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(54) AN ACOUSTIC PANEL HAVING A PROPERTY OF SHAPING A DIRECTIVITY CHARACTERISTIC OF A REFLECTED ACOUSTIC WAVE

AKUSTISCHE TAFEL MIT EINER EIGENSCHAFT ZUR FORMUNG EINER RICHTCHARAKTERISTIK EINER REFLEKTIERTEN AKUSTISCHEN WELLE

PANNEAU ACOUSTIQUE AYANT UNE PROPRIÉTÉ DE MISE EN FORME D'UNE CARACTÉRISTIQUE DE DIRECTIVITÉ D'UNE ONDE ACOUSTIQUE RÉFLÉCHIE

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EP-A1- 3 936 445
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Description

Technical Field

[0001] The subject of the invention is an acoustic panel comprising: a rear wall, side walls and a front wall having a longitudinal and transverse direction and comprising an area consisting of elongated cellular elements connected by their longer sides in the transverse direction of the front wall, wherein each of the cellular elements comprise at least one mirror-like sound-reflecting surface and at least one recess changing the phase of a reflected acoustic wave. Such a panel can be used to shape the acoustic space, e.g. as a ceiling panel in concert halls, but also as a device for redirecting acoustic waves wherever such redirection is beneficial, e.g. in production halls, especially around noise sources.

Background Art

[0002] Commonly used acoustic structures include sound-absorbing structures designed to absorb excess acoustic energy in rooms and the environment. The second type of structures are scattering structures, most often in the form of Schroeder diffusers and their various modifications, designed to reflect the acoustic wave evenly in all directions. Another type of sound-reflecting structures are flat reflective panels that direct the wave in a manner consistent with Snell's law of reflection, i.e. with the dominant share of mirror reflection.

[0003] From document JP 2020187219 A, there is known a solution of an acoustic system that controls the acoustic wave by means of many cellular elements filled with Helmholtz resonators, including those with elongated necks. Such structure functions as an element that dampens acoustic wave in a wide range of low frequencies. The solution encompasses a set of cellular elements absorbing acoustic wave connected in series or forming an array. The elements controlling the acoustic wave may have an elongated neck, i.e. reaching into the centre of the Helmholtz resonator. The thickness of the cellular element may be less than one-quarter of the wavelength affected. Also, the total thickness of the structure may be less than the wavelength. Each cellular element achieves a maximum reduction of its acoustic energy at its resonant frequency. Cellular elements can be made of metal or resin material.

[0004] The document EP 3570560 A1 discloses a solution of an ultra-thin broadband acoustic wave scattering structure with many elements. The waveguide-shaped cavities that focus the acoustic wave have a variable cross-section and end with a rigid closure. The maximum length of a path for wave propagation in these waveguides can reach hundreds of the thickness of the scattering structure. These cavities can take the form of folded and wrapped labyrinth structures with one inlet arranged on one layer or in multiple layers.

[0005] From the patent specification PL 227198 B1 there is a known solution of an above-stage reflective panel reflecting sound with recesses in the side parts of the face of a rectangular structure. Diffusing elements in the form of wells, modelled on one-dimensional Schroeder diffusers, are organised at the edges of the acoustic panel, so that its surface directed at the acoustic wave consists of a scattering surface, a reflecting surface, and then a scattering surface again. The surface width of Schroeder diffusers is greater than the maximum length of the scattered wave and is defined by the lower and upper cutoff frequencies. The main function of this panel is to widen the frequency range of sound reflection and to prevent the formation of a comb filter.

[0006] The prior Art EP 3 936 445 discloses an acoustic panel. The panel comprises a rear wall, side walls, and a front wall having a longitudinal and transverse direction.

Detailed Description of the Invention

Technical Problem

[0007] If achieving proper acoustic conditions of the interior requires installing an overhead or wall panel of appropriate thickness and inclination, in many spaces with complex architecture such installation can be a difficult to achieve challenge and is often not possible due to space constraints.

[0008] The invention aims to provide an acoustic panel that allows the acoustic wave to be directed to the desired angular range without the need to tilt it, which will shape the acoustic directivity characteristic of the reflected acoustic wave for a wide range of acoustic wave frequencies, while having a small thickness, compared to the conventional solutions used so far.

Summary of the Invention

[0009] The summary of the invention is to provide an acoustic panel comprising: a rear wall, side walls, and a front wall having a longitudinal and transverse direction and comprising an area consisting of elongated cellular elements connected by their longer sides in the transverse direction of the front wall, wherein each of the cellular elements comprises at least one mirror-like sound-reflecting surface and at least one recess changing the phase of a reflected acoustic wave, characterized in that the recess changing the phase of the reflected acoustic wave has a shape of a well to which at least one acoustic resonator is substantially perpendicularly attached, wherein at least two cellular elements:

- are connected so that their acoustic resonators are aligned along the transverse direction of the front wall and have the same orientation; and
- constitute a system having a property of shaping dissymmetrically the directivity characteristic of the reflected acoustic wave in a plane normal to the longitudinal direction of the front wall.

[0010] A person skilled in the art understands the concept of dissymmetry as a technical feature that imposes on an object the condition that the symmetry group of that object does not have symmetry elements being isometries that do not preserve orientation (anti-conformal isometries). In other words, the skilled person can understand and recognise if the directivity characteristic of a reflected wave is dissymmetrical by analysing the symmetry group of the directivity characteristic for the presence of symmetry elements that do not preserve orientation among the symmetry elements of this characteristic. Moreover, if the symmetry group of a certain object does not have any non-trivial symmetry elements, then such an object is not only dissymmetrical, but also asymmetrical.

[0011] The skilled person also knows the definition of dissymmetry of wave scattering as applied to light scattering and can use it mutatis mutandis. For example, he may use the definition that was published in the article: International Union of Pure and Applied Chemistry - Physical Chemistry Division - Commission on Colloid and Surface Chemistry Including Catalysis. Manual of Symbols and Terminology for Physicochemical Quantities and Units. Appendix II - Definitions, Terminology and Symbols in Colloid and Surface Chemistry, Part 1.14: Light Scattering. Pure Appl. Chem. 1983, 55 (6), 931-941. and 'dissymmetry of scattering' [In:] IUPAC Compendium of Chemical Terminology, 3rd Ed, International Union of Pure and Applied Chemistry: 2006. Online version 3.0.1, 2019. https://doi.org/10.1351/goldbook.D01808.

[0012] The panel according to any aspect of the invention may preferably have the shape of any prism, particularly preferably with a rectangular, square, or regular hexagonal base, and further preferably it may have the shape of a cuboid plate.

[0013] In the case of a plate having symmetries other than cuboid, the distinguished directions should be understood as the direction along the main symmetry axis of the front surface - where the said axis lies on this surface (longitudinal direction), and as the direction perpendicular to the longitudinal direction (transverse direction).

[0014] Preferably, according to any aspect of the invention, the front wall may be in the shape of a flat surface.

[0015] Preferably, according to any aspect of the invention, the acoustic resonator may be attached to the well at any height, preferably at a hight half the depth of the said well.

[0016] It is obvious to a person skilled in the art that the acoustic resonator can also be attached close to the bottom of the well or, in the same or another embodiment, close to the mouth of the well. If - in a preferred embodiment - there are at least two cellular elements, the resonator can be placed in each of the cellular elements at a different height or in all of them at the same height relative to the depth of the well.

[0017] Preferably, according to any aspect of the invention, the acoustic resonator may be any acoustic resonator known to a person skilled in the art, selected from the group comprising, inter alia: a Helmholtz resonator, a quarter-wave resonator, a wrapped quarter-wave resonator, e.g. in the form of a waveguide, or combinations thereof. The group of resonators that can be used is not limited only to the above-mentioned examples. A person skilled in the art can select in each case the most appropriate type of acoustic resonator for particular embodiments of the invention.

[0018] The construction and application of acoustic resonators are described inter alia in the book: Kinsler, L. E.; Frey, A. R.; Coppens, A. B.; Sanders, J. V. Fundamentals of Acoustics, 4th Ed.; John Wiley & Sons: New York, 2000, in chapter 10, on pages: 272-301, to which reference is hereby made.

[0019] Preferably, different acoustic resonators may be attached to different wells in one embodiment of the present invention. For example, a Helmholtz resonator may be attached to the first well, a quarter-wave resonator to the second well, and a Helmholtz resonator to the third well.

[0020] The invention is not limited to embodiments in which only one acoustic resonator is attached to each well. Among the preferred embodiments of the invention, there are those in which at least two acoustic resonators are attached to one well.

[0021] Preferably, according to any aspect of the invention, the well has the shape of a cuboidal trough. The longitudinal axis of this trough may be located parallel to the longitudinal direction of the front wall.

[0022] It is obvious to the skilled person that the well may also have a different shape. In the longitudinal direction of the front wall, the well may have a dimension equal to the width of the plate, i.e. start on one of the side walls and extend to another side wall, but it is also possible to have an embodiment in which the wells have a dimension in the longitudinal direction such that they can form a two-dimensional grid.

[0023] Preferably, according to any aspect of the invention, the acoustic panel consists of a material with an acoustic impedance of not less than 150 000 $kg \cdot m^{-2} \cdot s^{-1}$.

[0024] Preferably, according to any aspect of the invention, the material is selected from the group of materials comprising an EPS polystyrene material with a fibreglass surface, wood, wood-like materials, aluminium, composite materials, in particular resin composite materials, and combinations thereof.

[0025] A material suitable for producing the acoustic panel according to the invention can be obtained in numerous ways. It can preferably be produced by casting in a mould, machining, extrusion, or 3D printing, e.g. by laminating subsequent layers of material in accordance with a pattern saved in the 3D printer's memory. The last method mentioned above is particularly preferable due to the freedom of design of the materials produced by this method. In the case of plastic materials, it is also preferable to use the extrusion method, preferably hot melt extrusion (HME).

[0026] Preferably, according to any aspect of the invention, at least two mirror-like sound-reflecting surfaces form a common plane. In other words, these surfaces may be flush with the surface of the front wall. A person skilled in the art knows that an embodiment in which the sound-reflecting surfaces are not flush is also possible. In such an embodiment, the cellular elements may be separated by optional walls projecting substantially perpendicularly to the surface of the front wall.

[0027] Preferably, according to any aspect of the invention, the acoustic panel comprises at least 5, preferably at least 20, further preferably at least 30 cellular elements.

[0028] It is obvious to a person skilled in the art that in a preferred embodiment it is also possible to place the cellular elements in the panel in such a way that they will form a two-dimensional grid (array), which means, they will be connected in series in both distinguished directions of the front wall (longitudinal and transverse), and that they will form a periodic or aperiodic flat tessellation system, e.g. tessellation 6^3.

[0029] Preferably, according to any aspect of the invention, for the direction of incidence of the acoustic wave at an angle of incidence of 0°, the directivity characteristic of the reflected acoustic wave is shaped so that for an angle in the range of from +30° to +60°, the average level of sound pressure is higher by at least 6 dB relative to an average level of sound pressure reflected from the reference panel for an angle in the range of from +30° to +60°, further preferably the average level of sound pressure is higher by at least 12 dB.

[0030] Herein, the 'reference panel' should be understood as a flat panel with dimensions and acoustic impedance equal to the dimensions and acoustic impedance of the acoustic panel according to the invention.

[0031] 'Angle of incidence' as used herein has a meaning commonly accepted in the technical field and is to be understood as the angle made by the direction of incidence of the wave to the normal to the surface upon which the wave falls.

[0032] By the term 'shaping the directivity characteristic of an acoustic wave', as used herein, a person skilled in the art understands the change in the directivity characteristic relative to the directivity characteristic of a perfectly flat surface reflecting sound in accordance with Snell's law of mirror reflection, or relative to a surface isotropically scattering sound in all directions equally. The directivity characteristics that lie between these two extreme situations are each shaped by the geometric shape of the surface from which the sound is reflected or scattered.

[0033] The directivity characteristic of an acoustic wave is a function assigning the levels of sound pressure of an acoustic wave normalised to the maximum value, expressed by the formula:

$$L_{p,n}(\theta) = 10\log\left(\frac{|p_s(\theta)|}{\max(|(p_s(\theta)|)}\right)^2$$

to values of observation angles ranging from -90° to +90°. A directivity characteristic is usually plotted in a polar coordinate system. The normalised levels of sound pressure of an acoustic wave at a given frequency are plotted along a radial coordinate, while the observation angle is plotted as an angular coordinate ranging between -90° and +90°. Typically, the directivity characteristic is prepared for an angle of incidence equal to 0°, and the direction for this angle is drawn vertically upwards on the plot, so that the plot ultimately has the shape of a semicircle limited at the bottom by the diameter. For the acoustic panel according to the invention, it is generally sufficient to plot the characteristic in a plane normal to the longitudinal direction of the surface of the front wall according to the invention.

[0034] Unless explicitly stated otherwise, herein and elsewhere in the description, if an angle is mentioned, e.g. +30°, -90°, etc., such notation should be understood as the directed angle that is between the normal to the surface of incidence and the other side of an angle, counting from the normal positive semi-axis to the positive semi-axis forming the other side of an angle. Herein, the direction 'normal to' and the 'transverse' direction of the front wall surface of the acoustic panel according to the invention have distinguished arrow-heads, in such a way that the angle from the positive semi-axis of the said normal to the positive semi-axis of the transverse axis is a positive angle. Herein and elsewhere in the description, the arrowhead of the axis of the transverse direction is such that the cellular elements according to the invention lie on it in such a way that the wells 'precede' the resonators. Thus, an angle of +30° will lie 'to the right' of the positive semi-axis of normal to the incident surface, while an angle of -30° will lie 'to the left' of it when looking at the panel, such that when the transverse direction of the surface is placed horizontally, each cellular element will have a well on the left side and a resonator on the right side. Adopting such a convention means that positive angles, i.e. those directed 'to the right', correspond to the angles located in the right part of the directivity characteristic plot, while negative angles, i.e. angles directed 'to the left', correspond to angles located in the left part of the directivity characteristic plot.

[0035] In particular, knowing how to draw a plot of the directivity characteristic of a reflected acoustic wave, the skilled person is easily able to notice that when the 'right part' of the plot is non-superimposable with the mirror image of the 'left part' and vice versa, the directivity characteristics are dissymmetrical.

[0036] Preferably, according to any aspect of the invention, the reflected wave has a frequency in the range of from 800 to 4000 Hz, preferably from 1000 to 3150 Hz, and further preferably from 1250 to 2500 Hz.

[0037] Herein and elsewhere in the description, unless expressly stated otherwise, a single frequency value should be understood as determined with precision to the one-third octave band, i.e. as the middle value of this one-third octave band. It should therefore be understood that the given value determines the range of values of the one-third octave band. For example, if the description refers to the frequency of 315 Hz, it should be understood that this is an acoustic wave whose frequency is in the range of values within the measurement one-third octave for which the middle value is the value of 315 Hz, i.e. in the range of 280.6 to 353.6 Hz.

[0038] Moreover, if the description mentions the frequency range from 315 to 1000 Hz, it should be understood that the lower limit of this range may vary in the range from 280.6 to 353.6 Hz and the upper limit in the range from 890.9 to 1122.5 Hz, which means that the entire range is between the 15^{th} and 20^{th} measurement one-third octave.

[0039] Preferably, according to any aspect of the invention, the depth of the recess changing the phase of the reflected acoustic wave may be less than one-quarter of the length of the acoustic wave affected.

[0040] Preferably, according to any aspect of the invention, the thickness of the acoustic panel may be less than 70 mm.

[0041] Unless expressly stated otherwise, all values of physical parameters except frequency, which are defined by measurement one-third octaves, herein and elsewhere in the description are to be understood as values determined with an accuracy of ±10 % of the stated value. This means that if the description mentions a length of 10 mm, it should be understood as a length in a range of from 9 to 11 mm inclusively.

[0042] All angle measurements should be understood as being determined to an accuracy of ±5° and the expression 'substantially perpendicular' as 'at an angle of (90 ± 5)°, i.e. from 85° to 95°'.

[0043] Preferably, according to any aspect of the invention, the acoustic panel has a value of the normalised sound diffusion coefficient d_n for an incidence angle of 0° and the frequency ranging between 1000 and 8000 Hz, being in a range of from 0.30 to 0.70, preferably from of from 0.40 to 0.60.

[0044] A person skilled in the art understands the expression 'normalised sound diffusion coefficient' d_n as the diffusion coefficient d_n determined in accordance with the ISO 17497-2 standard entitled: *Acoustics - Sound scattering properties of surfaces - Part 2: Measurement of the directional diffusion coefficient in a free field,* to which reference is hereby made.

[0045] Preferably, according to any aspect of the invention, the rear wall of the panel and the side walls constitute a uniform, sound-impermeable layer.

[0046] Preferably, according to any aspect of the invention, the side walls may be equipped with elements enabling the panels according to the invention to be connected together into larger systems having a property of shaping the directivity characteristic of the reflected acoustic wave.

[0047] Herein and elsewhere in the description, unless it is expressly stated otherwise, the phrase 'from ... to ...' in relation to the range of numerical values should be understood as a mutually closed range, which means that the extreme values also belong to the mentioned range.

[0048] It is obvious to the skilled person that all features that are 'preferred according to any aspect of the invention' are optional features and may or may not be present in embodiments of the invention and may be freely combined independently of each other as long as it does not contradict the laws of physics and is technically realizable.

[0049] Herein and elsewhere in the description, a person skilled in the art understands that 1° means the angular measure of the plane and phase angle equal to 1/360 part of the full angle, and that bel and decibel, equal to one-tenth of a bel, are used to express the logarithmic values of quotient quantities whose numerical values are based on decimal logarithm. The statement $L_X = m$ dB = (m/10) B (where m is a number) is interpreted as $m = 10\log_{10}(X/X_0)$ as defined in: *International System of Units (SI) Brochure, 9th ed.* the International Bureau of Weights and Measures (BIPM), 2019 (version V2.01 December 2022) in Table 8 on page 145 and in the description of this Table, to which reference is hereby made.

Advantageous Technical Effects

[0050] The use of a passive sound diffuser with subwavelength characteristics, and therefore of small thickness in relation to the acoustic wave it affects, allows for the control of the first sound reflections, and thus allows shaping the propagation of acoustic waves in rooms or the environment.

[0051] Individual resonators forming the panel introduce local changes in the phase of sound reflection, which makes it possible to shape the directivity characteristic of the wave reflected from the panel surface. By changing the cell geometry, thickness and width of the panel, it is possible to shape the panel parameters depending on the user's needs, in particular the frequency range of the directed sound. Broadband sound diffusion with dominant non-mirror reflection is possible, which overcomes the limitation of a mirror-like reflecting panel, i.e. the need to tilt the panel. This allows the panel to be placed more freely in the space above the stage and in the wall area.

Brief Description of Drawings

[0052] The invention will be described below with the help of preferred embodiments shown in the drawing, in which:

Fig. 1 shows a cross-section of an acoustic panel according to the invention with 30 cellular elements in a plane perpendicular to the longitudinal direction of the cellular elements, as described in Example 1,

Fig. 2 shows a perspective view of the panel according to the invention with seven cellular elements in a schematic view from above,

Fig. 3 shows a schematic cross-sectional view of a single cellular element projected in the same plane as in Fig. 1.

The preferred embodiments of the invention shown in the Figures and Examples are intended to illustrate the invention and are in no way intended to limit the invention. It will be obvious to the skilled person that both the number of cellular elements and the individual parameters of each of these cellular elements can be adjusted to their needs without undue burden, as well as to the spatial conditions where the acoustic panel according to the invention is used, each time using the procedure described in the Example below.

Example 1

[0053] The acoustic panel 1 was formed as a flat, cuboid product made of material with dimensions (length l1: width w1: thickness h1) of 100 × 150 × 6.5 cm, having a rear wall 3, four side walls 4, and a front wall 2. The front wall 2 is equipped with thirty cellular elements 7 having flat sound-reflecting surfaces and sound-scattering recesses 6 in the form of wells 8 in the shape of elongated troughs of various depths arranged along the longitudinal direction of the front wall 2 of the panel so that each trough starts with an opening on one side wall 4 and ends with an opening on the opposite side wall 4. An acoustic resonator 9 is attached to each of these troughs at half the depth of the trough. The shape parameters of the well 8 and the resonator 9 are presented in Table 1:

Table 1.

Cell number	Parameter value [m]					
	l8	w8	ln9	wn9	lc9	wc9
1	0.0550	0.0068	0.0115	0.0348	0.0167	0.0382
2	0.0199	0.0339	0.0059	0.0065	0.0050	0.0086
3	0.0370	0.0334	0.0054	0.0099	0.0054	0.0169
2	0.0387	0.0235	0.0077	0.0228	0.0120	0.0276
5	0.0543	0.0268	0.0092	0.0418	0.0067	0.0420
6	0.0286	0.0310	0.0071	0.0129	0.0063	0.0137
7	0.0509	0.0328	0.0061	0.0225	0.0058	0.0309
8	0.0501	0.0140	0.0127	0.0308	0.0112	0.0384
9	0.0577	0.0146	0.0112	0.0208	0.0157	0.0357
10	0.0204	0.0274	0.0089	0.0069	0.0065	0.0092
11	0.0256	0.0087	0.0079	0.0107	0.0205	0.0108
12	0.0532	0.0319	0.0069	0.0189	0.0051	0.0303
13	0.0531	0.0124	0.0070	0.0222	0.0165	0.0353
14	0.0584	0.0084	0.0123	0.0442	0.0093	0.0467
15	0.0150	0.0334	0.0061	0.0050	0.0052	0.0050
16	0.0310	0.0333	0.0051	0.0178	0.0055	0.0196

(continued)

Cell number	Parameter value [m]					
	l8	w8	ln9	wn9	lc9	wc9
17	0.0479	0.0336	0.0052	0.0077	0.0053	0.0220
18	0.0571	0.0337	0.0059	0.0421	0.0051	0.0444
19	0.0598	0.0237	0.0107	0.0455	0.0092	0.0464
20	0.0512	0.0151	0.0116	0.0317	0.0092	0.0407
21	0.0550	0.0079	0.0235	0.0123	0.0122	0.0247
22	0.0210	0.0336	0.0055	0.0088	0.0054	0.0096
23	0.0291	0.0269	0.0123	0.0123	0.0055	0.0154
24	0.0495	0.0230	0.0098	0.0102	0.0088	0.0169
25	0.0162	0.0291	0.0074	0.0052	0.0064	0.0059
26	0.0278	0.0348	0.0050	0.0137	0.0050	0.0157
27	0.0433	0.0339	0.0058	0.0256	0.0050	0.0285
28	0.0575	0.0337	0.0052	0.0446	0.0051	0.0466
29	0.0502	0.0179	0.0151	0.0266	0.0066	0.0392
30	0.0588	0.0192	0.0144	0.0277	0.0068	0.0314

wherein l8, w8, ln9, wn9, lc9, wc9 mean respectively: well depth l8, well width w8, length of resonator neck ln9, width of resonator neck wn9, length of the resonator cavity lc9, width of the resonator cavity wc9. In those cases where the value of the wn9 parameter is approximately equal to the value of wc9 (e.g. for well no. 15), the acoustic resonator 9 is a quarter-wave resonator type, in other cases, when wn9 is smaller than wc9, the acoustic resonator 9 is a Helmholtz resonator type.

[0054] The cellular elements 7 connected in series are flush with the front wall 2, i.e. the outer front flat reflecting surface of the cellular elements 7 has a common axis and the geometry of the cellular elements 7 varies along the depth dimension. In this version, the acoustic resonator 9 is attached at half the depth of the trough on one of its side walls.

[0055] Dimensions that effectively direct sound reflection to the selected angular range for the acoustic panel according to the invention can, for example, be obtained using a selected optimization algorithm, e.g. a particle swarm algorithm with a population equal to at least the number of cellular elements multiplied by the number of searched parameters and a cost function maximizing sound reflection in a given angular range, defined as:

$$j = \frac{\sum_{n=0}^{N} \sum_{k=0}^{180} |p_s(\theta_k, f_n)|}{\sum_{n=0}^{N} \sum_{k=120}^{150} |p_s(\theta_k, f_n)|}$$

wherein: $k \in \mathbb{Z} \cap [0, 180]: \theta_k = -90° + k \cdot 1°$; $n \in \mathbb{Z} \cap [0, N]: f_n = f_0 \cdot \left(\sqrt[3]{2}\right)^n$; where:

j	cost function maximizing sound reflection over a given angular range;
θ_k	k-th observation angle for the reflected acoustic wave;
f_n	frequency of the n-th analysed acoustic wave;
N	number of analysed frequency ranges for which optimisation is performed;
$p_s(\theta_k, f_n)$	sound pressure depending on the angle of observation and the frequency of the analysed acoustic wave.

[0056] In Example 1, the values of the six parameters shown in Table 1 for thirty cellular elements were optimized using a particle swarm algorithm. The range of analysed frequencies was from f_0 = 800 Hz to f_7 = 4000 Hz $\left(f_n = f_0\left(\sqrt[3]{2}\right)^n\right.$, i.e. the analyzed frequency f increases with increasing n in a geometric progression at third intervals, i.e. ⅓-octave), the angular range was analysed with a resolution of 1° (degree).

[0057] Parameter values were searched in the ranges:

l8:	from 0.015 to 0.060 m;
w8:	from *x* to (d7 - 0.015) m;
ln9:	from *x* to (d7 - w8 - 0.010) m;
wn9:	from *x* to (l8 - 0.010) m;
lc9:	from *x* to (d7 - w8 - 0.010) m;
wc9:	from wn9 to (l8 - 0.010) m,

wherein x was 0.005 m and d7 is the width of the cellular element, which in Example 1 was 0.05 m.

[0058] The acoustic panel 1 according to Example 1 is made of aluminium. The acoustic impedance value was: 900 000 $kg \cdot m^{-2} \cdot s^{-1}$. The width of the panel allows for a construction with many recesses of different from each other shapes.

[0059] The normalized sound diffusion coefficient d_n measured in accordance with the ISO 17497-2 standard for an incidence angle of 0° in the range of frequency from 1000 to 8000 Hz was 0.50.

[0060] The results of measuring the dissymmetry of the directivity characteristic of the reflected acoustic wave are presented in Table 2, which lists the values of the gain function, described by the formula:

$$X_f(\theta_k|k_l, k_u) = 10\log\frac{\sum_{k=k_l}^{k_u}|p_s(\theta_k, f)|}{\sum_{k=k_l}^{k_u}|p_{ref}(\theta_k, f)|}$$

where:

$X_f(\theta_k\|k_l, k_u)$	gain relative to the level of sound pressure of the wave reflected from the reference panel in the range from θ_{k_l}, to θ_{k_u}, expressed in dB;
θ_k	*k*-th angle of observation for the reflected acoustic wave;
f	acoustic wave;
k_l	lower range of the analysed angular range for which the gain of the level of sound pressure of the wave *f* was measured relative to the reflection from the reference panel;
k_u	upper range of the analysed angular range for which the gain of the level of sound pressure of the wave *f* was measured relative to reflection from the reference panel;
$p_s(\theta_k, f)$	sound pressure reflected from the panel depending on the angle of observation for a given acoustic wave frequency;
$p_{ref}(\theta_k, f)$	sound pressure reflected from the reference panel depending on the angle of observation for a given frequency of the acoustic wave,

wherein the reference panel is a flat plate with dimensions of 100 × 150 × 6.5 cm with an impedance equal to the panel impedance (like the panel but without grooves).

Table 2. Shaping the directivity characteristic of the reflected acoustic wave for Example 1 according to the invention

f - frequency [Hz]	X_f - gain [dB]					
	for angles from -90° to -60° k_l = 0 k_u = 30	for angles from -60° to -30° k_l = 30 k_u = 60	for angles from -30° to 0° k_l = 60 k_u = 90	for angles from 0° to +30° k_l = 90 k_u = 120	for angles from +30° to +60° k_l = 120 k_u = 150	for angles from +60° to +90° k_l = 150 k_u = 180
800 Hz	-3.2	6.8	-1.8	-2.1	9.5	10.6
1000 Hz	8.5	5.6	-4.2	-3.2	6.2	14.0
1250 Hz	10.6	11.9	-4.6	-2.0	12.3	9.7
1600 Hz	6.1	8.2	-4.0	-7.3	16.3	16.0
2000 Hz	9.9	6.0	-6.1	-2.1	16.5	12.2
2500 Hz	9.6	10.9	-4.7	-1.5	16.5	15.6
3150 Hz	11.6	16.6	-1.6	-2.5	18.9	16.3

(continued)

f - frequency [Hz]	X_f - gain [dB]					
	for angles from -90° to -60° k_l = 0 k_u = 30	for angles from -60° to -30° k_l = 30 k_u = 60	for angles from -30° to 0° k_l = 60 k_u = 90	for angles from 0° to +30° k_l = 90 k_u = 120	for angles from +30° to +60° k_l = 120 k_u = 150	for angles from +60° to +90° k_l = 150 k_u = 180
4000 Hz	20.1	13.9	-0.5	-3.1	15.3	13.1

[0061] As can be seen from the Table above, for the values of the angles corresponding to the symmetrical reflections 'to the left' and 'to the right' relative to the direction of incidence of the acoustic wave, the values of the gain function are clearly higher for angles outside the range from -30 to +30.

[0062] This means that the reflected acoustic wave is directed dissymmetrically with respect to the surface normal to the surface and perpendicular to the longitudinal direction of the front wall (2) of the acoustic panel (1) according to the invention.

Industrial Applicability of the Invention

[0063] The panel according to the invention can be used to shape the acoustic space in concert halls, e.g. as a ceiling panel replacing traditionally used acoustic reflectors. Moreover, it can be used as a device for redirecting acoustic waves in production halls around noise sources in order to reduce noise annoyance.

Reference Signs List

[0064]

1	acoustic panel;
2	front wall;
3	rear wall;
4	side wall;
5	mirror-like sound-reflecting surface;
6	recess changing the phase of the reflected acoustic wave;
7	cellular element;
8	well;
9	acoustic resonator;
11	length of the acoustic panel;
w1	width of the acoustic panel;
h1	thickness of the acoustic panel;
d7	width of the cellular element;
18	well depth;
w8	well width;
ln9	length of resonator neck;
wn9	width of resonator neck;
lc9	length of the resonator cavity;
wc9	width of the resonator cavity.

Claims

1. An acoustic panel (1), comprising:

- a rear wall (3),
- side walls (4), and
- a front wall (2) having a longitudinal and transverse direction and comprising an area consisting of elongated cellular elements (7) connected by their longer sides in the transverse direction of the front wall (2), wherein each of the cellular elements (7) comprises at least one mirror-like sound-reflecting surface (5) and at least one recess (6) changing the phase of a reflected acoustic wave,

characterized in that
the recess (6) changing the phase of the reflected acoustic wave has a shape of a well (8) to which at least one acoustic resonator (9) is substantially perpendicularly attached, wherein at least two cellular elements (7):

- are connected so that their acoustic resonators (9) are aligned along the transverse direction of the front wall and have the same orientation; and
- constitute a system having a property of shaping dissymmetrically a directivity characteristic of the reflected acoustic wave in a plane normal to the longitudinal direction of the front wall (2).

2. The acoustic panel (1) according to claim 1, wherein the acoustic resonator (9) is attached to the well (8) at a height half the depth of the said well (8).

3. The acoustic panel (1) according to claim 1 or claim 2, wherein the acoustic resonator (9) is an acoustic resonator (9) selected from the group consisting of a Helmholtz resonator, a quarter-wave resonator, a wrapped quarter-wave resonator, or a combination thereof.

4. The acoustic panel (1) according to any one of claims 1-3, wherein the well (8) has the shape of a cuboidal trough.

5. The acoustic panel (1) according to any one of claims 1-4, wherein the said acoustic panel (1) consists of a material with an acoustic impedance of not less than 150 000 $kg \cdot m^{-2} \cdot s^{-1}$.

6. The acoustic panel (1) according to claim 5, wherein the material is selected from the group of materials consisting of an EPS polystyrene material with a fibreglass surface, wood, wood-like materials, aluminium, composite materials, especially resin composite materials, and combinations thereof.

7. The acoustic panel (1) according to any one of claims 1-6, wherein at least two mirror-like sound-reflecting surfaces (5) form a common plane.

8. The acoustic panel (1) according to any one of claims 1-7, wherein the front wall (2) comprises the area consisting of at least 5 cellular elements (7).

9. The acoustic panel (1) according to claim 8, wherein the front wall (2) comprises the area consisting of at least 20, preferably at least 30, cellular elements (7).

10. The acoustic panel (1) according to any one of claims 1-9, wherein for the direction of incidence of the acoustic wave at an angle of incidence of 0°, the directivity characteristic of the reflected acoustic wave is shaped so that for an angle in the range of from +30° to +60°, the average level of sound pressure is higher by at least 6 dB relative to an average level of sound pressure of the wave reflected from a reference plate for an angle in the range of from +30° to +60°, preferably is higher by at least 12 dB higher.

11. The acoustic panel (1) according to claim 10, wherein the reflected wave has a frequency in a range of from 800 to 4000 Hz, preferably in a range of from 1000 to 3150 Hz, further preferably in a range of from 1250 to 2500 Hz.

12. The acoustic panel (1) according to any one of claims 1-11, wherein the depth of the recess (6) changing the phase of the reflected acoustic wave is less than one-quarter of the length of the acoustic wave affected.

13. The acoustic panel (1) according to any one of claims 1-12, wherein the thickness of the said acoustic panel (1) is less than 70 mm.

14. The acoustic panel (1) according to any one of claims 1-13, wherein the said acoustic panel (1) has an average value of the normalised sound diffusion coefficient d_n for an incidence angle of 0° and frequency ranging between 1000 and 8000 Hz, being in a range of from 0.30 to 0.70.

15. The acoustic panel (1) according to claim 14, wherein the said acoustic panel (1) has an average value of the normalised sound diffusion coefficient d_n for an incidence angle of 0° and frequency ranging between 1000 and 8000 Hz, being in a range of from 0.40 to 0.60.

Patentansprüche

1. Akustikplatte (1), umfassend:

   - eine Rückwand (3),
   - Seitenwände (4) und
   - eine Vorderwand (2), die eine Längs- und eine Querrichtung aufweist und die einen Bereich umfasst, der aus länglichen Zellelementen (7) besteht, die an ihren längeren Seiten in Querrichtung der Vorderwand (2) verbunden sind, wobei jedes der Zellelemente (7) mindestens eine spiegelartig schallreflektierende Oberfläche (5) und mindestens eine die Phase einer reflektierten Schallwelle verändernde Vertiefung (6), aufweist,

   dadurch gekennzeichnet, dass
   die die Phase einer reflektierten Schallwelle verändernde Vertiefung (6), die Form eines Brunnens (8) hat, an der mindestens ein akustischer Resonator (9) im Wesentlichen senkrecht angebracht ist, wobei mindestens zwei Zellelemente (7):

   - so verbunden sind, dass ihre akustischen Resonatoren (9) entlang der Querrichtung der Vorderwand ausgerichtet sind und die gleiche Orientierung aufweisen; und
   - ein System bilden, das die Richtcharakteristik der reflektierten Schallwelle in einer Ebene senkrecht zur Längsrichtung der Vorderwand (2) dissymmetrisch formt.

2. Akustikplatte (1) nach Anspruch 1, wobei der Akustikresonator (9) in dem Brunnen (8) in halber Höhe des Brunnens (8) befestigt ist.

3. Akustikplatte (1) nach Anspruch 1 oder 2, wobei der Akustikresonator (9) aus der Gruppe bestehend aus: ein Helmholtz-Resonator, ein Viertelwellenresonator, ein gewickelter Viertelwellenresonator oder eine Kombination davon, ausgewählt ist.

4. Akustikplatte (1) nach einem der Ansprüche 1-3, wobei der Brunnen (8) die Form einer quaderförmigen Rinne hat.

5. Akustikplatte (1) nach einem der Ansprüche 1-4, wobei die Akustikplatte (1) aus einem Material mit einer akustischen Impedanz von mindestens 150.000 $kg \cdot m^{-2} \cdot s^{-1}$ besteht.

6. Akustikplatte (1) nach Anspruch 5, wobei das Material aus der Gruppe bestehend aus: EPS-Polystyrol mit Glasfaseroberfläche, Holz, holzähnlichen Materialien, Aluminium, Verbundwerkstoffen, insbesondere Harzverbundwerkstoffen, und Kombinationen davon, ausgewählt ist.

7. Akustikplatte (1) nach einem der Ansprüche 1-6, wobei mindestens zwei spiegelartige, schallreflektierende Oberflächen (5) eine gemeinsame Ebene bilden.

8. Akustikplatte (1) nach einem der Ansprüche 1-7, wobei die Vorderwand (2) einen Bereich umfasst, der aus mindestens fünf Zellen (7) besteht.

9. Akustikplatte (1) nach Anspruch 8, wobei die Vorderwand (2) einen Bereich umfasst, der aus mindestens 20, vorzugsweise mindestens 30, Zellelementen (7) besteht.

10. Akustikplatte (1) nach einem der Ansprüche 1-9, wobei die Richtcharakteristik der reflektierten Schallwelle bei einem Einfallswinkel von 0° so geformt ist, dass der durchschnittliche Schalldruckpegel bei einem Winkel im Bereich von +30 ° bis +60 ° um mindestens 6 dB höher als der durchschnittliche Schalldruckpegel der von einer Referenzplatte reflektierten Welle bei einem Winkel im Bereich von +30 ° bis +60 °, vorzugsweise um mindestens 12 dB höher ist.

11. Akustikplatte (1) nach Anspruch 10, wobei die reflektierte Welle eine Frequenz im Bereich von 800 bis 4000 Hz, vorzugsweise im Bereich von 1000 bis 3150 Hz, weiter vorzugsweise im Bereich von 1250 bis 2500 Hz, aufweist.

12. Akustikplatte (1) nach einem der Ansprüche 1-11, wobei die Tiefe der Vertiefung (6), die die Phase der reflektierten Schallwelle verändert, weniger als ein Viertel der Länge der betroffenen Schallwelle beträgt.

13. Akustikplatte (1) nach einem der Ansprüche 1-12, wobei die Dicke der Akustikplatte (1) weniger als 70 mm beträgt.

14. Akustikplatte (1) nach einem der Ansprüche 1-13, wobei die Akustikplatte (1) einen Durchschnittswert des normalisierten Schalldiffusionskoeffizienten d_n für einen Einfallswinkel von 0 ° und eine Frequenz zwischen 1000 und 8000 Hz im Bereich von 0,30 bis 0,70 aufweist.

15. Akustikplatte (1) nach Anspruch 14, wobei die Akustikplatte (1) einen Durchschnittswert des normalisierten Schalldiffusionskoeffizienten d_n für den Einfallswinkel von 0 ° und eine Frequenz zwischen 1000 und 8000 Hz im Bereich von 0,40 bis 0,60 aufweist.

Revendications

1. Panneau acoustique (1) comprenant :

   - une paroi arrière (3),
   - des parois latérales (4) et
   - une paroi avant (2) présentant une direction longitudinale et transversale et comprenant une zone constituée d'éléments cellulaires allongés (7) reliés par leurs côtés les plus longs dans la direction transversale de la paroi avant (2), dans laquelle chacun des éléments cellulaires (7) comprend au moins une surface réfléchissante acoustique (5) de type miroir et au moins un renfoncement (6) modifiant la phase d'une onde acoustique réfléchie.

   caractérisé en ce que
   le renfoncement (6) modifiant la phase de l'onde acoustique réfléchie a la forme d'un puits (8) auquel au moins un résonateur acoustique (9) est fixé sensiblement perpendiculairement, dans lequel au moins deux éléments cellulaires (7) :

   - sont reliés de telle façon que leurs résonateurs acoustiques (9) soient alignés dans la direction transversale de la paroi avant et aient la même orientation ; et
   - constituent un système ayant la propriété de former de manière dissymétrique une caractéristique de directivité de l'onde acoustique réfléchie dans un plan normal à la direction longitudinale de la paroi avant (2).

2. Panneau acoustique (1) selon la revendication 1, dans lequel le résonateur acoustique (9) est fixé au puits (8) à une hauteur égale à la moitié de la profondeur dudit puits (8).

3. Panneau acoustique (1) selon la revendication 1 ou 2, dans lequel le résonateur acoustique (9) est sélectionné dans le groupe constitué de : un résonateur de Helmholtz, un résonateur quart d'onde, un résonateur quart d'onde enveloppé, ou une combinaison de ceux-ci.

4. Panneau acoustique (1) selon l'une quelconque des revendications 1 à 3, dans lequel le puits (8) a la forme d'une cuvette cuboïde.

5. Panneau acoustique (1) selon l'une quelconque des revendications 1 à 4, dans lequel le panneau est constitué d'un matériau dont l'impédance acoustique est d'au moins 150 000 $kg \cdot m^{-2} \cdot s^{-1}$.

6. Panneau acoustique (1) selon la revendication 5, dans lequel le matériau est sélectionné dans le groupe constitué de : le polystyrène EPS avec une surface en fibre de verre, le bois, les matériaux similaires au bois, l'aluminium, les matériaux composites, notamment les matériaux composites à base de résine, et leurs combinaisons.

7. Panneau acoustique (1) selon l'une quelconque des revendications 1 à 6, dans lequel au moins deux surfaces réfléchissantes (5) de type miroir forment un plan commun.

8. Panneau acoustique (1) selon l'une quelconque des revendications 1 à 7, dans lequel la paroi avant (2) comprend une zone constituée d'au moins 5 éléments cellulaires (7).

9. Panneau acoustique (1) selon la revendication 8, dans lequel la paroi avant (2) comprend une zone constituée d'au moins 20, de préférence au moins 30, éléments cellulaires (7).

10. Panneau acoustique (1) selon l'une quelconque des revendications 1 à 9, dans lequel, pour la direction d'incidence de l'onde acoustique à un angle d'incidence de 0°, la caractéristique de directivité de l'onde acoustique réfléchie est

formée de telle sorte que, pour un angle compris entre +30° et +60°, le niveau moyen de pression acoustique est supérieur d'au moins 6 dB par rapport au niveau moyen de pression acoustique de l'onde réfléchie par une plaque de référence pour un angle compris entre +30° et +60°, de préférence supérieur d'au moins 12 dB.

11. Panneau acoustique (1) selon la revendication 10, dans lequel l'onde réfléchie a une fréquence comprise entre 800 et 4000 Hz, de préférence entre 1000 et 3150 Hz, et de préférence encore entre 1250 et 2500 Hz.

12. Panneau acoustique (1) selon l'une quelconque des revendications 1 à 11, dans lequel la profondeur du renfoncement (6) modifiant la phase de l'onde acoustique réfléchie est inférieure au quart de la longueur de l'onde acoustique affectée.

13. Panneau acoustique (1) selon l'une quelconque des revendications 1 à 12, dans lequel l'épaisseur du panneau acoustique (1) est inférieure à 70 mm.

14. Panneau acoustique (1) selon l'une quelconque des revendications 1 à 13, dans lequel le panneau acoustique (1) a une valeur moyenne du coefficient de diffusion sonore, normalisé *dn* pour un angle d'incidence de 0° et une fréquence comprise entre 1 000 et 8 000 Hz, comprise entre 0,30 et 0,70.

15. Panneau acoustique (1) selon la revendication 14, dans lequel le panneau acoustique (1) a une valeur moyenne du coefficient de diffusion sonore, normalisé *dn* pour un angle d'incidence de 0° et une fréquence comprise entre 1 000 et 8 000 Hz, comprise entre 0,40 et 0,60.

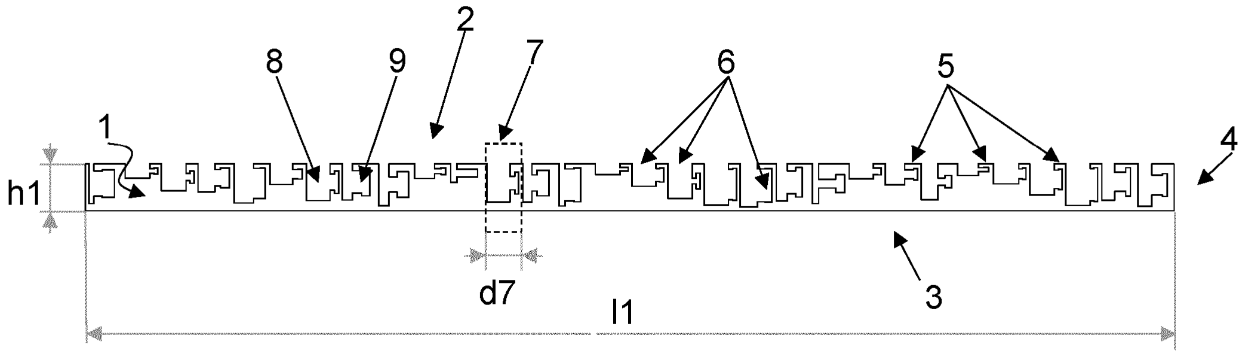

FIG. 1

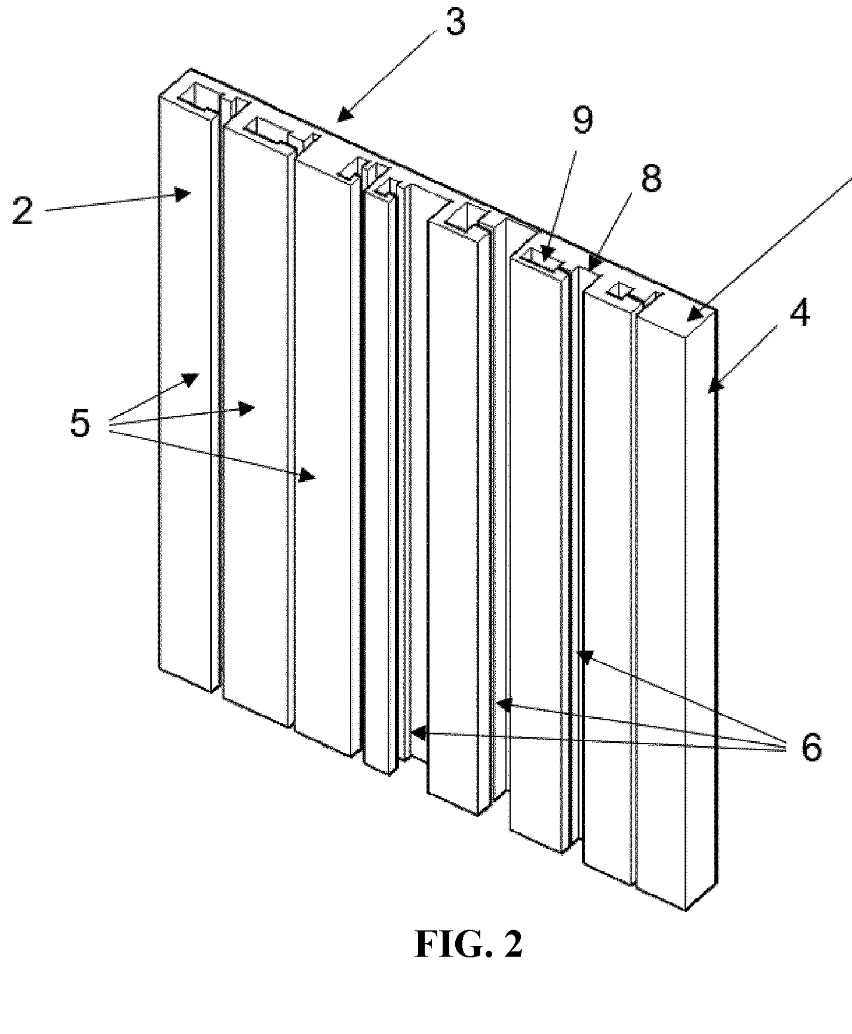

FIG. 2

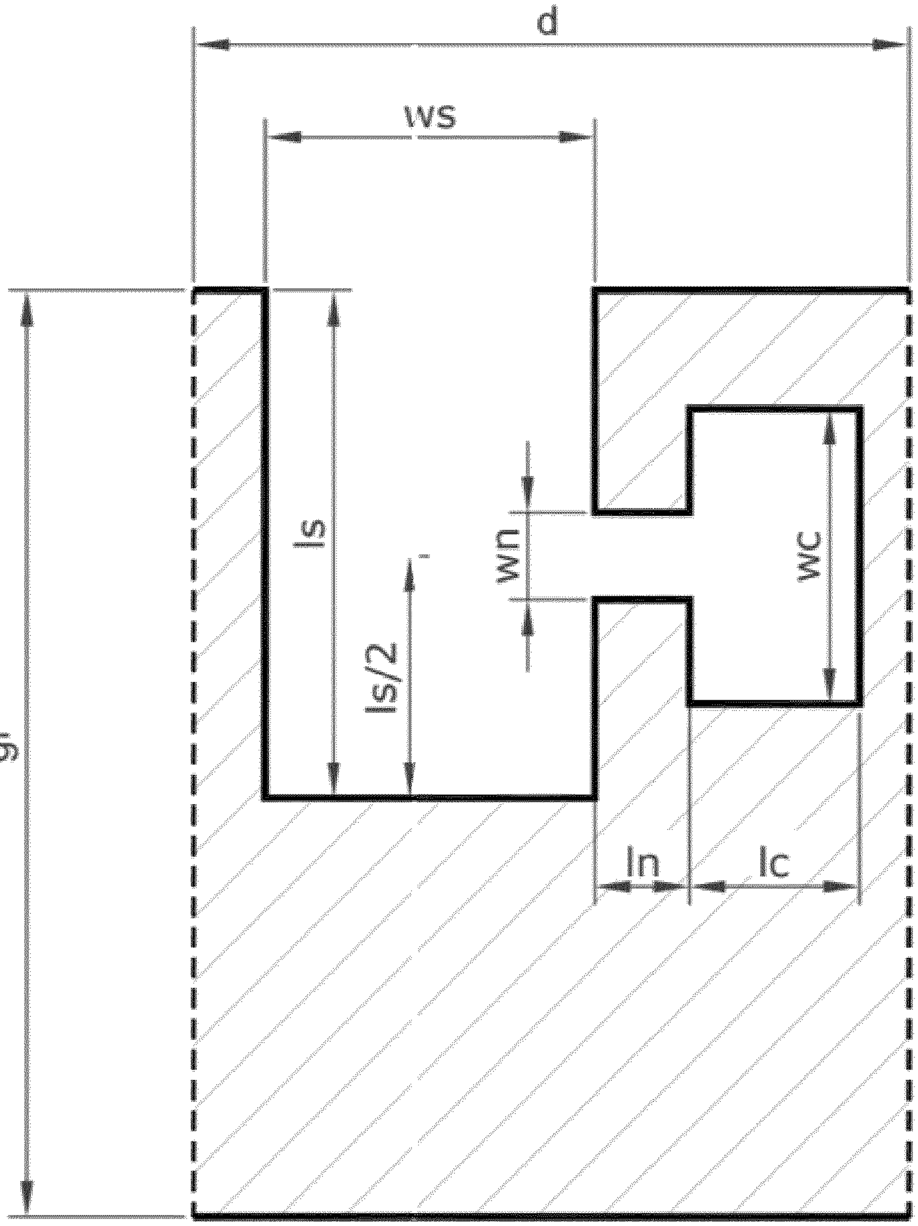

FIG. 3

REFERENCES CITED IN THE DESCRIPTION

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