



(12) **EUROPEAN PATENT APPLICATION**

(43) Date of publication:  
**20.07.2022 Bulletin 2022/29**

(51) International Patent Classification (IPC):  
**G10K 11/172** <sup>(2006.01)</sup> **G10K 11/168** <sup>(2006.01)</sup>  
**G10K 1/06** <sup>(2006.01)</sup> **G10K 11/00** <sup>(2006.01)</sup>

(21) Application number: **21382026.9**

(52) Cooperative Patent Classification (CPC):  
**G10K 11/172; G10K 11/168; G10K 1/06;**  
**G10K 11/002**

(22) Date of filing: **15.01.2021**

(84) Designated Contracting States:  
**AL AT BE BG CH CY CZ DE DK EE ES FI FR GB  
GR HR HU IE IS IT LI LT LU LV MC MK MT NL NO  
PL PT RO RS SE SI SK SM TR**  
Designated Extension States:  
**BA ME**  
Designated Validation States:  
**KH MA MD TN**

(72) Inventors:  
• **Oliver Olivella, Francisco Javier**  
**08750 Molins de Rei (ES)**  
• **Cante Terán, Juan Carlos**  
**08320 El Masnou (ES)**  
• **Roca Cazorla, David**  
**08552 Taradell (ES)**  
• **Lloberas Valls, Oriol**  
**08036 Barcelona (ES)**

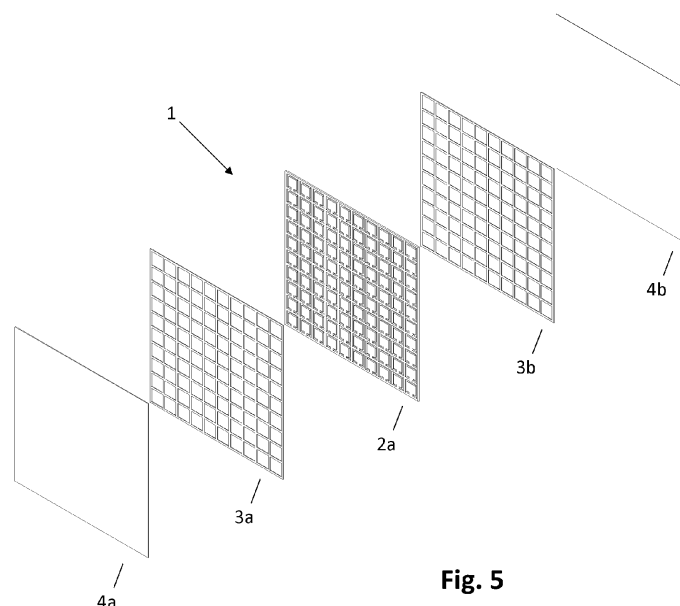
(71) Applicant: **Centre Internacional de Metodes  
Numerics a  
l'Enginyeria**  
**08034 Barcelona (ES)**

(74) Representative: **Clarke Modet & Co.**  
**C/ Suero de Quiñones 34-36**  
**28002 Madrid (ES)**

(54) **ACOUSTIC METAMATERIAL AND PROCESS FOR MANUFACTURING THE SAME**

(57) An acoustic metamaterial, which comprises at least one resonating layer (2a, 2b) made of a single material having a constant resonating thickness ( $t_2$ ) and a plurality of resonating unit cells (20); wherein each resonating unit cell (20) comprises a resonating opening (21) and a resonating element (22) extending into said resonating opening (21); wherein the resonating elements (22) are coplanar to the resonating layer (2a, 2b), having

said resonating layer (2a, 2b) and said resonating elements (22) the same constant resonating thickness ( $t_2$ ). A process for manufacturing an acoustic metamaterial, comprising the steps of laminating a solid single material to obtain an unfinished resonating layer of a constant resonating thickness ( $t_2$ ); and die cutting the unfinished resonating layer to obtain a resonating layer (2a, 2b) having a plurality of resonating unit cells (20).



**Fig. 5**

**Description**Field of the invention

**[0001]** The present invention relates to an acoustic metamaterial for noise control and sound attenuation, which is introduced as Multi-resonant Layered Acoustic Metamaterial (MLAM), and which is especially intended for a broad range of applications from different fields, such as building construction, transport industries (trains, aircrafts,...), etc.

**[0002]** The present invention also relates to a process for manufacturing said acoustic metamaterial.

Background of the invention

**[0003]** In acoustics, the problem of noise control and attenuation is of interest in a broad range of applications, such as the ones mentioned before. The use of panels has been traditionally considered to address this subject. Sound attenuation through these devices can be achieved, conventionally, by two mechanisms. In the low-frequency range (typically below 1000 Hz), attenuation is controlled by the mass law and so the most effective way to reduce noise is by employing thick panels with high mass density materials. For higher frequencies, damping mechanisms (usually involving dissipative or viscoelastic phenomena) also become effective options.

**[0004]** In this context, acoustic metamaterials (AM) appear as an alternative solution to both mechanisms, due to their ability of producing frequency bandgaps, that translate into huge levels of attenuation at selected frequency ranges. Since these bandgaps are not constrained by mass considerations, acoustic metamaterials show great potential in becoming interesting lightweight solutions for noise reduction in the low-frequency range. In addition, since their conception, acoustic metamaterials have evolved into a collection of different designs and configurations intended to exploit local resonance effects, which are responsible for the frequency bandgaps generation.

**[0005]** Local resonance appears when the metamaterial is excited by an acoustic wave at a frequency in the vicinity of the frequencies triggering its internal modes. For these modes to arise, the lower scale of acoustic metamaterials is typically composed of a resonating element, in the form of a coated inclusion, a membrane or some equivalent geometrical contraption, embedded in a stiff matrix or some other kind of structural support. These aspects present two main problems that prevent acoustic metamaterials from becoming a practical alternative or replacement to conventional solutions.

**[0006]** The first problem is that, since local resonance effects are a highly localized phenomenon, the associated frequency bandgaps tend to be narrowband. There are some ways to try to overcome this issue, including coupling local resonance with other attenuating phenomena (for instance, damping) or using different resonating elements. These solutions often add complexity in the overall metamaterial configuration or result in other undesired effects. For example, notice in Figure 22 the dip between two sound transmission loss peaks caused by different uncoupled local resonators in an acoustic metamaterial panel.

**[0007]** The second problem is that, for acoustic metamaterials to operate in the frequency range of interest, a proper selection of materials and geometrical properties needs to be made, which usually entails challenging manufacturing processes (3d printing and other additive manufacturing technologies are often considered). The complexity of such techniques and geometries makes them inadequate for large scale and economically feasible production.

**[0008]** The acoustic metamaterial for noise control and sound attenuation of the present invention resolves the previously mentioned problems, thanks to a simplified configuration which makes it easy to produce by manufacturing processes like, for instance, lamination and die cutting. In addition, by adequately connecting layers containing different resonating elements, their respective internal modes can be coupled in order to produce an extended attenuation band unperturbed by undesired effects.

**[0009]** The present invention also relates to a simplified process for easily and economically manufacturing said acoustic metamaterial.

Description of the invention

**[0010]** The acoustic metamaterial of the present invention, also called Multi-resonant Layered Acoustic Metamaterial (MLAM), comprises at least one resonating layer made of a single or homogenous material having a constant resonating thickness and a plurality of resonating unit cells, wherein each resonating unit cell comprises:

- a resonating opening (hole, cavity...); and
- a resonating element extending into said resonating opening;

wherein the resonating elements are coplanar to the resonating layer, having said resonating layer and said resonating elements the same constant resonating thickness.

**[0011]** That is, each resonating layer forms a thin laminate of constant thickness and a single material (homogeneous

material), which makes it easy to massively manufacture (large scale production) using manufacturing processes like, for instance, lamination and die cutting. This laminate concept (or flat configuration) avoids, for example, issues related to the manufacture of composite material concepts based on complex inclusions embedded in a matrix.

**[0012]** Each resonating layer contains a number of periodically repeating patterns, referred to resonating unit cells. Said unit cells contain the resonating elements responsible for producing local resonance effects at specific target frequencies. The material and topology (thickness, geometric properties, unit cell patterns, etc.) of these resonating layers are relevant to determine the resonating capabilities of the acoustic metamaterial of the present invention. For example, the density of the material plays an important role to improve the attenuation properties, providing the higher densities a better overall performance.

**[0013]** The topology (thickness, geometric properties, holes distribution, shape of the resonating elements, etc.) of the resonating unit cells can be designed to target specific resonance frequencies in the range of operation, and can be adjusted to modify and improve the attenuating capabilities of the acoustic metamaterial of the present invention.

**[0014]** Each resonating element extends into the respectively resonating opening, occupying or covering part of the same, thus forming a flat vibrating element in the form of a tab, flap, strip, or any extending element, etc. attached to one internal side of the resonating unit cell. Preferably, the resonating elements are T-shaped or U-shaped, thus making easier the manufacture of the same. Nonetheless, other configurations are also possible, involving circular or linear geometries, or a combination of the same, as for example, a T-shaped configuration with a substantially circular head, etc. Even irregular shapes would be admissible, as long as they function as resonating elements, i.e. providing a resonance mode in the desired frequency range.

**[0015]** Preferably, the acoustic metamaterial comprises at least one separating layer made of a single or homogenous material having a constant separating thickness and a plurality of separating unit cells, wherein each separating unit cell comprises a separating opening (hole, cavity...). The separating layer is arranged adjacent to the resonating layer, partially or completely overlapping the separating openings with the resonating openings to allow the vibration of the resonating elements.

**[0016]** The separating openings may adopt different geometries, such as: square, rectangular, hexagonal, circular, elliptical, or any other shape, regular or irregular, accommodating the resonating elements.

**[0017]** Each separating layer forms a thin laminate of constant thickness and a single material (homogeneous material), which makes it easy to massively manufacture (large scale production) using manufacturing processes like, for instance, lamination and die cutting. This laminate concept (or flat configuration) avoids, for example, issues related to the manufacture of composite material concepts based on complex inclusions embedded in a matrix.

**[0018]** The separating layers separate the resonating layers from other layers, or from the construction elements acting as support. They can also be used to create cavities between other types of layers in case effects caused by air resonances are to be considered in the design. The separating thickness of these layers can be used to adjust the cavity size.

**[0019]** A separating layer attached to a resonating layer forms a resonating set. The acoustic metamaterial may comprise a plurality of resonating sets of different configurations connected between them to obtain an extended attenuation band. Thus, improving the attenuating capabilities of the acoustic metamaterial of the present invention.

**[0020]** Preferably, the acoustic metamaterial, comprises at least one skin layer made of a solid single or homogeneous material having a constant skin thickness, which is arranged adjacent to a separating layer.

**[0021]** The skin layers are homogeneous solid layers located at each end of the stack forming the acoustic metamaterial. Their purpose is to provide a foundation or support for the rest of the layers conforming the stack. Additionally, they can be used as a protective casing for transporting and installing the acoustic metamaterial, thus protecting the inner layers between said skin layers. The relevant property for the material in such layers is the stiffness (with higher stiffness values providing overall better performance). The skin layers can be removed in case the acoustic metamaterial is stacked onto another kind of construction element (e.g. wall, panel, structure) acting as support.

**[0022]** Each skin layer forms a thin laminate of constant thickness and a single material (homogeneous material), which makes it easy to massively manufacture (large scale production) using manufacturing processes like, for instance, lamination and die cutting. This laminate concept (or flat configuration) avoids, for example, issues related to the manufacture of composite material concepts based on complex inclusions embedded in a matrix.

**[0023]** According to a first preferred embodiment, the acoustic metamaterial of the present invention comprises two separating layers formed by a first separating layer and a second separating layer, wherein the first separating layer is arranged adjacent to a front side of a resonating layer, and wherein the second separating layer is arranged adjacent to a rear side of said resonating layer, partially or completely overlapping the separating openings of the first separating layer and the second separating layer with the resonating openings of the resonating layer to allow the vibration of the resonating elements.

**[0024]** According to a second preferred embodiment, the acoustic metamaterial of the present invention comprises two resonating layers formed by a first resonating layer and a second resonating layer, wherein the first resonating layer and the second resonating layer have a similar or different configuration, in order to obtain an extended attenuation band.

**[0025]** Preferably, the acoustic metamaterial comprises a connecting layer made of a single or homogeneous material

having a constant connecting thickness and a plurality of connecting unit cells, wherein each connecting unit cell comprises a connecting opening. The connecting layer is arranged adjacent to the first resonating layer and to the second resonating layer, partially or completely overlapping the connecting openings of the connecting layer with the resonating openings of the first resonating layer and the second resonating layer to allow the vibration of the resonating elements.

**[0026]** The connecting layer forms a thin laminate of constant thickness and a single material (homogeneous material), which makes it easy to massively manufacture (large scale production) using manufacturing processes like, for instance, lamination and die cutting. This laminate concept (or flat configuration) avoids, for example, issues related to the manufacture of composite material concepts based on complex inclusions embedded in a matrix.

**[0027]** The connecting layer is placed between two resonating layers to couple their respective attenuating capabilities and produce an extended attenuation band. The material and topology of these layers is important to establish a proper coupling between resonances. The relevant material property in this case is the stiffness (higher compliance, or lower stiffness, provides overall better performance).

**[0028]** The materials can be different for each layer. Preferably, the single or homogenous materials that may be used for any of the previous layers (resonating layers, separating layers, skin layers, connecting layers) are polymers or standard polymers (e.g. polyamides, PVC, etc.), rubber-like materials (e.g. silicone rubber), or metals (e.g. steel, aluminum, etc.). Table 1 shows an example of the properties for these types of materials.

Table 1

| Material                            | Density (kg/m <sup>3</sup> ) | Young's Modulus (MPa)  | Poisson's ratio  |
|-------------------------------------|------------------------------|------------------------|------------------|
| Polymer-like<br>e.g. Polyamide      | 900-1200<br>950              | 1000-5000<br>1650      | 0.4-0.48<br>0.4  |
| Rubber-like<br>e.g. Silicone rubber | 1000-1500<br>1060            | 0.1-100<br>0.15        | 0.45-0.5<br>0.47 |
| Metal-like<br>e.g. Steel            | 2000-10000<br>7860           | 50000-300000<br>200000 | 0.25-0.35<br>0.3 |

**[0029]** The constant thickness can be different for each layer. The sum of the thicknesses of all the layers conforming the acoustic metamaterial determines its total thickness. The thickness and material properties of each layer can be chosen to adjust the attenuation level of the acoustic metamaterial. Typical magnitude ranges for each layer's thickness depend on the material type employed.

**[0030]** Preferably, the constant thickness for any of the previous layers (resonating layers, separating layers, skin layers, connecting layers) ranges from 0.5 to 20 mm.

**[0031]** Preferably, the constant thickness for any any of the previous layers (resonating layers, separating layers, skin layers, connecting layers) ranges:

- from 0.5 to 10 mm for a polymer-type single material;
- from 0.5 mm to 20 mm for a rubber-type single material; or
- from 0.5 to 5 mm for a metal-type single material.

**[0032]** The size of each unit cell, parameters  $p$  and  $q$ , can be adjusted to target a range of operation in terms of frequencies and attenuation level. A practical magnitude range for these dimensions is from 10 to 100 mm.

**[0033]** Preferably, each unit cell (resonating unit cell, separating unit cell, connecting unit cell) for any of the previous layers (resonating layers, separating layers, connecting layers) has:

- a cell height  $q$  that ranges from 10 mm to 100 mm; and
- a cell width  $p$  that ranges from 10 mm to 100 mm.

**[0034]** The surface size of the acoustic metamaterial, parameters  $H$  and  $W$ , is determined according to the specific needs of each application. A practical magnitude range for such dimensions is from 10 cm to 2 m.

**[0035]** Preferably, the acoustic metamaterial has:

- a surface height  $H$  that ranges from 10 cm to 2 m; and
- a surface width  $W$  that ranges from 10 cm to 2 m.

**[0036]** The acoustic metamaterial of the present invention may adopt different constructive configurations depending

on the intended use of the same. Preferably, the acoustic metamaterial is presented in the form of a panel or liner, depending on the total thickness and the stiffness of the employed materials. A panel configuration is normally associated with a rigid product. On the other hand, a liner configuration may be associated with a product of flexible character (such as a flexible covering), due to the small thickness of some embodiments, allowing its use for covering irregular surfaces, or no flat surfaces, that may be present in some applications.

**[0037]** Thus, the acoustic metamaterial of the present invention forms a collection of different stacked layers of constant thickness joined in the form of a panel or liner for sound attenuation at selected frequency ranges. Its constant thickness layered configuration makes it easy to produce by manufacturing processes like, for instance, lamination and die cutting.

**[0038]** The following tables show different examples of the acoustic metamaterial of the present invention.

**[0039]** Table 2 shows a first example of the acoustic metamaterial of the present invention forming a panel, wherein all the layers are made of polymer-like materials. The openings between adjacent layers coincide or completely overlap, and the layers are disposed symmetrically.

Table 2

| Width [W] (mm)                                  | Height [H] (mm)       | Thickness [ $t_1$ ] (mm) | unit cells (*)            |
|-------------------------------------------------|-----------------------|--------------------------|---------------------------|
| 400                                             | 400                   | 7                        | 10 x 10                   |
| Layer                                           | Type                  | Material                 | Thickness, [ $t_i$ ] (mm) |
| 4a                                              | Skin                  | Polymer-like             | 1                         |
| 3a                                              | Separating            | Polymer-like             | 1                         |
| 2a                                              | Resonating (T-shaped) | Polymer-like             | 3                         |
| 3b                                              | Separating            | Polymer-like             | 1                         |
| 4b                                              | Skin                  | Polymer-like             | 1                         |
| (*) Unit cell width [p] and height [q] of 40 mm |                       |                          |                           |

**[0040]** Table 3 shows a second example of the acoustic metamaterial of the present invention forming a panel, wherein the layers are made of different materials. The openings between adjacent layers partially overlap, and the layers are disposed symmetrically.

Table 3

| Width [W] (mm)                                  | Height [H] (mm)       | Thickness [ $t_1$ ] (mm) | unit cells (*)            |
|-------------------------------------------------|-----------------------|--------------------------|---------------------------|
| 400                                             | 400                   | 7.7                      | 10 x 10                   |
| Layer                                           | Type                  | Material                 | Thickness, [ $t_i$ ] (mm) |
| 4a                                              | Skin                  | Polymer-like             | 0.65                      |
| 3a                                              | Separating            | Polymer-like             | 0.5                       |
| 2a                                              | Resonating (U-shaped) | Metal-like               | 0.7                       |
| 5                                               | Connecting            | Rubber-like              | 4                         |
| 2b                                              | Resonating (U-shaped) | Metal-like               | 0.7                       |
| 3b                                              | Separating            | Polymer-like             | 0.5                       |
| 4b                                              | Skin                  | Polymer-like             | 0.65                      |
| (*) Unit cell width [p] and height [q] of 40 mm |                       |                          |                           |

**[0041]** Table 4 shows a third example of the acoustic metamaterial of the present invention forming a panel without metallic layers. The openings between adjacent layers partially overlap, and the layers are disposed asymmetrically, having no front skin layer.

Table 4

| Width [W] (mm)                                  | Height [H] (mm)       | Thickness [ $t_1$ ] (mm) | unit cells (*)            |
|-------------------------------------------------|-----------------------|--------------------------|---------------------------|
| 400                                             | 400                   | 20                       | 10 x 10                   |
| Layer                                           | Type                  | Material                 | Thickness, [ $t_i$ ] (mm) |
| 3a                                              | Separating            | Polymer-like             | 0.5                       |
| 2a                                              | Resonating (T-shaped) | Polymer-like             | 4                         |
| 5                                               | Connecting            | Rubber-like              | 10                        |
| 2b                                              | Resonating (U-shaped) | Polymer-like             | 3.5                       |
| 3b                                              | Separating            | Polymer-like             | 0.5                       |
| 4b                                              | Skin                  | Polymer-like             | 1.5                       |
| (*) Unit cell width [p] and height [q] of 40 mm |                       |                          |                           |

**[0042]** Table 5 shows a fourth example of the acoustic metamaterial of the present invention forming a liner, wherein all the layers are made of rubber-like materials. The openings between adjacent layers coincide or completely overlap, and the layers are disposed symmetrically, having no skin layers.

Table 5

| Width [W] (mm)                                  | Height [H] (mm)       | Thickness [ $t_1$ ] (mm) | unit cells (*)            |
|-------------------------------------------------|-----------------------|--------------------------|---------------------------|
| 400                                             | 800                   | 12                       | 20 x 40                   |
| Layer                                           | Type                  | Material                 | Thickness, [ $t_i$ ] (mm) |
| 3a                                              | Separating            | Rubber-like              | 1                         |
| 2a                                              | Resonating (T-shaped) | Rubber-like              | 3                         |
| 5                                               | Connecting            | Rubber-like              | 4                         |
| 2b                                              | Resonating (T-shaped) | Rubber-like              | 3                         |
| 3b                                              | Separating            | Rubber-like              | 1                         |
| (*) Unit cell width [p] and height [q] of 40 mm |                       |                          |                           |

**[0043]** Table 6 shows the resonating unit cells dimensions for each of the previous examples.

Table 6

| Dimensions (mm)                                                                                                                                                                                                                   | First example | Second example | Third example | Fourth example |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------|----------------|---------------|----------------|
| Hole width [r]                                                                                                                                                                                                                    | 35            | 36/36          | 38/38         | 38/38          |
| Hole height [s]                                                                                                                                                                                                                   | 35            | 36/36          | 38/38         | 38/38          |
| Resonating element width [a]                                                                                                                                                                                                      | 25            | 20/28          | 34/30         | 34/34          |
| Resonating element height [b]                                                                                                                                                                                                     | 20            | 28/32          | 36/34         | 36/ 36         |
| Union width [c]                                                                                                                                                                                                                   | 8             | - / -          | 5 / -         | 10/20          |
| Union height [d]                                                                                                                                                                                                                  | 5             | - / -          | 8 / -         | 2/2            |
| - The "/" is to distinguish among two resonating layers.<br>- The union dimensions [c] and [d] are only given for the "T-shaped" resonating elements. For "U-shaped", these dimensions don't exist (or they can be considered 0). |               |                |               |                |

**[0044]** Table 7 shows the separating/connecting unit cells dimensions for each of the previous examples.

Table 7

| Dimensions (mm) | First example | Second example | Third example | Fourth example |
|-----------------|---------------|----------------|---------------|----------------|
| Hole width [r]  | 35            | 39             | 38            | 38             |
| Hole height [s] | 35            | 39             | 38            | 38             |

**[0045]** The present invention also refers to a process for manufacturing an acoustic metamaterial, comprising the following steps:

- laminating a solid single material to obtain an unfinished resonating layer of a constant resonating thickness; and
- die cutting the unfinished resonating layer to obtain a resonating layer having a plurality of resonating unit cells, wherein each resonating unit cell comprises a resonating opening and a resonating element extending into said resonating opening, and wherein the resonating elements are coplanar to the resonating layer, having said resonating layer and said resonating elements the same constant resonating thickness.

**[0046]** Preferably, the process further comprises the steps of:

- laminating a solid single material to obtain an unfinished separating layer of a constant separating thickness;
- die cutting the unfinished separating layer to obtain a separating layer having a plurality of separating unit cells, wherein each separating unit cell comprises a separating opening; and
- arranging a side of the separating layer adjacent to a side of the resonating layer, partially or completely overlapping the separating openings of the separating layer with the resonating openings of the resonating layer to allow the vibration of the resonating elements.

**[0047]** Preferably, the process comprises the steps of:

- laminating a solid single material to obtain an unfinished connecting layer of a constant connecting thickness;
- die cutting the unfinished connecting layer to obtain a connecting layer having a plurality of connecting unit cells, wherein each connecting unit cell comprises a connecting opening; and
- arranging the connecting layer adjacent to a first resonating layer and to a second resonating layer, disposed between them, partially or completely overlapping the connecting openings of the connecting layer with the resonating openings of the resonating layers to allow the vibration of the resonating elements.

**[0048]** Preferably, the process comprises the steps of:

- laminating or providing one or more solid single materials to obtain one or more skin layers of a constant skin thickness; and
- arranging a skin layer adjacent to the outer side of each separating layer, as a structural or protective support for the inner layers forming the acoustic metamaterial.

**[0049]** The different layers are stacked in an orderly manner to form a panel or liner. Preferably, the adjacent layers are joined or attached between them by means of mechanical fastenings, such as screws or bolts, or by welding means, or by gluing, to avoid undesired vibrations.

#### Brief description of the drawings

**[0050]** What follows is a very brief description of a series of drawings that aid in better understanding the invention, and which are expressly related to two embodiments of said invention that are presented by way of non-limiting examples of the same

Figure 1 represents a general view of the acoustic metamaterial of the present invention, forming a panel or liner.

Figure 2 represents a front view of the acoustic metamaterial of Fig. 1.

Figure 3 represents a profile view of the acoustic metamaterial of Fig. 1.

Figure 4 represents the layer structure of the acoustic metamaterial of the present invention, according to a first preferred embodiment of the same that comprises one resonating layer.

Figure 5 represents an exploded perspective view of the acoustic metamaterial of the present invention, according

to the first preferred embodiment of Fig 4.

Figure 6 represents a front view of the resonating layer of Fig. 5.

Figure 7 represents a profile view of the resonating layer of Fig. 6.

Figure 8 represents the detail "V" of Fig. 6, corresponding to one of the resonating unit cells of the resonating layer.

Figure 9 represents a front view of a separating layer of Fig. 5.

Figure 10 represents a profile view of the separating layer of Fig. 9.

Figure 11 represents the detail "X" of Fig. 9, corresponding to one of the separating unit cells of the separating layer.

Figure 12 represents a front view of a skin layer of Fig. 5.

Figure 13 represents a profile view of the skin layer of Fig. 12.

Figure 14 represents the layer structure of the acoustic metamaterial of the present invention, according to a second preferred embodiment of the same that comprises two resonating layers.

Figure 15 represents an exploded perspective view of the acoustic metamaterial the present invention, according to the second preferred embodiment of Fig. 14.

Figure 16 represents a front view of the second resonating layer of Fig. 15.

Figure 17 represents a profile view of the second resonating layer of Fig. 16.

Figure 18 represents the detail "Y" of Fig. 16, corresponding to one of the resonating unit cells of the second resonating layer.

Figure 19 represents a front view of the connecting layer of Fig. 15.

Figure 20 represents a profile view of the connecting layer of Fig. 19.

Figure 21 represents the detail "Z" of Fig. 19, corresponding to one of the connecting unit cells of the connecting layer.

Figure 22 represents the sound transmission loss curve of the acoustic metamaterial of the present invention, according to the second preferred embodiment of the same, in comparison with the corresponding curves of other materials.

Figure 23 represents a schematic operating sequence of the manufacturing process of the present invention.

#### Detailed description of the invention

**[0051]** Figures 1 - 3 represent different views of the acoustic metamaterial (1) of the present invention. As seen, the acoustic metamaterial (1) is presented in the form of panel or liner, depending on the stiffness of the materials employed in the same, as demonstrated in the previous examples.

**[0052]** The acoustic metamaterial (1) has a width (W), a height (H) and a thickness ( $t_1$ ).

**[0053]** Figures 4 and 5 respectively represent the layer structure and an exploded view of the acoustic metamaterial of the present invention, according to a first preferred embodiment of the same.

**[0054]** As seen, the acoustic metamaterial (1) comprises one resonating layer (2a) disposed between two separating layers (3a, 3b), and two skin layers (4a, 4b) which provide a foundation or support for the rest of the layers conforming the stack. The two separating layers (3a, 3b) are formed by a first separating layer (3a) and a second separating layer (3b). The two skin layers (4a, 4b) are formed by a first skin layer (4a) and a second skin layer (4b).

**[0055]** Figures 6 - 8 represent different views of the resonating layer (2a). As seen, the resonating layer (2a) is made of a single or homogenous material having a constant resonating thickness ( $t_2$ ) and a plurality of resonating unit cells (20). The resonating layer (2a) has a width (W) and a height (H).

**[0056]** In turn, each resonating unit cell (20) comprises:

- a resonating opening (21); and
- a resonating element (22) extending into said resonating opening (21);

wherein the resonating elements (22) are coplanar to the resonating layer (2a), having said resonating layer (2a) and said resonating elements (22) the same constant resonating thickness ( $t_2$ ).

**[0057]** As seen, each resonating element (22) extends into the respectively resonating opening (21), occupying or covering part of the same, thus forming a vibrating element in the form of a tab, flap, strip, extending from an internal side or inner contour (23) of the resonating unit cell (20). The resonating elements (22) of the present example are T-shaped.

**[0058]** The dimension of each resonating unit cell (20) are defined by a unit cell width (p), a unit cell height (q), a hole width (r), a hole height (s), a resonating element width (a), a resonating element height (b), a union width (c) and a union height (d).

**[0059]** The T-shaped resonating layer (2a) forming the acoustic metamaterial (1) of the present example may be perfectly replaced with the U-shaped resonating layer (2b) of Figures 16 - 18, providing the same advantages.

**[0060]** Figures 9 - 11 represent different views of the first separating layer (3a) or the second separating layer (3b). As seen, each separating layer (3a, 3b) is made of a single or homogenous material having a constant separating

thickness ( $t_3$ ) and a plurality of separating unit cells (30). Each separating layer (3a, 3b) has a width (W) and a height (H).

**[0061]** In turn, each separating unit cell (30) comprises a separating opening (31). In this case, a square separating opening (31).

**[0062]** The first separating layer (3a) is arranged adjacent to a front side of the resonating layer (2a), and the second separating layer (3b) is arranged adjacent to a rear side of said resonating layer (2a), partially or completely overlapping the separating openings (31) of the first separating layer (3a) and the second separating layer (3b) with the resonating openings (21) of the resonating layer (2a) to allow the vibration of the resonating elements (22), Figure 5.

**[0063]** Thus, the separating layers (3a, 3b) separate the resonating layer (2a) from other layers, or from the construction elements acting as support.

**[0064]** The dimension of each separating unit cell (30) are defined by a unit cell width (p), a unit cell height (q), a hole width (r) and a hole height (s).

**[0065]** Figures 12 and 13 respectively represent a front view and a profile view of the first skin layer (4a) or the second skin layer (4b). As seen, each skin layer (4a, 4b) is made of a solid single or homogeneous material having a constant skin thickness ( $t_4$ ). Each skin layer (4a, 4b) has a width (W) and a height (H).

**[0066]** The first skin layer (4a) is arranged adjacent to a front side of the first separating layer (3a), and the second skin layer (4b) is arranged adjacent to a rear side of the second separating layer (3b), Figure 5.

**[0067]** Thus, the skin layers (4a, 4b) are homogeneous solid layers located at each end of the stack forming the acoustic metamaterial (1). Their purpose is to provide a foundation or support for the rest of the layers conforming the stack.

**[0068]** Figures 14 and 15 respectively represent the layer structure and an exploded view of the acoustic metamaterial of the present invention, according to a second preferred embodiment of the same.

**[0069]** As seen, the acoustic metamaterial (1) comprises two resonating layers (2a, 2b) formed by a first resonating layer (2a) and a second resonating layer (2b), wherein the first resonating layer (2a) and the second resonating layer (2b) have a different configuration, in order to obtain an extended attenuation band. The configuration of the first resonating layer (2a) is shown in Figures 6 - 8, having T-shaped resonating elements (22). The configuration of the second resonating layer (2b) is shown in Figures 16 - 18, having U-shaped resonating elements (22).

**[0070]** The acoustic metamaterial (1) of the present embodiment also comprises a first separating layer (3a) arranged adjacent to a front side of the first resonating layer (2a), and a second separating layer (3b) arranged adjacent to a rear side of the second resonating layer (2b), partially or completely overlapping the separating openings (31) of the first separating layer (3a) and the second separating layer (3b) respectively with the resonating openings (21) of the first resonating layer (2a) and the second resonating layer (2b) to allow the vibration of the resonating elements (22). The configuration of the first separating layer (3a) and the second separating layer (3b) is shown in Figures 9 - 11, having square resonating openings (31).

**[0071]** The acoustic metamaterial (1) of the present embodiment also comprises a first skin layer (4a) arranged adjacent to a front side of the first separating layer (3a), and a second skin layer (4b) arranged adjacent to a rear side of the second separating layer (3b). The configuration of the first skin layer (4a) and the second skin layer (4b) is shown in Figures 12 - 13.

**[0072]** A separating layer (3a, 3b) attached to a resonating layer (2a, 2b) forms a resonating set (RSa, RSb). So, the first resonating layer (2a) together with the first separating layer (3b) form a first resonating set (RSa), whereas the second layer (2b) together with the second separating layer (3b) form a second resonating set (RSb). Thus, improving the attenuating capabilities of the acoustic metamaterial of the present invention.

**[0073]** The acoustic metamaterial (1) of the present embodiment also comprises a connecting layer (5) which is placed between the two resonating layers (2a, 2b) to couple their respective attenuating capabilities and produce an extended attenuation band. Therefore, the connecting layer (5) connects the two resonating sets (RSa, RSb).

**[0074]** Figures 16 - 18 represent different views of the second resonating layer (2b). As seen, the second resonating layer (2b) is also made of a single or homogenous material having a constant resonating thickness ( $t_2$ ) and a plurality of resonating unit cells (20). The second resonating layer (2b) has a width (W) and a height (H).

**[0075]** In turn, each resonating unit cell (20) comprises:

- a resonating opening (21); and
- a resonating element (22) extending into said resonating opening (21);

wherein the resonating elements (22) are coplanar to the resonating layer (2a), having said resonating layer (2b) and said resonating elements (22) the same constant resonating thickness ( $t_2$ ).

**[0076]** As seen, each resonating element (22) extends into the respectively resonating opening (21), occupying or covering part of the same, thus forming a vibrating element in the form of a tab, flap, strip, extending from an internal side or inner contour (23) of the resonating unit cell (20). The resonating elements (22) of the present example are U-shaped.

**[0077]** The dimension of each resonating unit cell (20) are defined by a unit cell width (p), a unit cell height (q), a hole

width (r), a hole height (s), a resonating element width (a) and resonating element height (b).

**[0078]** Figures 19 - 21 represent different views of the connecting layer (5). As seen, the connecting layer (5) is made of a single or homogeneous material having a constant separating thickness ( $t_5$ ) and a plurality of connecting unit cells (50). The connecting layer (5) has a width (W) and a height (H).

**[0079]** In turn, each connecting unit cell (50) comprises a connecting opening (51). In this case, a square connecting opening (51).

**[0080]** The dimension of each connecting unit cell (50) are defined by a unit cell width (p), a unit cell height (q), a hole width (r) and a hole height (s).

**[0081]** The connecting layer (5) is arranged adjacent to a rear side of the first resonating layer (2a) and to a front side of the second resonating layer (2b), partially or completely overlapping the connecting openings (51) of the connecting layer (5) with the resonating openings (21) of the first resonating layer (2a) and the second resonating layer (2b) to allow the vibration of the resonating elements (22).

**[0082]** Figure 22 shows a comparative of the sound transmission loss computed with a numerical simulation for panels under normally incident acoustic plane waves. Each curve corresponds to a different panel configuration with a given area density (in  $\text{kg/m}^2$ ).

**[0083]** For panels with an area density of  $10 \text{ kg/m}^2$ , it can be observed that the acoustic metamaterial configurations (dashed and solid lines), both provide increased levels of attenuation around the internal resonance frequencies at 360 and 440 Hz when compared with an equivalent homogeneous panel (dashed line). Furthermore, it can be noticed that the acoustic metamaterial of the present invention (MLAM, solid line) provides a continuous increased level of attenuation between 360 and 480 Hz, comparable in magnitude to that of a homogeneous panel with four times its area density (dash-dotted line). For the standard uncoupled acoustic metamaterial case (dotted line) the same attenuation band is interrupted with an undesired dip at 380 Hz between the two internal resonance frequencies.

**[0084]** Figure 23 represents a schematic operating sequence of the manufacturing process of the present invention.

**[0085]** The process for manufacturing an acoustic metamaterial comprises the steps of:

- laminating a solid single material to obtain an unfinished resonating layer of a constant resonating thickness ( $t_2$ ), Fig. 23(a); and
- die cutting the unfinished layer to obtain a resonating layer (2a, 2b) having a plurality of resonating unit cells (20), wherein each resonating unit cell (20) comprises a resonating opening (21) and a resonating element (22) extending into said resonating opening (21), and wherein the resonating elements (22) are coplanar to the resonating layer (2a, 2b), having said resonating layer (2a,2b) and said resonating elements (22) the same constant resonating thickness ( $t_2$ ), Fig. 23(b).

**[0086]** According to the first preferred embodiment, the process further comprises the steps of:

- laminating a solid single material to obtain an unfinished separating layer (3a, 3b) of a constant separating thickness ( $t_3$ ), Fig. 23(a);
- die cutting the unfinished separating layer to obtain a separating layer (3a, 3b) having a plurality of separating unit cells (30), wherein each separating unit cell (30) comprises a separating opening (31), Fig. 23(b); and
- arranging a side of the separating layer (3a, 3b) adjacent to a side of the resonating layer (2a, 2b), partially or completely overlapping the separating openings (31) of the separating layer (3a, 3b) with the resonating openings (21) of the resonating layer (2a, 2b) to allow the vibration of the resonating elements (22), Fig. 23(c).

**[0087]** According to the second preferred embodiment, the process further comprises the steps of:

- laminating a solid single material to obtain an unfinished connecting layer of a constant connecting thickness ( $t_5$ ), Fig. 23(a);
- die cutting the unfinished connecting layer to obtain a connecting layer (5) having a plurality of connecting unit cells (50), wherein each connecting unit cell (50) comprises a connecting opening (51), Fig. 23(b); and
- arranging the connecting layer (5) between a first resonating layer (2a) and a second resonating layer (2b), adjacent to both resonating layers (2a, 2b), partially or completely overlapping the connecting openings (51) of the connecting layer (5) with the resonating openings (21) of the resonating layers (2a, 2b) to allow the vibration of the resonating elements (22).

**[0088]** For both embodiments, the process further comprises the steps of:

- laminating or providing one or more solid single materials to obtain one or more skin layers (4a, 4b) of a constant skin thickness ( $t_4$ ); and

- arranging each skin layer (4a, 4b) adjacent to the outer side of each separating layer (3a, 3b), as a structural or protective support for the inner layers forming the acoustic metamaterial.

**[0089]** The previous steps are repeated to obtain the necessary number of different layers forming the acoustic metamaterial (1). The different layers are stacked in an orderly manner to form a panel or liner, according to any of the embodiments and/or examples previously mentioned. The adjacent layers are joined or attached between them by means of mechanical fastenings, such as screws or bolts, or by welding means, or by gluing, to avoid undesired vibrations.

## Claims

1. An acoustic metamaterial, **characterised in that** it comprises at least one resonating layer (2a, 2b) made of a single material having a constant resonating thickness ( $t_2$ ) and a plurality of resonating unit cells (20), wherein each resonating unit cell (20) comprises:

- a resonating opening (21); and
- a resonating element (22) extending into said resonating opening (21);

wherein the resonating elements (22) are coplanar to the resonating layer (2a, 2b), having said resonating layer (2a, 2b) and said resonating elements (22) the same constant resonating thickness ( $t_2$ ).

2. The acoustic metamaterial according to claim 1, **characterised in that** the resonating elements (22) are T-shaped or U-shaped.

3. The acoustic metamaterial according to any of claims 1 to 2, **characterised in that** it comprises at least one separating layer (3a, 3b) made of a single material having a constant separating thickness ( $t_3$ ) and a plurality of separating unit cells (30), wherein each separating unit cell (30) comprises:

- a separating opening (31);

wherein the separating layer (3a, 3b) is arranged adjacent to the resonating layer (2a, 2b), partially or completely overlapping the separating openings (31) with the resonating openings (21) to allow the vibration of the resonating elements (22).

4. The acoustic metamaterial according claim 3, **characterised in that** it comprises at least one skin layer (4a, 4b) made of a solid single material having a constant skin thickness ( $t_4$ ), which is arranged adjacent to the separating layer (3a, 3b).

5. The acoustic metamaterial according to any of claims 1 to 4, **characterised in that** it comprises two separating layers (3a, 3b) formed by a first separating layer (3a) and a second separating layer (3b), wherein the first separating layer (3a) is arranged adjacent to a front side of a resonating layer (2a, 2b), and wherein the second separating layer (3b) is arranged adjacent to a rear side of said resonating layer (2a, 2b), partially or completely overlapping the separating openings (31) of the first separating layer (3a) and the second separating layer (3b) with the resonating openings (21) of the resonating layer (2a, 2b) to allow the vibration of the resonating elements (22).

6. The acoustic metamaterial according to any of claims 1 to 5, **characterised in that** it comprises two resonating layers (2a, 2b) formed by a first resonating layer (2a) and a second resonating layer (2b), wherein the first resonating layer (2a) and the second resonating layer (2b) have a similar or different configuration.

7. The acoustic metamaterial according to claim 6, **characterised in that** it comprises a connecting layer (5) made of a single material having a constant separating thickness ( $t_5$ ) and a plurality of connecting unit cells (50), wherein each connecting unit cell (50) comprises:

- a connecting opening (51);

wherein the connecting layer (5) is arranged adjacent to the first resonating layer (2a) and to the second resonating layer (2b), partially or completely overlapping the connecting openings (51) of the connecting layer (5) with the resonating openings (21) of the first resonating layer (2a) and the second resonating layer (2b) to allow the vibration

of the resonating elements (22).

8. The acoustic metamaterial according to any of claims 1 to 7, **characterised in that** the single material for any of the layers (2a, 2b, 3a, 3b, 4a, 4b, 5) is a polymer, a rubber-like material, or a metal.

9. The acoustic metamaterial according to any of claims 1 to 8, **characterised in that** the constant thickness ( $t_2$ ,  $t_3$ ,  $t_4$ ,  $t_5$ ) for any of the layers (2a, 2b, 3a, 3b, 4a, 4b, 5) ranges from 0.5 to 20 mm.

10. The acoustic metamaterial according to any of claims 1 to 9, **characterised in that** the constant thickness ( $t_2$ ,  $t_3$ ,  $t_4$ ,  $t_5$ ) for any of the layers (2a, 2b, 3a, 3b, 4a, 4b, 5) ranges:

- from 0.5 to 10 mm for a polymer-type single material;
- from 0.5 mm to 20 mm for a rubber-type single material; or
- from 0.5 to 5 mm for a metal-type single material.

11. The acoustic metamaterial according to any of claims 1 to 10, **characterised in that** each unit cell (20, 30, 50) for any of the layers (2a, 2b, 3a, 3b, 5) has:

- a cell height (q) that ranges from 10 mm to 100 mm; and
- a cell width (p) that ranges from 10 mm to 100 mm.

12. The acoustic metamaterial according to any of claims 1 to 11, **characterised in that** it has:

- a surface height (H) that ranges from 10 cm to 2 m; and
- a surface width (W) that ranges from 10 cm to 2 m.

13. The acoustic metamaterial according to any of claims 1 to 12, **characterised in that** it is a panel or liner.

14. A process for manufacturing an acoustic metamaterial, **characterised in that** it comprises the steps of:

- laminating a solid single material to obtain an unfinished resonating layer of a constant resonating thickness ( $t_2$ ); and
- die cutting the unfinished resonating layer to obtain a resonating layer (2a, 2b) having a plurality of resonating unit cells (20), wherein each resonating unit cell (20) comprises a resonating opening (21) and a resonating element (22) extending into said resonating opening (21), and wherein the resonating elements (22) are coplanar to the resonating layer (2a, 2b), having said resonating layer (2a, 2b) and said resonating elements (22) the same constant resonating thickness ( $t_2$ ).

15. The process according to claim 14, **characterised in that** it comprises the steps of:

- laminating a solid single material to obtain an unfinished separating layer of a constant separating thickness ( $t_3$ );
- die cutting the unfinished separating layer to obtain a separating layer (3a, 3b) having a plurality of separating unit cells (30), wherein each separating unit cell (30) comprises a separating opening (31); and
- arranging a side of the separating layer (3a, 3b) adjacent to a side of the resonating layer (2a, 2b), partially or completely overlapping the separating openings (31) of the separating layer (3a, 3b) with the resonating openings (21) of the resonating layer (2a, 2b) to allow the vibration of the resonating elements (22).

16. The process according to any of claims 14 to 15, **characterised in that** it comprises the steps of:

- laminating a solid single material to obtain an unfinished connecting layer of a constant connecting thickness ( $t_5$ );
- die cutting the unfinished connecting layer to obtain a connecting layer (5) having a plurality of connecting unit cells (50), wherein each connecting unit cell (50) comprises a connecting opening (51); and
- arranging the connecting layer (5) adjacent to a first resonating layer (2a) and to a second resonating layer (2b), partially or completely overlapping the connecting openings (51) of the connecting layer (5) with the resonating openings (21) of the resonating layers (2a, 2b) to allow the vibration of the resonating elements (22).

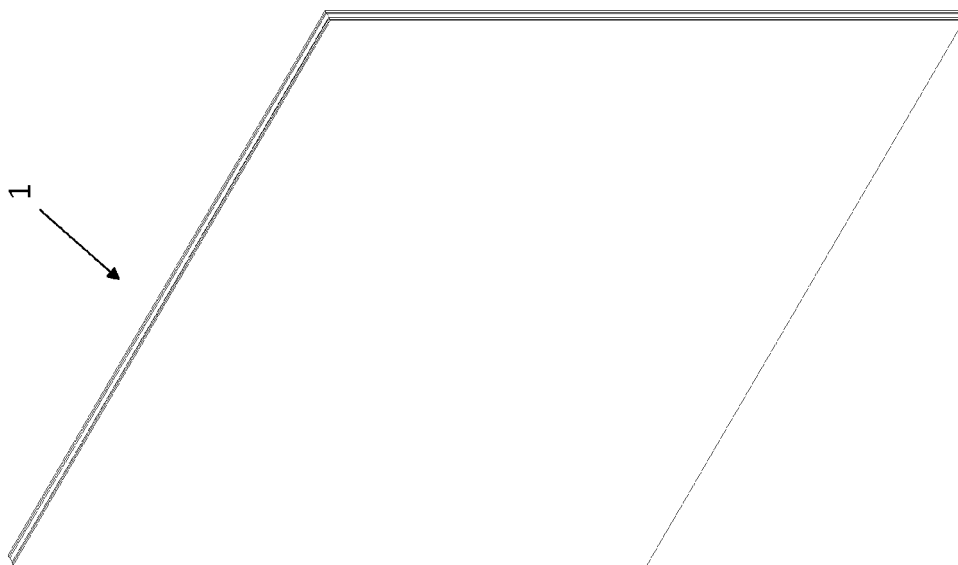


Fig. 1

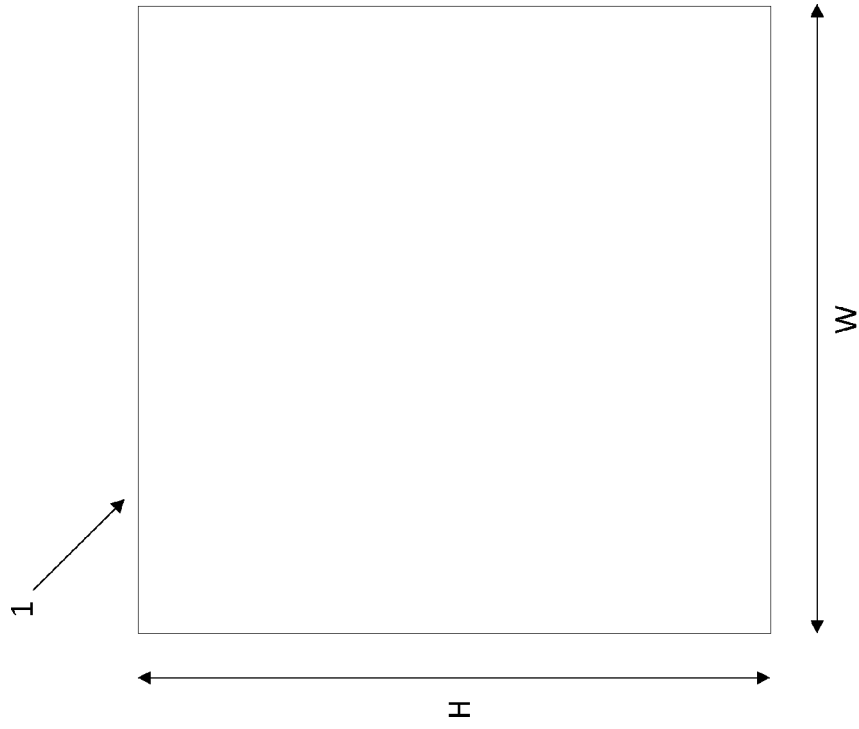


Fig. 2

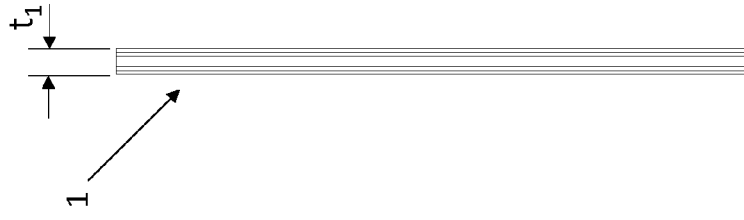


Fig. 3

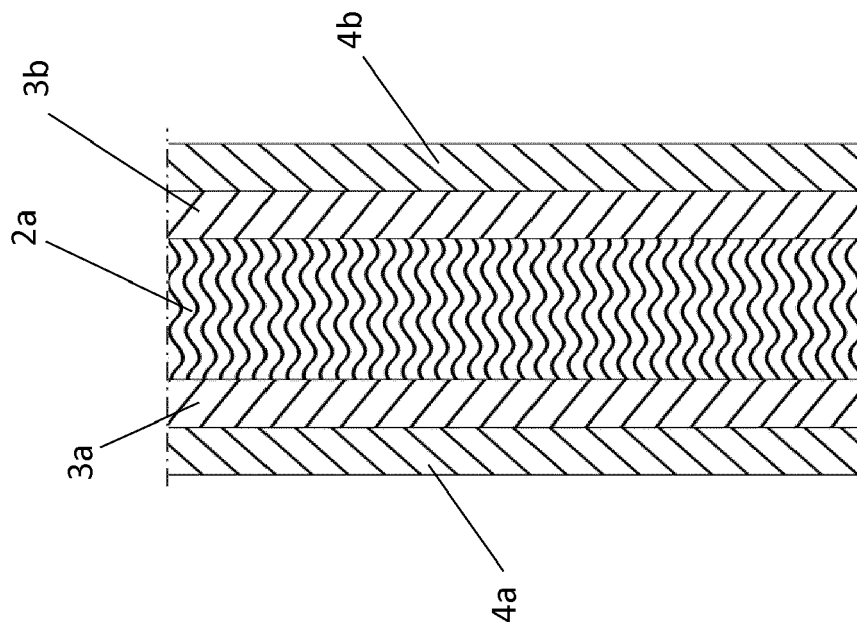


Fig. 4

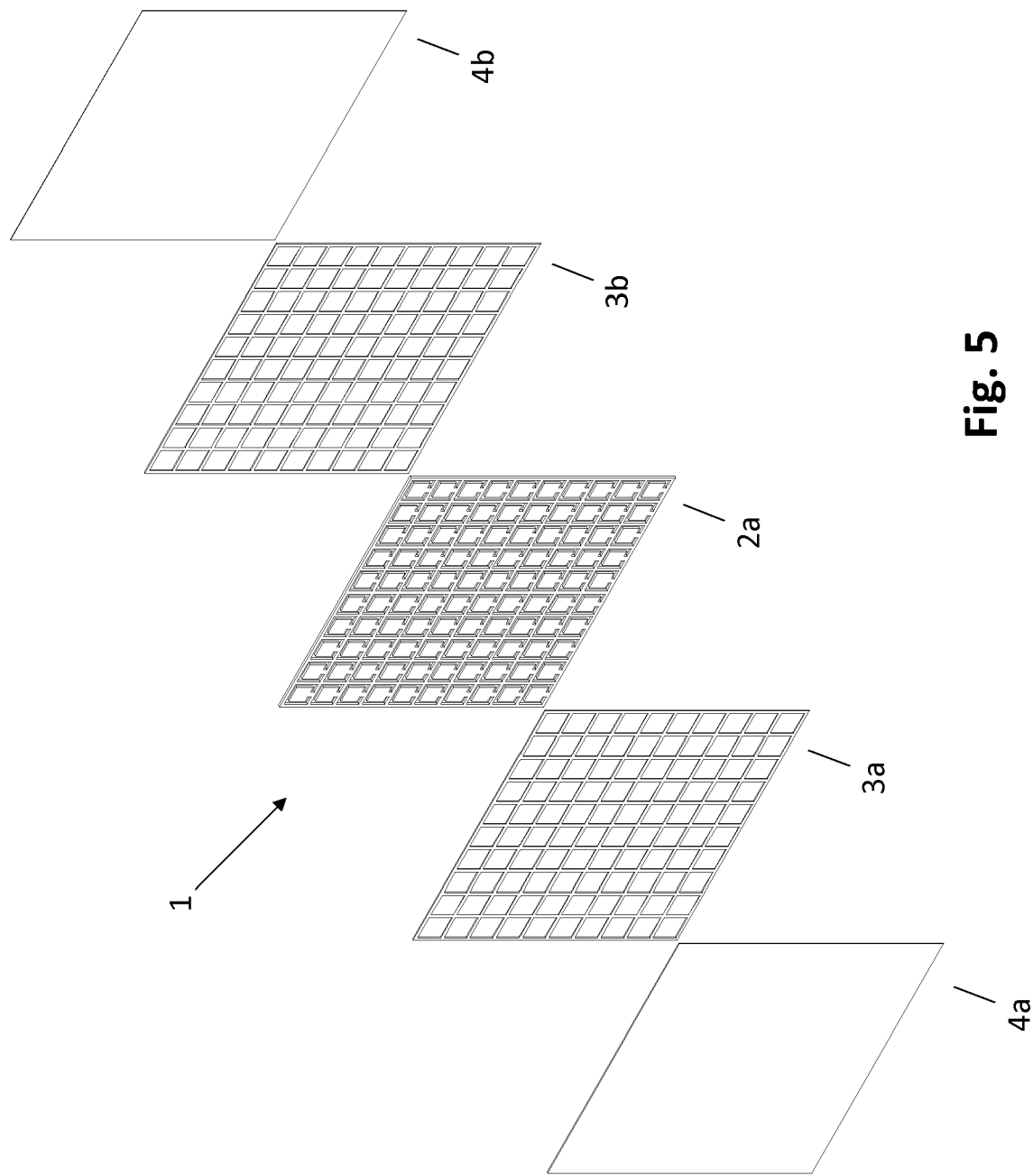


Fig. 5

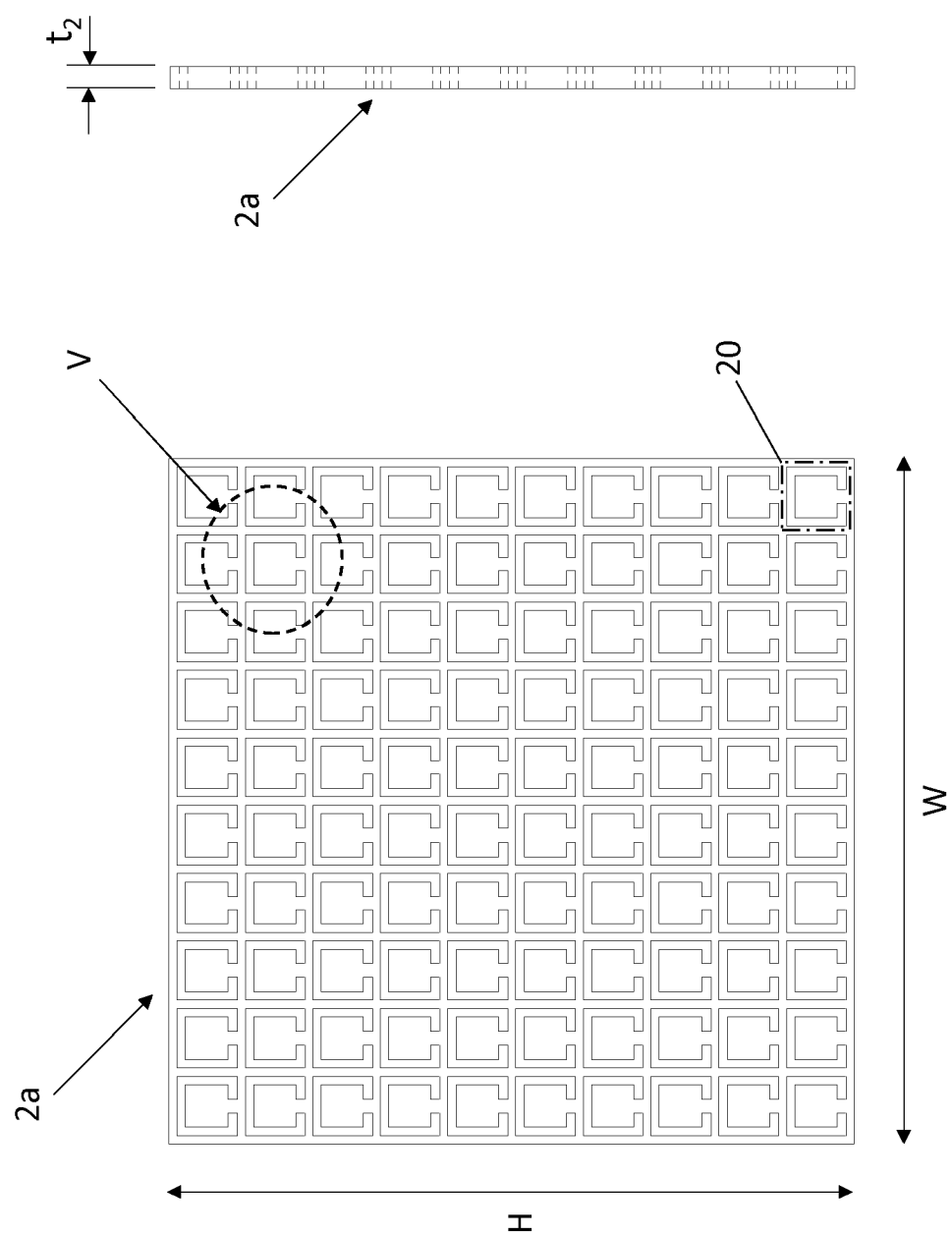


Fig. 7

Fig. 6

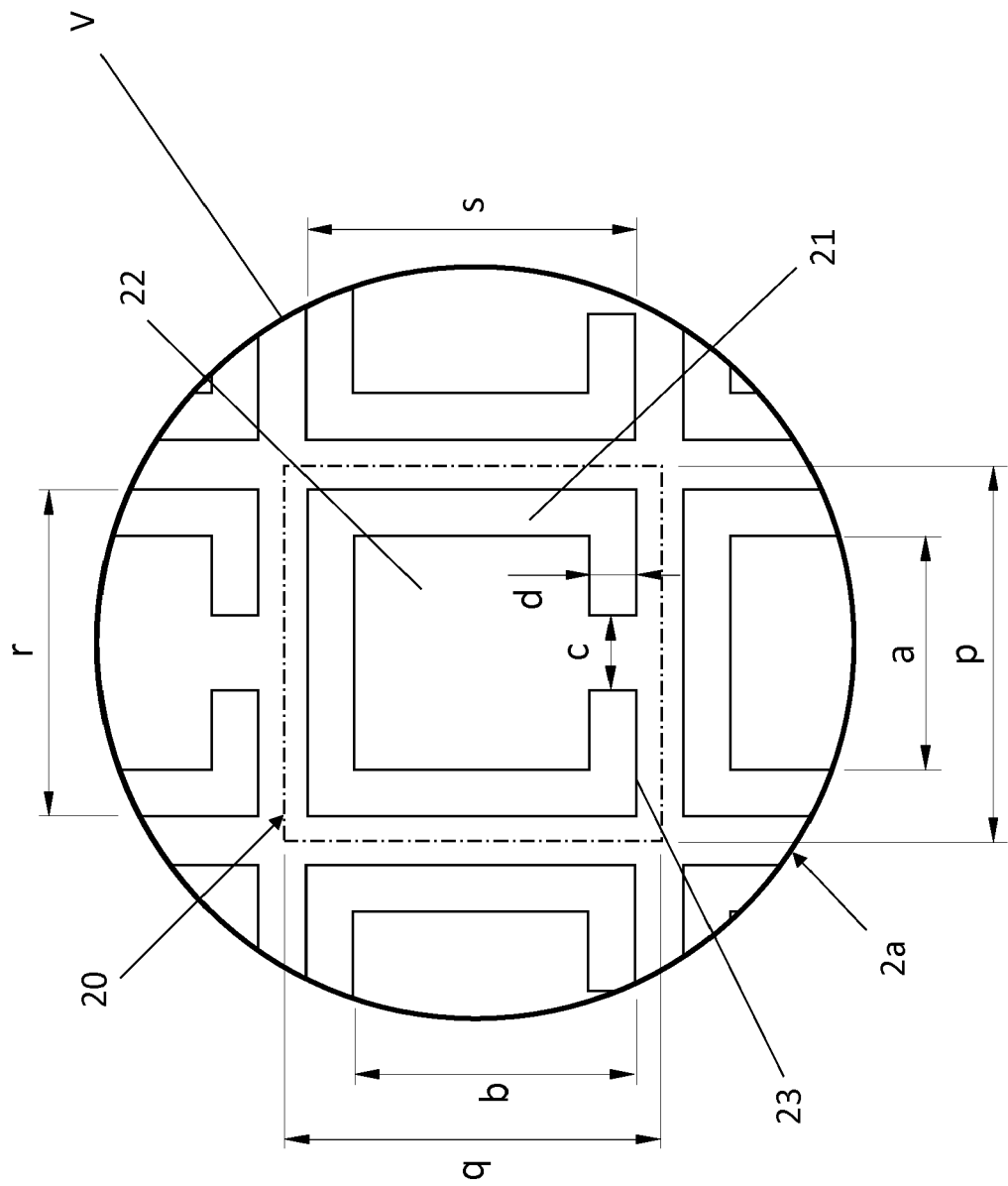


Fig. 8

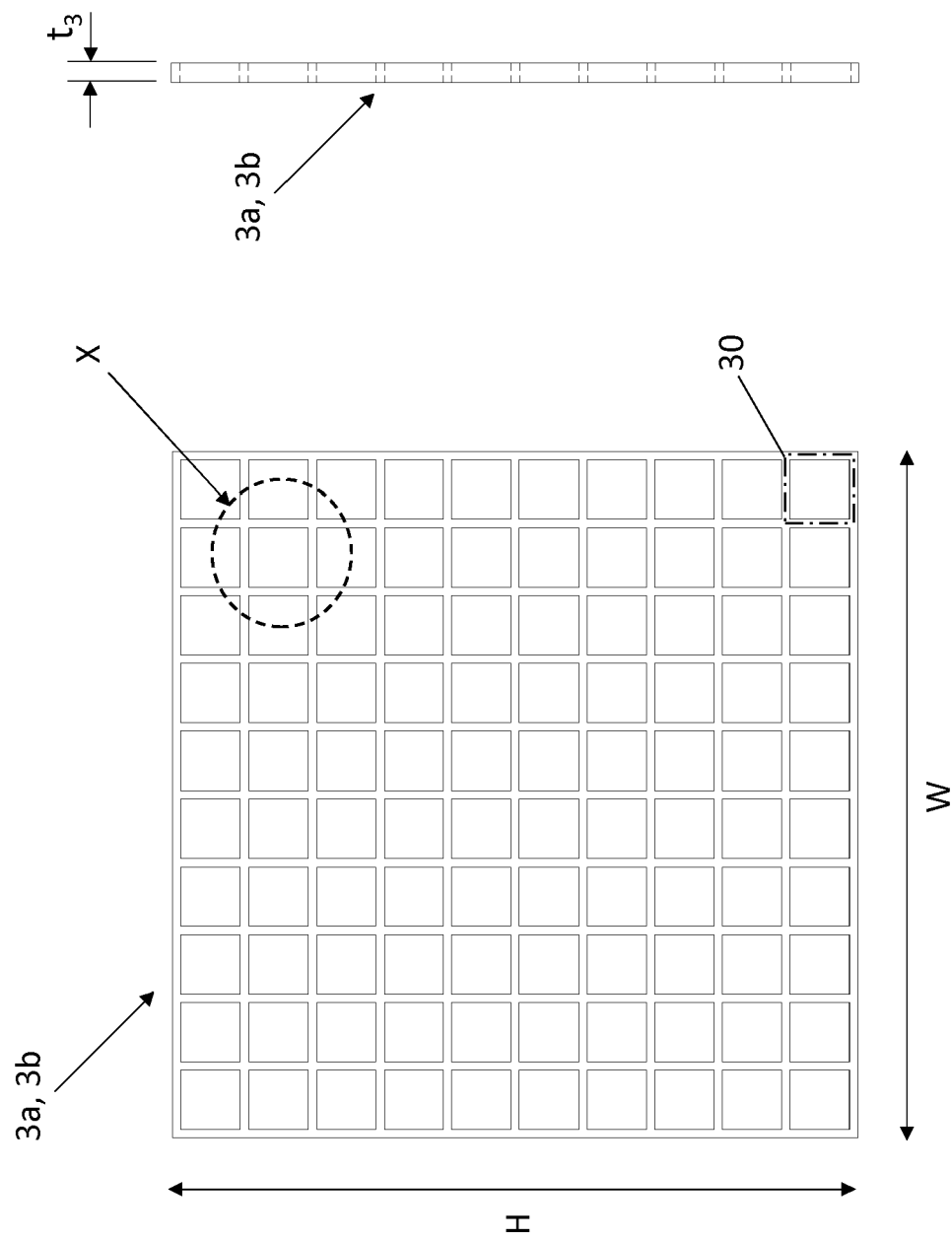


Fig. 10

Fig. 9

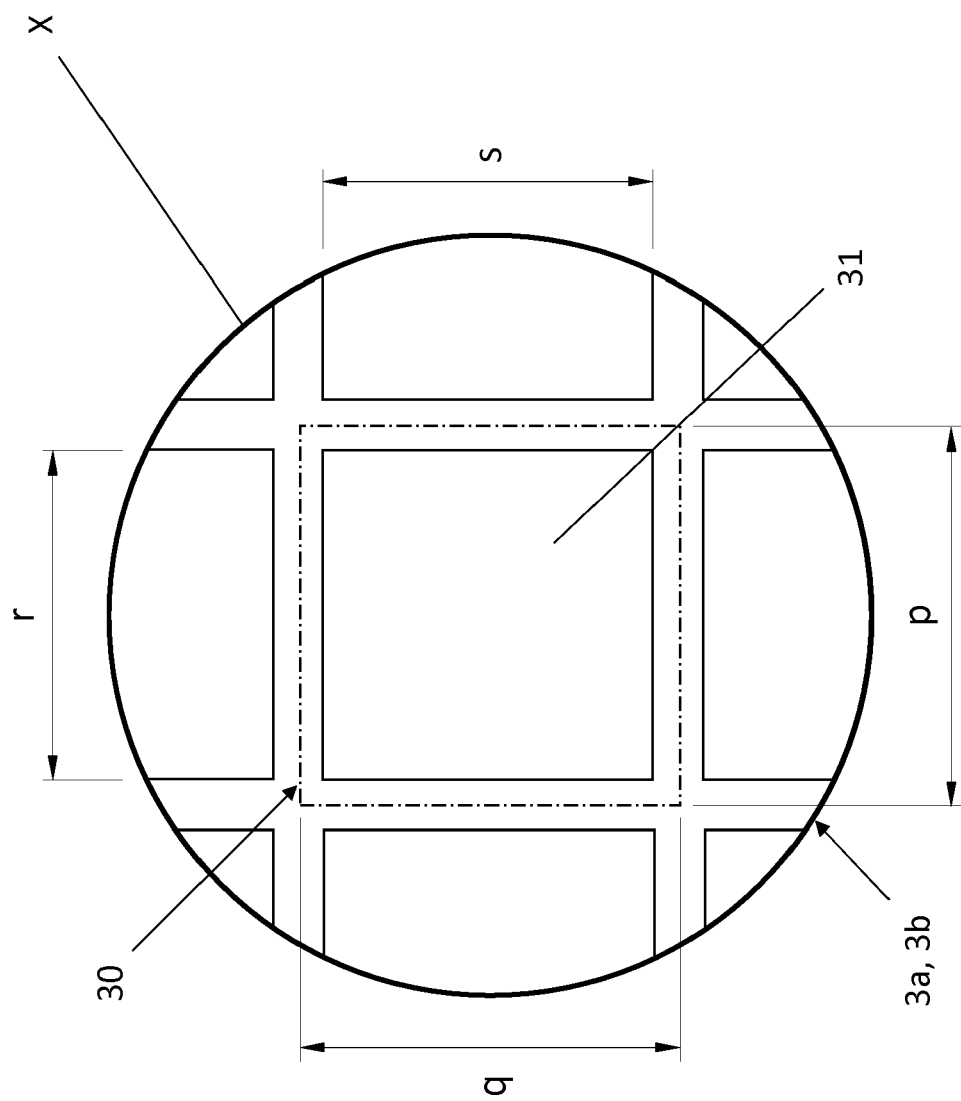


Fig. 11

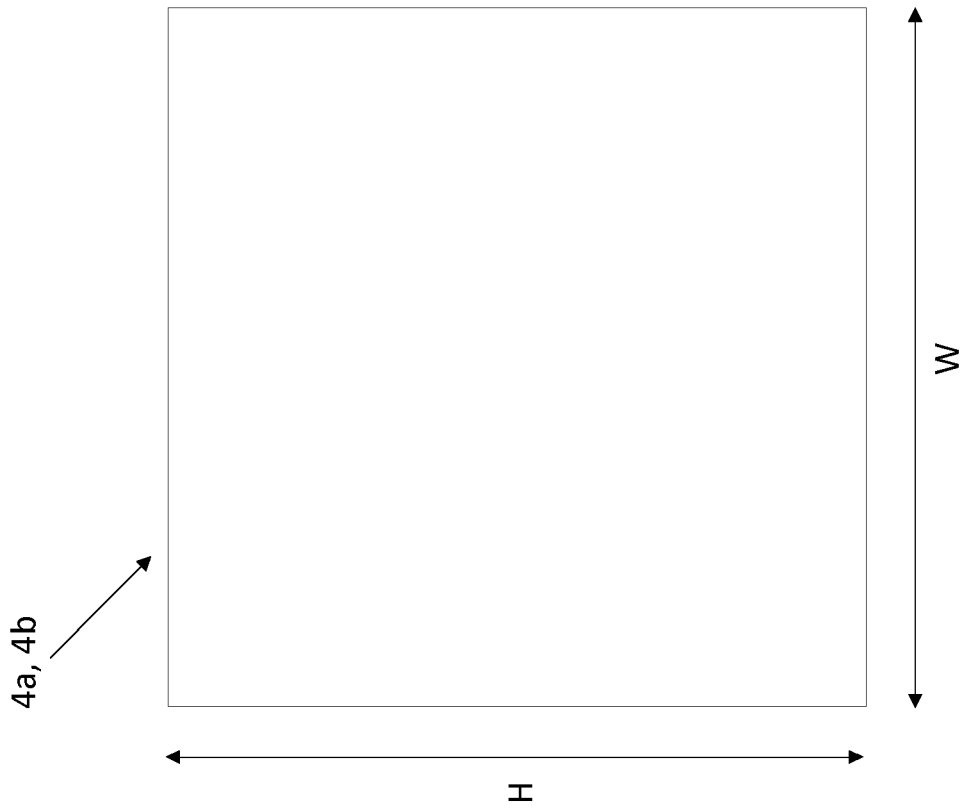


Fig. 12

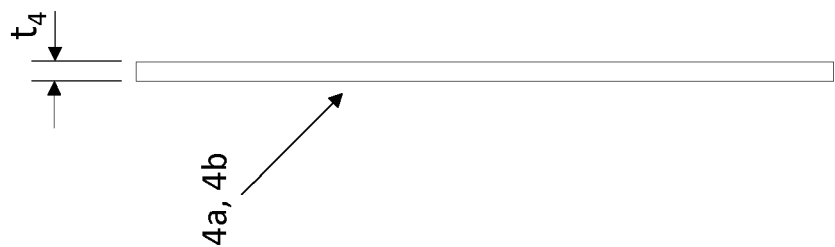


Fig. 13

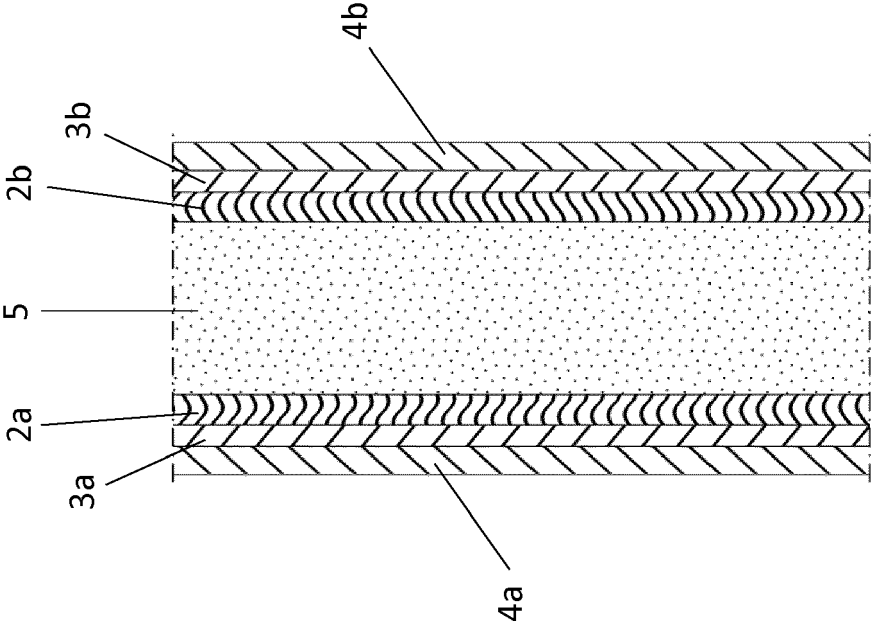


Fig. 14

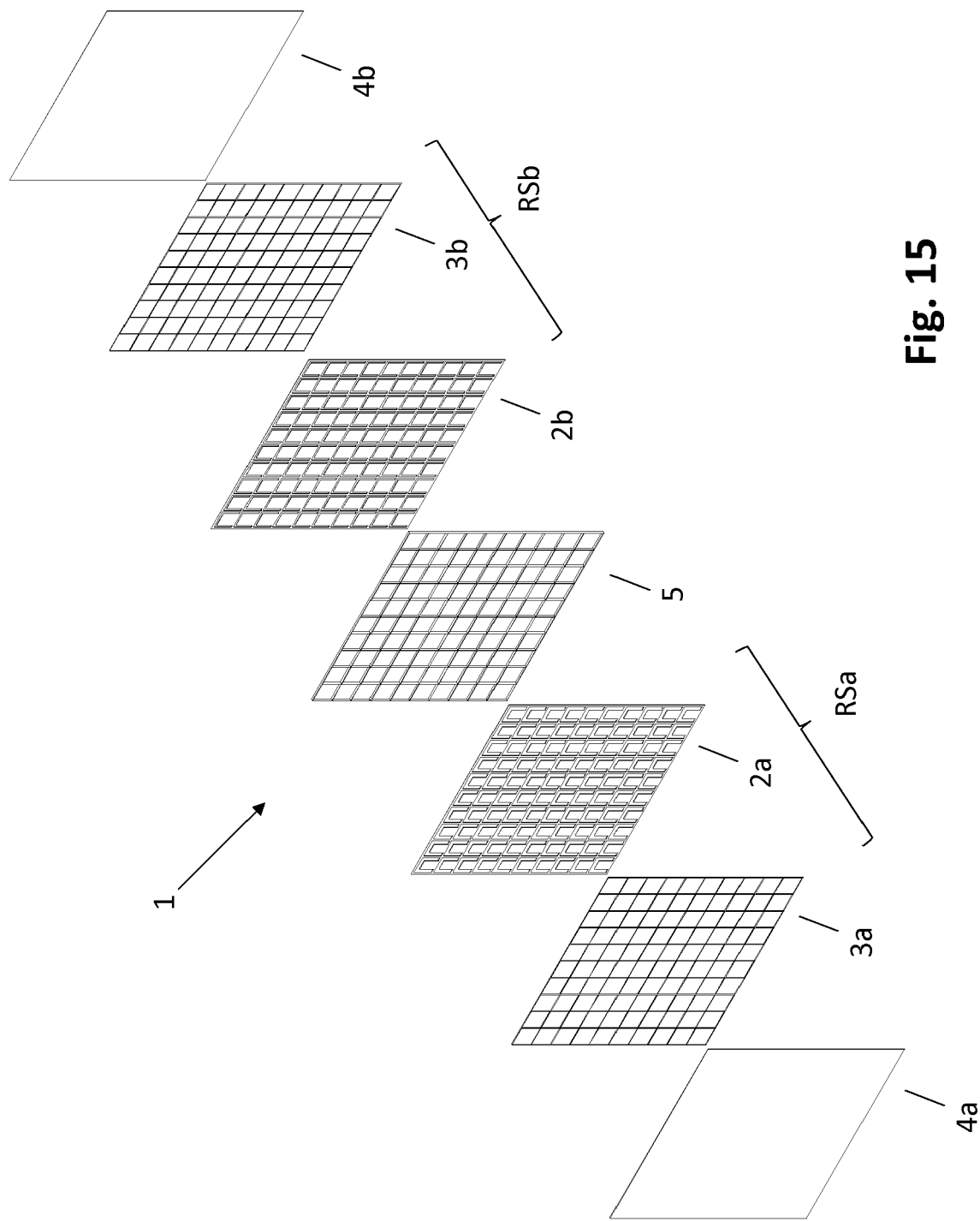


Fig. 15

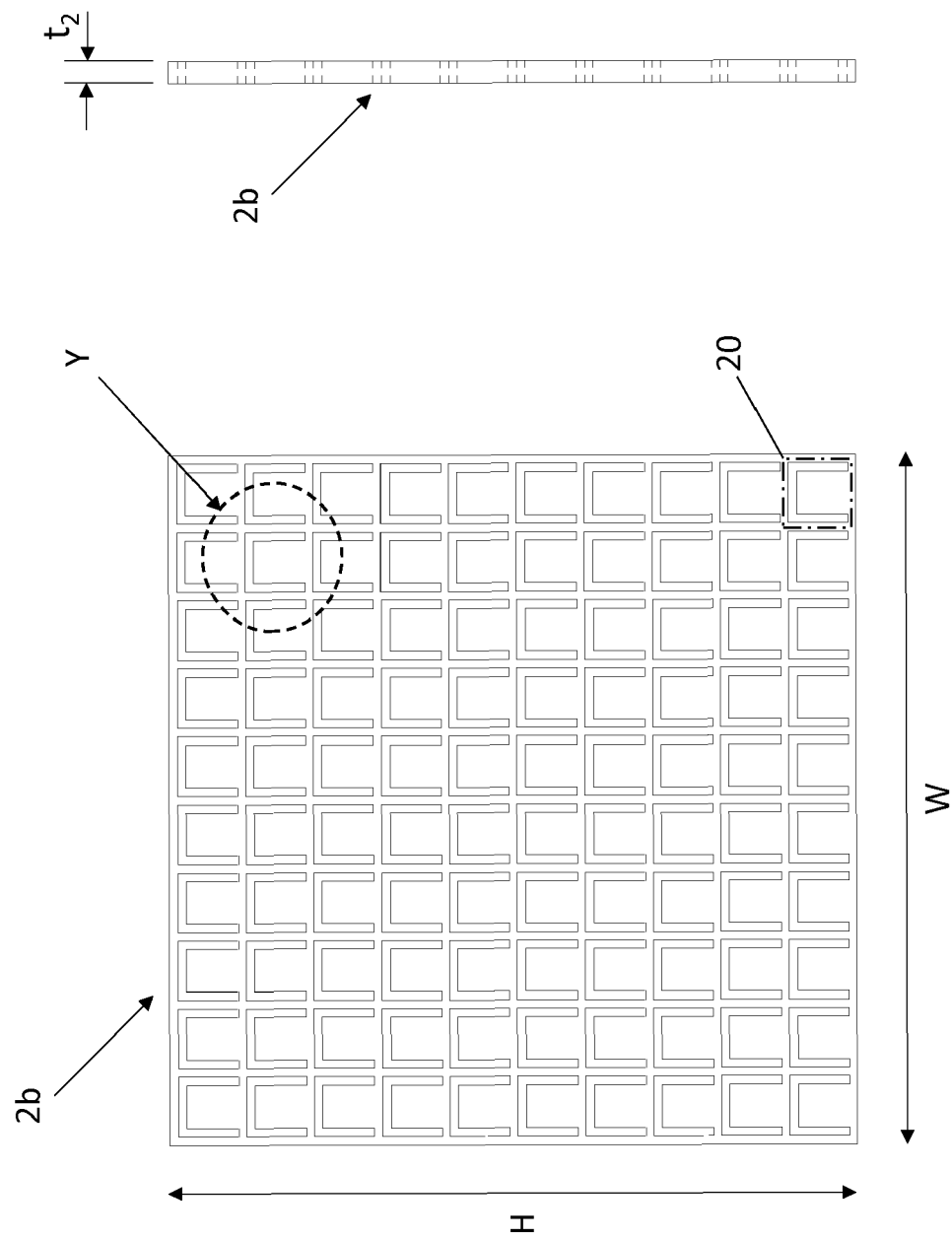


Fig. 17

Fig. 16

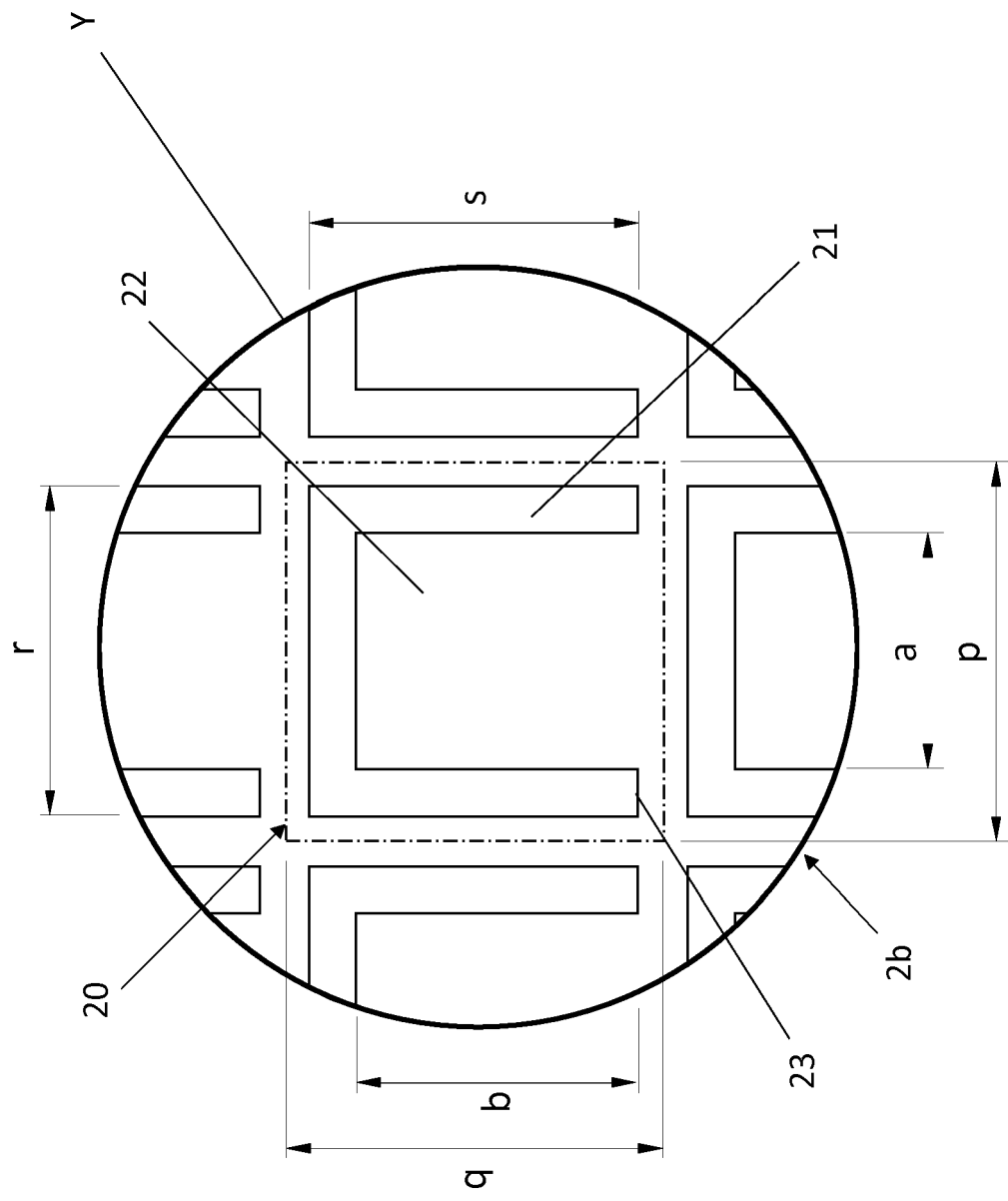


Fig. 18

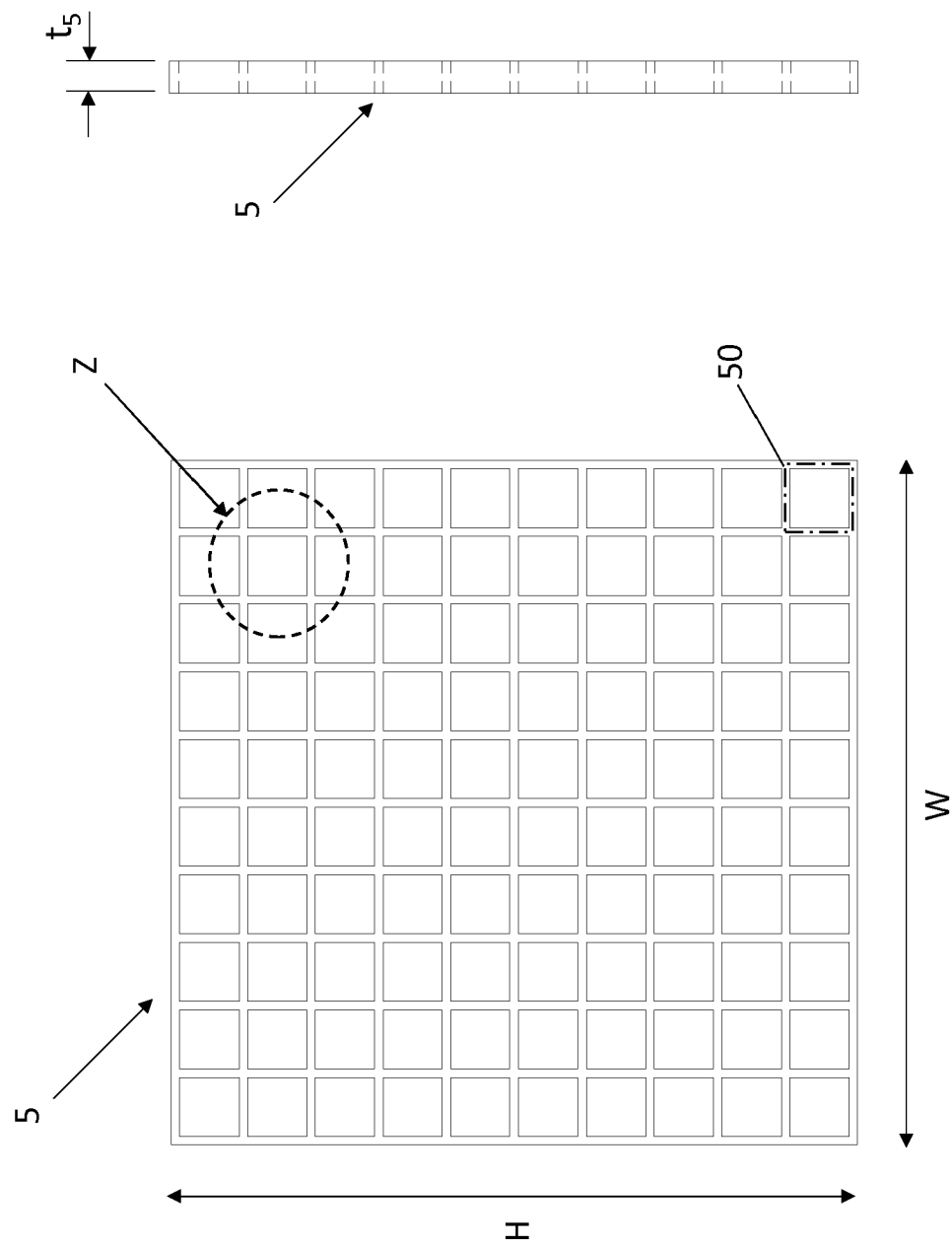


Fig. 19

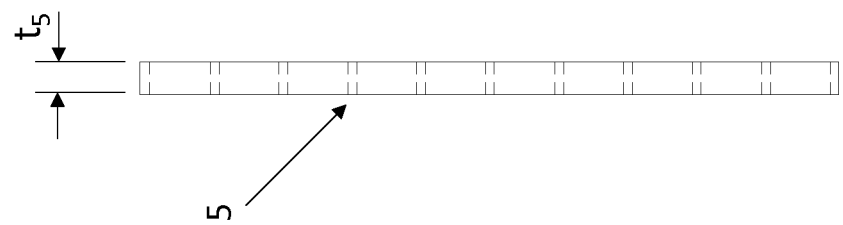


Fig. 20

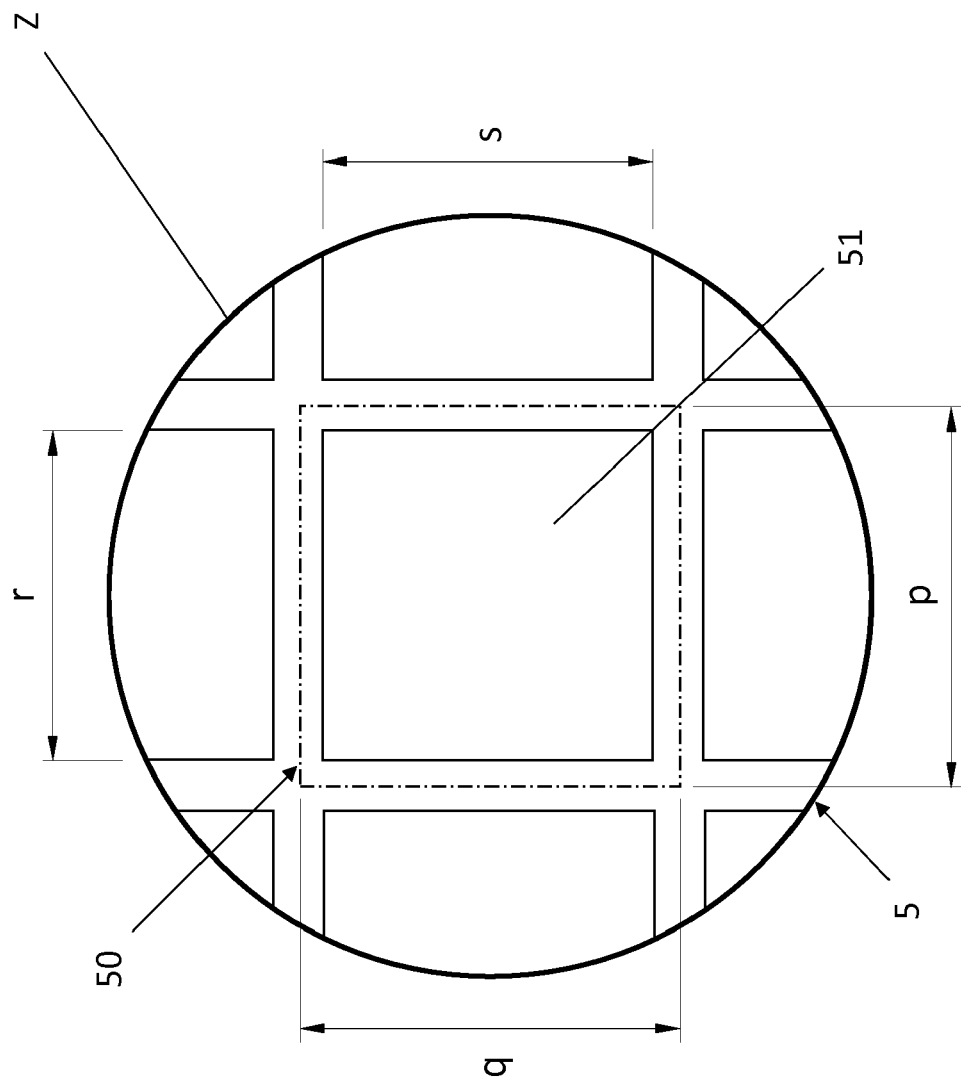


Fig. 21

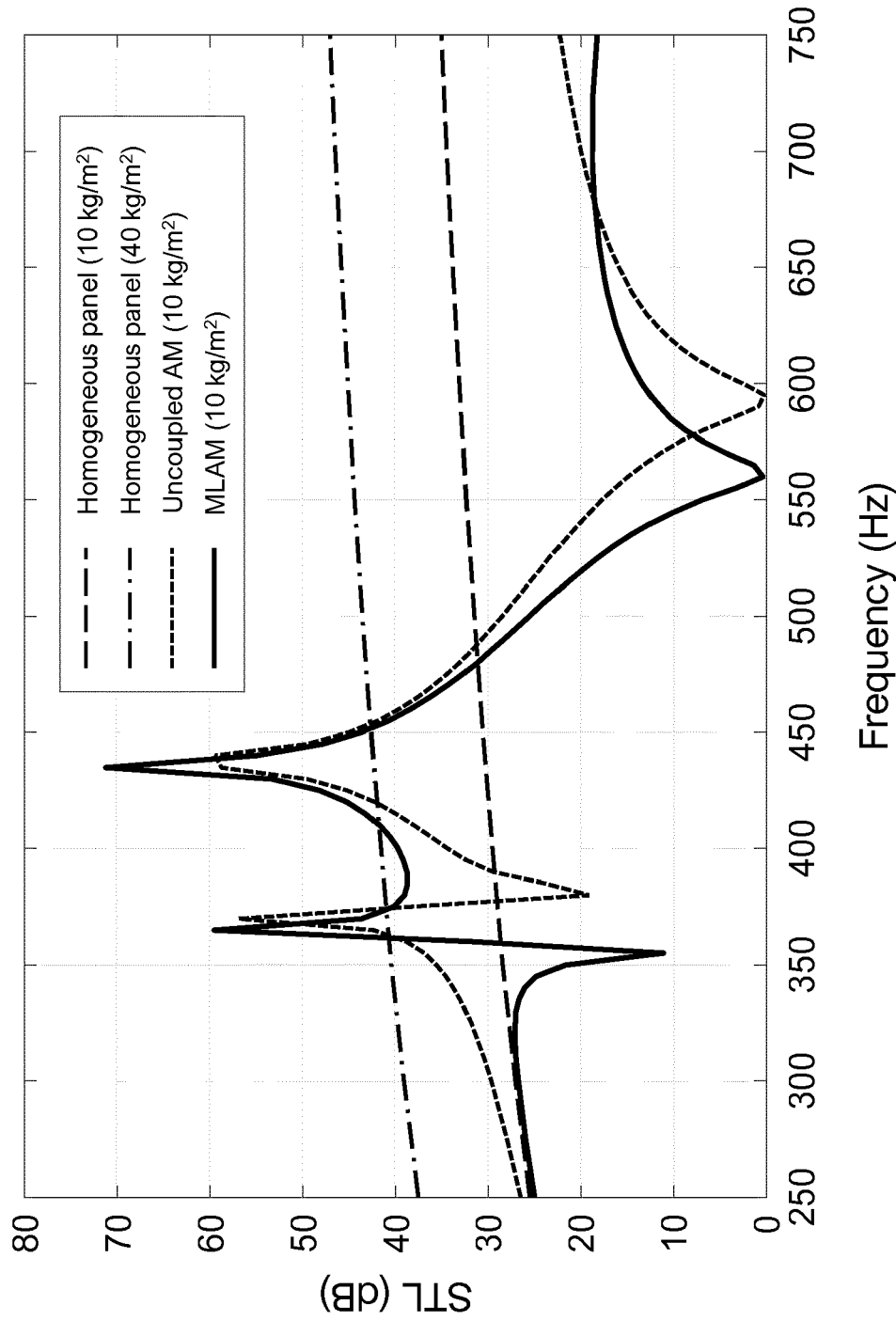


Fig. 22

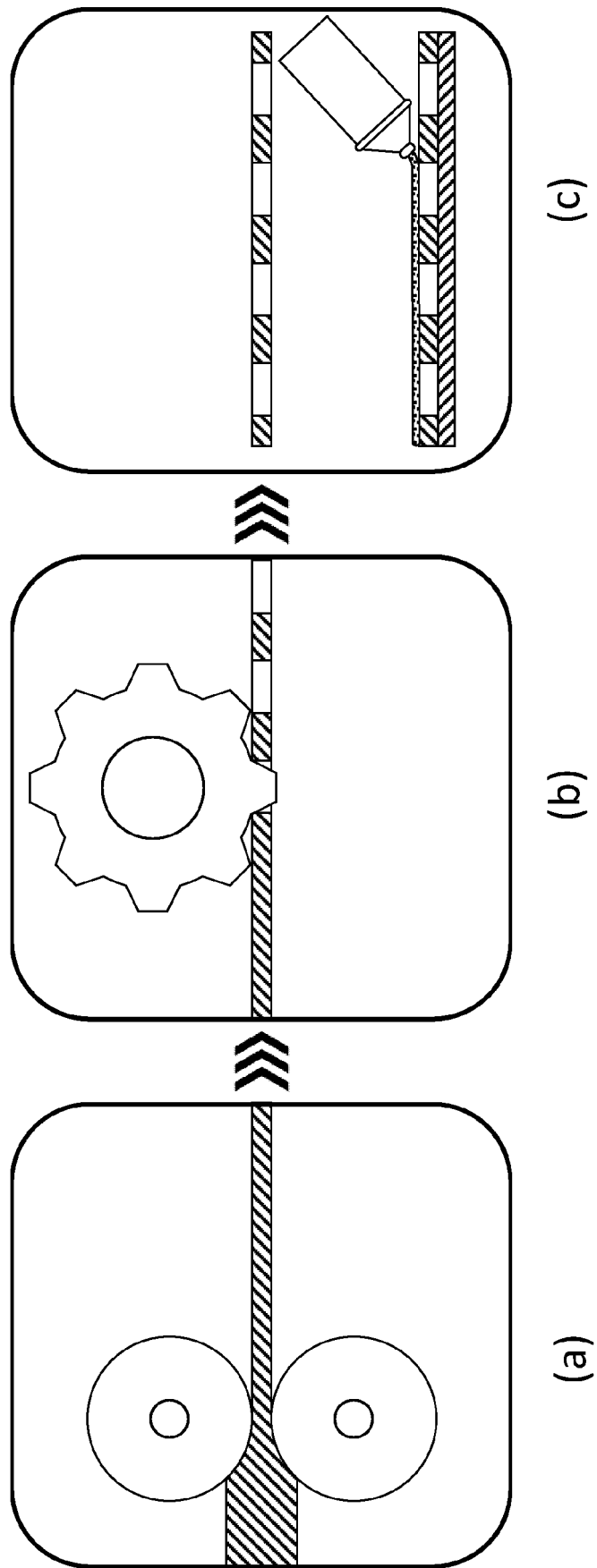


Fig. 23



## EUROPEAN SEARCH REPORT

Application Number  
EP 21 38 2026

5

10

15

20

25

30

35

40

45

50

55

| DOCUMENTS CONSIDERED TO BE RELEVANT                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                                                                                                                                            |                                                  |                                         |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------|-----------------------------------------|
| Category                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Citation of document with indication, where appropriate, of relevant passages                                                              | Relevant to claim                                | CLASSIFICATION OF THE APPLICATION (IPC) |
| X                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | JP 2019 045789 A (ASAHI KASEI CORP)<br>22 March 2019 (2019-03-22)<br>* paragraphs [0014], [0015], [0063], [0064]; figures 1,5-17, 44, 45 * | 1-16                                             | INV.<br>G10K11/172<br>G10K11/168        |
| A                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | CN 108 447 467 A (CHONGQING SUKUO INTELLIGENT TECH CO LTD)<br>24 August 2018 (2018-08-24)<br>* abstract; figures 1, 2, 5 *                 | 1-16                                             | ADD.<br>G10K1/06<br>G10K11/00           |
| A                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | US 2019/333495 A1 (LEE TAEHWA [US] ET AL)<br>31 October 2019 (2019-10-31)<br>* paragraph [0027]; figure 1B *                               | 1-16                                             |                                         |
| A                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | US 2019/035373 A1 (CHUNREN YU [CN] ET AL)<br>31 January 2019 (2019-01-31)<br>* paragraphs [0045] - [0048]; figure 1 *                      | 1-16                                             |                                         |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                                                                                                                            |                                                  | TECHNICAL FIELDS SEARCHED (IPC)         |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                                                                                                                            |                                                  | G10K                                    |
| The present search report has been drawn up for all claims                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                                                                                                                                            |                                                  |                                         |
| Place of search<br>The Hague                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                                                                                                                                            | Date of completion of the search<br>28 June 2021 | Examiner<br>Naujoks, Marco              |
| CATEGORY OF CITED DOCUMENTS<br>X : particularly relevant if taken alone<br>Y : particularly relevant if combined with another document of the same category<br>A : technological background<br>O : non-written disclosure<br>P : intermediate document<br>T : theory or principle underlying the invention<br>E : earlier patent document, but published on, or after the filing date<br>D : document cited in the application<br>L : document cited for other reasons<br>& : member of the same patent family, corresponding document |                                                                                                                                            |                                                  |                                         |

EPO FORM 1503 03.82 (P04C01)

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

EP 21 38 2026

5 This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report.  
The members are as contained in the European Patent Office EDP file on  
The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

28-06-2021

| Patent document<br>cited in search report | Publication<br>date | Patent family<br>member(s) | Publication<br>date |
|-------------------------------------------|---------------------|----------------------------|---------------------|
| JP 2019045789 A                           | 22-03-2019          | NONE                       |                     |
| CN 108447467 A                            | 24-08-2018          | NONE                       |                     |
| US 2019333495 A1                          | 31-10-2019          | NONE                       |                     |
| US 2019035373 A1                          | 31-01-2019          | US 2019035373 A1           | 31-01-2019          |
|                                           |                     | WO 2017041283 A1           | 16-03-2017          |