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(54) **Loudspeaker system with double chamber enclosure**

(57) A loudspeaker system is presented which comprises an enclosure (4,6) with two separate air volumes (3,5) which are acoustically linked by a port (7); the port enclosing a plug of air; and an electro-acoustical transducer (1) that converts electrical power into acoustical power and that comprises a diaphragm (2) having a front side and a rear side; the front side of the diaphragm radiates sound into a listening environment and the rear

side is directly acoustically coupled to one (5) of the volumes of the enclosure (4,6). The air volume (5) which is directly coupled to the diaphragm (2) and the plug of air located in the port are tuned to form a resonant system driven by the transducer; and the volume (3) that is not directly coupled to the diaphragm (2), is coupled to the plug of air in the port (7).

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Description

BACKGROUND

5 1. Technical Field

[0001] This invention relates to loudspeaker systems and, more specifically, to a novel low frequency loudspeaker system for vehicles.

10 2. Related Art

[0002] When a loudspeaker driver unit is mounted into a small sealed enclosure, the diaphragm is primarily influenced by the stiffness of the air as it is compressed into the finite volume of the sealed enclosure. One effect of this is to raise the coupled resonance of the driver-cabinet system which may undesirably curtail the low frequency (LF) extension. Additionally, in vehicles, mounting the loudspeaker into the body in white often means presenting a complicated impedance condition to the drive unit and may generate turbulent noise, pressure imbalance and acoustic short circuit. Furthermore it is often an unknown quantity, and forces the driver performance outside its carefully predicted bounds. Mounting the driver unit into a small enclosure (e.g., cabinet, box) requires that it should be mechanically very stiff and heavy to minimise the influence of the enclosed air stiffness - this in turn will make the driver unit expensive.

[0003] The cavity into which the drive unit is placed, usually some available space in the vehicle bodywork and doors, typically includes a number of interconnected pathways often resulting in a non-uniform pressure distribution presented to the rear of the diaphragm. This loading has been observed to drive asymmetrical mode-shapes in the driver's more compliant suspension components, in particular, resulting in so-called "rocking" modes. These modes are not controlled by the dominant motor damping element in the driver unit and are therefore frequently of a magnitude sufficient to cause fouling of the software parts against the motor system metalwork. In view of the above, there is a need for improvements in designing loudspeakers into small and complex cavities.

SUMMARY

[0004] A loudspeaker system is presented which comprises an enclosure with two separate air volumes which are acoustically linked by a port enclosing a plug of air; and an electro-acoustical transducer that converts electrical power into acoustical power and that includes a diaphragm having a front side and a rear side; the front side of the diaphragm radiates sound into a listening environment and the rear side is directly acoustically coupled to one of the volumes of the enclosure. The air volume which is directly coupled to the diaphragm and the plug of air in the port are tuned to form a resonant system driven by the transducer; and the volume that is not directly coupled to the diaphragm, is coupled to the plug of air in the port.

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] These and other objects, features, and advantages of the present invention will become apparent in light of the drawings and detailed description of the present invention provided below. The components in the figures are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention. Moreover, in the figures, like reference numerals designate corresponding parts throughout the different views.

FIG. 1 is a cross-sectional view of a novel loudspeaker system having two air volumes coupled by a short port;

FIG. 2 is an exploded perspective view of the system shown in FIG. 1;

FIG. 3 is a cross-sectional view of another example of a loudspeaker system having two air volumes coupled by a long port;

FIG. 4 is block diagram illustrating a mechanical model of a novel loudspeaker system having two air volumes coupled by a port;

FIG. 5 is a diagram depicting the sound pressure levels of a free air loudspeaker and a loudspeaker placed in a conventional enclosure;

FIG. 6 is a diagram depicting the sound pressure levels of a free air loudspeaker and a novel loudspeaker system

having two air volumes coupled through a port;

FIG. 7 is a diagram depicting the sound pressure level of a loudspeaker placed in a sealed enclosure in comparison to the sound pressure level of a loudspeaker of a novel loudspeaker system having two air volumes coupled by a port;

FIG. 8 is a diagram depicting the diaphragm displacement spectra of an Adapter for Passive Diaphragm Control (APDC);

FIG. 9 is a diagram depicting the calculated Sound Pressure Level (SPL) based on the diaphragm displacement of an Adapter for Passive Diaphragm Control (APDC);

FIG. 10 illustrates the pressure distribution within an exemplary enclosure for the case where a driver alone is placed into the enclosure; and

FIG. 11 illustrates the pressure distribution within an exemplary enclosure for the case where an APDC is used.

DETAILED DESCRIPTION

[0006] FIGS. 1 and 2 illustrate a novel loudspeaker system comprising a loudspeaker drive unit 1 that includes a sound-producing conical diaphragm 2 having front and rear faces, and a two parts enclosure located on the rear of said loudspeaker drive unit 1 creating an acoustical path from the rear face of said diaphragm 2 into the rear enclosure. The enclosure forms a rear diaphragm control system and includes two air volumes, an air volume 3 enclosed in an enclosure piece 4 and an air volume 5 enclosed in an enclosure piece 6, which are acoustically coupled to each other through a port 7 in a partition wall of enclosure piece 6. Enclosure piece 6 including port 7 will be also referred to as Adapter for Passive Diaphragm Control (APDC) in the following description. Volume 5 is directly coupled to the diaphragm 2. Volume 3 is coupled to a plug of air in the intervening port 7 and, accordingly, not directly coupled to the diaphragm 2.

[0007] The drive unit 1 is mounted in the enclosure piece 6 that serves as a ported coupling device and interfaces the drive unit 1 with the environment into which it is placed, e.g., in the present case enclosure piece 4 having a tube-like shape with an end wall. FIGS. 1 and 2 illustrate a system in which the volume 5 is predetermined and volume 3 does not need to be predetermined. Volume 3 may be replaced with any alternative sealed or even leaky volume representing a less deterministic part of the enclosure and may therefore be a more hostile acoustic environment, e.g., a cavity within a vehicle bodywork.

[0008] In the system of FIGS. 1 and 2, the enclosure piece 6 is a tube-like ring with a cone-shaped end piece (partition wall) carrying port 7 and extending into enclosure 4. However, enclosure piece 6 may have any other shape that encloses the same volume. As the first volume 3 is larger than the second volume 5, the distance from the diaphragm 2 to the rear of the enclosure piece 6 is relatively short and the intended operating frequency sufficiently low, such that standing waves in that direction within enclosure piece 6 are not a problem. If desired, sound absorbent material (not shown) can be provided within enclosure piece 6, enclosure piece 4 or both to provide an additional damping element should this prove to be necessary as an optimisation step.

[0009] The port 7 may be, e.g., a simple aperture or a connector tube that may run at virtually any angle to the loudspeaker drive unit's axis. The aperture (or apertures) may be in the form of a circular hole in the partition wall as shown in FIGS. 1 and 2. As shown in FIG. 3, the aperture may be a connector tube 14 arranged in the centre of the partition wall extending outwardly from the front and (or) the rear of the partition wall of the enclosure piece 6. The tube 14 has a specific diameter and a specific length defining an acoustic mass in the tube 14 referred to as plug of air. Many other arrangements of apertures and tubes are applicable such as multiple coupling ports, apertures/tubes placed out of the central regions of the partition wall, or apertures/tubes having a cross-section other than circular. Tubes with dimensions which change with distance from the loudspeaker drive unit are applicable as well. For specific applications, a second diaphragm 15 suspended in the aperture/tube interconnecting the two volumes of the enclosure, e.g., in or at the port, may be used to increase the port mass (plug of air) and reduce turbulence and losses at high power.

[0010] Beside the diaphragm 2, the drive unit 1 includes an apertured chassis 8, a magnet assembly 9, a voice coil 10, a surround 11, a spider 12, and a dust cap 13 in the centre of the diaphragm 4. When the loudspeaker drive unit 1 is in operation, sound waves are able to pass rearwardly from the rear of the diaphragm 2 into the sound path established by the two enclosure pieces 4, 6 and the port 7. From the front of the diaphragm 2 sound waves travel through the apertured chassis 3 to the listening environment. The loudspeaker drive unit 1 is of the modern reduced physical depth type, also known as inverse motor loudspeaker, where the magnet assembly 9 is arranged at the front side of the diaphragm 2, i.e., in the sound path leading to the listening environment. Therefore, beside the minimum depth of the loudspeaker system, this loudspeaker design provides also very good heat dissipation for the motor system, i.e., the magnet assembly 9 and the voice coil 10.

[0011] FIG. 4 shows a mechanical abstraction of the loudspeaker system of FIGS. 1-3 using standard dynamic theory for modelling purposes. In the model, an air mass M_v enclosed in the port 7 is tied to ground G by a spring (spring constant K_1) provided by the first volume 3 and to the diaphragm 2 (mass M_{md}) by another spring (spring constant K_2) provided by volume 5. A force F is applied to the diaphragm 2 moving its mass M_{md} which is tied to ground G by a spring (spring constant K_3) and a damper (damping constant C) provided by the suspension 11 and the spider 12.

[0012] The system is similar in many ways to the traditional bass reflex design, however the air mass M_v in the port 7, being enclosed, does not form part of the acoustic radiation and is thus tied to ground G via the spring having spring constant K_1 in the mechanical model. This second degree of freedom serves only to provide the necessary rear loading to control the diaphragm in the tuned system. The force F applied to the driver and that experienced by the air mass M_v in the port 7 are expressed mathematically and the resulting equations solved to provide the diaphragm displacement. The sound pressure level (SPL) at 1m, assuming the system radiates from an infinite baffle can be calculated from the diaphragm displacement. Solving the equations below for x_1 will provide a prediction of the piston displacement x_1 from which diaphragm displacement and, accordingly, SPL predictions can be made.

[0013] Force F acting upon piston:

$$F = \left(-\omega^2 M_{md} + j\omega C + K_{tot} + K_2 S_d^2 \right) x_1 - (K_1 + K_2) S_v^2 x_2$$

[0014] Force acting upon air mass in port (losses ignored):

$$0 = \left(-\omega^2 M_v + (K_1 + K_2) S_v^2 \right) x_2 - K_2 S_d^2 x_1$$

wherein $K_{tot} = (K_1 \cdot K_2) / (K_1 + K_2) + K_3$, K_3 is the acoustical stiffness element of the loudspeaker, S_d is the area of the diaphragm, S_v is the area of the port, and x_2 is the displacement of the plug of air in the port.

[0015] FIG. 5 depicts the results of a comparison of a loudspeaker drive unit operated in free air (solid line) and a loudspeaker drive unit placed in an enclosure enclosing a 5.5 litre (L) air volume (dotted line). As can be seen, the sound pressure level (SPL) in dB over frequency f in Hz of the free air drive unit exhibits a higher sound pressure level at low frequencies (e.g., below 100 Hz) than the boxed drive unit exhibiting a peak at frequencies above 100Hz.

[0016] FIG. 6 depicts the results of a comparison of a loudspeaker drive unit operated in free air (solid line) and loudspeaker drive unit placed in an enclosure enclosing a 5.5 litre (L) air volume and having an APDC (dotted line) as shown in FIGS. 1-3 (the sum of the two air volumes are equal to the volume of a conventional enclosure). In the present example, the port diameter is 20mm, the port length is 20mm, the coupler volume (of enclosure piece 6) is 0.2L and the rear volume (of enclosure 4) is 5.3L. The sound pressure level (SPL) in dB over frequency f in Hz of the free air drive unit exhibits a higher sound pressure level at low frequencies (e.g., below 100 Hz) than the drive unit that has ripples at frequencies below and above 100Hz.

[0017] However, comparing the loudspeaker drive unit in a sealed enclosure with APDC with the same drive unit in a sealed enclosure without APDC, the low frequency peak in the response provides an improvement in the bass extension for woofer and subwoofer applications and the following dip in the response forms the roll off which may be augmented with an active or passive filter, e.g., an active filter implemented in a digital signal processor (DSP). FIG. 7 depicts the results of the comparison of the loudspeaker drive unit in the sealed enclosure with APDC (dotted line), and the same drive unit in the sealed enclosure without APDC (solid line), where the loudspeaker drive unit in the sealed enclosure with APDC is supplied with double input power (+3dB). The driver used in the modelling was the JM85 Land Rover rear door woofer. The system is scalable and can be used also with loudspeakers with lower bass extension. It can be seen from FIG. 7 that while adding a sealed box reduces the low frequency efficiency, the APDC restores this efficiency to equal the free air case at lower frequencies facilitating bass reproduction in small boxes.

[0018] FIGS. 8 and 9 show results of the experimentally measured diaphragm displacements over a range of low frequencies at both 1v and 6v using a Klippel analyser. These measurement results are compared to the simulation from the derived equations. From these displacement curves, it is possible to predict the SPL in an infinite baffle. It can be seen that there is some loss effect at high power levels due to turbulent effects. Changing (in particular increasing) the port dimensions can optimize this even at the expense of a little of the desired coupler effect. The results demonstrate that the diaphragm is indeed influenced in the same manner as predicted.

[0019] The plug of air in the port is separating the tuned air volume coupled directly to the diaphragm from the untuned volume established by, e.g., a car body cavity. So the hardly controllable behaviour of the untuned air volume is no longer determining the acoustic properties of the complete loudspeaker system. As shown in the examples of FIGS. 1

and 3, an appealing aspect of this is that the second volume 5 directly coupled to the diaphragm and the port can be formed from a simple funnel-shaped moulding (e.g., even part of the basket or frame) and therefore would be cheap to add. The benefits would be reducing or eliminating coil rubs due to rocking modes and knowing precisely what the in-situ diaphragm velocity is and being able to simulate or tune the full system more accurately. The APDC may also function as a simple protective rainwater cowl.

[0020] Referring to FIGS. 10 and 11, a conceptual enclosure 15 was created representing a vented subwoofer box having an opening 16. The opening 16 is to interface with the vehicle bodywork and a convenient boundary condition was applied to simulate entry into a long pipe so it is neither sealed nor vented by design. A driver having a diaphragm 17 was loaded into the enclosure both with and without an APDC coupler 18. A coupled acoustic analysis (half model) of the driver plus enclosure and driver in APDC plus enclosure was computed. The results are shown in FIGS. 10 and 11 illustrating the pressure distribution within the enclosure 15 up to the rear surface of the diaphragm 17 for the case where a driver alone is placed into the enclosure 15 (FIG. 10) and where an APDC coupler 16 is added to the system (FIG. 11). Only the air is shown as a volume which extends to the rear surface of the diaphragm 17 and the pressure variation is described by a change on a grey scale (dark - higher pressure, pale - lower pressure).

[0021] At higher frequencies - in the present case 310Hz, where pressure within the enclosure varies spatially, there is an uneven acoustic loading at the rear of the loudspeaker diaphragm. This means that loudspeakers that have structural rocking modes located in this frequency range are vulnerable to having these activated by the pressure imbalance at the rear of the diaphragm. The dominant motor damping mechanism is ineffective for this type of mode as the motion of the coil does not orthogonally cut the flux lines in the motor system. In the case where an APDC is used, the fluid load acting directly upon the rear of the diaphragm is more uniform, decoupled from the strong pressure variation by the structure of the APDC housing. This means that little energy is transferred into rocking modes and therefore are only weakly excited.

[0022] The novel loudspeaker system provides a deterministic rear load and alleviates rocking modes. It is tuneable where an increased port diameter restores the original response and retains uniform loading to the rear of the loudspeaker drive unit, e.g., a woofer or subwoofer. The use of an Adaptor for Passive Diaphragm Control (APDC) provides a sharper roll in/roll off. Furthermore, the acoustic radiation is performed by the diaphragm only and the tuning parameters will be optimised such that no audible port noise is evident.

[0023] The performance of the novel loudspeaker system is - compared to conventional systems - predictable and a small enclosure can be added with little or no change in designed system resonance. Natural sharp roll off after the Helmholtz resonance of the enclosure reduces interference with other drivers complementing electronic filtering. Having an engineered multi degree of freedom acoustical system controlling the diaphragm, a low frequency extension is possible without adding acoustically absorbent wadding within an enclosure which is often impractical for car audio applications.

[0024] Due to a lower efficiency, novel loudspeaker systems may be used in connection with D-Class amplifiers in order to have more power available. In this case, when using an inverse motor loudspeaker drive unit as outlined above, the potentially hot motor is on the outside of the enclosure providing very good heat dissipation to the atmosphere considering the higher power supplied. When subwoofers are used in conjunction with small enclosures, they are often designed to have very stiff suspension and high moving mass to minimise the effect of the added stiffness of the sealed box. Such a driver must be driven at high power to achieve reasonable acoustical power output and efficiency is generally quite low. In the novel loudspeaker system, lower cost drive units having a lower mass and/or lower stiffness and/or magnetic flux density may be used.

[0025] Although examples of the present invention have been described herein above in detail, it is desired, to emphasis that this has been for the purpose of illustrating the present invention and should not be considered as necessarily limitative of the invention, it being understood that many modifications and variations can be made by those skilled in the art while still practising the invention claimed herein.

Claims

1. A loudspeaker system comprising:

an enclosure that comprises two separate air volumes which are acoustically linked by a port; the port enclosing a plug of air; and

an electro-acoustical transducer that converts electrical power into acoustical power and that comprises a diaphragm having a front side and a rear side; the front side of the diaphragm radiates sound into a listening environment and the rear side is directly acoustically coupled to one of the volumes of the enclosure; where

the air volume which is directly coupled to the diaphragm and the plug of air in the port are tuned to form a resonant system driven by the transducer; and

the volume that is not directly coupled to the diaphragm, is coupled to the plug of air in the port.

2. The loudspeaker system of claim 1 where the port has a tube-like shape.

5 3. The loudspeaker system of claim 1 or 2 where the port and the volume directly coupled to the diaphragm, are tuned using standard dynamic theory.

10 4. The loudspeaker system of one of claims 1-3 where the volume not directly coupled to the diaphragm is larger than the volume directly coupled to the diaphragm.

5. The loudspeaker system of one of claims 1-4 where the plug of air comprises a volume that is smaller than the two volumes.

15 6. The loudspeaker system of one of claims 1-5 where the diaphragm of the electro-acoustical transducer has a cone-like shape.

7. The loudspeaker system of one of claims 1-6 where the volume coupled directly to the diaphragm has a cone-like shape.

20 8. The loudspeaker system of one of claims 1-7 where the enclosure comprises rigid walls.

9. The loudspeaker system of one of claims 1-8 where the electro-acoustical transducer comprises a motor system that is arranged on the side of the diaphragm being opposite to the enclosure.

25 10. The loudspeaker system of one of claims 1-9 where the volume that is not directly coupled to the diaphragm, is formed by body parts of a vehicle.

11. The loudspeaker system of one of claims 1-10 further comprising another diaphragm located at or in the port.

30 12. The loudspeaker system of one of claims 1-11 where the electro-acoustical transducer is a woofer or subwoofer.

13. The loudspeaker system of one of claims 1-12 where the transducer comprises a frame and the enclosure comprises two parts; one part of which being also part of the transducer's frame.

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FIG 1

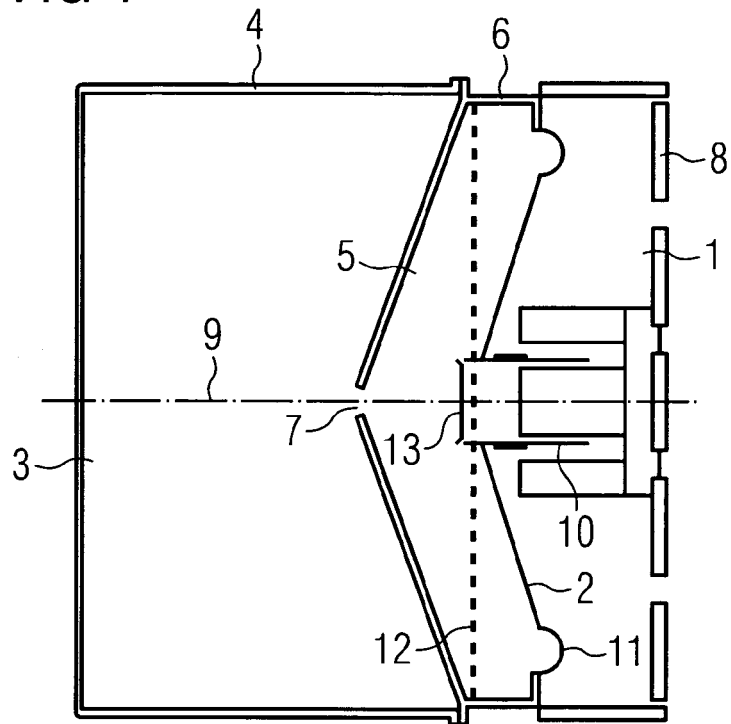


FIG 2

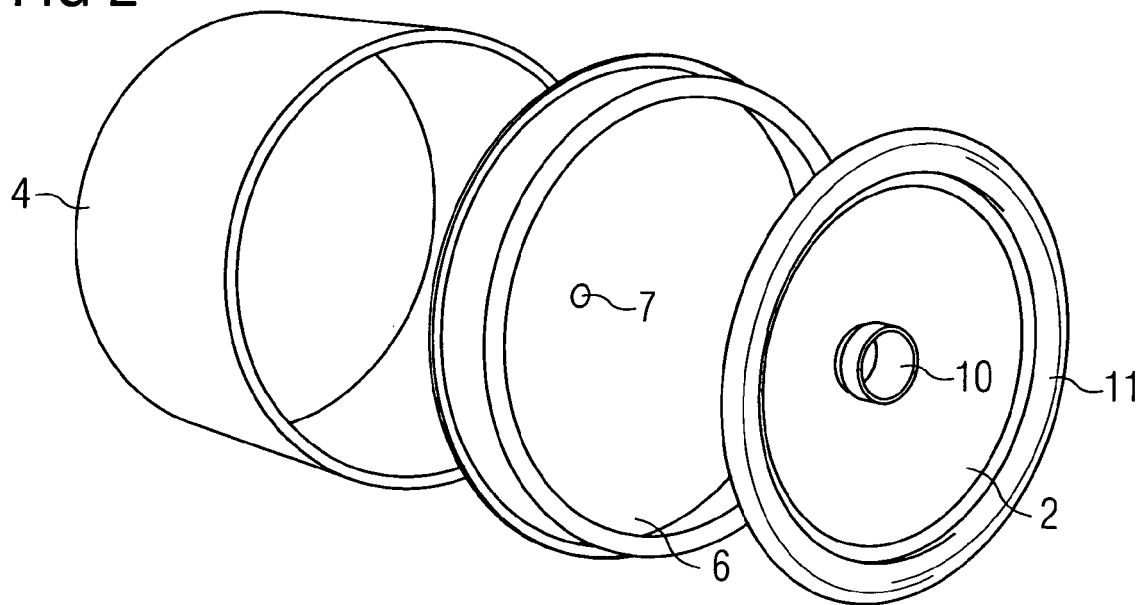


FIG 3

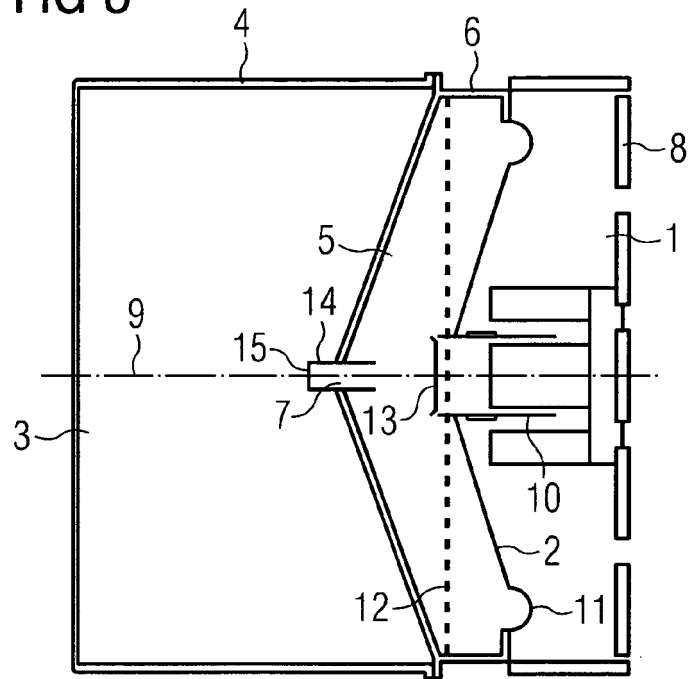


FIG 4

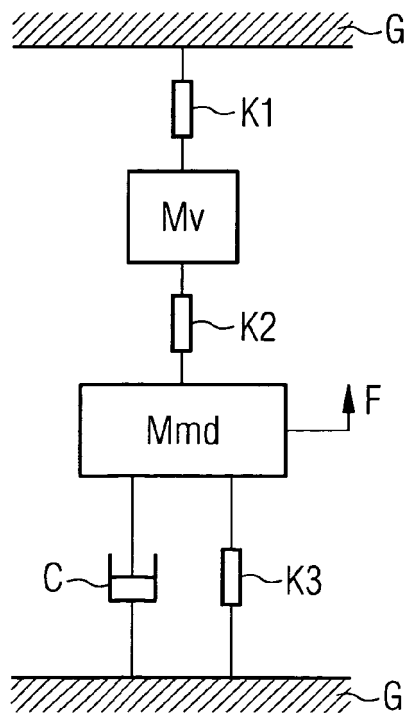


FIG 5

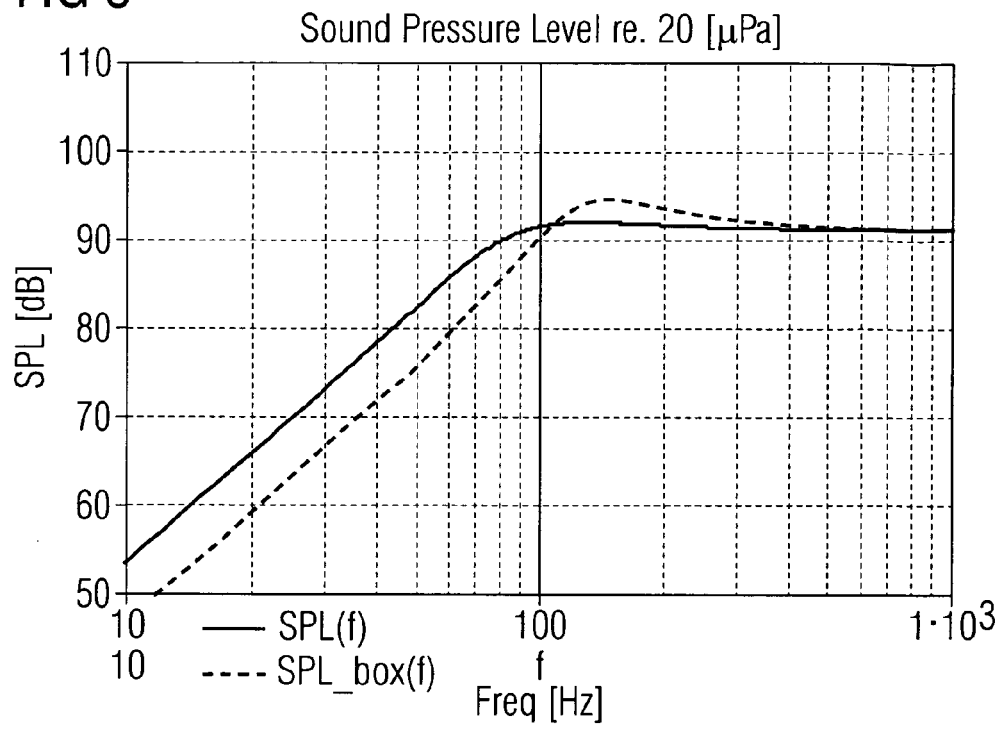


FIG 6

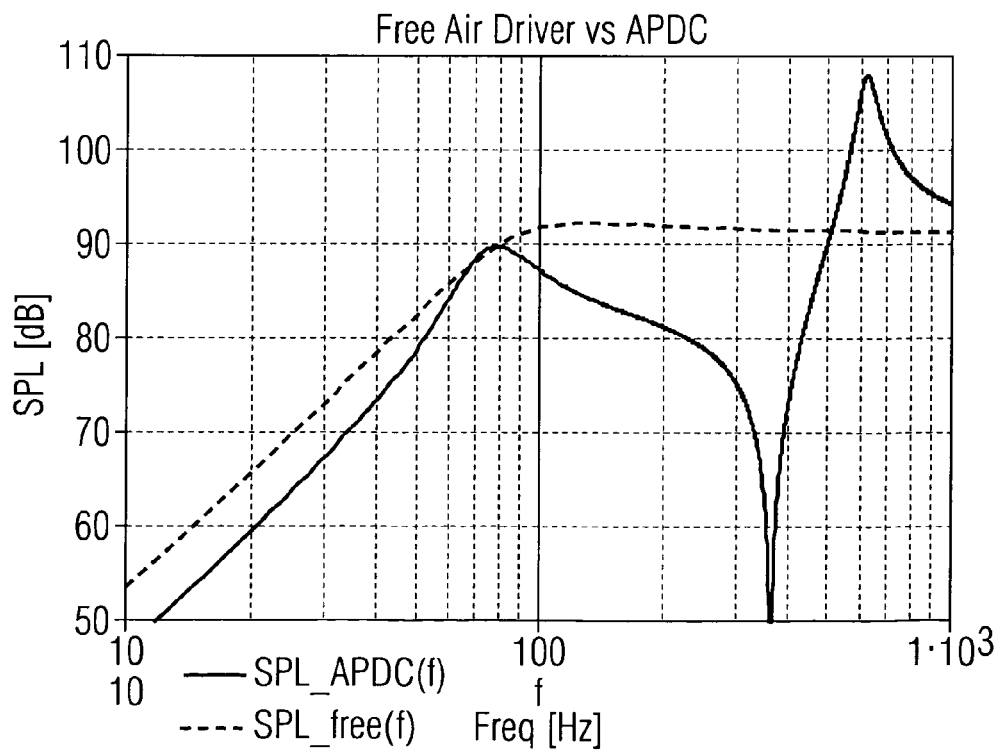


FIG 7

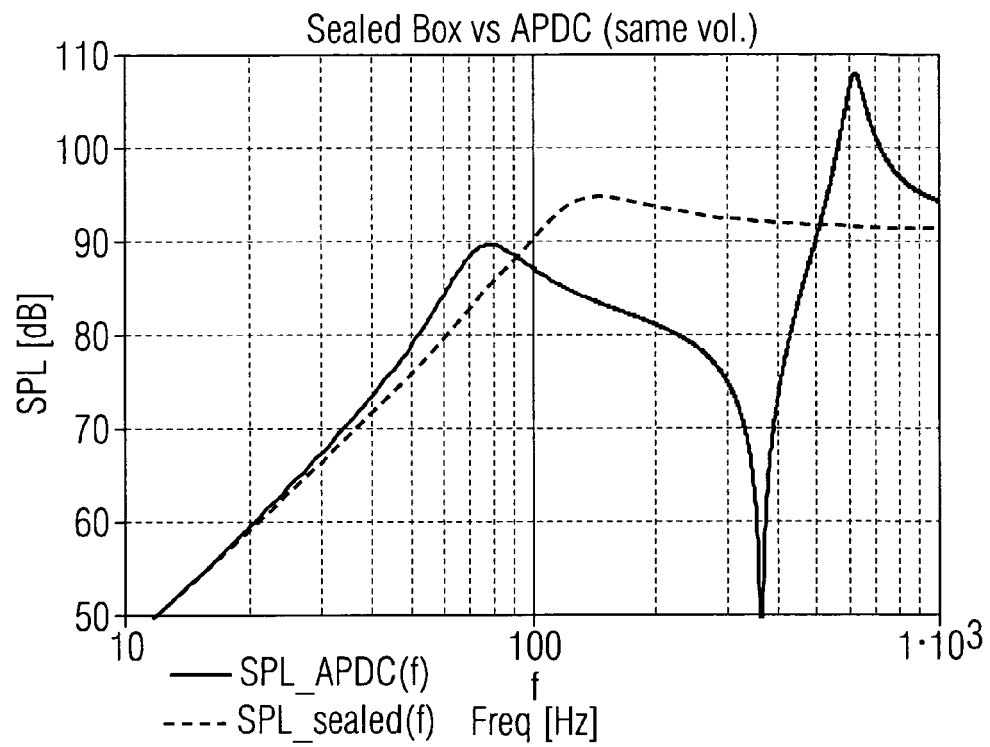


FIG 8

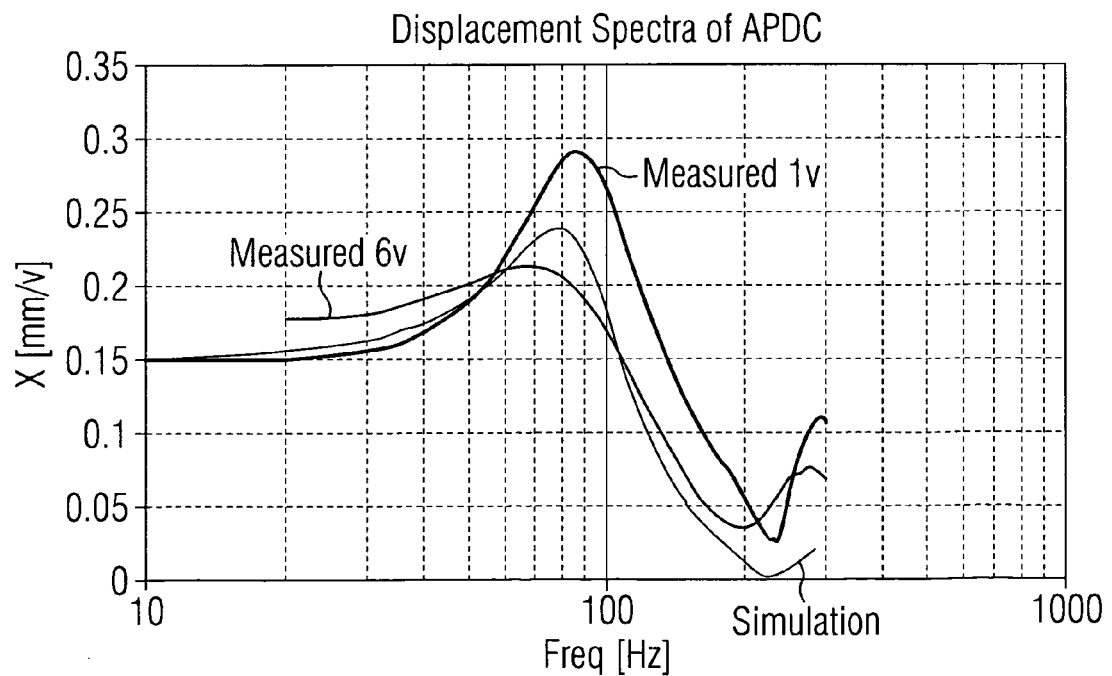


FIG 9

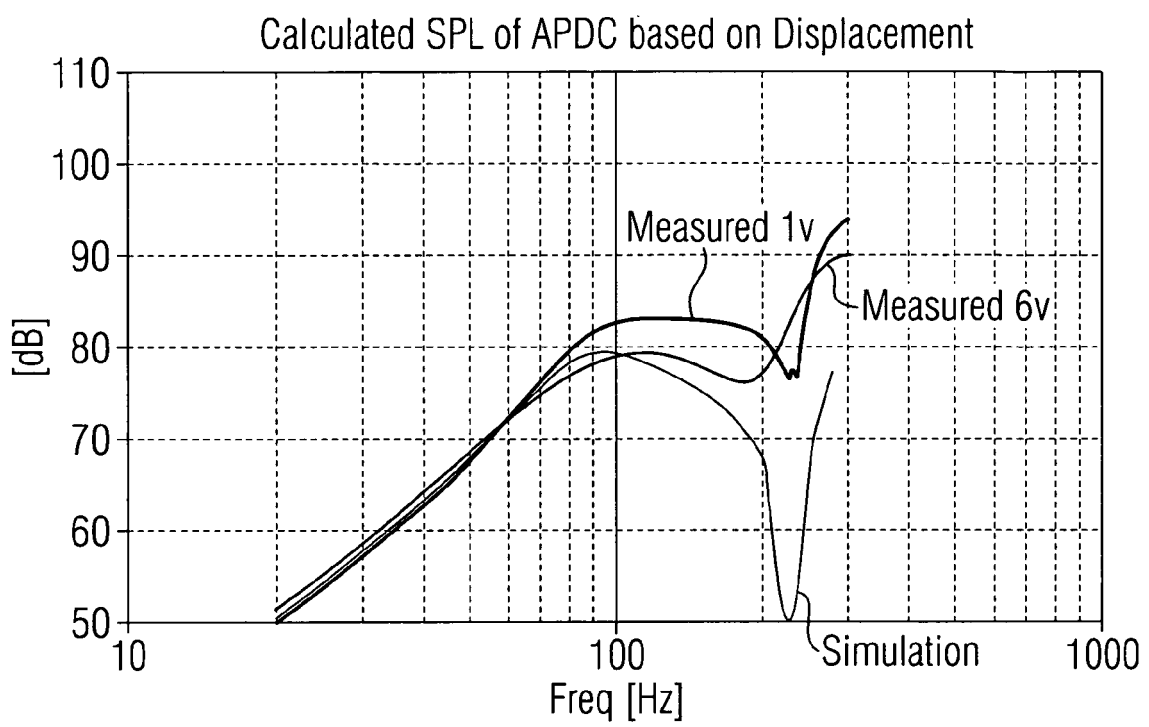


FIG 10

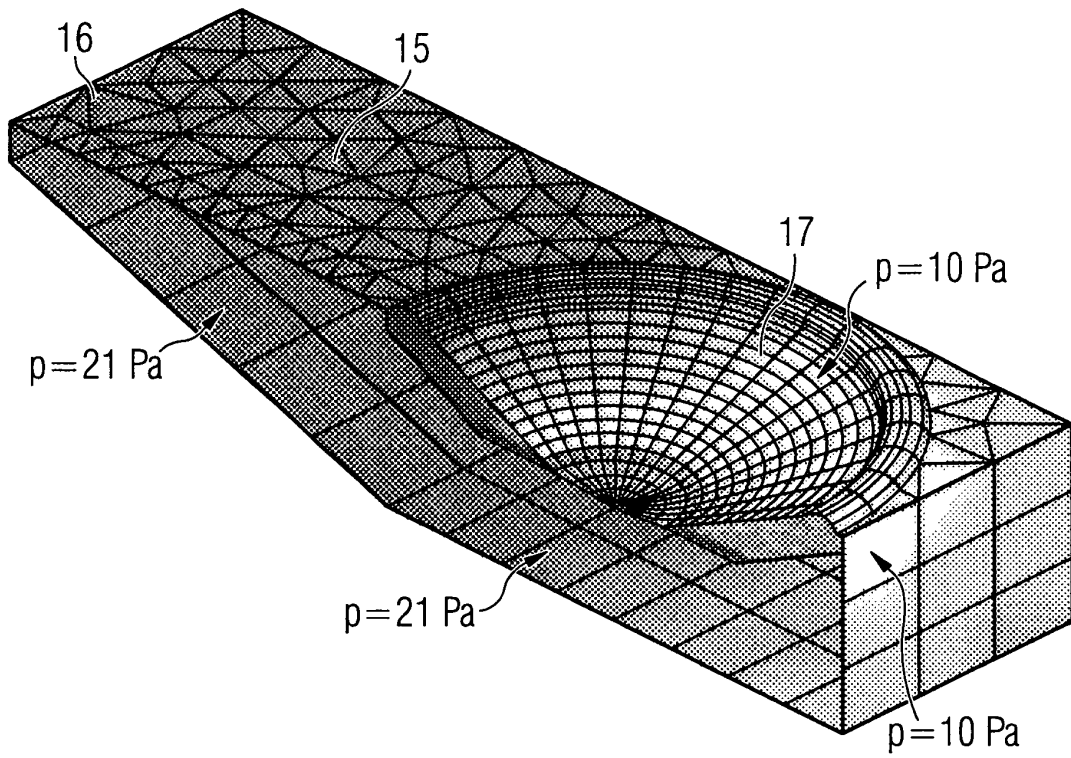
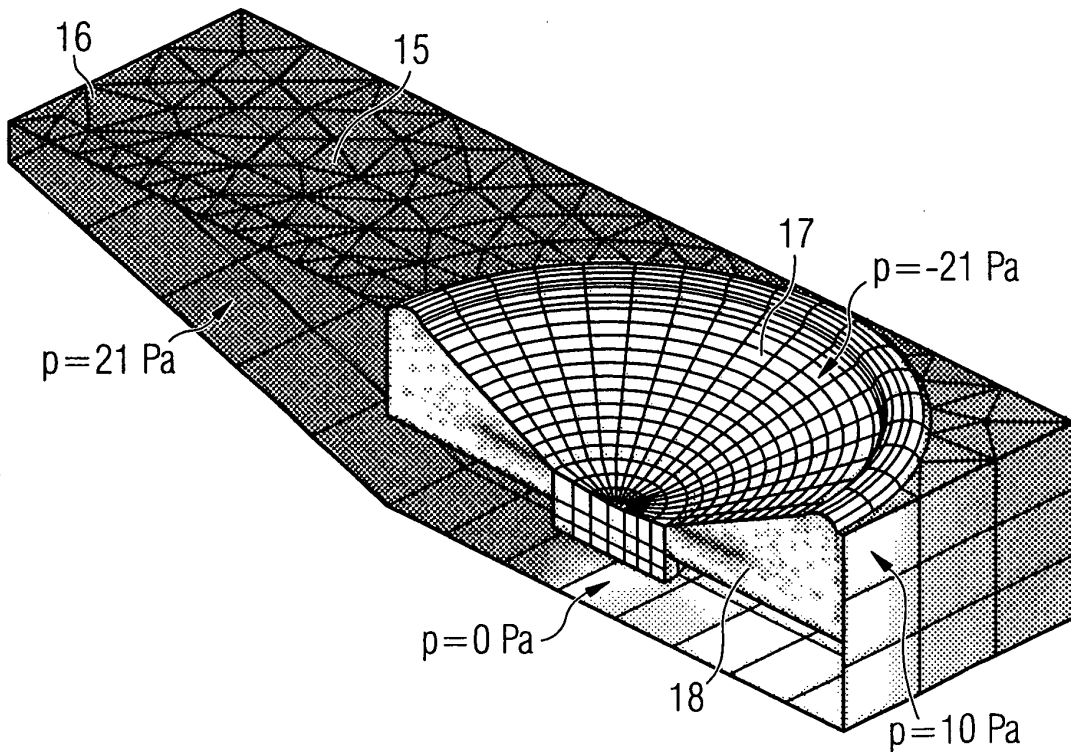


FIG 11





European Patent
Office

EUROPEAN SEARCH REPORT

Application Number
EP 07 02 4287

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The present search report has been drawn up for all claims			
Place of search Munich		Date of completion of the search 15 April 2008	Examiner Borowski, Michael
CATEGORY OF CITED DOCUMENTS X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document			

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EPO FORM 1503 03.82 (P04C01)

**ANNEX TO THE EUROPEAN SEARCH REPORT
ON EUROPEAN PATENT APPLICATION NO.**

EP 07 02 4287

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report.
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