sound guide configured to guide sound produced by a first radiating surface of a diaphragm in the first subset to a second outlet such that the sound propagates out of the loudspeaker unit from the second outlet, wherein the loudspeaker unit is configured for use with a second ear of a user located at a second listening position that is 25cm or less from the second outlet, whilst the first ear of the user is located at the first listening position.

10. A loudspeaker unit according any of claims 6 to 9, wherein the loudspeaker unit has multiple operational modes, wherein:

in a first operational mode, the drive circuitry is configured to provide the drive unit(s) configured to move the first subset of diaphragms with an electrical signal that is out of phase with respect to an electrical signal that is provided to the drive unit(s) configured to move the second subset of diaphragms; and

in a second operational mode, the drive circuitry is configured to provide the drive unit(s) configured to move the first subset of diaphragms with an electrical signal that is in phase with respect to an electrical signal that is provided to the second subset of the diaphragms.

11. A loudspeaker unit according to any previous claim, wherein one or more sound guides form multiple passages which extend from a radiating surface to multiple outlets.

12. A loudspeaker unit according to any previous claim, wherein one or more passages formed by a sound guide have a cross-sectional area that is less than the effective radiating surface area of the radiating surface from which the passage extends.

13. A loudspeaker unit according to any previous claim, wherein an upper limit of the operational bandwidth of the loudspeaker unit is 200 Hz or lower.

14. A loudspeaker unit according to any previous claim, wherein the tuning frequency of a Helmholtz resonator formed by the/each sound guide is above an operational bandwidth of the loudspeaker unit.

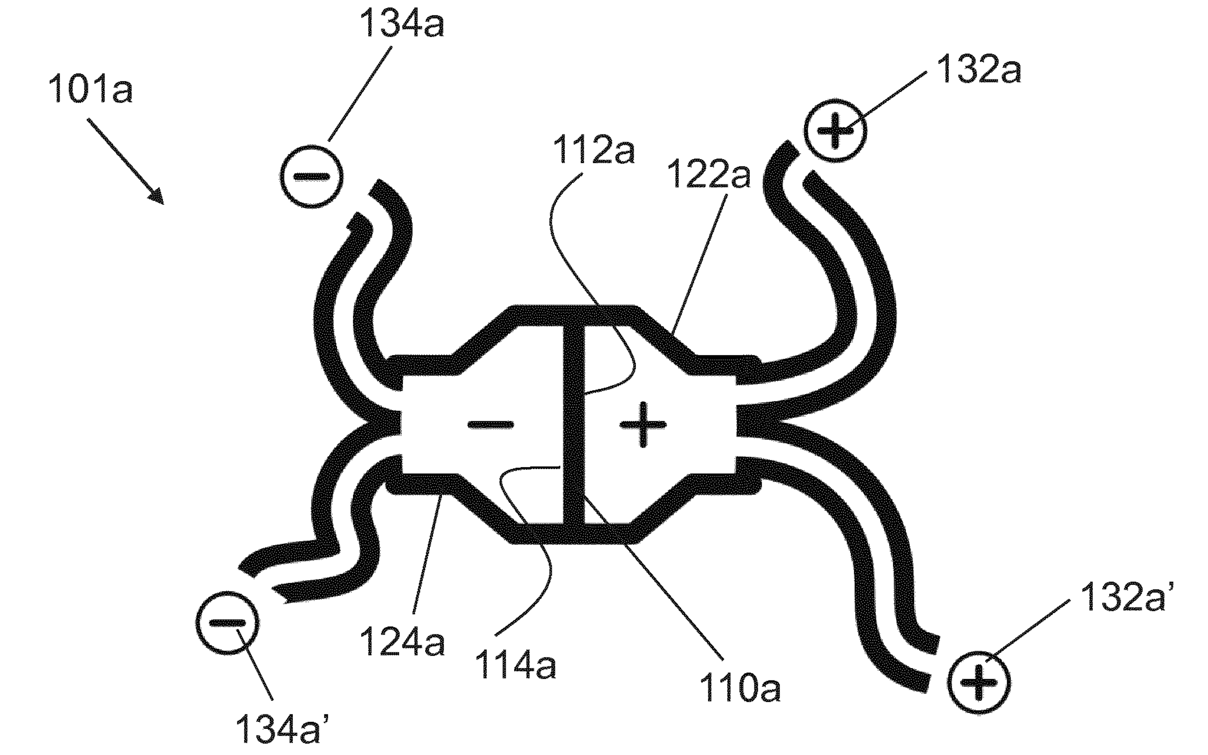
15. A seat assembly including:

a seat; and

a loudspeaker unit according to any previous claim;

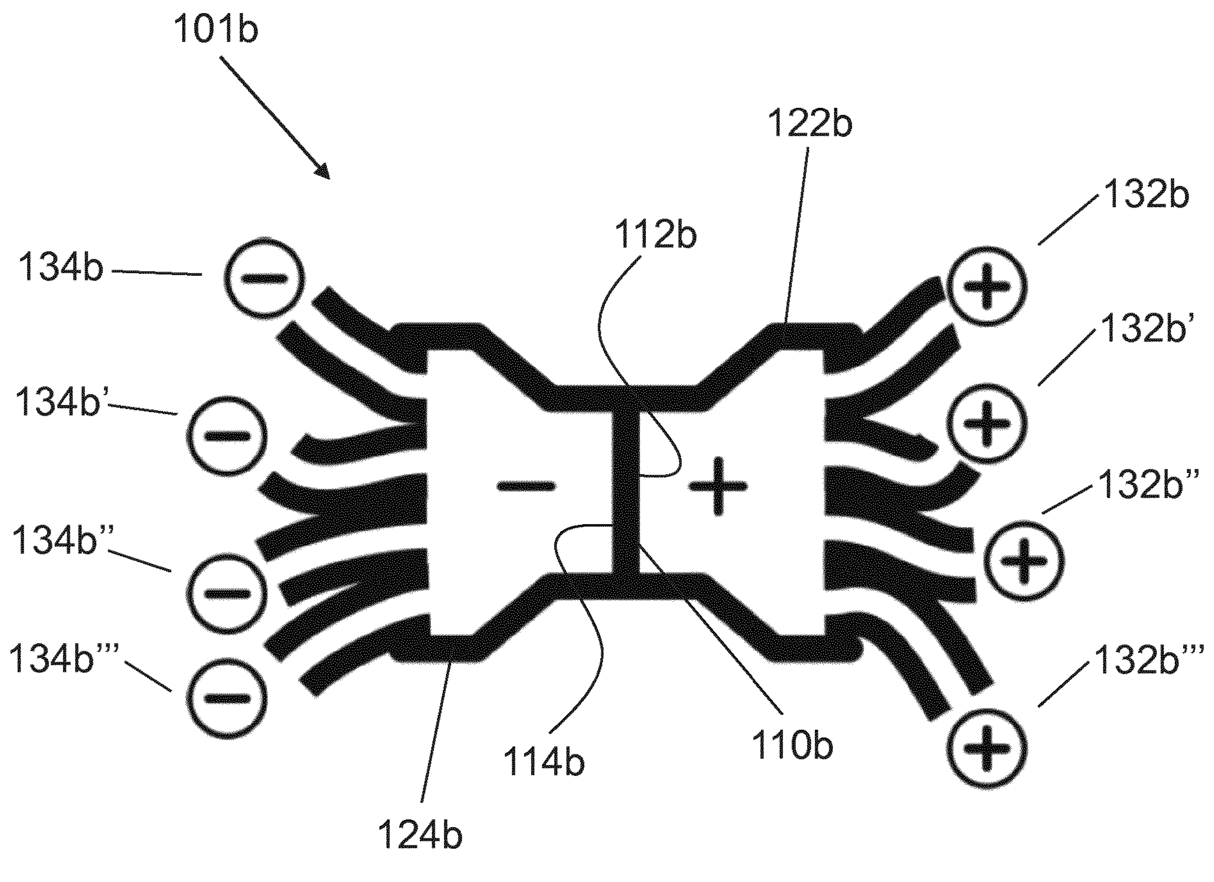
wherein the seat is configured to position a user who is sat down in the seat such that an ear of the user is located at a listening position according to any one of claims 4-5 or claims 8-9.

16. A seat assembly according to claim 14, wherein the seat assembly includes additional loudspeaker units having an operational bandwidth which extends above 200 Hz.



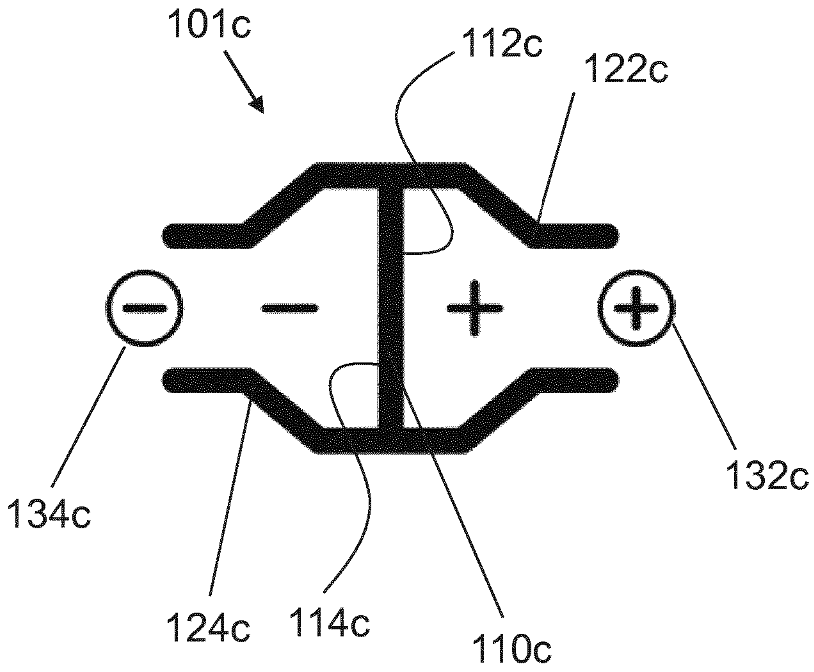
101a
134a
132a
112a
122a
−
+
124a
114a
110a
132a'
134a'

FIG. 1(a)



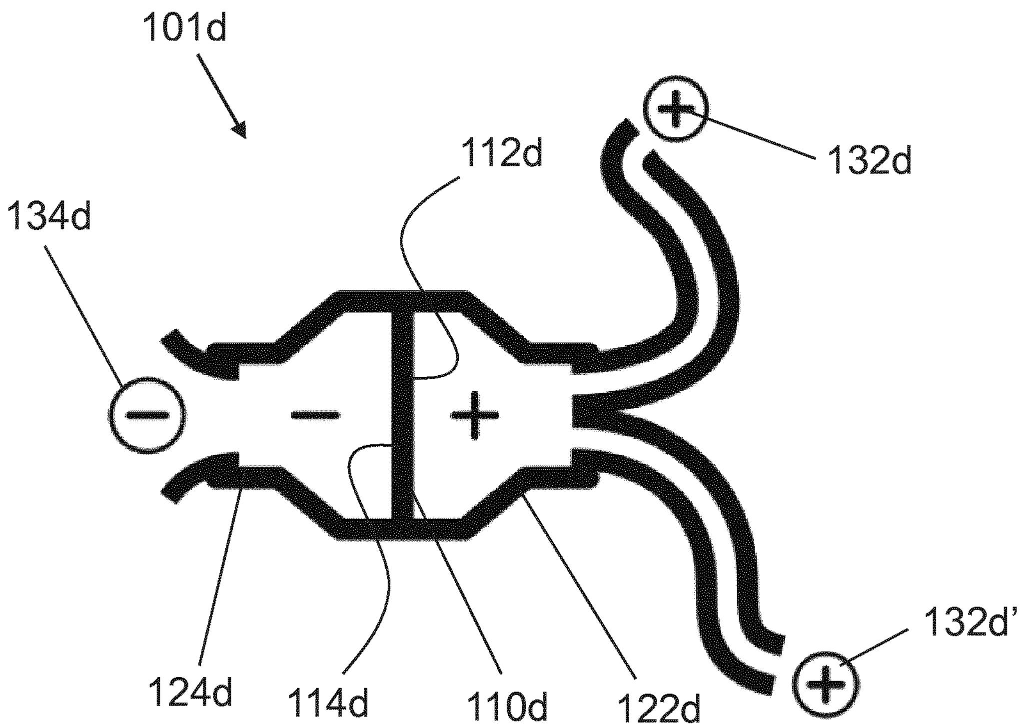
101b
122b
132b
112b
134b
134b'
132b'
−
+
132b"
134b"
134b'''
132b'''
114b
110b
124b

FIG. 1(b)



101c
112c
122c
134c
132c
124c
114c
110c

FIG. 1(c)



101d
112d
132d
134d
132d'
124d
114d
110d
122d

FIG. 1(d)

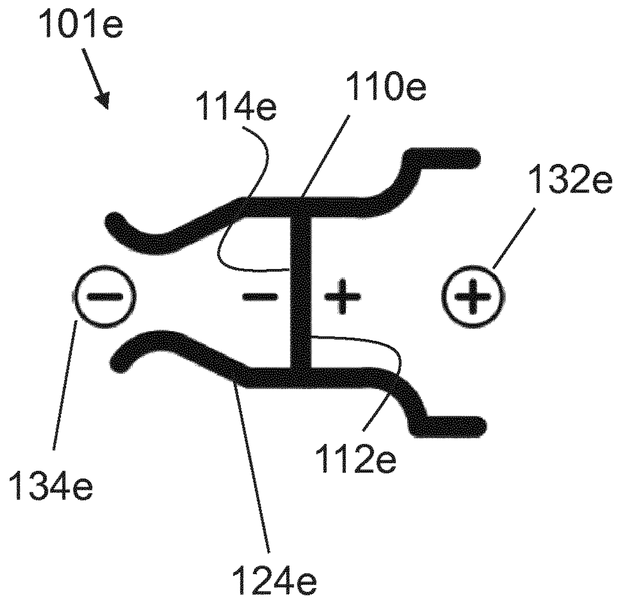

101e
114e
110e
132e
134e
112e
124e

FIG. 1(e)

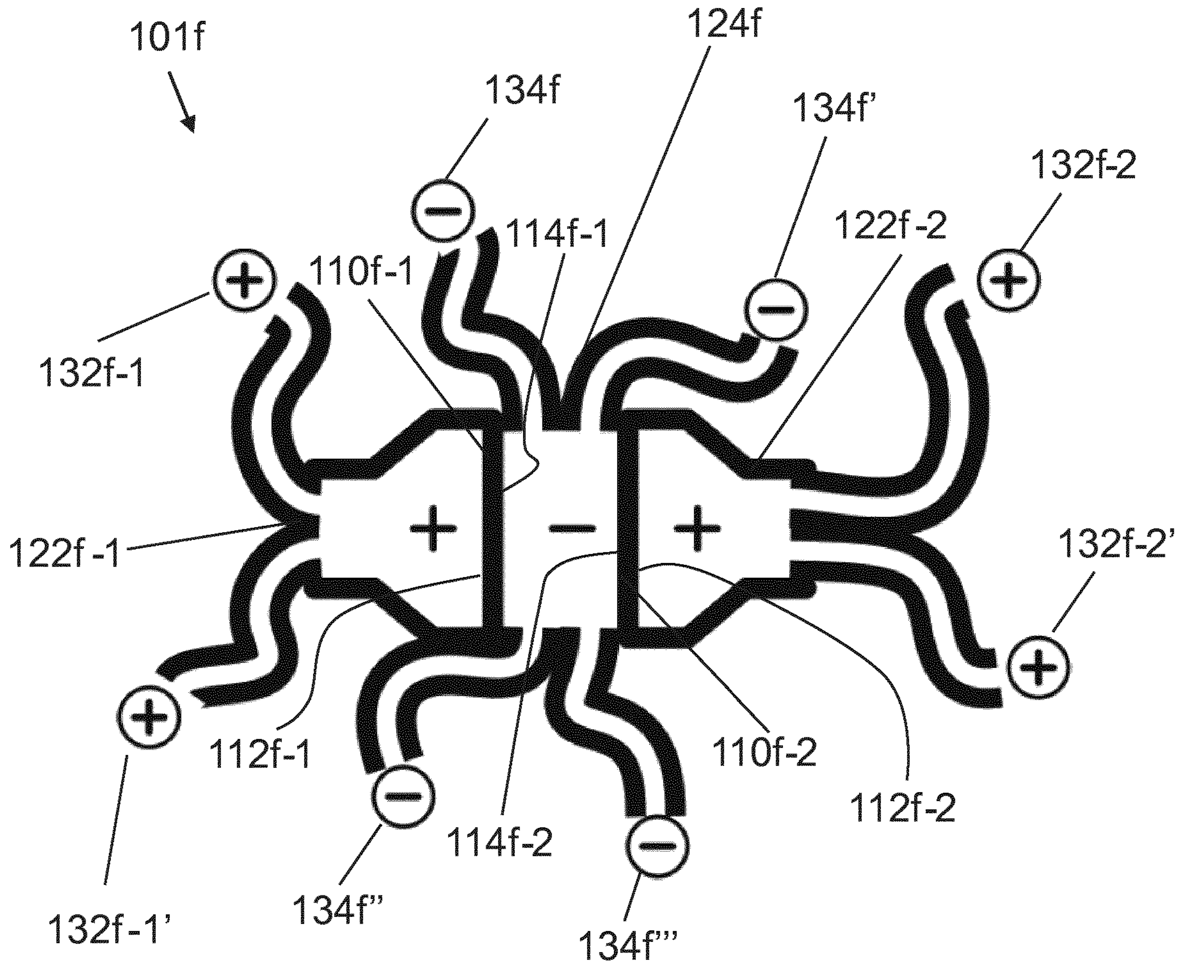

101f
124f
134f
134f'
132f-2
114f-1
122f-2
110f-1
132f-1
122f-1
132f-2'
112f-1
110f-2
112f-2
114f-2
132f-1'
134f"
134f'''

FIG. 1(f)

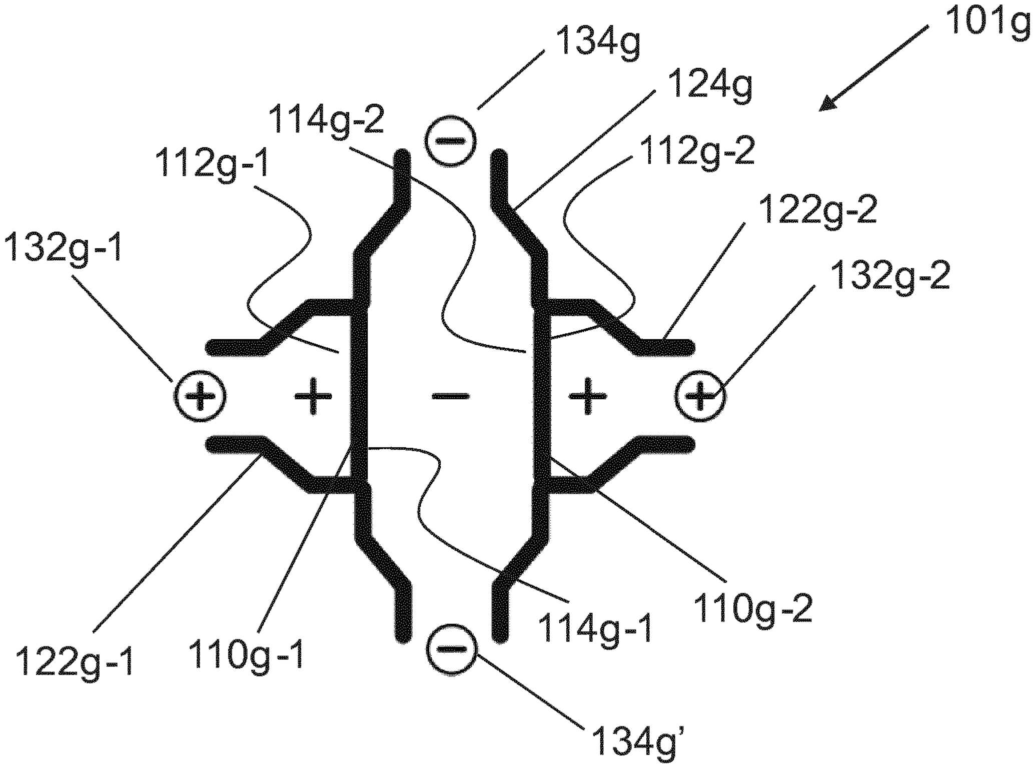

101g
134g
124g
114g-2
112g-1
112g-2
122g-2
132g-1
132g-2
+
−
+
122g-1
110g-1
114g-1
110g-2
134g'

FIG. 1(g)

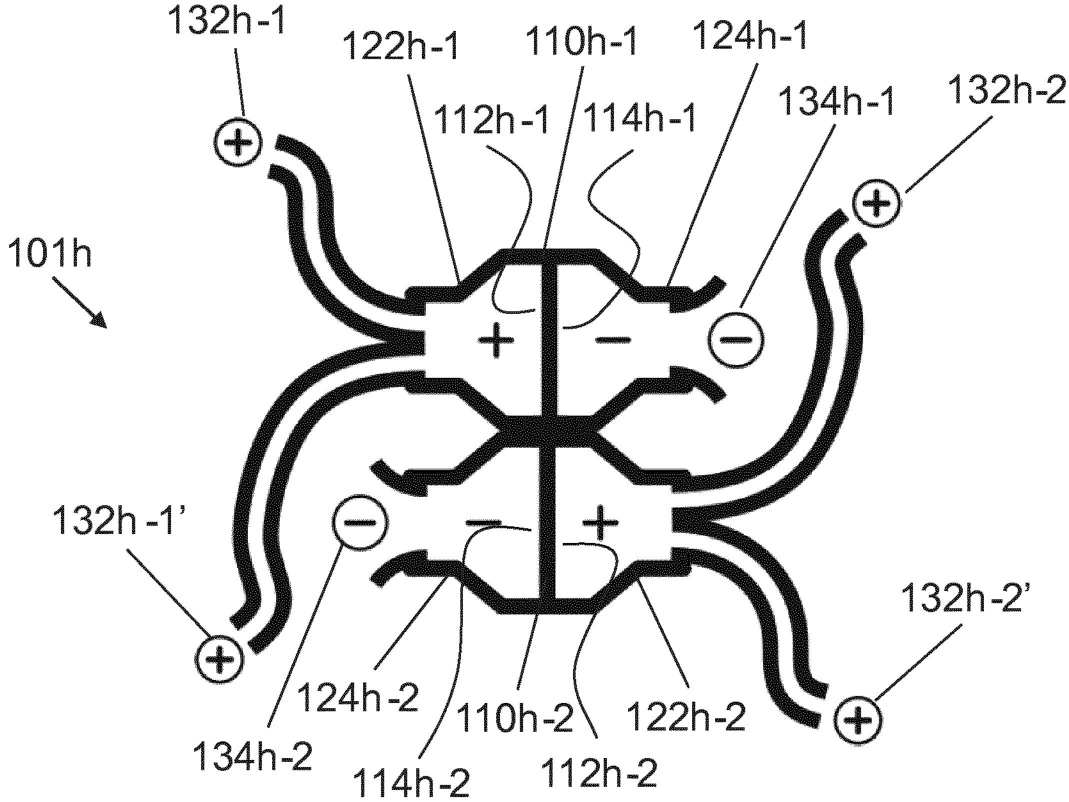

132h-1
122h-1
110h-1
124h-1
112h-1
114h-1
134h-1
132h-2
101h
+
−
132h-1'
−
+
132h-2'
124h-2
110h-2
122h-2
134h-2
114h-2
112h-2

FIG. 1(h)

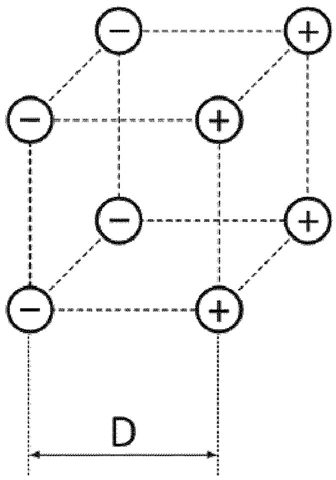


FIG. 2(a)

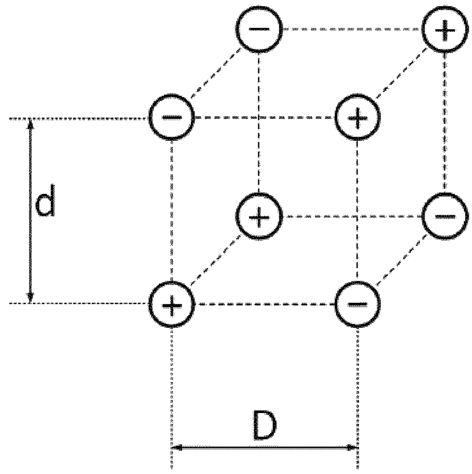


FIG. 2(b)

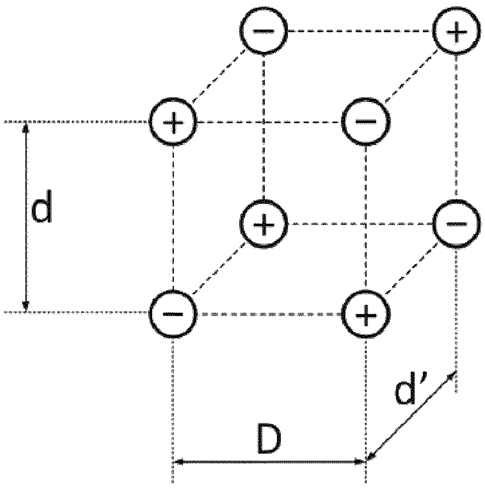


FIG. 2(c)

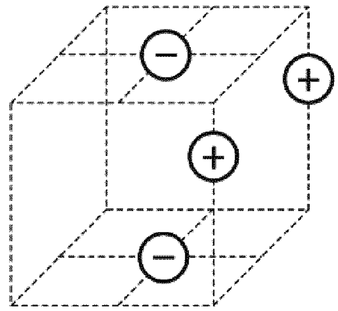


FIG. 2(d)

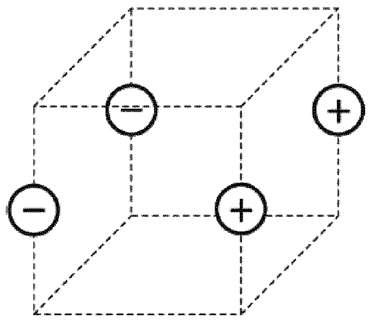


FIG. 2(e)

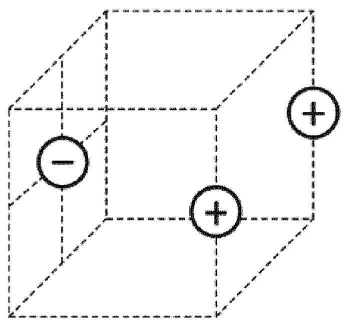


FIG. 2(f)

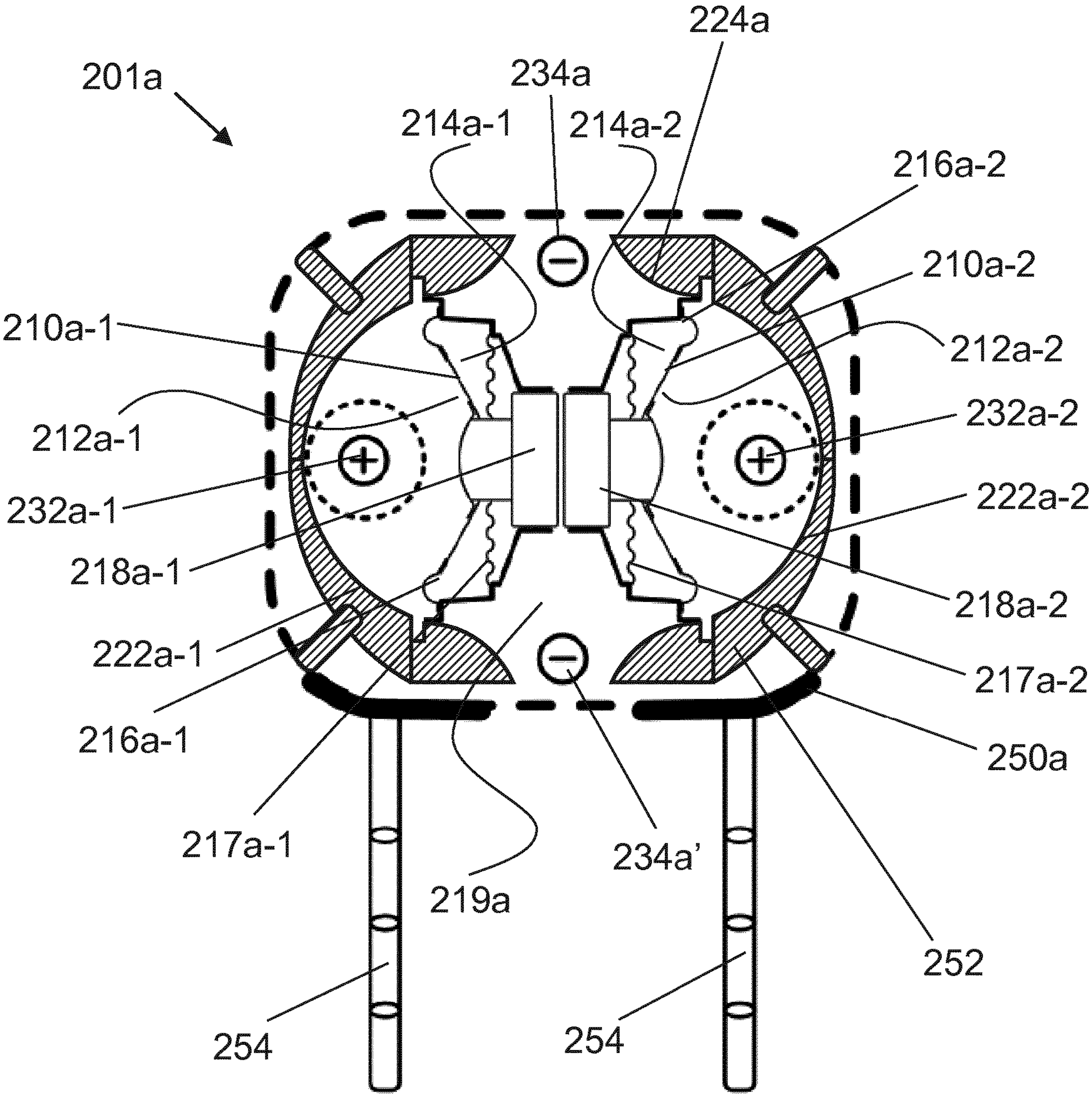

201a
234a
224a
214a-1
214a-2
216a-2
210a-2
210a-1
212a-2
232a-2
212a-1
232a-1
222a-2
218a-1
218a-2
222a-1
217a-2
216a-1
250a
217a-1
234a'
219a
252
254
254

FIG. 3(a)

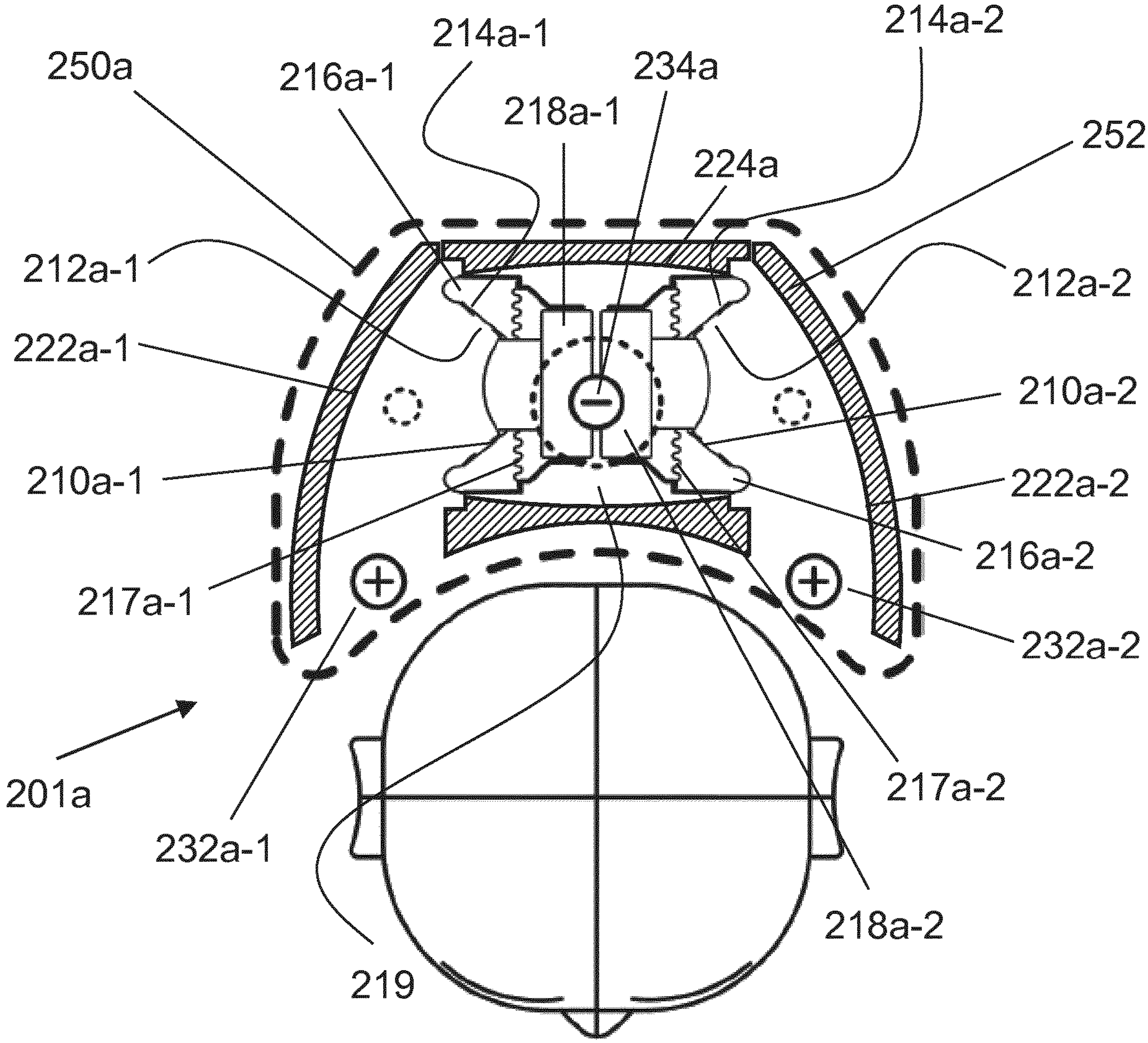

250a
216a-1
214a-1
218a-1
234a
214a-2
224a
252
212a-1
212a-2
222a-1
210a-2
210a-1
222a-2
216a-2
217a-1
232a-2
201a
232a-1
217a-2
218a-2
219

FIG. 3(b)

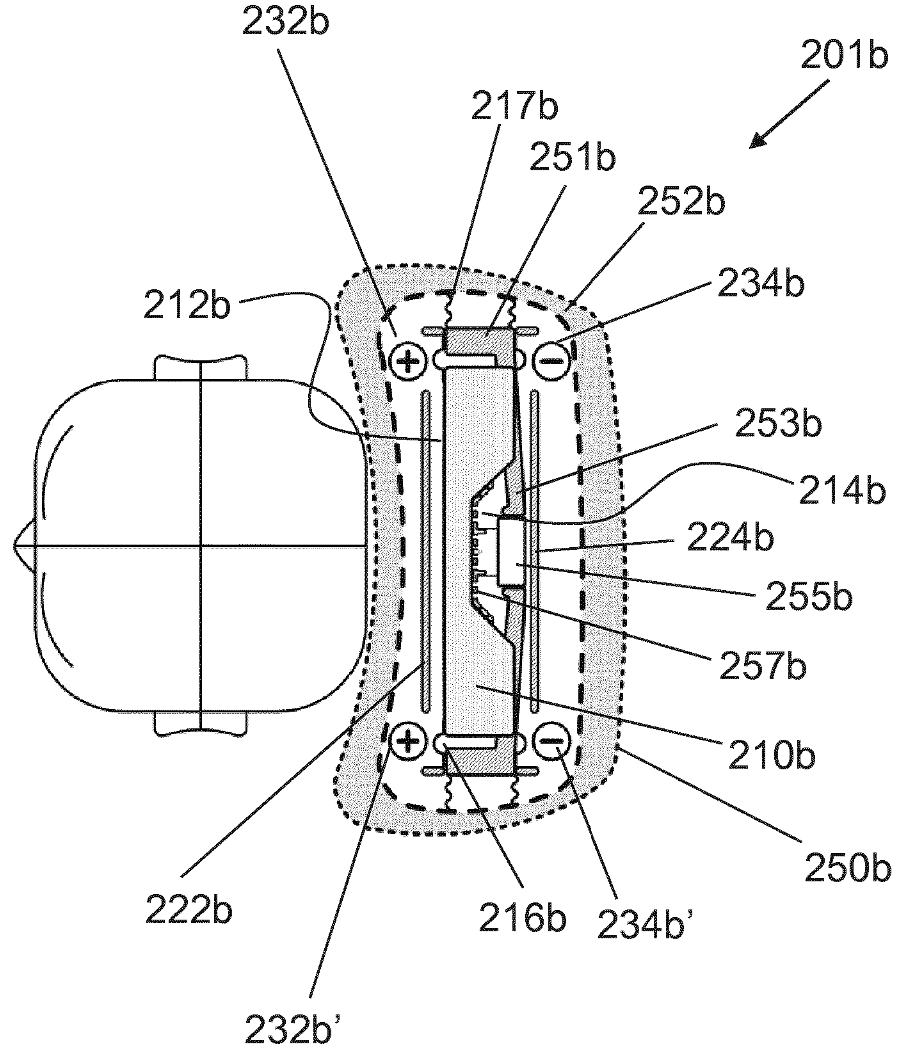

232b
201b
217b
251b
252b
212b
234b
253b
214b
224b
255b
257b
210b
250b
222b
216b
234b'
232b'

FIG. 4

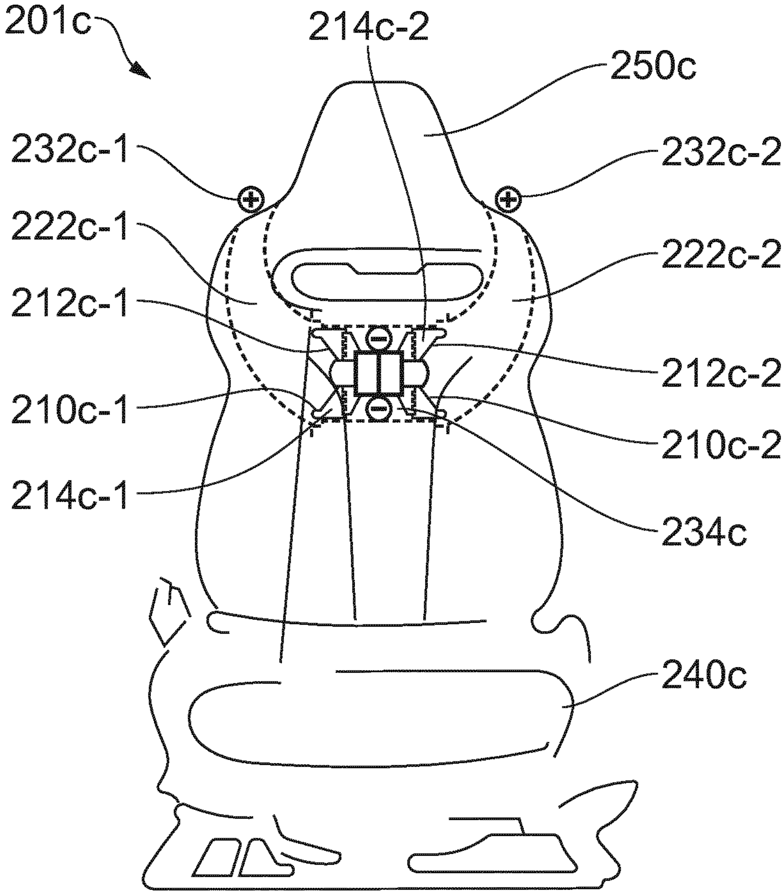

201c
214c-2
250c
232c-1
232c-2
222c-1
222c-2
212c-1
212c-2
210c-1
210c-2
214c-1
234c
240c

FIG. 5(a)

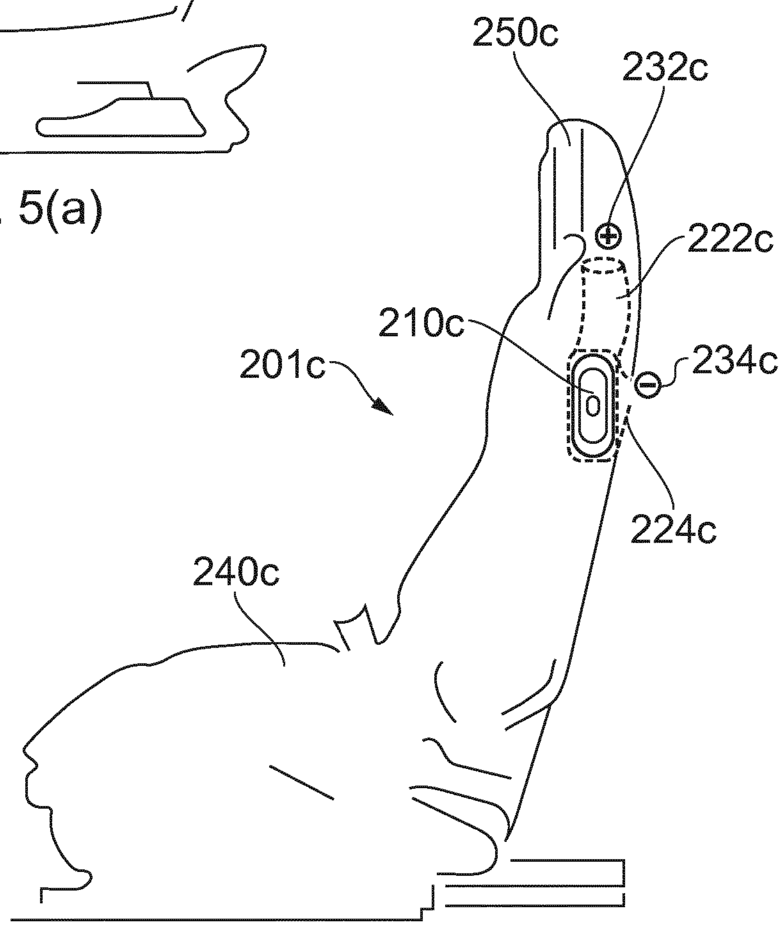

250c
232c
222c
210c
201c
234c
224c
240c

FIG. 5(b)

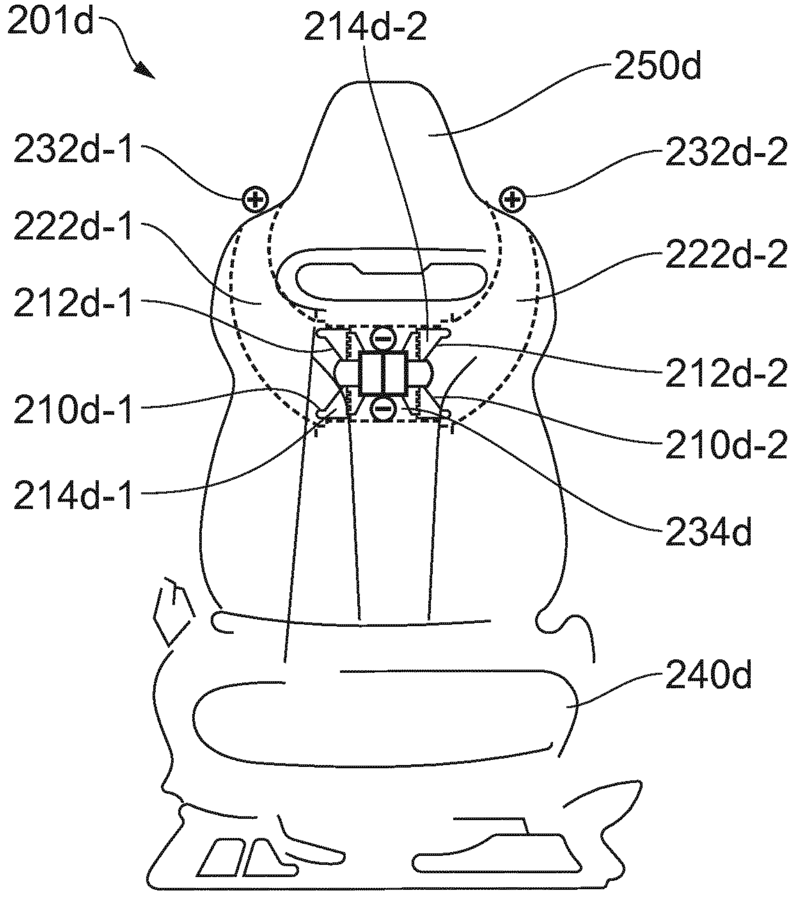

201d
214d-2
250d
232d-1
232d-2
222d-1
222d-2
212d-1
212d-2
210d-1
210d-2
214d-1
234d
240d

FIG. 6(a)

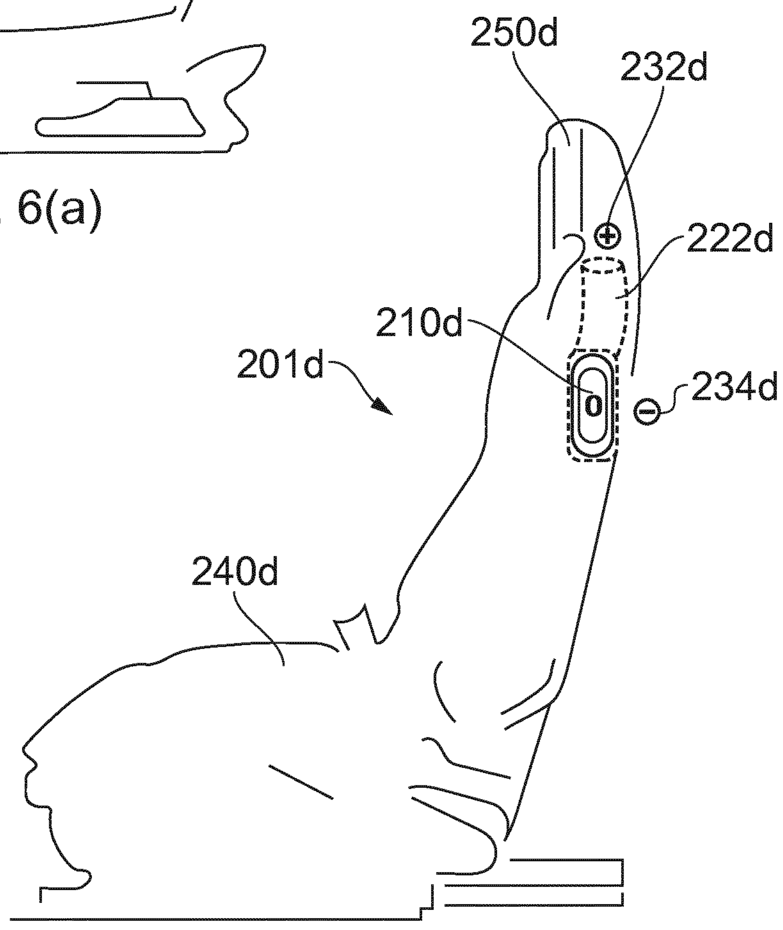

250d
232d
222d
210d
201d
234d
240d

FIG. 6(b)

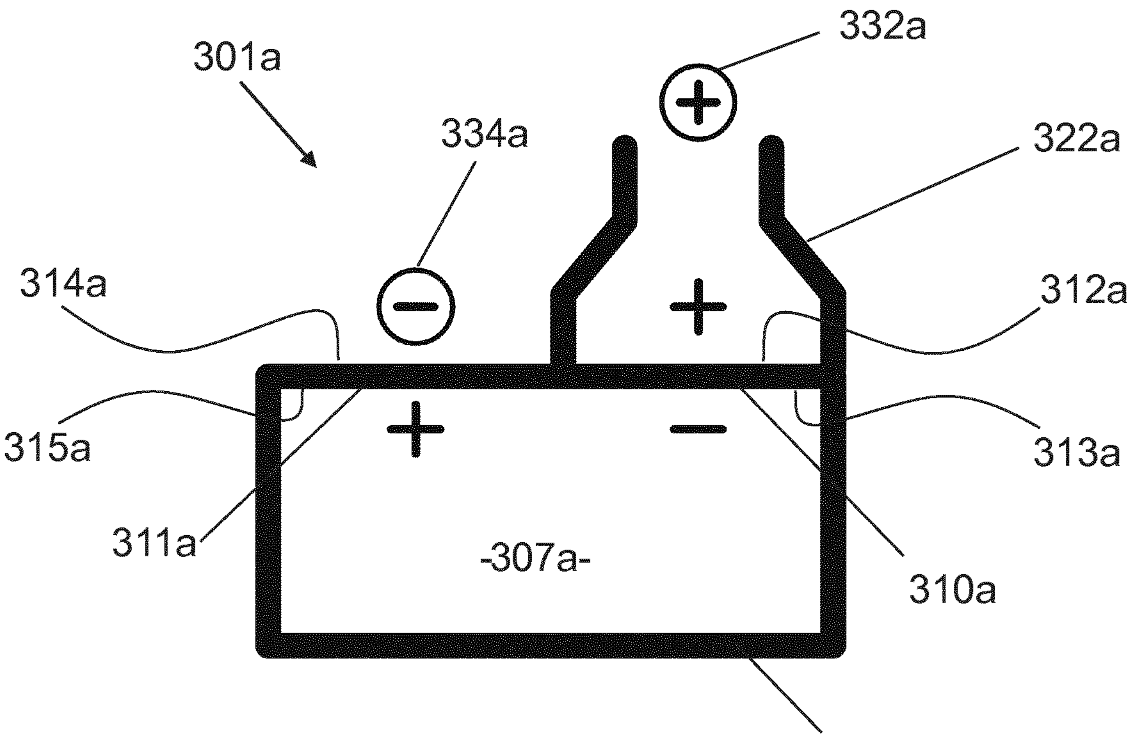

301a
332a
334a
322a
314a
312a
315a
313a
311a
-307a-
310a
306a

FIG. 7(a)

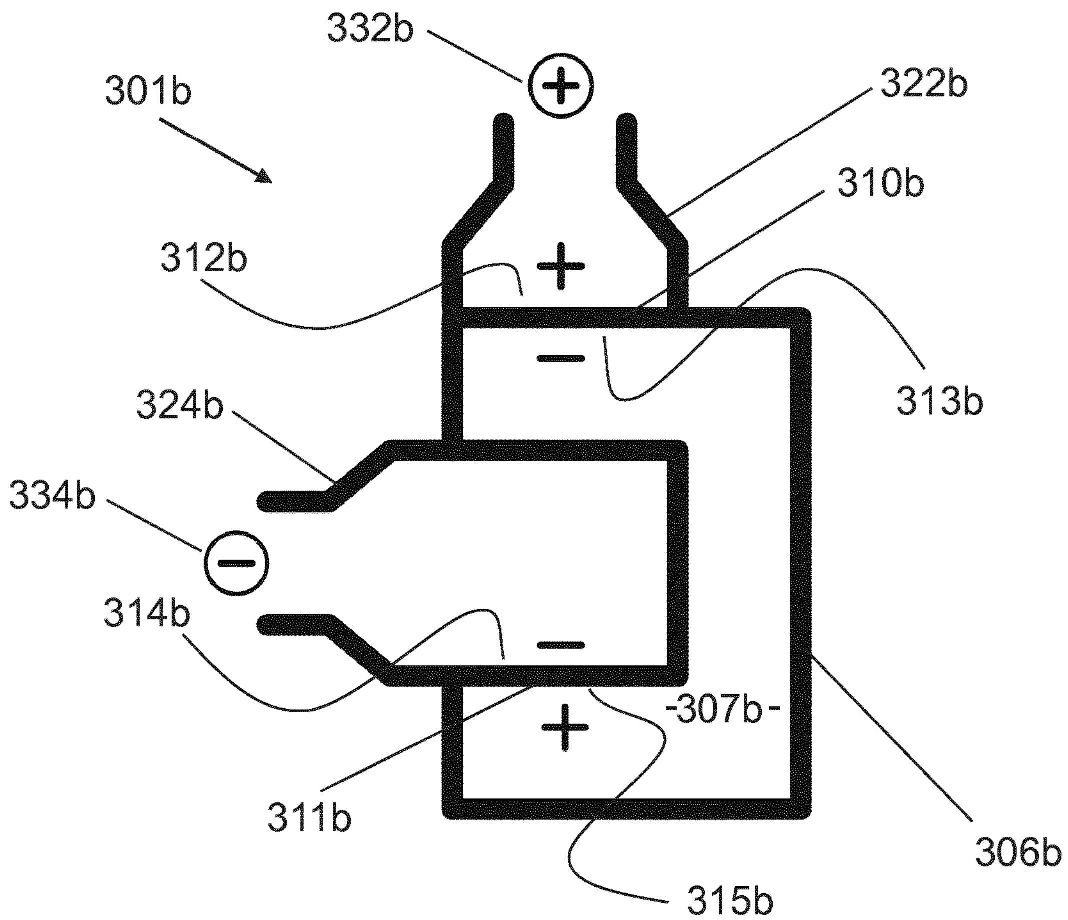

332b
301b
322b
310b
312b
313b
324b
334b
314b
-307b-
311b
306b
315b

FIG. 7(b)

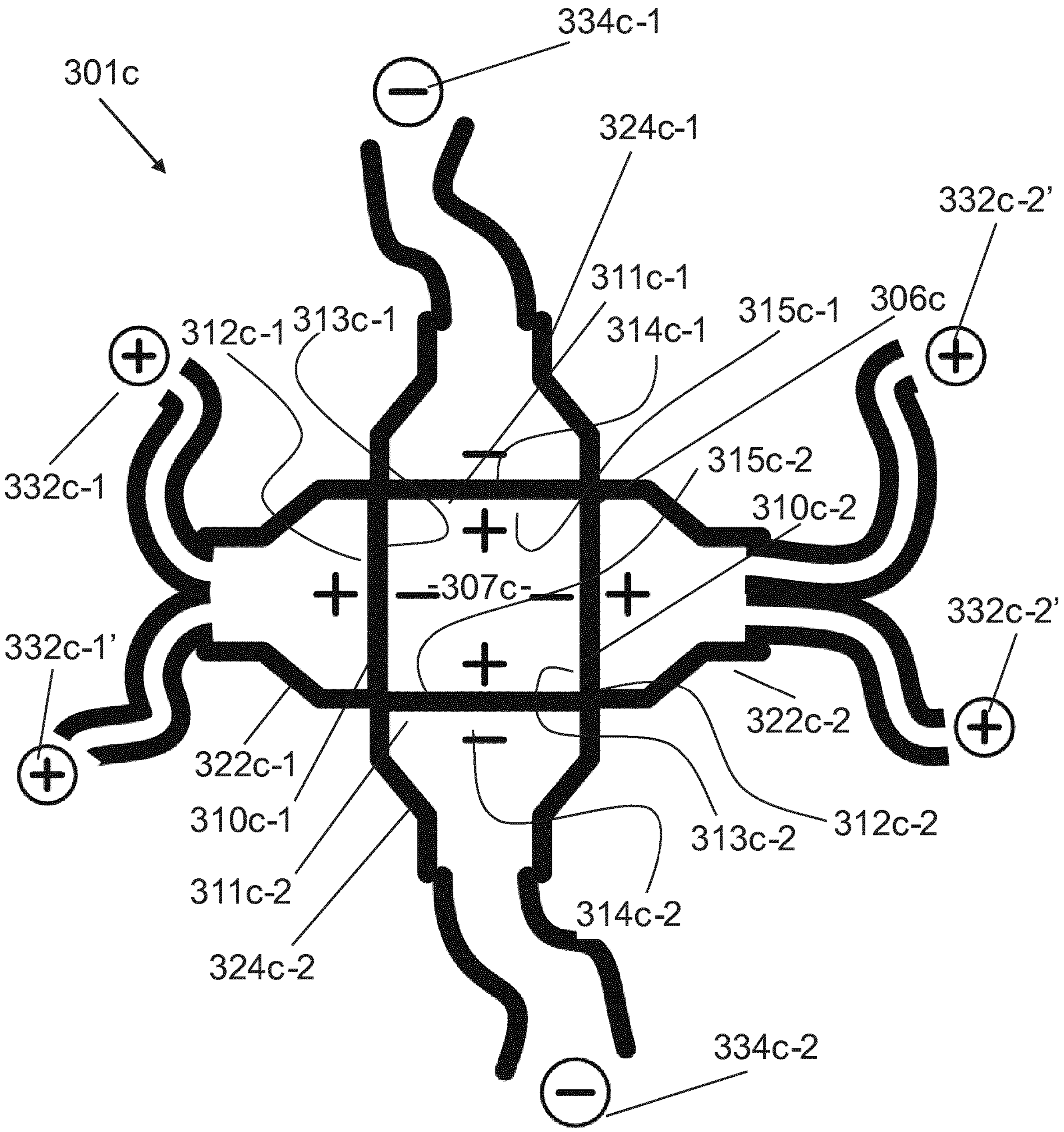
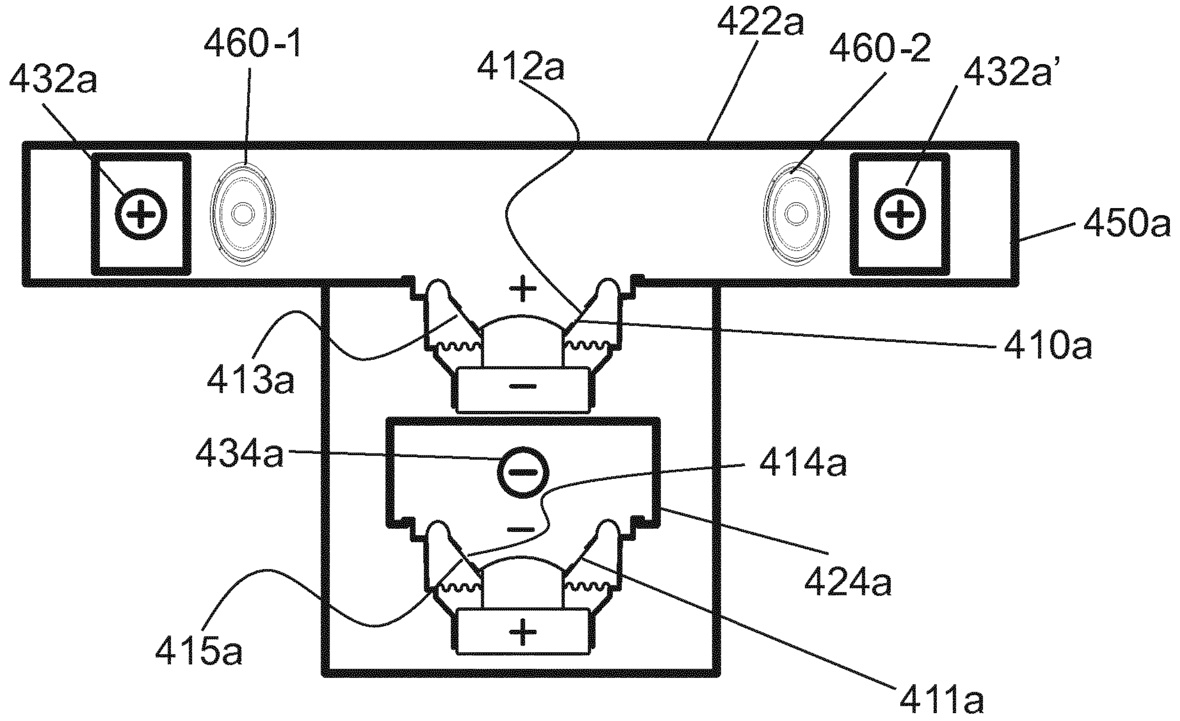
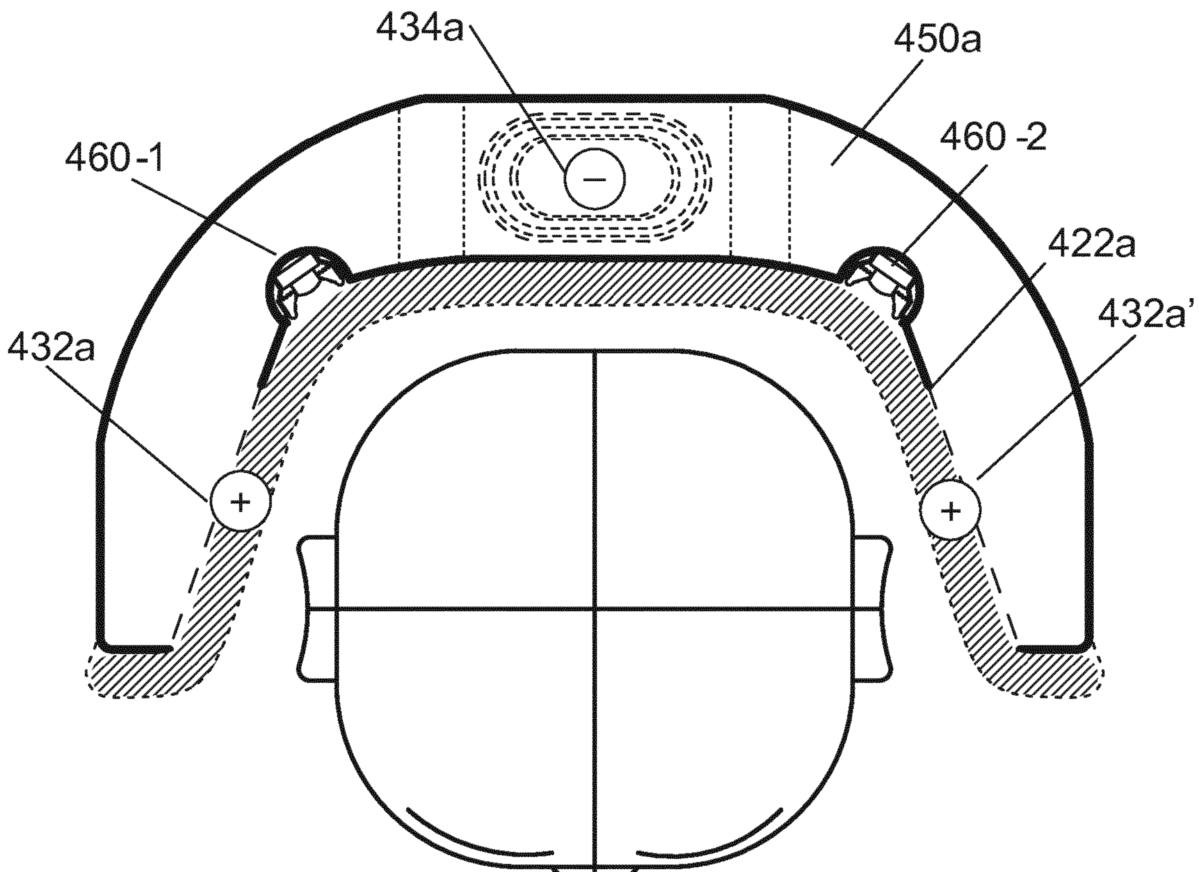

334c-1
301c
324c-1
332c-2'
311c-1
315c-1
306c
312c-1
313c-1
314c-1
332c-1
315c-2
310c-2
307c
332c-2'
332c-1'
322c-2
322c-1
310c-1
313c-2
312c-2
311c-2
314c-2
324c-2
334c-2

FIG. 7(c)



422a
460-1
460-2
432a
412a
432a'
450a
410a
413a
434a
414a
424a
415a
411a

FIG. 8(a)



434a
450a
460-1
460 -2
422a
432a
432a'

FIG. 8(b)

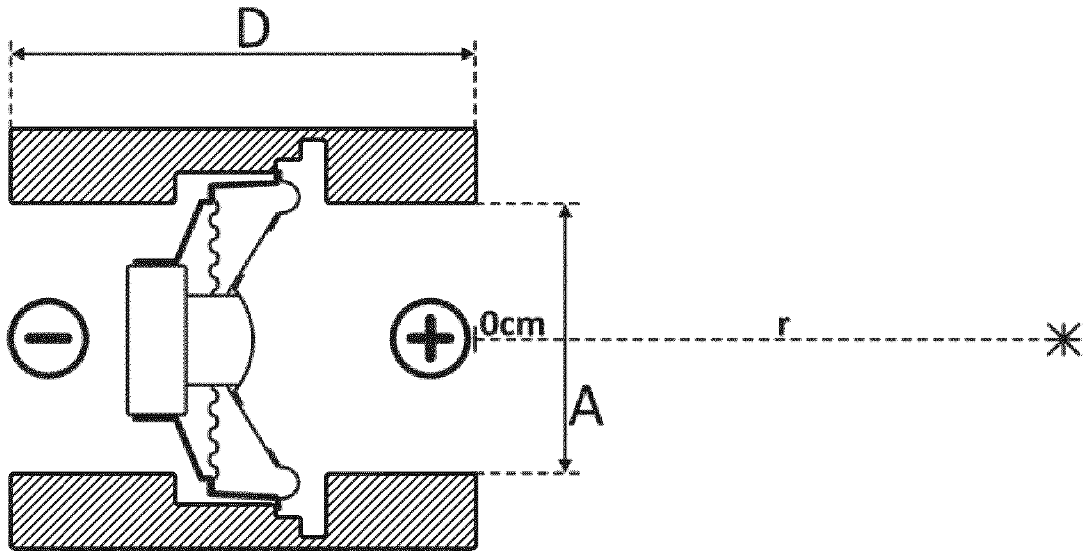


FIG. 9(a)

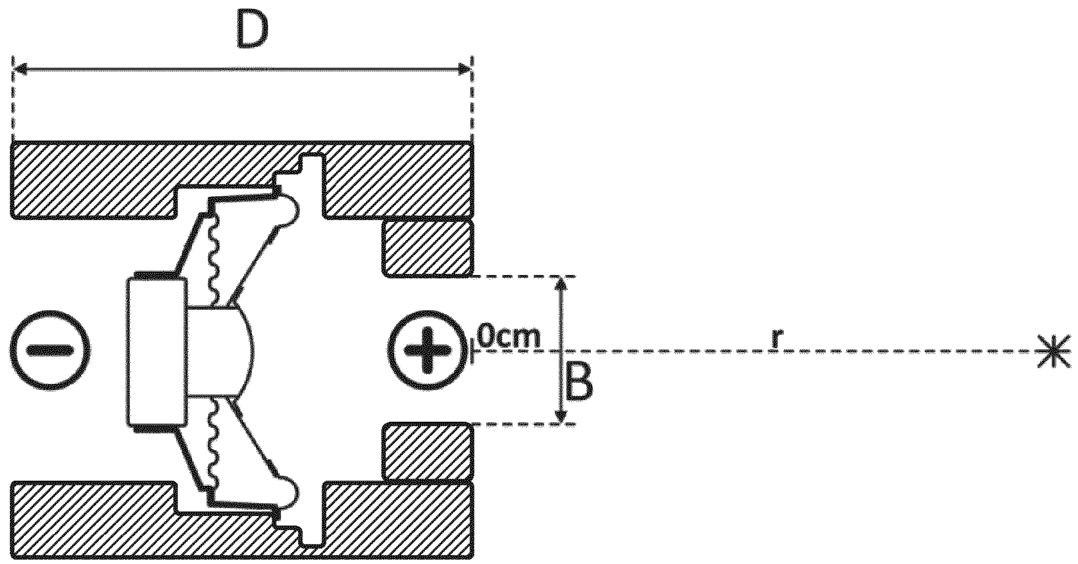


FIG. 9(b)

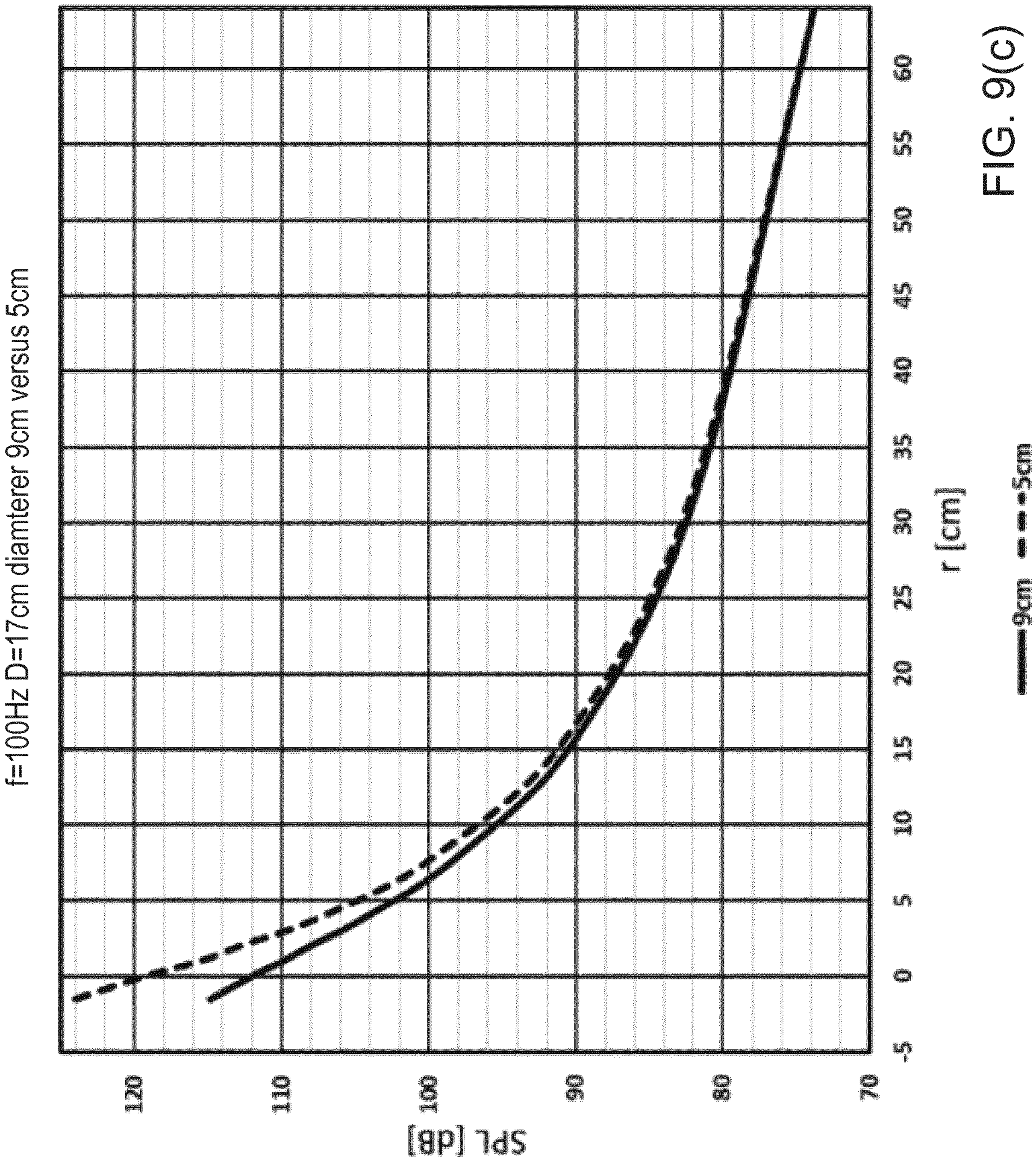

f=100Hz D=17cm diamterer 9cm versus 5cm
SPL [dB]
120
110
100
90
80
70
r [cm]
-5
0
5
10
15
20
25
30
35
40
45
50
55
60
9cm
5cm

FIG. 9(c)

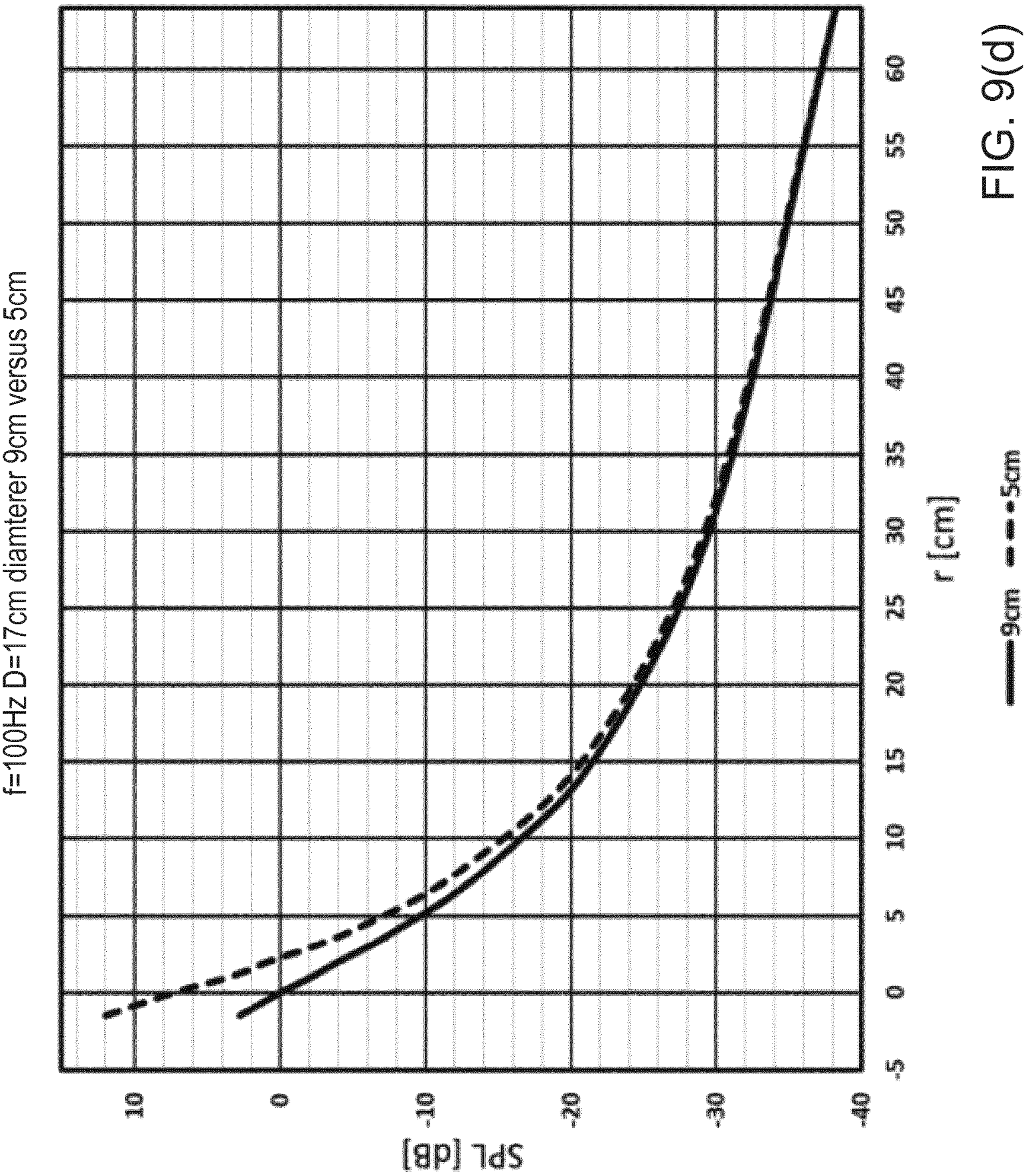

f=100Hz D=17cm diamterer 9cm versus 5cm
SPL [dB]
10
0
-10
-20
-30
-40
r [cm]
-5
0
5
10
15
20
25
30
35
40
45
50
55
60
9cm
5cm

FIG. 9(d)

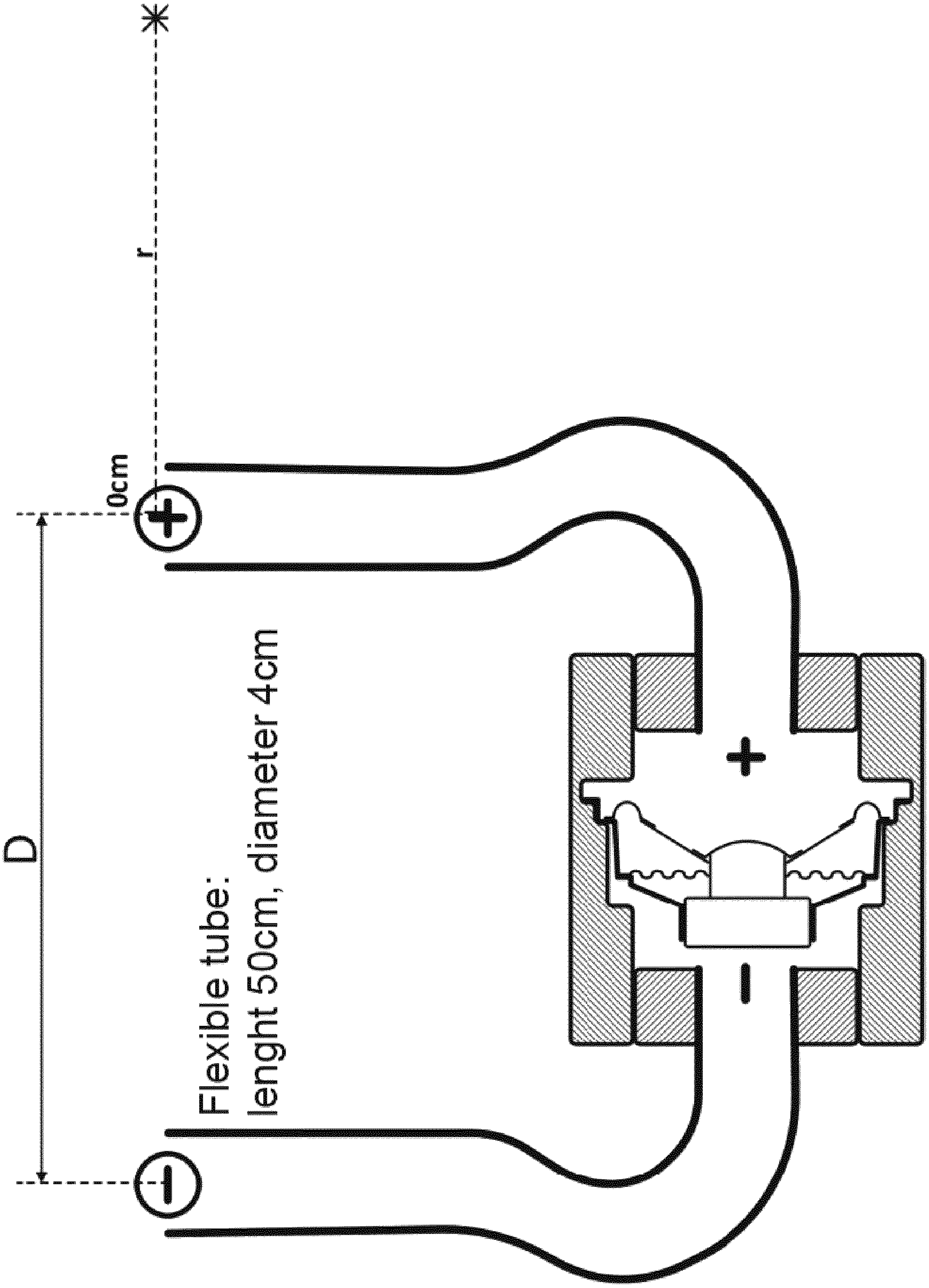


FIG. 10(a)

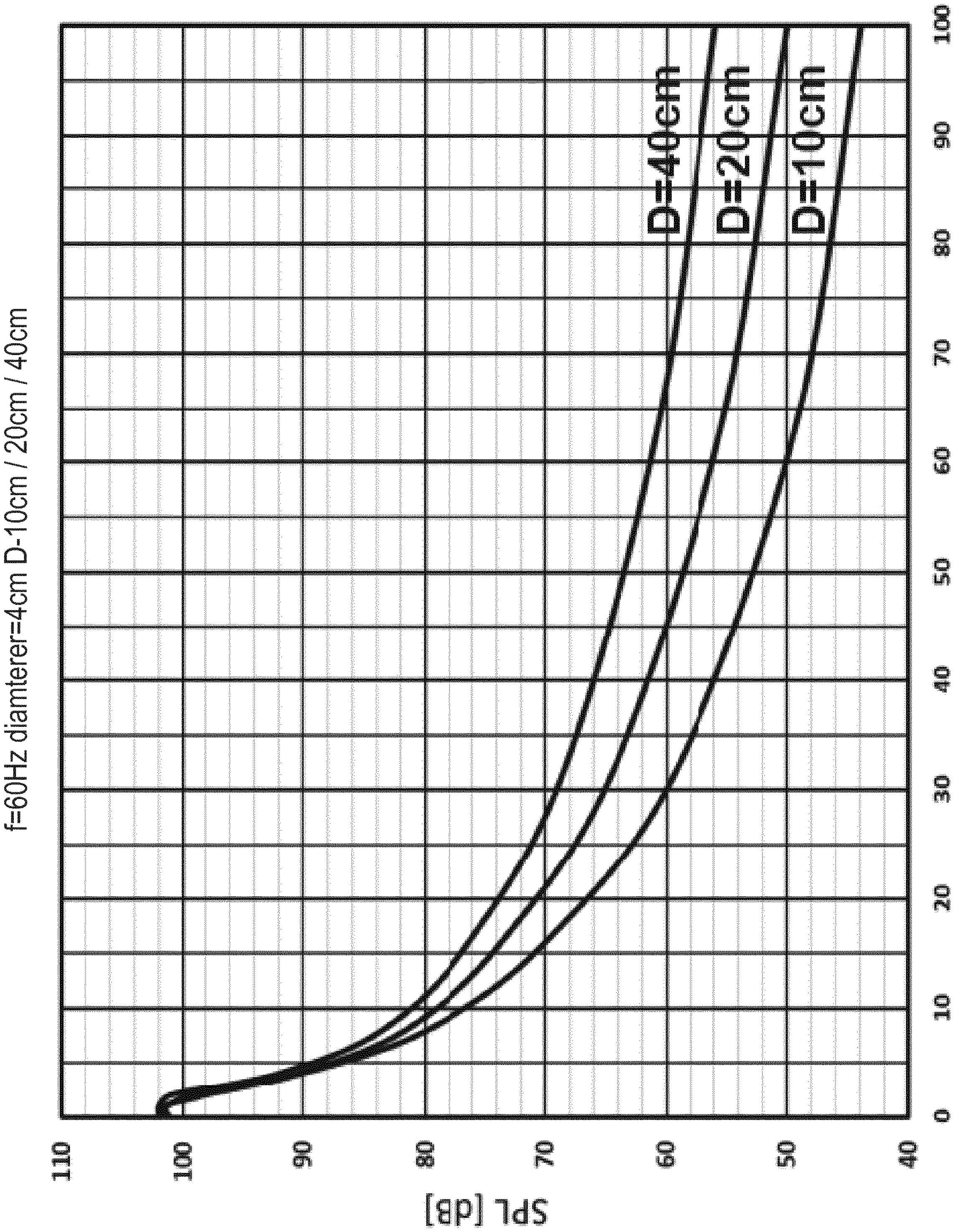

f=60Hz diamterer=4cm D-10cm / 20cm / 40cm
D=40cm
D=20cm
D=10cm
SPL [dB]
110
100
90
80
70
60
50
40
r [cm]
0
10
20
30
40
50
60
70
80
90
100

FIG. 10(b)

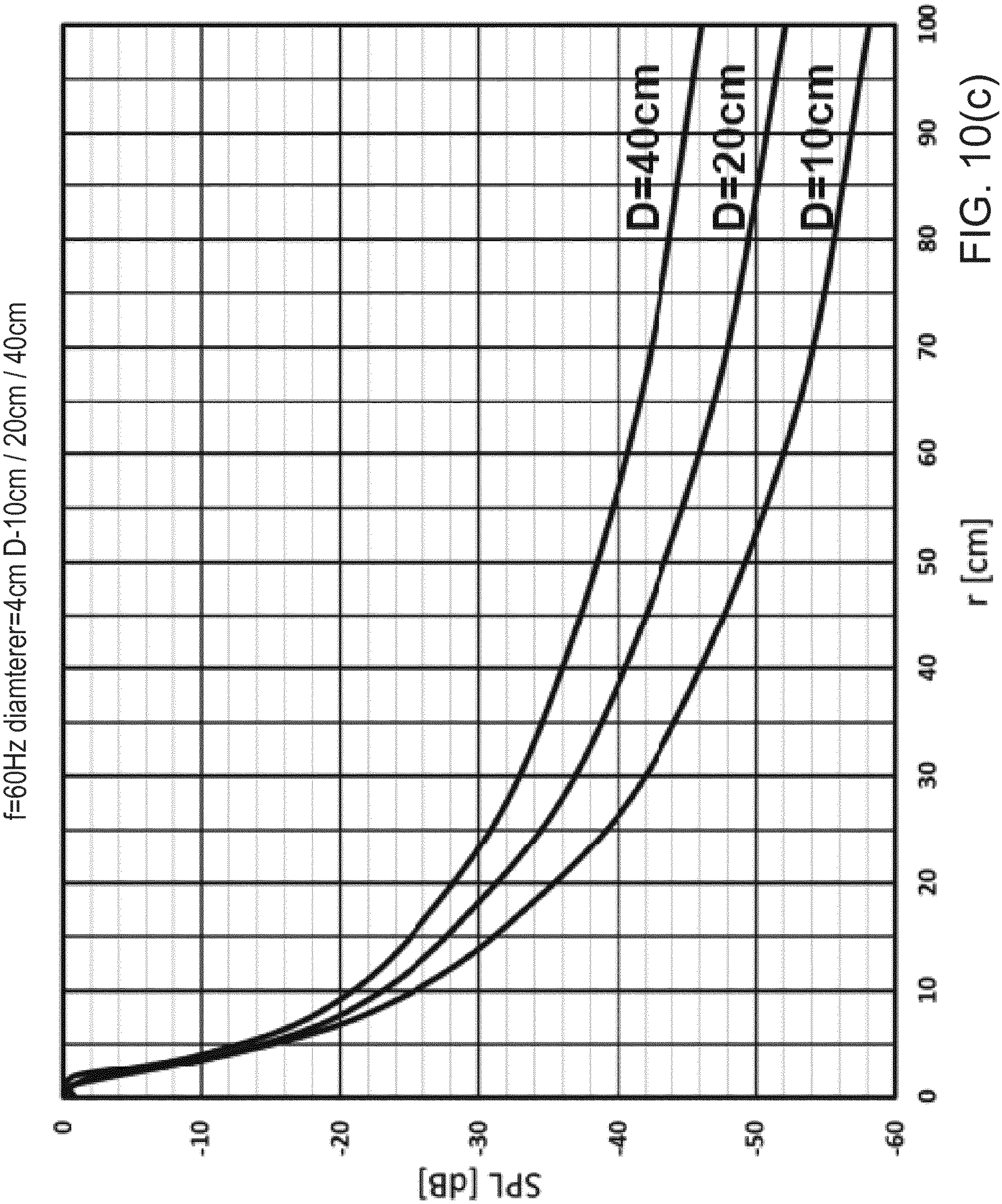

f=60Hz diamterer=4cm D-10cm / 20cm / 40cm
SPL [dB]
0
-10
-20
-30
-40
-50
-60
r [cm]
0
10
20
30
40
50
60
70
80
90
100
D=40cm
D=20cm
D=10cm

FIG. 10(c)

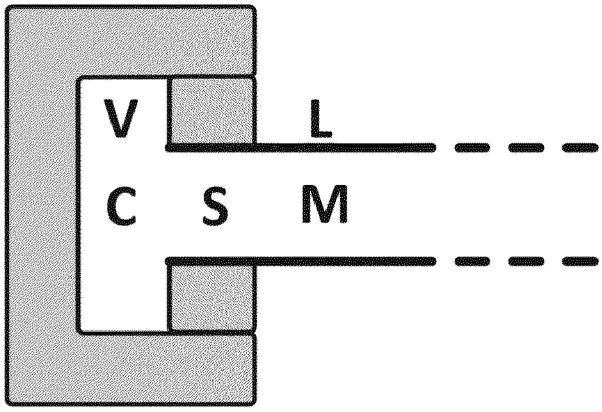


FIG. 11(a)

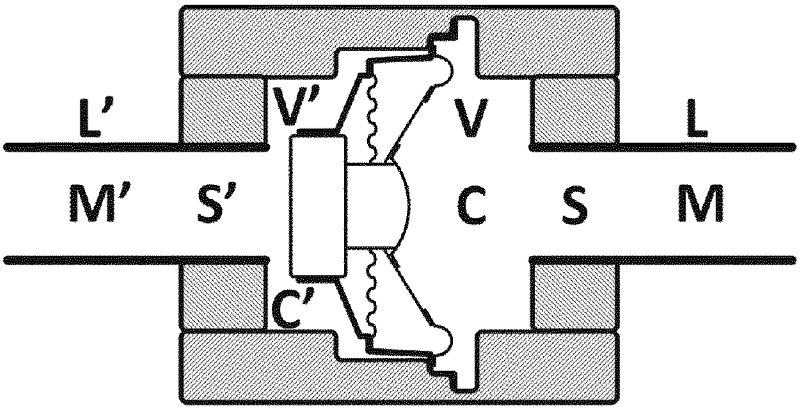


FIG. 11(b)

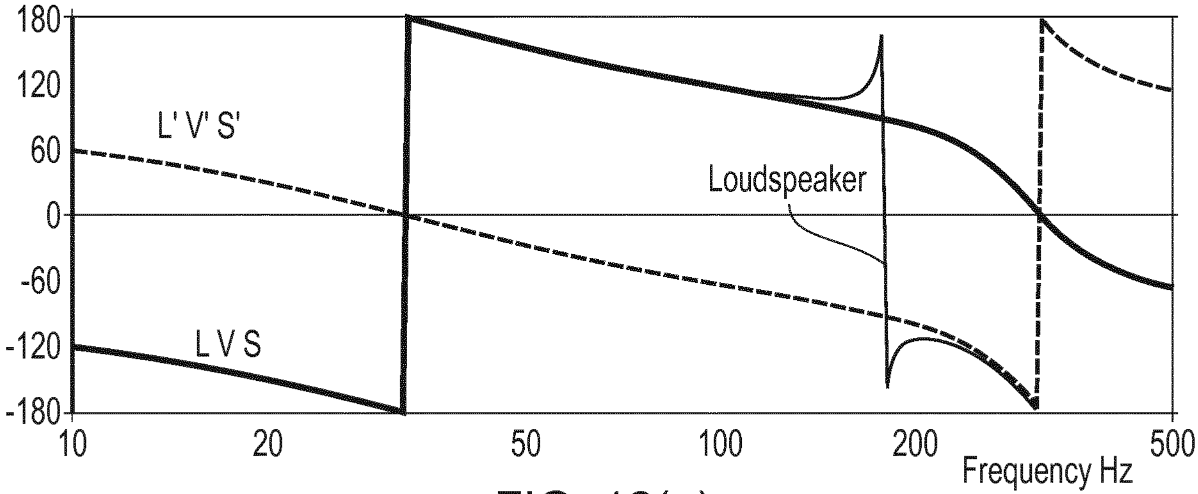


FIG. 12(a)

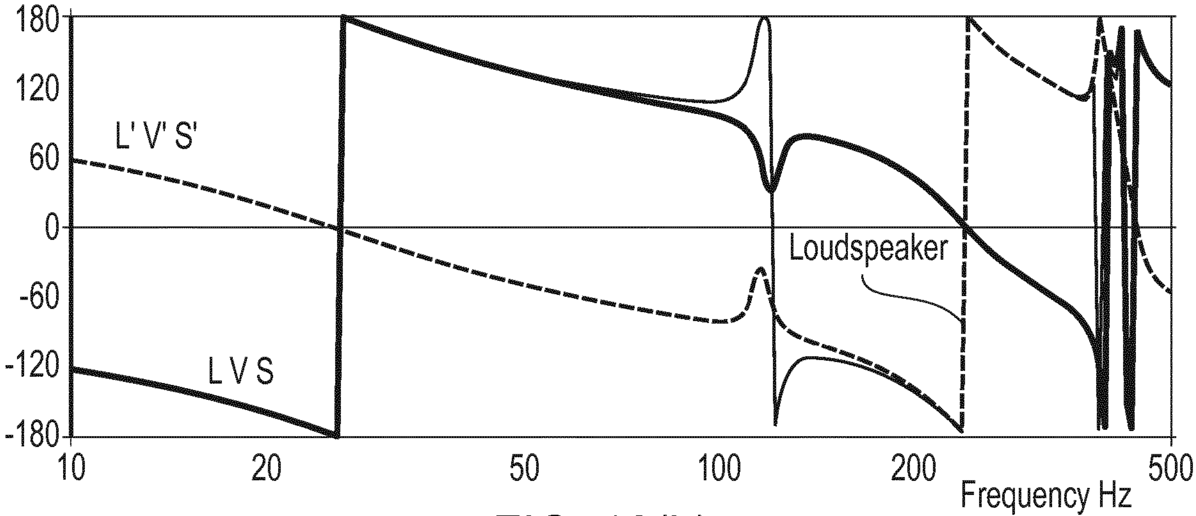


FIG. 12(b)

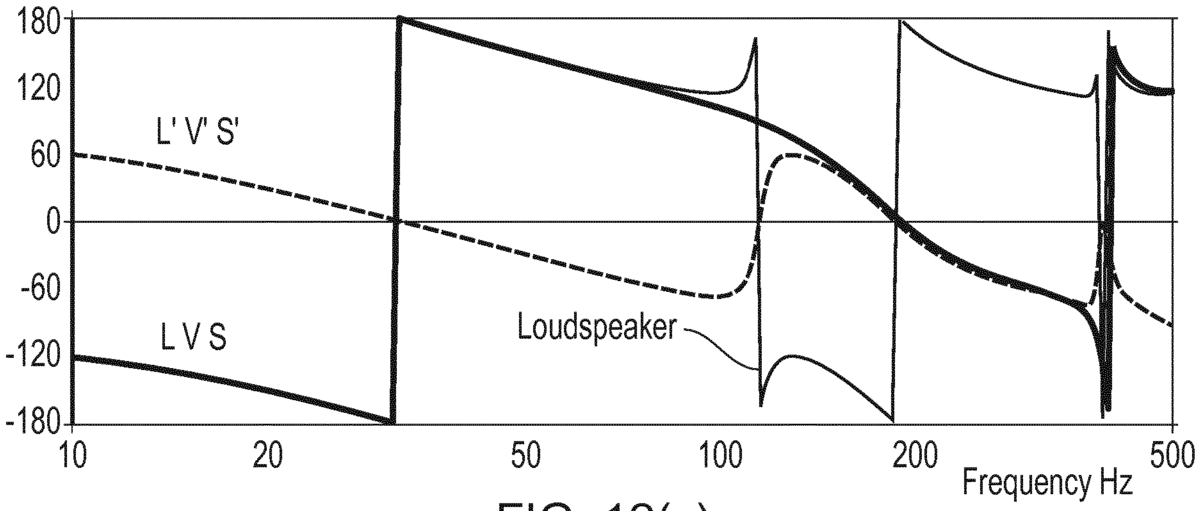


FIG. 12(c)

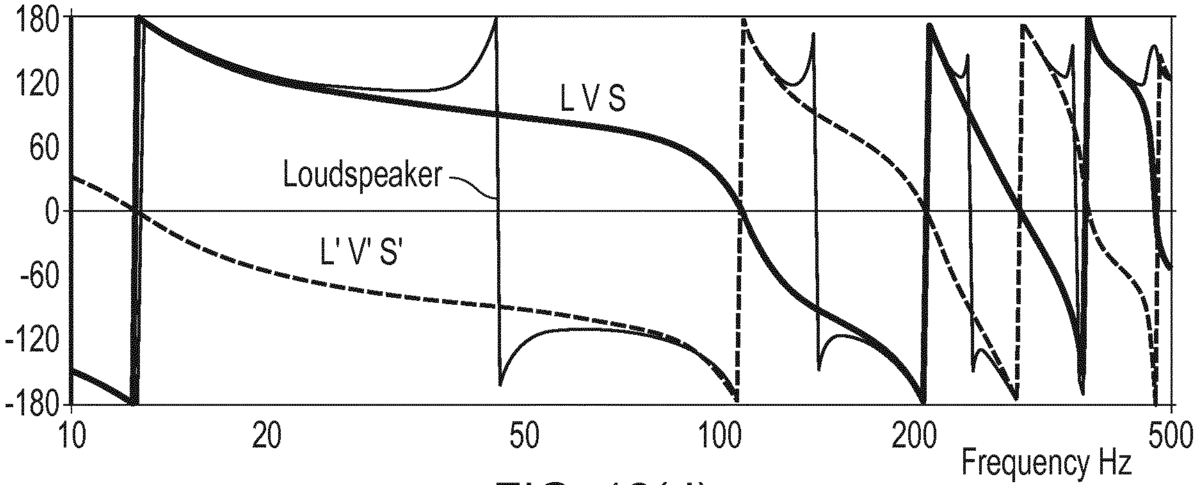


FIG. 12(d)

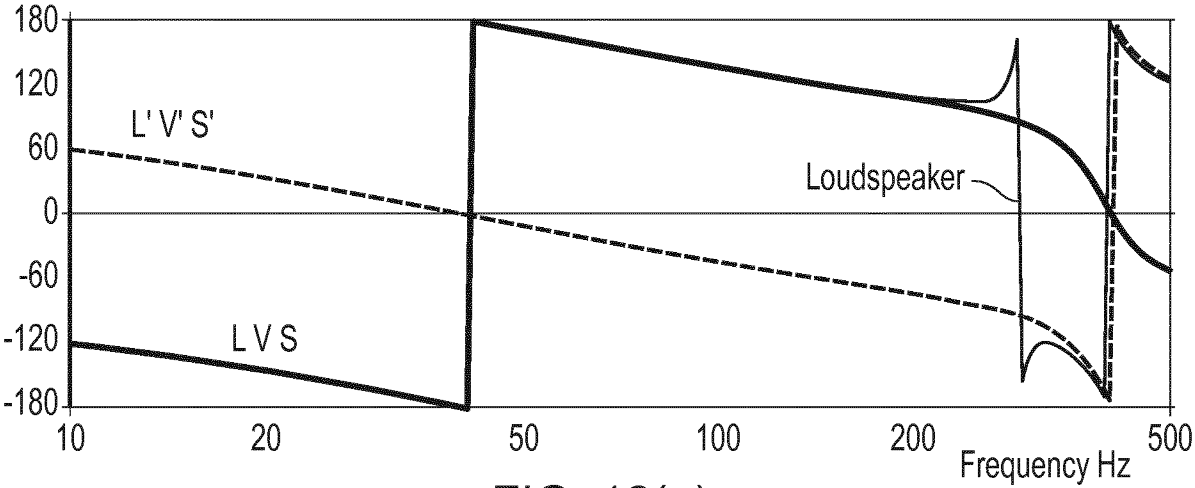


FIG. 12(e)

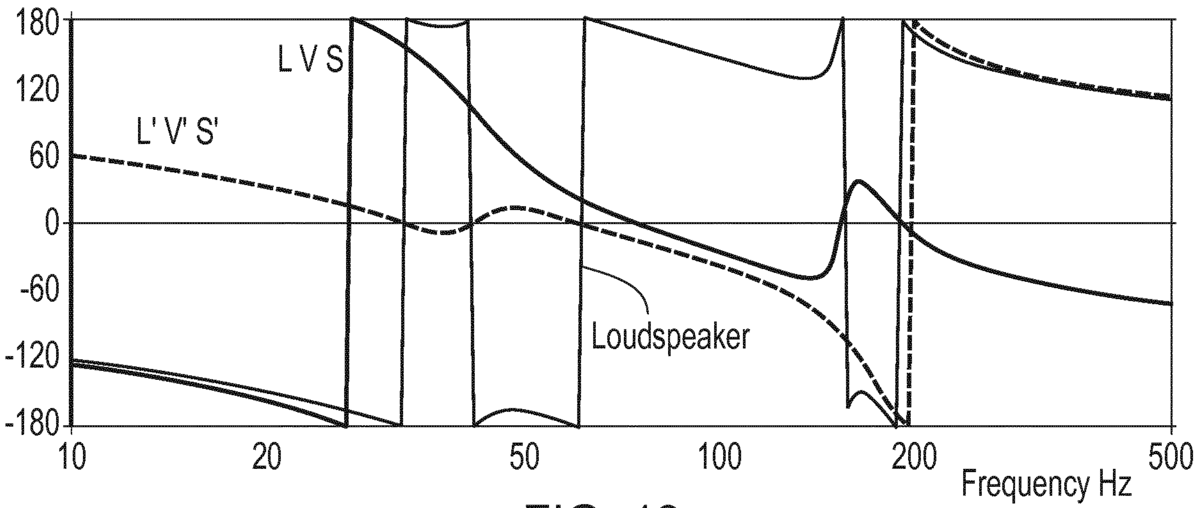


FIG. 13

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2019/056352

A. CLASSIFICATION OF SUBJECT MATTER
INV. H04R1/40
ADD. H04R1/34

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	EP 0 717 916 A1 (NORTHERN TELECOM LTD [CA]) 26 June 1996 (1996-06-26) paragraphs [0006], [0021], [0028]; figures 1, 6	1-10,14
X	EP 1 763 281 A2 (BOSE CORP [US]) 14 March 2007 (2007-03-14) paragraphs [0001], [0023]; figures 1, 2A, 3 paragraph [0044]; figure 9	1-9, 12-16
X	US 2006/056650 A1 (HOFMANN MARCUS [DE] ET AL) 16 March 2006 (2006-03-16) paragraph [0026]; figure 3 paragraph [0029]; figure 5 paragraph [0028]; figure 4a paragraphs [0034], [0038]; figures 9-11	1,4-9, 11,12, 14-16

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

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"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
9 May 2019	16/05/2019

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	Betgen, Benjamin

1

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	JP 2008 188099 A (TOYOTA BOSHOKU CORP; TOYOTA MOTOR CORP) 21 August 2008 (2008-08-21) abstract; figures 1, 3 -----	1-5,12, 15
X	US 2014/219492 A1 (PELLICCIO JOHN R [US] ET AL) 7 August 2014 (2014-08-07) paragraph [0023]; figure 6 -----	1,3-5,15

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2019/056352

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
EP 0717916	A1	26-06-1996	AU	690987	B2	07-05-1998
			CA	2169077	A1	14-12-1995
			CN	1129511	A	21-08-1996
			DE	69528693	D1	05-12-2002
			DE	69528693	T2	20-03-2003
			EP	0717916	A1	26-06-1996
			JP	2884017	B2	19-04-1999
			JP	H08511151	A	19-11-1996
			KR	100227218	B1	15-10-1999
			TW	275742	B	11-05-1996
			WO	9534184	A1	14-12-1995
EP 1763281	A2	14-03-2007	AT	448650	T	15-11-2009
			CN	1933675	A	21-03-2007
			EP	1763281	A2	14-03-2007
			HK	1101107	A1	15-01-2010
			JP	2007082220	A	29-03-2007
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