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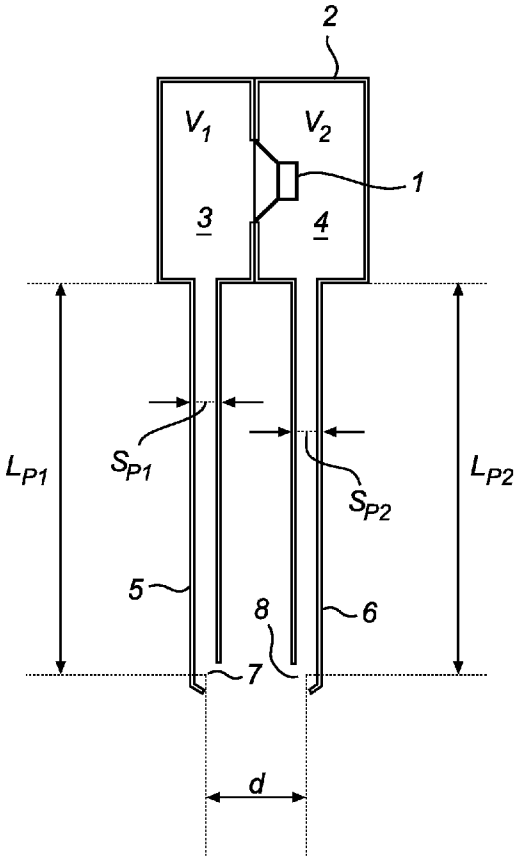
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[Continued on next page]

(54) Title: PULSATING COOLING SYSTEM



(57) Abstract: A cooling device comprising at least one transducer (1) having a membrane adapted to generate pressure waves at a working frequency, characterized by a first and a second cavity (3, 4), said transducer being arranged between said first and second cavities, such that said membrane forms an fluid tight seal between said cavities, each cavity having at least one opening (7, 8) adapted to emit a pulsating net output fluid flow, wherein said cavities and openings are formed such that, at said working frequency, a first harmonic fluid flow emitted by said opening(s) (7) of a first one of said cavities is in anti-phase with a second harmonic fluid flow emitted by said opening(s) (8) of a second one of said cavities, so that a sum of harmonic fluid flow from said openings is essentially zero. With this design, sound reproduction at the working frequency is largely cancelled due to the counter phase of the outlets resulting in a close to zero far-field volume velocity.

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Pulsating cooling system

FIELD OF THE INVENTION

The present invention relates to a pulsating cooling system, i.e. a cooling system where a transducer induces an oscillation creating a pulsating fluid stream that can be directed towards an object that is to be cooled. It may be advantageous to drive the system at, or at least close to, its resonance frequency, in order to obtain a high fluid velocity.

BACKGROUND OF THE INVENTION

The need for cooling has increased in various applications due to higher heat flux densities resulting from newly developed electronic devices, being, for example, more compact and/or higher power than traditional devices. Examples of such improved devices include, for example, higher power semiconductor light-sources, such as lasers or light-emitting diodes, RF power devices and higher performance micro-processors, hard disk drives, optical drives like CDR, DVD and Blue ray drives, and large-area devices such as flat TVs and luminaires.

As an alternative to cooling by fans, document WO 2005/008348 discloses a synthetic jet actuator and a tube for cooling purposes. The tube is connected to a resonating cavity, and a pulsating jet stream is created at the distal end of the tube, and can be used to cool an object. The cavity and the tube form a Helmholtz resonator, i.e. a second order system where the air in the cavity acts as a spring, while the air in the tube acts as the mass.

Another example is given by N. Beratlis et al, Optimization of synthetic jet cooling for microelectronics applications, 19th SEMITHERM San Jose, 2003. Here a synthetic jet is disclosed having two diaphragms each communicating with the same orifice.

A pulsating fluid stream (typically air stream) of this kind has been found to be more efficient for cooling than laminar flow, as typically used in conventional cooling systems (e.g. cooling fans). The resonance cooling systems further require less space, and generates less noise.

However, in previously proposed systems, e.g. as disclosed in WO 2005/008348, a certain level of sound reproduction, related to the frequency of the oscillating air flow, remains.

SUMMARY OF THE INVENTION

It is an object of the present invention to reduce the noise level in a pulsating cooling system even further.

According to the present invention, this and other objects are achieved by a cooling device comprising two cavities, the transducer being arranged between the two cavities, such that the membrane forms a fluid tight seal between the cavities, each cavity having at least one opening adapted to emit a pulsating net output fluid flow, wherein the cavities and openings are formed such that, at the working frequency, a first harmonic fluid flow emitted by the opening(s) of a first one of the cavities is in anti-phase with a second harmonic fluid flow emitted by the opening(s) of a second one of the cavities, so that a sum of harmonic fluid flow from the openings is essentially zero.

The transducer arranged between two cavities will act as a dipole, i.e. two acoustical sources in anti-phase. The invention is based on the idea that the harmonic parts of the sound from these two sources will cancel out. The non-harmonic parts, which represent the dominating part of the cooling effect, will not add coherently, and will thus not cancel out.

With this design, an improved cooling effect is achieved by means of an oscillating air stream, while at the same time sound reproduction at the working frequency is largely cancelled due to the counter phase of the outlets resulting in a close to zero far-field volume velocity. Consequently, the cooling system according to the present invention has significantly lower sound reproduction than prior art "synthetic jet" cooling devices.

The cooling device according to the present invention may be used for cooling a large variety of objects through directed outflow of various liquid or gaseous fluids, not only air. It is, however, particularly useful for air-cooling of such objects as electronic circuitry.

Each cavity may have only one opening, or have more than one opening. It is important however that the sum of harmonic contributions from all openings is essentially zero.

More than one transducer may be arranged between the cavities. For example, two, oppositely positioned transducers operating in counter phase will result in a larger air flow. By "oppositely positioned" is intended a situation where pressure waves from one transducer are directed into one cavity, while pressure waves of the other transducer are directed into the other cavity.

A "transducer" is here a device capable of converting an input signal to a corresponding pressure wave output. The input signal may be electric, magnetic or mechanical. Examples of suitable transducers include various types of membranes, pistons, piezoelectric structures and so on. In particular, a suitably dimensioned electrodynamic loudspeaker may be used as a transducer.

The distance between the openings should be short compared to the wavelength at the working frequency. For two sources (e.g. two openings) of strength A at a distance d from each other, the pressure p at distance r from these sources will be $p = \frac{Akd\sin(\theta)}{r}$, where k is the wave number (ω/c) and θ is the angle of observation. In order to keep this pressure small, according to a preferred embodiment, the distance d is less than 0.2 λ, and even more preferably less than 0.1 λ.

There are no absolute requirements on the working frequency. However, the working frequency is preferably chosen such that the air velocities and air displacement through the openings have a local maximum, and typically this occurs in a neighborhood of a resonance frequency of the device, i.e. a frequency corresponding to a local maximum of the electric input impedance of the device (the transducer in combination with the cavities and openings). Typically the lowest such frequency is chosen.

Alternatively, the working frequency can be chosen such that the cone excursion of said transducer has a local minimum at this working frequency. Typically, this occurs at an anti-resonance frequency of the device, i.e. a frequency corresponding to a local minimum of the electric input impedance of the device.

One way of ensuring that the air velocities are of essentially equal size and in counter-phase is to provide equal circumstances for all air streams. For example, the cavities can be formed to have equal volume, and the openings can be formed to have equal cross section area. However, this is not a requirement, and canceling air streams may be achieved also with different sized cavities and/or openings.

According to one embodiment, the openings are connected to respective cavity via a channel (or pipe). This allows for more design freedom, as the channels can be formed to direct several air streams towards the same location, and with desired direction. For the same reason as above, the channels can be formed to have equal length and cross section area.

According to one embodiment, such channels are sufficiently long to act more as tube resonators. According to an alternative embodiment, the length of the channels is instead sufficiently short to allow the cavities to act as conventional Helmholtz resonators.

A channel connecting at least one opening of the first cavity can extend through the second cavity, so that this opening is located on the same side of said device as the openings of the second cavity. In a case where the cavities have essentially planar extension and are arranged on top of each other (i.e. like two discs on top of each other), such a design will enable locating all the openings on the top or bottom side of the device.

Two or more devices according to the present invention may be combined, to form a cooling arrangement with a multiple of two openings. The average distance between the openings of a first device and the openings of a second device is then subject to the same requirements as the distance between the two openings of each device, and should thus preferably be less than 0.2 λ, and even more preferably less than 0.1 λ.

According to this design, four (or more) outlets are arranged close to each other, in relation to the wavelength at the working frequency. This results in a further reduction of noise during operation of the cooling arrangement. This is partly due to a more perfect symmetry of geometry, because of the presence of two (mirrored but identical) transducers, and partly due to a better compensation of nonlinear distortion generated by the two identical loudspeakers.

BRIEF DESCRIPTION OF THE DRAWINGS

This and other aspects of the present invention will now be described in more detail, with reference to the appended drawings showing a currently preferred embodiment of the invention.

Fig. 1 shows a cooling system according to a first embodiment of the present invention.

Fig 2 shows an example of the frequency responses of respectively the electric input impedance, the air velocities, the air displacement, and the cone displacement.

Fig. 3 shows a cooling system according to a second embodiment of the present invention.

Fig. 4 shows a cooling system according to a third embodiment of the present invention.

Fig. 5 shows a cooling system according to a variant of the third embodiment of the present invention.

Fig. 6 shows a cooling system according to another variant of the third embodiment of the present invention.

Fig. 7 shows a cooling system according to a fourth embodiment of the present invention.

Fig. 8 shows a cooling system according to a fifth embodiment of the present invention.

DETAILED DESCRIPTION

The cooling system in figure 1 comprises a transducer 1 arranged in an enclosure 2. The transducer 1 is arranged to divide the enclosure into two cavities 3, 4 having volumes V1 and V2 respectively. Each cavity is connected to the ambient atmosphere respectively via two passages, here pipes 5, 6 having lengths Lp1 and Lp2, and cross section areas Sp1 and Sp2. The pipes 5, 6 have outlets 7 and 8 positioned on a distance d from each other. The openings are illustrated as having round shape, but the invention is not limited to this shape. On the contrary, the openings may have any shape, and may also be tapered to influence the airflow in a desired manner.

The volumes V1 and V2 and the form of the pipes 5, 6 are chosen such that in use, the transducer will act as a pressure wave dipole, cause a pulsating flows of fluid present in the cavities through the outlets which are essential equal and in counter phase. When driving the transducer at a working frequency, the two fluid flows will thus counteract each other, thereby suppressing any pressure waves escaping from the dipole (i.e. disturbing sound).

It is noted that the principle is not limited any particular fluid, but the present description will be based on a device operated in air, i.e. a device that generates oscillating air streams.

According to the illustrated example, this is ensured by letting respectively V_1 and V_2, L_{p1} and L_{p2}, and S_{p1} and S_{p2} have the same value.

By keeping the distance d short compared to the wavelength, e.g. less than 0.1 λ, where λ is the wavelength in air corresponding to the working frequency, the air pressure radiating from the dipole is kept very small.

The volumes V_1 and V_2 and the form of the pipes 5, 6 (from Fig.1) can be chosen such that there is a specific frequency for which the air velocities v_1 and v_2 through each outlet 7, 8 have coinciding local maximums and are in counter phase. The working frequency can then be chosen to coincide with this frequency, to ensure a maximum air

velocity and thereby cooling effect. Often, these local maxima coincide with the most left electric input impedance peak on the frequency scale. This corresponds to a resonance frequency of the device.

According to an exemplifying embodiment, a device may have the following properties:

Moving mass		=	0.57 g		
Resonance frequency		=	370 Hz		
Bl-factor		=	2.57 N/A		
Effective diameter		=	24 mm		
DC Resistance		=	6.63 Ω		
Volumes:	V_1	=	3.77 cm^3		
	V_2	=	3.65 cm^3		
Port sizes:	L_{p1}	=	L_{p2}	=	8 cm
	S_{p1}	=	S_{p2}	=	$\pi \cdot (0.0025)^2$ m2

Electric Input: 2.83 V (1 Watt nominally)

For this device, fig. 2a) to 2d) show the frequency responses of respectively the electric input impedance, the air velocities v_1 and v_2, the displacement of the air particles in the outlets 7 and 8, and the transducer cone displacement. It is clear that in this illustrated case, the maxima of the v_1 and v_2 curves coincide with the first resonance frequency of the system (first local maximum of the input impedance). Note that, for reasons of clarity, the volumes V_1 and V_2 have been chosen slightly different, so that the curves in figure 2 do not coincide completely.

Another embodiment is illustrated in Fig. 3, where the tubes 5 and 6 are curved to minimize the footprint, and to minimize the distance d. The unit consists of two spiral like elements 11, sandwiching between them a middle plate 12, and closed on their upper and lower sides by end plates 13. The membrane 14 of the transducer 1 is arranged in the center of the middle plate 12. The innermost space 15 of each spiral corresponds to the volumes V_1 and V_2 in fig 1.

Yet another embodiment is depicted in Fig. 4, where two cavities 21, 22 are arranged on top of each other, separated by a middle plate with a membrane 23. In the illustrated example, no pipes connect the cavities with the ambient air, only two holes, or very short tubes 24, 25 in the end plates 26, 27. In use, acoustic waves will radiate from the holes 24, 25 in anti phase, resulting in combination in very modest sound level.

The holes 24, 25 need not be arranged on opposite sides of the cavities. As shown in fig 5, they may also be located on the sides of each cavity. In the illustrated example, the holes 24a-d and 25a-d, are located pair-wise on respective cavities. The distribution of holes depends on the desired orientation of the resulting cooling jet, in figure 5 illustrated by arrow A.

In another variant of the device in figure 4, the air from both cavities 21, 22 may be directed through holes in one of the end plates 26. As shown in figure 6, this can be accomplished by providing channels 27 leading from the upper cavity 21 through the lower cavity 22 to holes 28 in the bottom end plate 26. Other holes 29 in the bottom plate 26 lead to the lower cavity 22. In order to provide similar passages from each cavity, the holes 29 are also connected to the lower cavity 22 via channels 30, similar in length and cross section to channels 27.

As a general comment, it is noted that the number of channels from each cavity must not be equal. For example, in the embodiments in figures 5 and 6, there may be more holes from one of the cavities than the other. It is important, however, that the total air flow from one cavity is equal in size and in counter phase compared to the air flow from the other cavity.

Figure 7 shows a further embodiment of the invention. In this case, two cavities 31, 32 are separated by a wall 33 supporting two oppositely arranged transducers 34, 35, operated in anti-phase. An advantage with this design is that any differences in geometry caused by the transducer are compensated for (see e.g. in fig 1, where the transducer consumes more volume in the cavity 4). Returning to figure 7, this embodiment also features one pipe 36 divided in two channels 37, 38 leading to the respective cavities.

According to yet another embodiment, illustrated in fig 8, two devices according to one of the previously described embodiments are used in combination, here devices 41, 42 according to the embodiment in figure 3. The two devices form a cooling system with two transducers 1and four openings 7a, 7b, 8a, 8b. All four openings should preferably be arranged in close proximity, most preferably within a distance D less than 0.2 λ, as described above. Further, as long as the distance is sufficiently small, the direction of the air streams from the various openings is not important. It should thus be realized that the openings need not be parallel and in the same plane, as in the example in figure 8, but on the contrary may be arranged in many other configurations. It should also be noted that the two devices 41 and 42 need not be identical, as in the present example. On the contrary, any two dipole devices may be advantageously combined.

The person skilled in the art realizes that the present invention by no means is limited to the preferred embodiments described above. On the contrary, many modifications and variations are possible within the scope of the appended claims. For example, the number of transducers may be increased further, and the placement and form of openings and channels may be varied depending on the application.

Further, the transducer may be implemented in micro electro-mechanical system (MEMS) technology, i.e. realized on a very small scale. More specifically, on such a small scale, an entire cooling device, including transducer, cavities, openings and any channels, can be completely embodied in silicon using e.g. etching technology. Such a device can advantageously be integrated with an IC to be cooled, e.g. a micro processor. By providing cooling by means of a cooling device on the same scale as the object to be cooled, the cooling may be made more efficient. Of course, a silicon device can be combined with additional channels connected to the silicon substrate.

CLAIMS:

1. A cooling device comprising at least one transducer (1) having a membrane adapted to generate pressure waves at a working frequency, characterized by

a first and a second cavity (3, 4), said transducer being arranged between said first and second cavities, such that said membrane forms a fluid tight seal between said cavities,

each cavity having at least one opening (7, 8) adapted to emit a pulsating net output fluid flow,

wherein said cavities and openings are formed such that, at said working frequency, a first harmonic fluid flow emitted by said opening(s) (7) of a first one of said cavities is in anti-phase with a second harmonic fluid flow emitted by said opening(s) (8) of a second one of said cavities, so that a sum of harmonic fluid flow from said openings is essentially zero.

2. The device according to claim 1, wherein each cavity has more than one opening.

3. The device according to claim 1 or 2, wherein two transducers (34, 35) are arranged in opposite positions between said cavities (31, 32).

4. The device according to any one of the preceding claims, wherein a distance d between any two openings is less than 0.2 λ, and preferably less than 0.1 λ, where λ is the wave length in said fluid corresponding to the working frequency.

5. The device according to any one of the preceding claims, wherein said working frequency is chosen such that velocities of said first and second harmonic flows have a local maximum at this working frequency.

6. The device according to any one of the preceding claims, wherein said cavities (3, 4) have essentially equal volume.

7. The device according to any one of the preceding claims, wherein said openings (7, 8) have essentially equal cross section area.

8. The device according to any one of the preceding claims, wherein said openings are connected to respective cavity via a channel (5, 6).

9. The device according to claim 8, wherein said cannels (5, 6) have essentially equal length.

10. The device according to claim 8, wherein said channels (5, 6) have essentially equal cross section.

11. The device according to one of claims 8-10, wherein a channel connecting at least one opening of said first cavity extends through said second cavity, so that said at least one opening is located on the same side of said device as the openings of said second cavity.

12. The device according to any one of the preceding claims, realized using micro electro-mechanical system (MEMS) technology.

13. The device according to claim 12, wherein the transducer is formed by etching a silicon substrate.

14. A cooling arrangement comprising two devices (41, 42) according to any one of the preceding claims, the openings of said devices arranged to cooperate to achieve an improved cooling.

15. A cooling arrangement according to claim 14, wherein an average distance between the openings of the first device and the openings of the second device is less than 0.2 λ, preferably less than 0.1 λ, where λ is the wave length in said fluid corresponding to the working frequency.

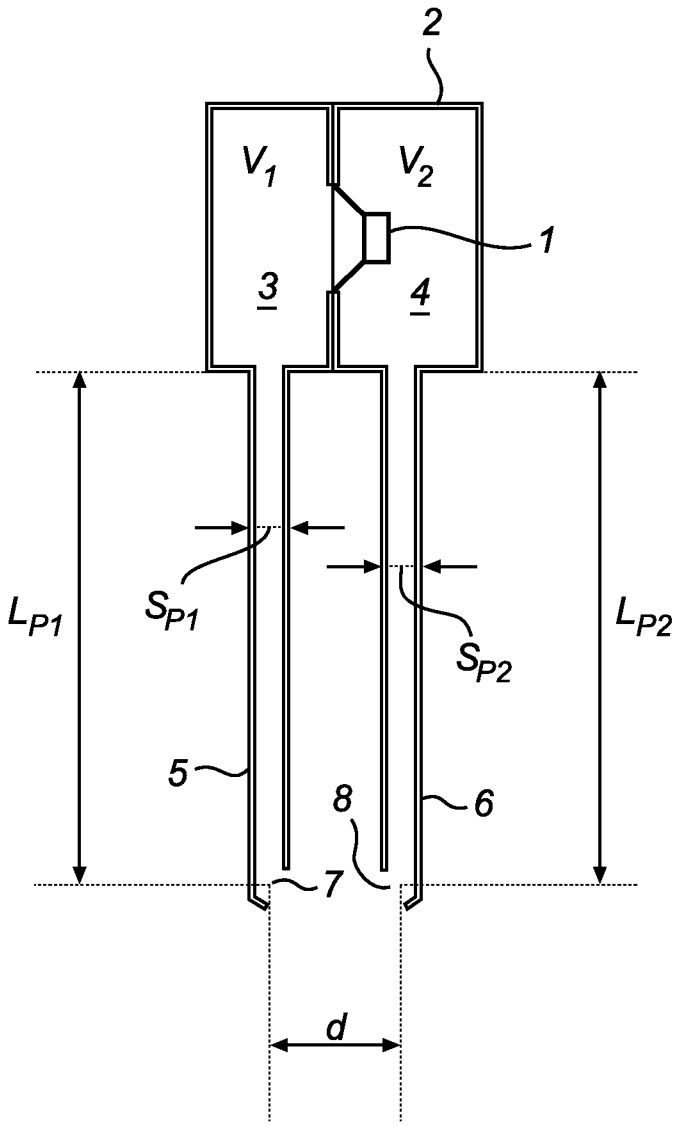


Fig. 1

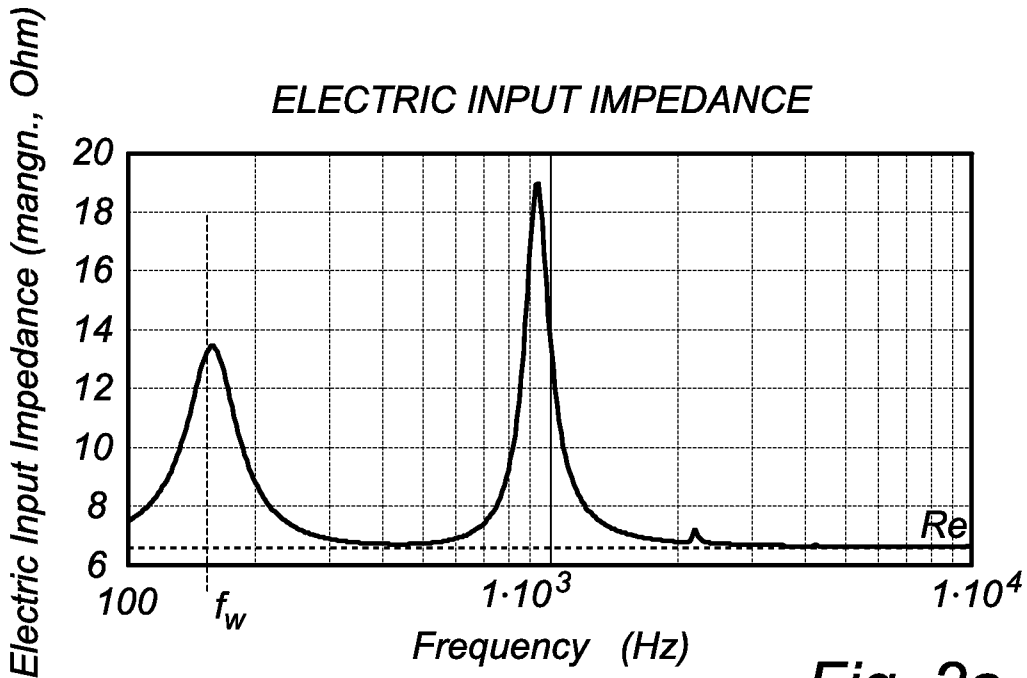

ELECTRIC INPUT IMPEDANCE
Electric Input Impedance (mangn., Ohm)
20
18
16
14
12
10
8
6
Re
100
f_w
$1 \cdot 10^3$
$1 \cdot 10^4$
Frequency (Hz)

Fig. 2a

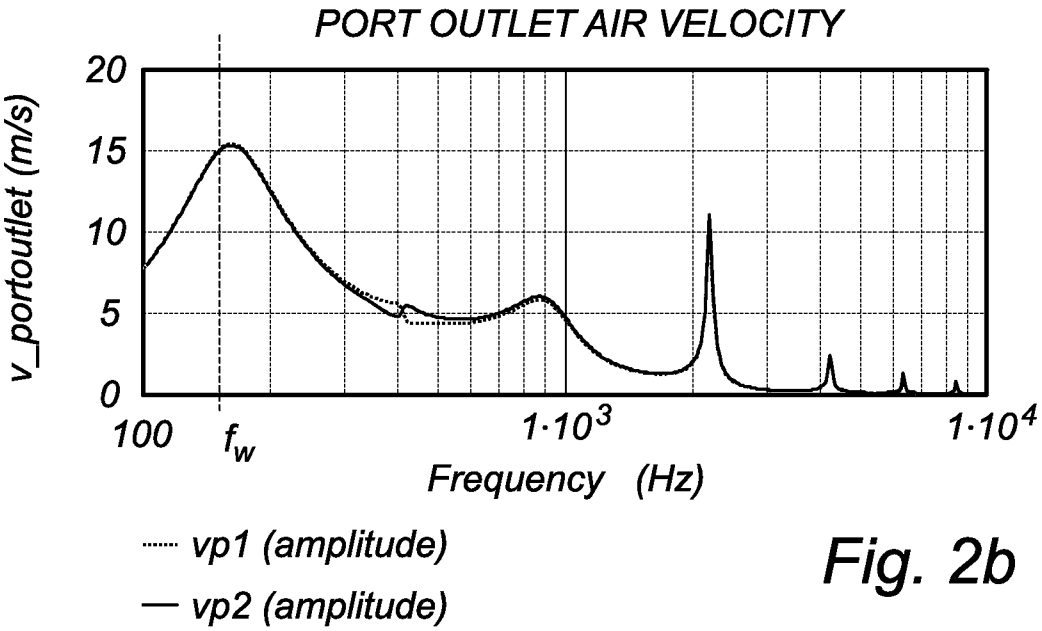

PORT OUTLET AIR VELOCITY
v_portoutlet (m/s)
20
15
10
5
0
100
f_w
$1 \cdot 10^3$
$1 \cdot 10^4$
Frequency (Hz)
vp1 (amplitude)
vp2 (amplitude)

Fig. 2b

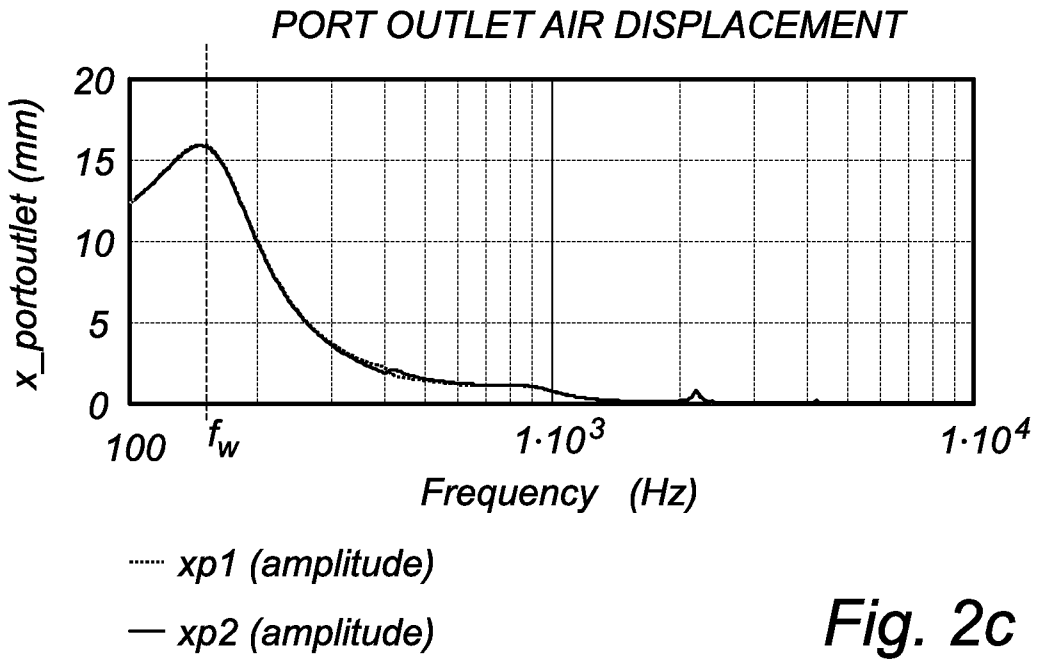

PORT OUTLET AIR DISPLACEMENT
x_portoutlet (mm)
20
15
10
5
0
100
f_w
$1 \cdot 10^3$
$1 \cdot 10^4$
Frequency (Hz)
xp1 (amplitude)
xp2 (amplitude)

Fig. 2c

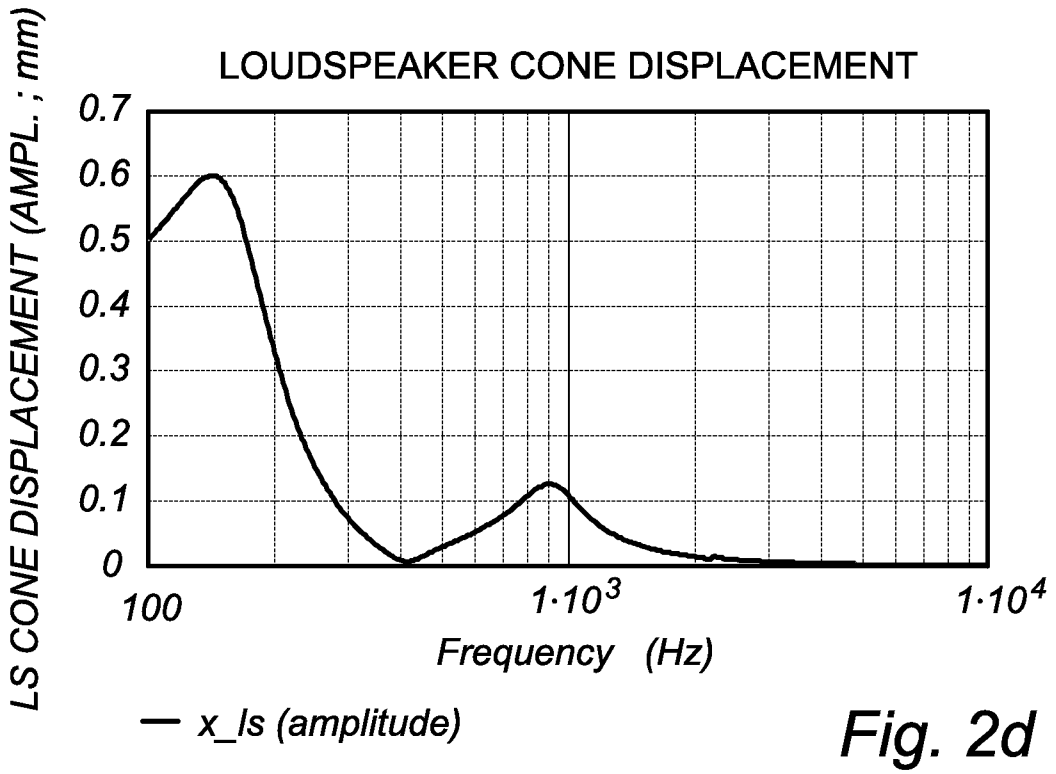

LOUDSPEAKER CONE DISPLACEMENT
LS CONE DISPLACEMENT (AMPL. ; mm)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
100
$1 \cdot 10^3$
$1 \cdot 10^4$
Frequency (Hz)
x_ls (amplitude)

Fig. 2d

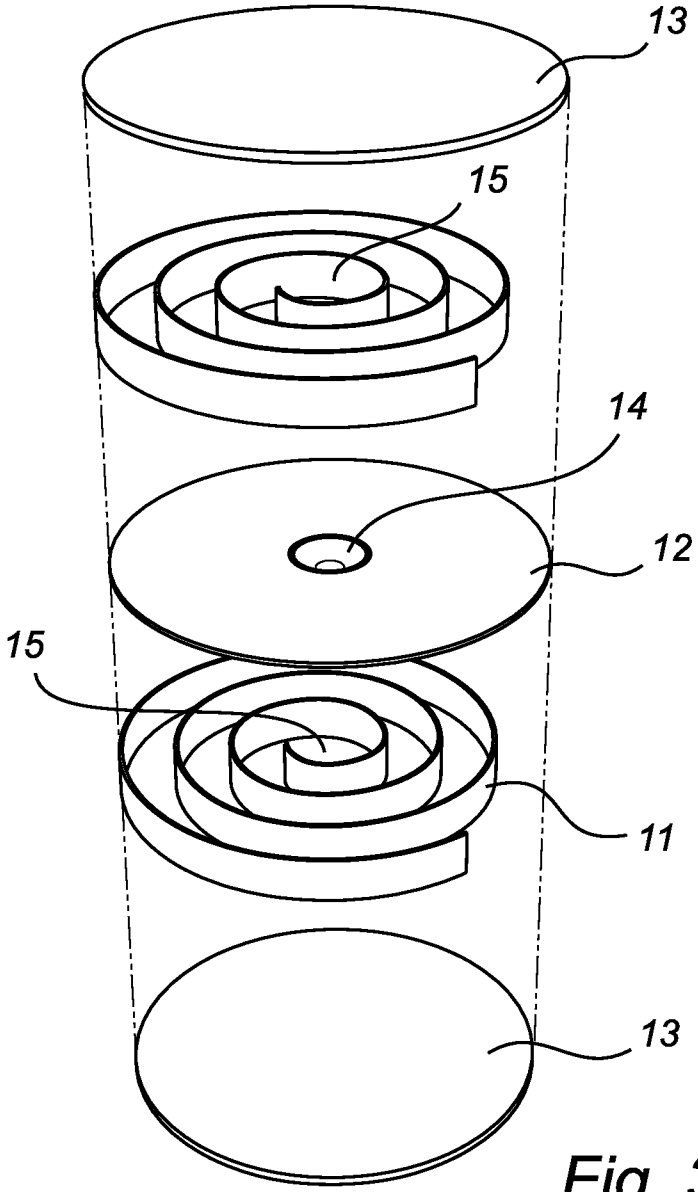


Fig. 3

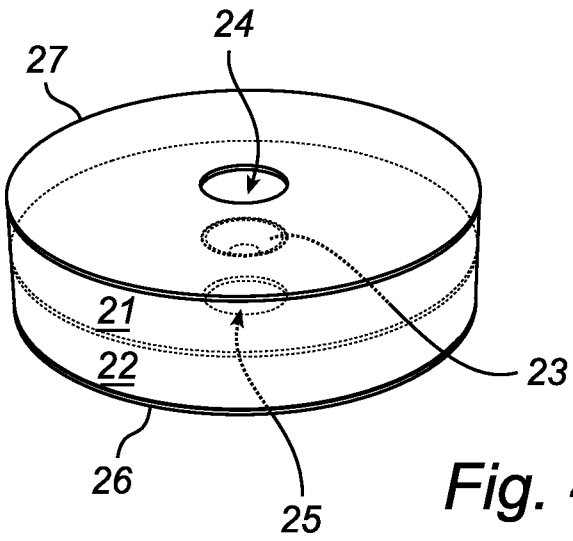


Fig. 4

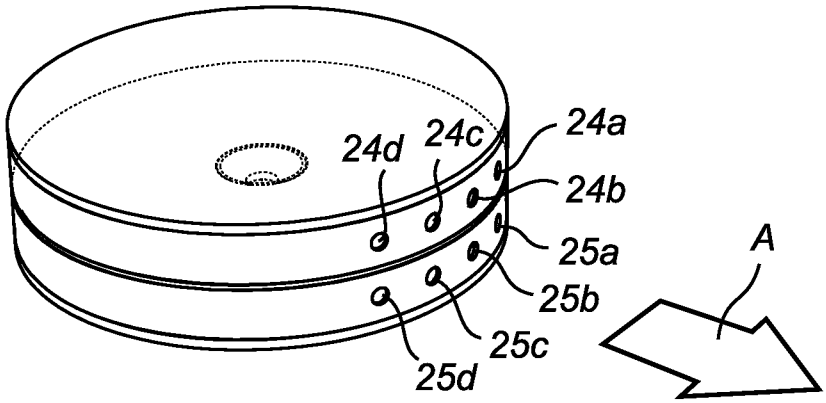


Fig. 5

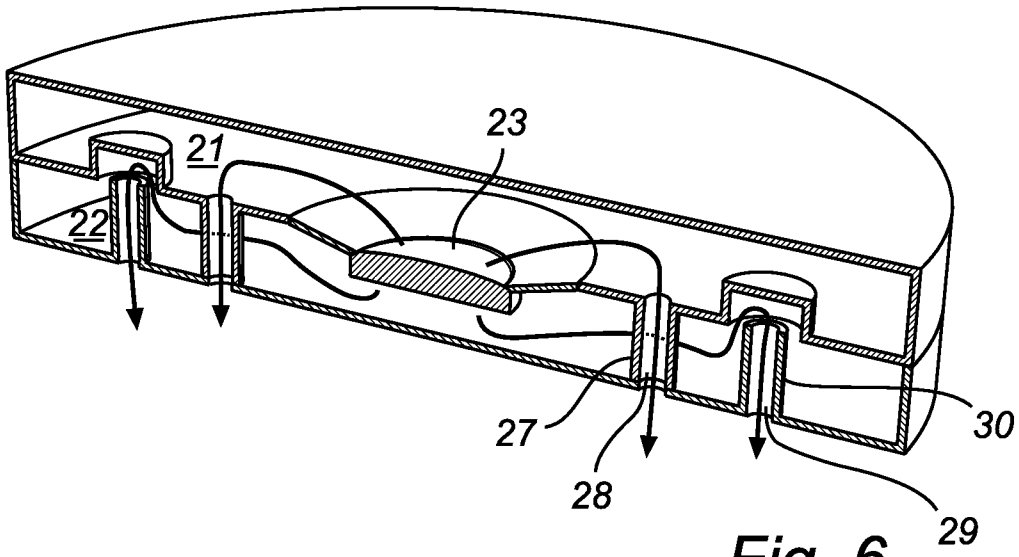


Fig. 6

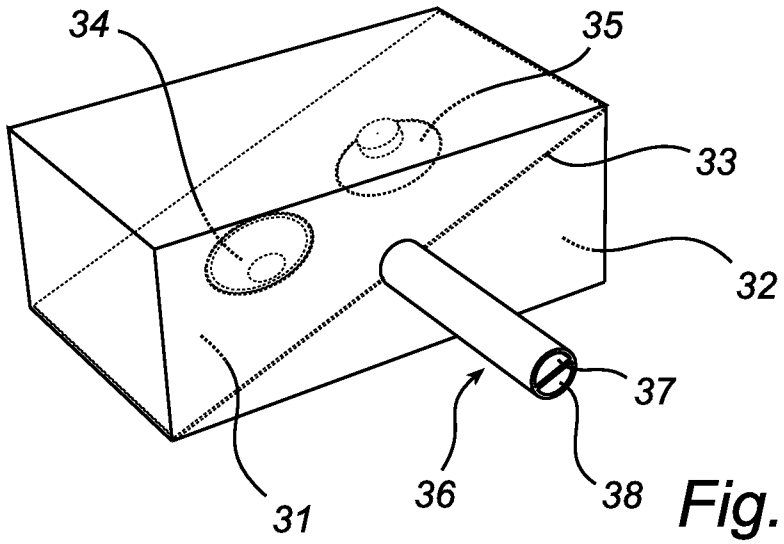


Fig. 7

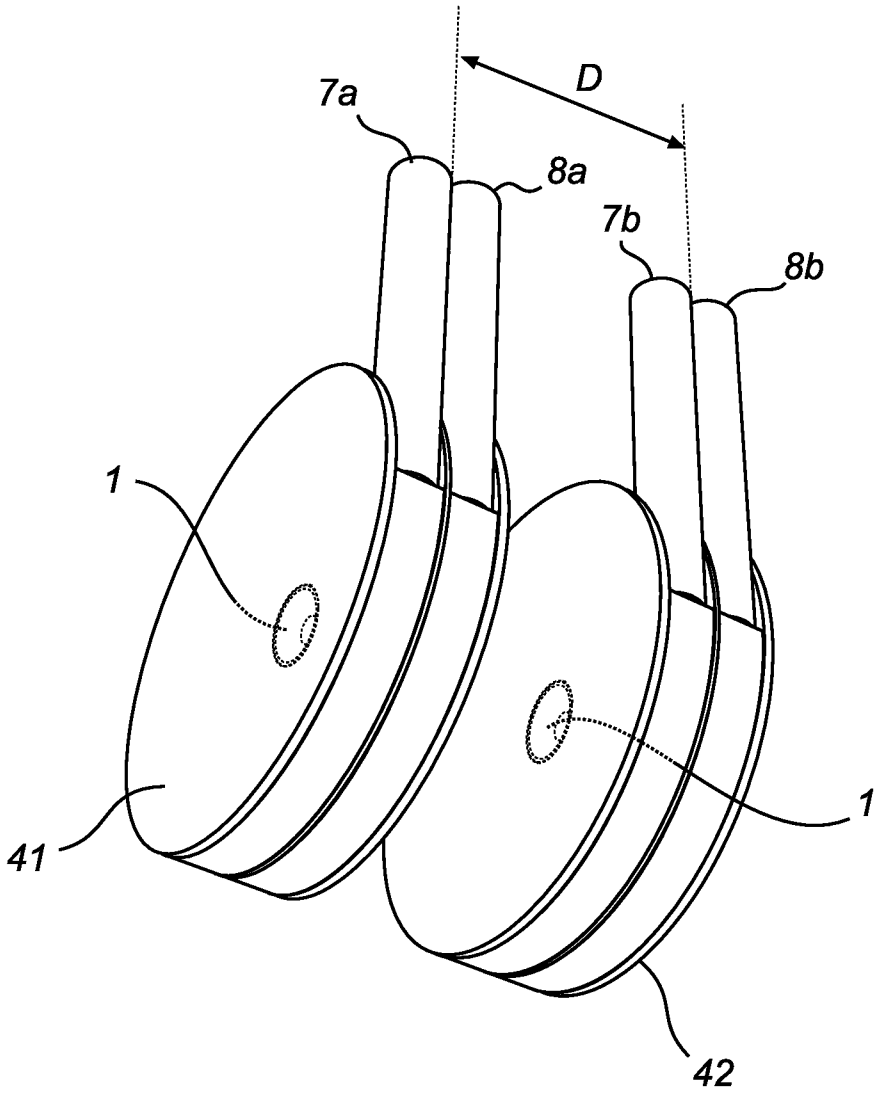


Fig. 8

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2007/054796

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01L23/467 H01L23/473

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)
H01L H05K G06F

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 practical, 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.
P,X	EP 1 762 725 A (SONY CORP [JP]) 14 March 2007 (2007-03-14)	1-3,5-13
P,Y	paragraph [0037] - paragraph [0075]; figures 1-17	4,14,15
X	& WO 2005/090789 A (SONY CORP [JP]; ISHIKAWA HIROICHI; MUKASA TOMOHARU) 29 September 2005 (2005-09-29)	1-3,5-13
Y		4,14,15

X	EP 1 529 963 A (SONY CORP [JP]) 11 May 2005 (2005-05-11)	1
Y	paragraph [0074] - paragraph [0114]; figures 1-12	4,14,15
A		2,3,5-13

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

[X] See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
27 March 2008	07/04/2008

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, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Krause, Joachim

INTERNATIONAL SEARCH REPORT

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