Three-dimensional metamaterial for wave attenuation, unit cell of a three-dimensional metamaterial, method for manufactering of a metamaterial, computer program for 3d printing a metamaterial

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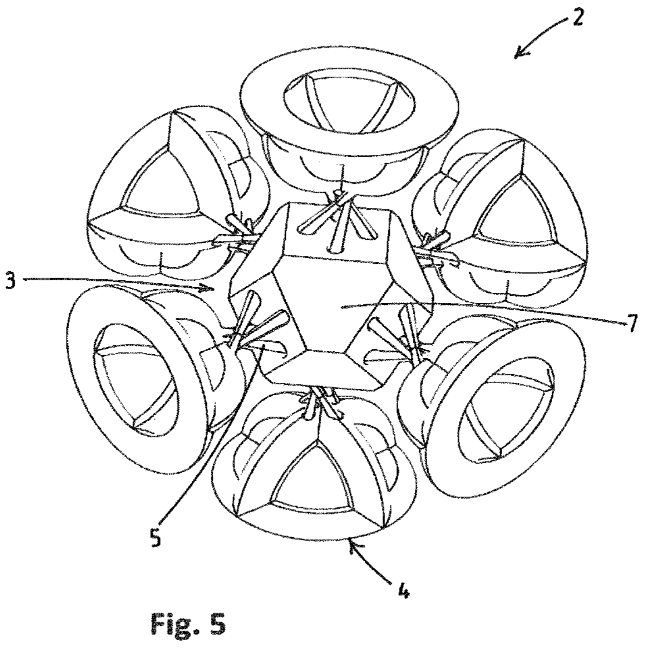

Fig. 5

(57) **Abstract:** The present invention relates to a three-dimensional metamaterial capable of attenuating acoustic waves and mechanical vibrations in broad low-frequency ranges. The three-dimensional metamaterial comprises multiple unit cells that form a three-dimensional lattice. The unit cells each comprise a central part and six satellite parts that are equally distributed around the central part. Each unit cell is connected to the central part by at least one corresponding connector. The invention further relates to a unit cell of a three-dimensional metamaterial capable of attenuating acoustic waves and mechanical vibrations in broad low-frequency ranges.

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The present invention relates to a three-dimensional metamaterial capable of attenuating elastic waves and mechanical vibrations in broad low-frequency ranges. The three-dimensional metamaterial comprises multiple unit cells that form a three-dimensional lattice. The invention further relates to a unit cell of a three-dimensional metamaterial capable of attenuating elastic waves and mechanical vibrations in broad low-frequency ranges.

Elastic waves and mechanical vibrations in broad low-frequency ranges may be generated by many different sources. For example, a passing train causes elastic waves and mechanical vibrations in the rails over which it travels. In another example, a washing machine causes elastic waves and mechanical vibrations in the floor on which it stands. In yet another example, earthquakes cause elastic waves and vibrations on the surface of the Earth’s crust. Attenuation of such waves is desirable to decrease damages and noise levels caused by these waves.

An attenuator preferably has a compact size and light weight. This allows cheaper manufacturing, as less material is required, and the attenuator occupies less space. Other desirable properties of the attenuator are related to load bearing capabilities of that material. Load bearing capabilities allow for the attenuator to support other structures, such as a table or a washing machine.

The combination of attenuation of low-frequency vibrations and waves, a compact size, load bearing capabilities, and light weight in an attenuator is difficult to achieve. The combination requires contradictory features of material properties with which to construct the attenuator.

Load-bearing capability is a result of using a stiff and strong material. The use of soft materials such as a foam, which may have better attenuation properties, results in a decrease of the overall material strength and stiffness.

Attenuation of low-frequency vibrations and waves requires efficient energy dissipation at low frequencies which requires either strong inertia or highly viscous elements in the material. Materials with highly viscous elements generally do not have very good load-bearing capabilities. At low frequencies the attenuation of waves in solids is governed by the mass density law, which states that the attenuation level is proportional to the mass per unit area of the material. Thus, a material for attenuation of elastic waves should have heavy inertial components to ensure a sufficient attenuation level, which increases the overall mass of the material. The mass density law further states that the attenuation level is independent from constituent material.

Thus, heavy inertial elements ensure sufficient attenuation of the material. However, these materials are in general heavy and more expensive to manufacture and do not allow the desired light-weight construction of compact size.

Metamaterials allow for the development of innovative material designs with interesting dynamic properties. Metamaterials are materials which have a structure that is architected. The structure of metamaterials is composed of carefully designed building blocks. The building blocks of a metamaterial are called unit cells. The geometry and composition of these unit cells serve as an organizational level between the macroscopic scale and atomic/molecular scale. Tuning the geometry and composition of the unit cells allows for additional ways to tune common relations between mechanical and mass properties of a material. This may allow for additional means of control over mechanical and mass properties. For example, the architecture of the metamaterials may lead to properties such as very high refraction of waves or even negative refraction.

Attenuation of low-frequency vibrations and waves is preferably achieved independent of the incident angle of the waves on the material. In known metamaterials attenuation of vibrations and waves is most efficiently achieved when those waves are incident on the material along a principal direction. In contrast the attenuation is not, or very poorly, achieved if the waves are incident along a direction which is not parallel to the principal direction, for example, which is perpendicular to the principal direction. These metamaterials may allow free wave propagation along the perpendicular direction.

It is an object of the invention to provide a material that allows for three-dimensional attenuation of elastic waves and mechanical vibrations in broad low-frequency ranges. It is a further object of the invention to provide an alternative material that allows for attenuation of elastic waves and mechanical vibrations in broad low-frequency ranges. As an advantage, the invention provides a material that is lighter and smaller. It is a further advantage of the invention that a metamaterial is provided that allows for attenuation of elastic waves and mechanical vibrations with an increased tunability of band gaps in the metamaterial.

The present invention provides a three-dimensional metamaterial capable of attenuating elastic waves and mechanical vibrations in broad low-frequency ranges according to claim 1.

The metamaterial of the invention allows for attenuation of waves in broad low-frequency ranges. The frequency ranges wherein the material attenuates waves depend on the dimensions of the unit cell and on the masses of the parts of the unit cell. For example, for a unit cell with a dimension of 4x4x4 cm and masses of 9.2 g and 0.26 g made of structural steel (with Young's modulus $E = 200$ GPa, Poisson's ratio $\nu = 0.33$, and mass density $\rho = 7850$ kg/m^3), waves in a frequency range from 6.9 kHz to 11.8 kHz are attenuated. The same unit cell with masses of 1.38 g and 0.04 g made of Nylon plastic (elastic material model with Young's modulus $E = 2$ GPa, Poisson's ratio $\nu = 0.4$, and mass density $\rho = 1150$ kg/m^3) attenuates waves in a frequency range from 1.8 kHz to 8.7 kHz. The unit cell of the same geometry with dimensions 10x10x10cm and masses 114 g and 12.33 g made of structural steel attenuates waves in a frequency range from 2.67 kHz to 4.7 kHz. The metamaterial according to the invention allows for the generation of band gaps at frequencies wherein the operating wavelength is larger than the size of the unit cell of the material.

The metamaterial of the invention comprises unit cells in a three-dimensional lattice. The unit cells are placed adjacent to each other wherein adjacent satellite parts of adjacent unit cells may form a single part. In this way adjacent unit cells may be connected to form a part of the metamaterial. The geometry of the unit cells allows the metamaterial to attenuate waves and vibrations. A unit cell is a component of the three-dimensional lattice such that the three-dimensional lattice may be built from the unit cells by translation of the unit cells.

An advantage of the three-dimensional metamaterial of the invention is that the material allows for attenuation of elastic waves and mechanical vibrations in broad low-frequency ranges while decreasing weight and size of the material, as compared to solid constituent material. The unit cells of the material comprise various parts and connectors, however the unit cells have an open construction and may not be a solid block. Space exists between the various parts of the unit cell, for example, the space is filled with air, making the metamaterial lighter than a solid material. Furthermore, because of the structure-driven attenuation mechanisms that allow for attenuation of elastic waves and mechanical vibrations in the metamaterial, the attenuating properties of the material are independent of the sort of material used. For example, the metamaterial may be constructed from a light plastic instead of a heavy steel. This makes the metamaterial lighter.

A further advantage of the three-dimensional metamaterial of the invention is that the material allows for attenuation of elastic waves and mechanical vibrations in broad low-frequency ranges independent of the incident angle of the waves and vibrations on the material. The unit cell has a three-dimensional symmetry because the satellite parts are distributed equally around the central part.

A characteristic of a metamaterial according to the invention is the ability to generate band gaps, i.e., frequency ranges at which wave propagation through the metamaterial is inhibited.

The metamaterial according to the invention attenuates waves by three mechanisms which induce destructive interference of waves and vibrations in the metamaterial. The attenuation mechanisms, and thus the invention, are driven by creating a contrast in wave velocities in the different structural elements of the material. Hence, wave attenuation is achieved by creating a contrast in wave velocities by the three below discussed mechanisms. These mechanisms depend on physical parameters, such as on the relative masses of the central part, satellite parts and connectors as well as on their relative orientation in the case of the inertial amplification mechanism. Other physical parameters may be considered.

A first mechanism is known as Bragg scattering which is present due to a periodic arrangement of inhomogeneities and a high contrast in mechanical properties, such as mass, of the connectors and parts. Bragg scattering in the metamaterial according to the invention is achieved by the periodic arrangement of the satellite parts and central parts along any x, y, or z-direction.

In Bragg scattering, when the half-wavelength of a wave propagating through the material is comparable to a pitch of a periodic lattice, such as the lattice of the metamaterial, scattered waves appear to be out-of-phase, and thus cancel the incoming wave field by inhibiting its transmission through the material. Bragg scattering in metamaterials with mm-size unit cells can activate band gaps at MHz frequencies. Attenuation at low frequencies, for example Hz-kHz frequencies, requires structural dimensions of the metamaterial in the meter range if the attenuation relies only on Bragg scattering.

Band gaps at frequencies with the corresponding wavelength larger than the lattice pitch are required to keep dimensions of the metamaterial smaller than the meter range. These band gaps may be induced by a second and a third mechanism that induce the destructive interference of waves and vibrations at these frequencies.

A second mechanism is known as a local resonance mechanism. The local resonance mechanism aims to introduce subwavelength resonators in each unit cell. The eigenfrequencies of these resonators are in a low-frequency range. When a frequency of an incoming wave is close to one of the eigenfrequencies of the resonators, the resonators are induced to move out-of-phase to the incident wave. These movements absorb the wave energy and convert it to heat. The resonators in each unit cell are formed by the satellite parts and central part. The local resonance mechanism is provided for by having a physical difference, e.g. a mass difference, between the central part and the satellite parts and on the lower mass of the connectors. The eigenfrequency of the resonator is not necessarily the eigenfrequency of a chain of equal bodies, e.g. of equal mass. The eigenfrequency of a resonator may be tuned by changing the physical parameter, e.g. the masses, of the satellite parts and the central part.

A third mechanism of wave attenuation is known as an inertial amplification mechanism. The inertial amplification mechanism increases the effective inertia of the metamaterial by the presence of local rotations in the metamaterial. Satellite parts and central parts are allowed to effectively rotate relative to each other because each connector extends non-perpendicularly from the central part and from the satellite part to which said connector connects. This mechanism is independent of the number of connectors between the central part and the satellite part.

Upon compression of the unit cell in a compression direction the central part of the unit cell rotates in a rotation direction. Upon compression of the unit cell at least some of the satellite parts are forced closer to each other and a force is applied to the central part through the connectors. The satellite parts are provided equally distributed and the connectors extend non perpendicularly from the central part and satellite part. Thus, when a compression force is applied to the unit cell the connectors change the relative direction of the compression force and induce a rotational motion of the central part relative to the satellite parts. Satellite parts which are not compressed by the compression force may restrict translational movement of the central part and may contribute to the rotational movement.

A band gap of the metamaterial may be tuned by tuning the masses of the central part and the satellite parts and the dimension of the connectors. For example, the band gap induced by Bragg scattering may be lowered by decreasing the effective wave propagation speed through the material. This may be achieved by reducing thickness of the connectors.

Tuning masses and dimensions allow the band gaps of the attenuation mechanisms, Bragg scattering, local resonance and inertial amplification, to overlap and thus to generate a broad band gap that is present at a desired low-frequency range. This is made possible by the features of the invention. Further this tuning may be achieved for waves incident from all directions by equal spacing of the satellite parts of the unit cell according to the invention. Wide band gaps induced by the interplay of Bragg scattering and local resonance may be amplified by the local resonance mechanism.

Each unit cell of the metamaterial comprises a central part and comprises six satellite parts. The central part and the satellite parts may have any shape. For example, the central part may be a polyhedron and the satellite part may be half spheres. In another example, the central part and the satellite part may have cubic shapes, such as a shape of a cube. The central part and the satellite parts may be made from any material, for example a plastic material.

The connectors of the metamaterial may be formed integral with the central part and the satellite parts. In another embodiment the connectors may be formed separately from the central parts and/or the satellite parts and connected to them through some connection technique such as gluing or welding. For example, to increase load-bearing capacity of the metamaterial, the number of connectors may be increased.

Satellite part pairs of the unit cell may lie along x, y, and z-directions in the unit cell. These pairs comprise two satellite parts that are located on opposite sides of the central body. These pairs of satellite parts and the central part allow for wave attenuation along the direction along which they are oriented.

In an embodiment, each satellite part forms a pair with another satellite part of the unit cell, wherein the satellite parts of each satellite body pair are located on opposite sides of the central part, wherein the connectors that connect a pair of satellite parts to the central body are mirror symmetric through a mirror plane of the unit cell that is located between the pair of satellite parts.

For example, a first satellite body pair is located along an x-direction, a second satellite body pair is located along a y-direction, and a third satellite body pair is located along a z-direction. Each satellite pair allows for wave attenuation along the direction on which they are oriented. Waves that are incident along directions that do not lie along a pure, for example, x-direction may be attenuated by multiple satellite body pairs.

In this embodiment upon mirroring the connectors on one side of the central body they are mapped onto the connectors on the other side of the central body. An advantage of this embodiment is that upon compression of the metamaterial in the direction defined by said satellite body pair the net rotational momentum of the metamaterial is zero. This is because the rotational momentum induced on a body by the connectors is mainly determined by the direction in which they are inclined from the perpendicular. If this direction is opposite to the direction of adjacent connectors, as is the case in this mirror symmetric embodiment, then the induced rotational momentum on adjacent parts is opposite in direction. Thus, the net rotational momentum over multiple unit cells will be zero. This leads to a stronger metamaterial that is less likely to break by accumulated rotational momentum.

In an embodiment, adjacent unit cells are connected to each other by the satellite parts of the unit cells. In another embodiment, two adjacent satellite parts of two adjacent unit cells form a single body. These embodiments allow for efficient connections between adjacent unit cells and efficient energy transfer between unit cells. Furthermore, this may allow for more efficient construction as two adjacent satellite parts may be formed from a single mold. In embodiments of the invention where this is not the case adjacent satellite parts may be connected by, for example, gluing.

The masses of the satellite parts may be less than half the mass of the central body. In this case, twice the mass of a satellite part is less than the mass of a central part. Thus, the mass of two adjacent satellite parts, which for example form a single body, is less than the mass of an adjacent central part. This allows the local resonance mechanism to work efficiently even when two satellite parts form a single body.

In embodiments the masses of the satellite parts are all equal. This makes the unit cell more symmetric and may make the unit cell easier to manufacture. Additionally, the tuning of the band gap frequencies may be easier. In this embodiment the wave attenuation is not only effective for incident waves coming from all directions but waves of similar frequencies are attenuated similarly independent of incident angles.

In embodiments the connectors have equal inclination relative to the central part and the corresponding satellite part. This makes the unit cell more symmetric and may make the unit cell easier to manufacture. In this embodiment the wave attenuation is not only effective for incident waves coming from all directions but waves of similar frequencies are attenuated similarly independent of incident angles. Additionally, the metamaterial may behave the same to compression of the metamaterial from different directions.

In embodiments the masses of the satellite parts are all equal and the connectors all have equal inclination relative to the central part. In this embodiment wave attenuation is even more independent on differences between directions of incident waves and frequencies.

In an embodiment the multiple unit cells are multiple cubic unit cells. A cubic unit cell is a unit cell with a cubic shape. For example, in this embodiment the unit cells have cube shapes. This may make the metamaterial easier to manufacture as stacking of unit cells may be easier. The metamaterial is not necessarily constructed from stacking unit cells. Additionally, in this embodiment the number of satellite parts in a unit cell may be six. For example, each satellite part is located on a different face of the cubic unit cell.

In an embodiment a shape of each of the satellite parts is equal, for example, a shape of each of the satellite parts is cubic. Similarly to other embodiments, this may make the unit cell easier to manufacture. The wave attenuation is independent on the shape of the satellite parts. Cubic satellite parts have the additional advantage that connectors may be easier to connect to the satellite parts because the satellite parts have flat faces. Additionally, the metamaterial may be more symmetric.

In an embodiment the number of connectors connecting each of the satellite parts to the central part is equal to four. The number of connectors may not be important for the wave attenuation of the metamaterial. However, increasing the number of connectors may increase the load-bearing capacity of the metamaterial. Furthermore, increasing the number of connectors may increase stiffness of the metamaterial. Four connectors per satellite part is advantageous because it allows for a stiff material which is relatively light.

In other embodiments the number of connectors connecting each of the satellite parts to the central part may be different. For example, in another embodiment the number of connectors connecting each of the satellite parts to the central part is equal to two. In yet another connector the number of connectors connecting each of the satellite parts to the central part is equal to five. It is also possible that, in embodiments, the number of connectors connecting different satellite parts to a central part varies.

In an embodiment the connectors are elongated. In this example the connectors are for example embodied as elongated rods. An advantage of this embodiment is that the connectors are sufficiently light to behave as nearly massless during wave attenuation. Furthermore, elongated connectors make resonance and relative rotation of the satellite parts and central part easier.

In an embodiment the central part is cubic. For the wave attenuation the shape of the central part is less relevant than the mass of the central part. A cubic shape may be easier to manufacture. Furthermore, the connectors may be easier connected to a cubic shape for example because the cubic shape has flat outer surfaces that may be turned towards the various satellite parts.

In an embodiment the central part and the satellite parts have an equal shape, for example wherein the shape of the central part and satellite parts is a cubic shape. The metamaterial according to this embodiment may be easier to manufacture.

In an embodiment the central parts, satellite parts and/or connectors are manufactured from structural steel. The metamaterial, or at least the unit cells, may be 3D printed. Depending on the printing technique various materials may be used for manufacturing the metamaterial. Additionally, the metamaterial may be constructed using other manufacturing techniques. The material from which the metamaterial is manufactured is not very relevant for the wave attenuation properties of the metamaterial but it may be relevant for other properties of the metamaterial such as stiffness and durability.

In an embodiment a dimension of each of the unit cells lies between 14mm-10cm. The unit cell may be a cubic unit cell with length 10mm-50cm. The dimension of the unit cell is a relevant tuning parameter in determining the wavelengths of the attenuated waves. A unit cell of the dimensions according to this embodiment may be relevant in attenuating waves produced in 1.8 kHz and higher. Increasing dimensions of the unit cell shifts the band gaps down to lower frequencies.

In an embodiment the connectors all have a same shape. For example, every connector has the shape of an elongated rod. This may make the metamaterial easier to manufacture.

The invention is further related to a unit cell of a three-dimensional metamaterial capable of attenuating elastic waves and mechanical vibrations in broad low-frequency ranges wherein the unit cell comprises a central part and six satellite parts, which six satellite parts are equally spaced around the central part,

wherein the unit cell further comprises connectors, wherein each satellite part is connected to the central part by at least one connector that extends between said satellite part and the central part, wherein the satellite parts have masses less than half the mass of the central part, and wherein each connector has a mass less than 1/10th the mass of a satellite part,

wherein each connector extends non-perpendicularly from the central part and from the satellite part to which said connector connects, so that at least partial rotation of the central part relative to each satellite part is possible. The unit cell may be used to manufacture the metamaterial according to the invention. The properties of the unit cell are related to the wave attenuating properties of the metamaterial.

The invention further relates to a use for manufacturing a metamaterial capable of attenuating elastic waves and mechanical vibrations in broad low-frequency ranges according to the invention.

The metamaterial may be manufactured by any of a number of known methods, for example by 3D printing of the metamaterial.

The invention further relates to a computer program comprising instructions for controlling a 3D printer for 3D printing a metamaterial according to the invention or a unit cell according to the invention.

For example, the computer program comprises instructions to 3D print the central body, satellite parts and connectors separately which may than be put together, for example, by gluing. In another example the computer program comprises instructions to 3D print the entire metamaterial with the desired dimensions in one printing session. In another example, the computer program comprises instructions to 3D print standard blocks of the metamaterial, for example, blocks of 10 cm x 10 cm x 10 cm.

The invention will now be described in a non-limiting way by reference to the accompanying drawings in which like parts are indicated by like reference numbers and in which:
Fig. 1 depicts a view of a metamaterial according to a first embodiment;
Fig. 2 depicts a second view of the metamaterial according to the first embodiment;
Fig. 3 depicts a front view of the metamaterial according to the first embodiment;
Fig. 4 depicts a front view of a unit cell of the metamaterial according to the first embodiment;
Fig. 5 depicts a perspective view of a unit cell of the metamaterial according to the first embodiment;
Fig. 6 depicts a unit cell of a metamaterial according to a second embodiment;
Fig. 7 depicts the unit cell of fig. 6 in a second position;

Fig. 8 depicts a perspective view of the unit cell of fig. 6;
Fig. 9 depicts a perspective view of the metamaterial according to the second embodiment;
Fig. 10 depicts a second view of the metamaterial according to the second embodiment;
Fig. 11 depicts a front view of the metamaterial according to the second embodiment;
Fig. 12 depicts a perspective view of a metamaterial according to a third embodiment;
Fig. 13 depicts a second view of the metamaterial according to the third embodiment;
Fig. 14 depicts a front view of the metamaterial according to the third embodiment;
Fig. 15 depicts a unit cell of the metamaterial according to the third embodiment;
Fig. 16 depicts a front view of the unit cell of the metamaterial according to the third embodiment; and
Fig. 17 depicts a perspective view of the unit cell of the metamaterial according to the third embodiment.

Figure 1 depicts a view of a metamaterial 1 according to a first embodiment. A lattice of the metamaterial 1 formed by four by four-by-four unit cells 2 is depicted. Thus, in total 64 unit cells 2 are shown in figure 1.

Each unit cell 2 comprises a central part 3 which, in this embodiment, has a polyhedron shape with 14 outer surfaces 7. The outer surfaces 7 do not all have connectors 5 extending therefrom.

The unit cell 2 of figure 1 comprises four connectors 5 between the central part 3 and each satellite part 4. As can be seen in figure 4 the connectors 5 extend non-perpendicularly from the central part 3 as well as the corresponding satellite part 4. This allows for the inertial amplification mechanism of wave attenuation.

As can be seen in figure 4, the connectors 5 that connect a pair of satellite parts 4 to the central part 3 are mirror symmetric through a mirror plane 8 of the unit cell 2 that is located between the pair of satellite parts 4. Figure 4 depicts a single mirror plane 8 corresponding to a single satellite body pair. As can be seen from the figure other satellite body pairs are also connected to the central part 3 in a mirror symmetric fashion.

The satellite parts 4 of each unit cell 2 are formed by a body in the shape of three intersecting donuts which is cut in half. Two adjacent satellite parts 4 of two adjacent unit cells 1 are, for example, connected by gluing the two satellite parts 4 such that the so formed body has the shape of the three intersection donuts. As can be seen from figure 5, the intersection donuts intersect perpendicularly and such that the connectors 5 extend from an intersection of two donuts.

As can be seen from figure 1, two adjacent satellite parts 4 which are connected together form a hollow body. Thus, even though the satellite parts 4 have about the same size as the central part 3 and may be formed from a same material, two satellite parts 4 are less massive than a central part 3 of a unit cell 2. This allows for the local resonance mechanism of wave attenuation.

As can be seen from figure 1, the metamaterial 1 is symmetric such that wave incident from different directions may be attenuated. Furthermore, due to the properties of the metamaterial 1 and the unit cell 2 the metamaterial 1 attenuates waves using three known attenuation mechanisms: Bragg scattering, local resonance, and inertial amplification.

Figure 2 depicts a second view of the metamaterial 1 according to the first embodiment and figure 3 depicts a front view of the metamaterial 1 according to the first embodiment. As can be seen from figure 3 parts of the metamaterial 1 are empty space, this makes the metamaterial 1 relatively light.

Figure 4 depicts a front view of a unit cell 2 of the metamaterial 1 according to the first embodiment. As discussed above, from this figure it can be seen that the connectors 5 are arranged in a mirror symmetric way, by mirroring the connectors 5 through the mirroring plane 8. An advantage of this symmetry is that upon compression of the metamaterial 1 the net rotational momentum of the central parts 3 and satellite parts 4 metamaterial 1 is zero. This is because the rotational momentum induced on a part by the connectors 5 is mainly determined by the direction in which the connectors 5 are inclined from the perpendicular relative to the part. If this direction is opposite to the direction of adjacent connectors 5, as is the case in this mirror symmetric embodiment, then the induced rotational momentum on adjacent parts is opposite in direction. Thus, the net rotational momentum over multiple unit cells 2 will be zero. This leads to a stronger metamaterial 1 that is less likely to break by accumulated rotational momentum.

Figure 5 depicts a perspective view of a unit cell 2 of the metamaterial 1 according to the first embodiment. This figure shows in detail the central part 3 and how, in this embodiment, the connectors 5 extend from the central part 3 to the satellite parts 4. As discussed above the central part 3 and the satellite parts 4 may have different shapes, which is the case in this embodiment.

Figure 6 depicts a unit cell 2 of a metamaterial 1 according to a second embodiment and Figure 7 depicts the unit cell of fig. 6 in a second position. The connection elements 5 of the unit cell 2 of figure 6 are inclined under a different angle relative to the connection elements 5 depicted in figure 7. This may be the result of a resonance in the unit cell 2 which is the result of wave attenuation.

The unit cell 2 comprises a central part 3 in the shape of a polyhedron and six satellite parts 4 which are each located on a different side of the central part 3. Each satellite body 4 is connected to the central part 3 by a single connector 5. This may make the metamaterial 1 less massive and may also reduce load-bearing capabilities of the metamaterial 1 compared to a metamaterial with more connectors 5.

Each satellite body 4 of the unit cell 1 has the shape of a half sphere. Thus, two adjacent satellite parts 4 form the shape of a sphere as can be seen in figure 9.

Figure 8 depicts a perspective view of the unit cell 2 according to the second embodiment. This figure 8 shows the connection between the central part 3, the satellite parts 4, and the connectors 5.

Figure 9 depicts a perspective view of the metamaterial 1 according to the second embodiment, wherein the metamaterial 1 is formed by a lattice of unit cells 2 shown in figure 6. Figure 10 depicts a second view of the metamaterial 1 according to the second embodiment and figure 11 depicts a front view of the metamaterial according to the second embodiment. As can be seen from these figures the metamaterial 1 depicted in these figures comprises 27 unit cells 2. However, more unit cells 2 may be present in the metamaterial 1 adjacent to the unit cells 2 shown in the figures.

Figure 12 depicts a perspective view of a metamaterial 1 according to a third embodiment. In this embodiment the central parts 3 have cubic shapes and the satellite parts 4 have a shape of a half ellipsoid. A total of eight connectors 5 are located between each satellite body 4 and the central part 3. This may be seen better in, for example, figure 15.

Figures 13 and 14 depict different views of the metamaterial 1 according to the third embodiment. As can be seen from the figures, 27 unit cells 2 are shown. The orientation of the satellite body 4 relative to the central part 3 may vary, for example as a result of wave attenuation.

Two adjacent satellite parts 4 form a shape of an ellipsoid.

Figure 15 depicts a unit cell of the metamaterial 1 according to the third embodiment, figure 16 depicts a front view of the unit cell of the metamaterial 1 according to the third embodiment, and figure 17 depicts a perspective view of the unit cell of the metamaterial according to the third embodiment.

As can be seen in figure 16, the connectors are inclined in a mirror symmetric fashion by mirroring through the mirror plane 8. This allows for a metamaterial 1 more resilient against rotational momentum of the varies central parts 3 and satellite parts 4 in the metamaterial 1.

The size of the unit cell 2 according to the third embodiment may be 3cm.

The metamaterial 1 depicted in the figures may be printed by a 3D printer instructed by a computer program according to the invention.

CLAIMS

1. Three-dimensional metamaterial capable of attenuating elastic waves and mechanical vibrations in broad low-frequency ranges, wherein the material comprises multiple unit cells of open construction that form a three-dimensional lattice, in which lattice the multiple unit cells are located adjacent to each other,

wherein each unit cell comprises a central part and six satellite parts, which six satellite parts are equally spaced around the central part of said unit cell,

wherein said unit cell further comprises multiple connectors, wherein each satellite part of said unit cell is connected to the central part of said unit cell by at least one connector that extends between said satellite part and the central part,

wherein the satellite parts of each unit cell have masses less than half the mass of the corresponding central part, and wherein each connector has a mass less than 1/10th the mass of a satellite part,

wherein each connector extends non-perpendicularly from the central part and non-perpendicularly from the satellite part to which said connector connects, so that, upon compression of the unit cell in a compression direction, the central part rotates relative to each satellite part in a rotation direction.

2. Three-dimensional metamaterial according to claim 1, wherein each satellite part forms a satellite pair with another satellite part of the unit cell, wherein the satellite parts of each satellite pair are located on opposite sides of the central part,

wherein the connectors that connect a pair of satellite parts to the central part are mirror symmetric through a mirror plane of the unit cell that is located between the satellite parts of the satellite pair.

3. Three-dimensional metamaterial according to one or more of the previous claims, wherein adjacent unit cells are connected to each other by satellite parts of the unit cells.

4. Three-dimensional metamaterial according to claim 3, wherein two adjacent satellite parts form a single body.

5. Three-dimensional metamaterial according to one or more of the previous claims, wherein the masses of the satellite parts are all equal.

6. Three-dimensional metamaterial according to one or more of the previous claims, wherein the connectors have equal inclination relative to the central body and corresponding satellite part.

7. Three-dimensional metamaterial according to one or more of the previous claims, wherein the multiple unit cells are multiple cubic unit cells.

8. Three-dimensional metamaterial according to one or more of the previous claims, wherein the satellite parts are equally shaped, for example wherein the satellite parts are cubic.

9. Three-dimensional metamaterial according to one or more of the previous claims, wherein the number of connectors connecting each of the satellite parts to the central part is equal to four.

10. Three-dimensional metamaterial according to one or more of the previous claims, wherein the connectors are elongated.

11. Three-dimensional metamaterial according to one or more of the previous claims, wherein the central part has a cubic shape.

12. Three-dimensional metamaterial according to one or more of the previous claims, wherein the central part and satellite parts have an equal shape, for example wherein the central parts and satellite parts have a cubic shape.

13. Three-dimensional metamaterial according to one or more of the previous claims, wherein the central part, satellite parts and/or connectors are manufactured from structural steel.

14. Three-dimensional metamaterial according to one or more of the previous claims, wherein a dimension of each of the unit cells lies between 10mm-50cm.

15. Three-dimensional metamaterial according to one or more of the previous claims, wherein the connectors all have a same shape.

16. Unit cell of a three-dimensional metamaterial capable of attenuating elastic waves and mechanical vibrations in broad low-frequency ranges, wherein the unit cell comprises a central part and six satellite parts, which six satellite parts are equally spaced around the central part,

wherein the unit cell further comprises connectors, wherein each satellite part is connected to the central part by at least one connector that extends between said satellite part and the central part,

wherein the satellite parts have masses less than half the mass of the central part, and wherein each connector has a mass less than 1/10th the mass of a satellite part,

wherein each connector extends non-perpendicularly from the central part and from the satellite part to which said connector connects, so that at least partial rotation of the central part relative to each satellite part is possible.

17. Use of a metamaterial according to one or more of the claims 1-15 for attenuating air-borne and structure-born waves and vibrations.

18. Computer program comprising instructions for controlling a 3D printer for 3D printing a metamaterial according to one or more of the claims 1-15 or a unit cell according to claim 16.

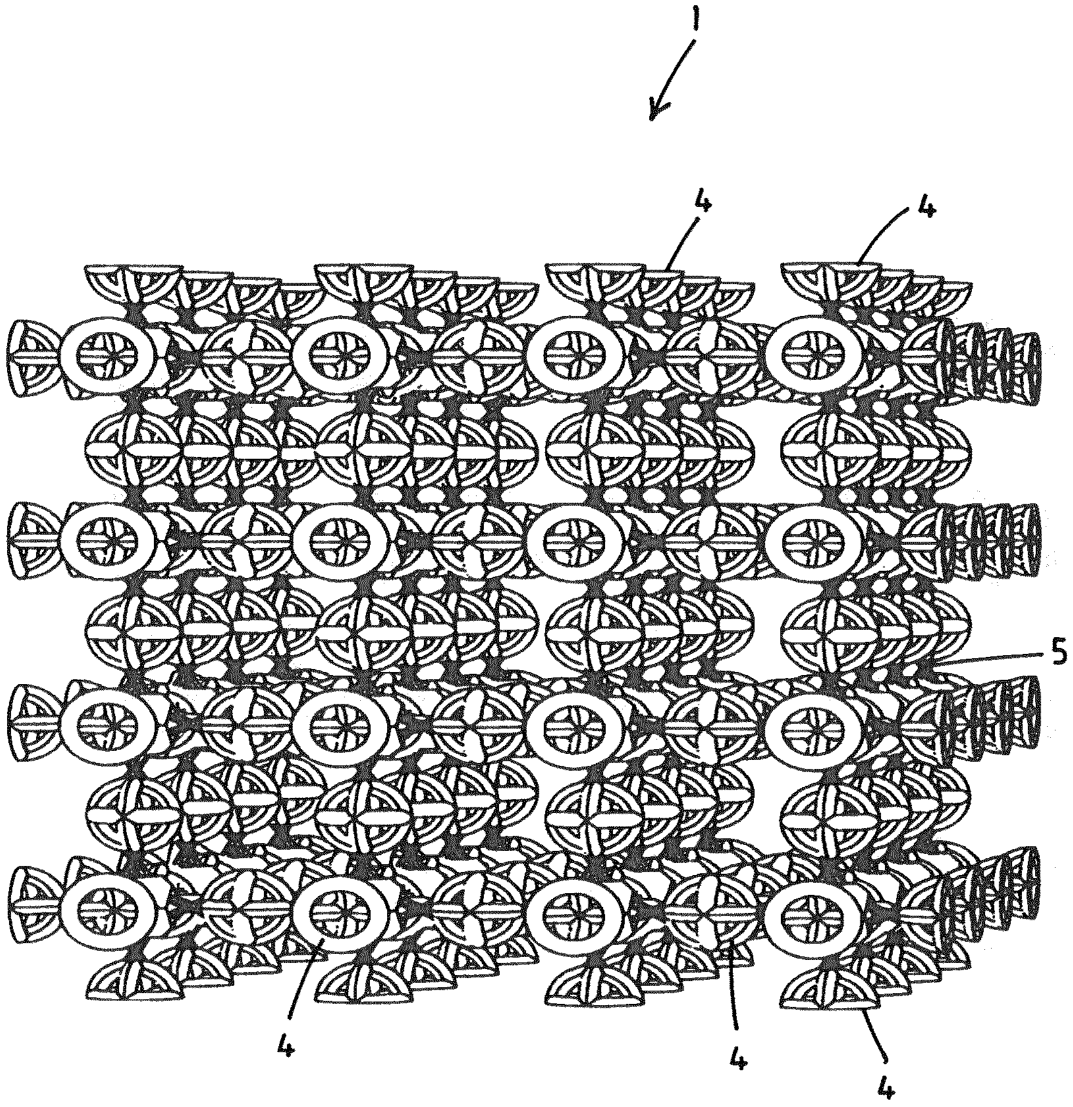

Fig.1

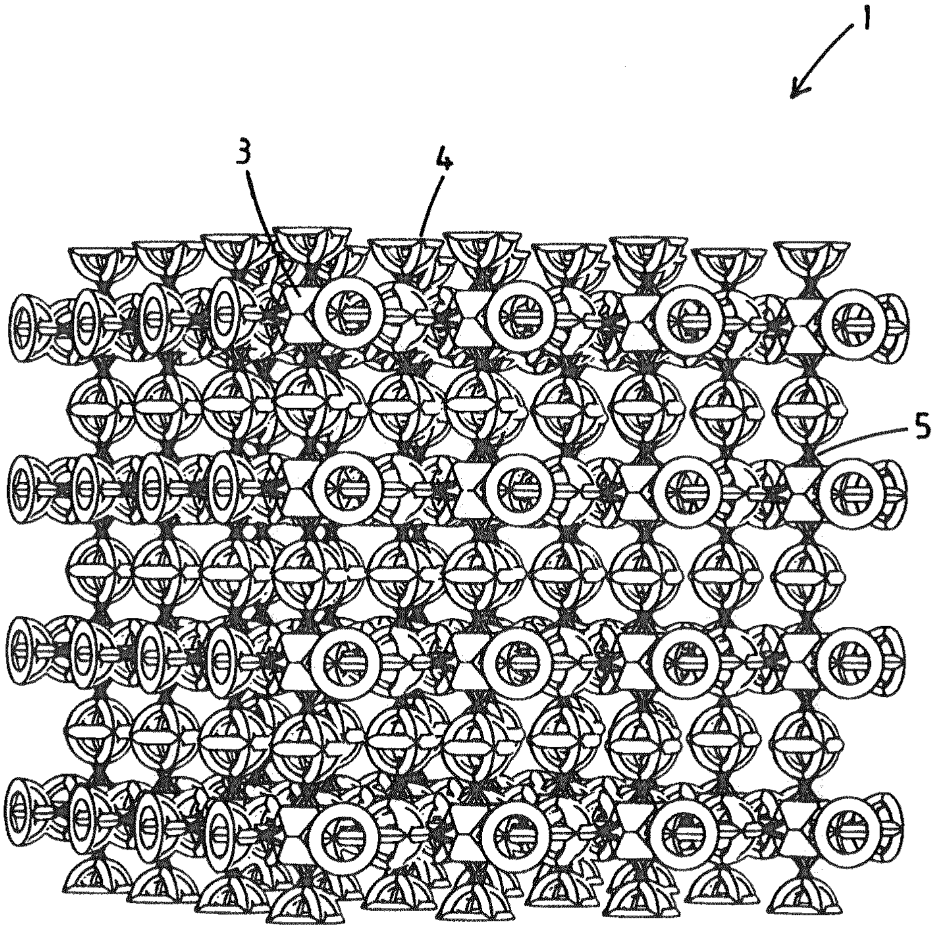

Fig. 2

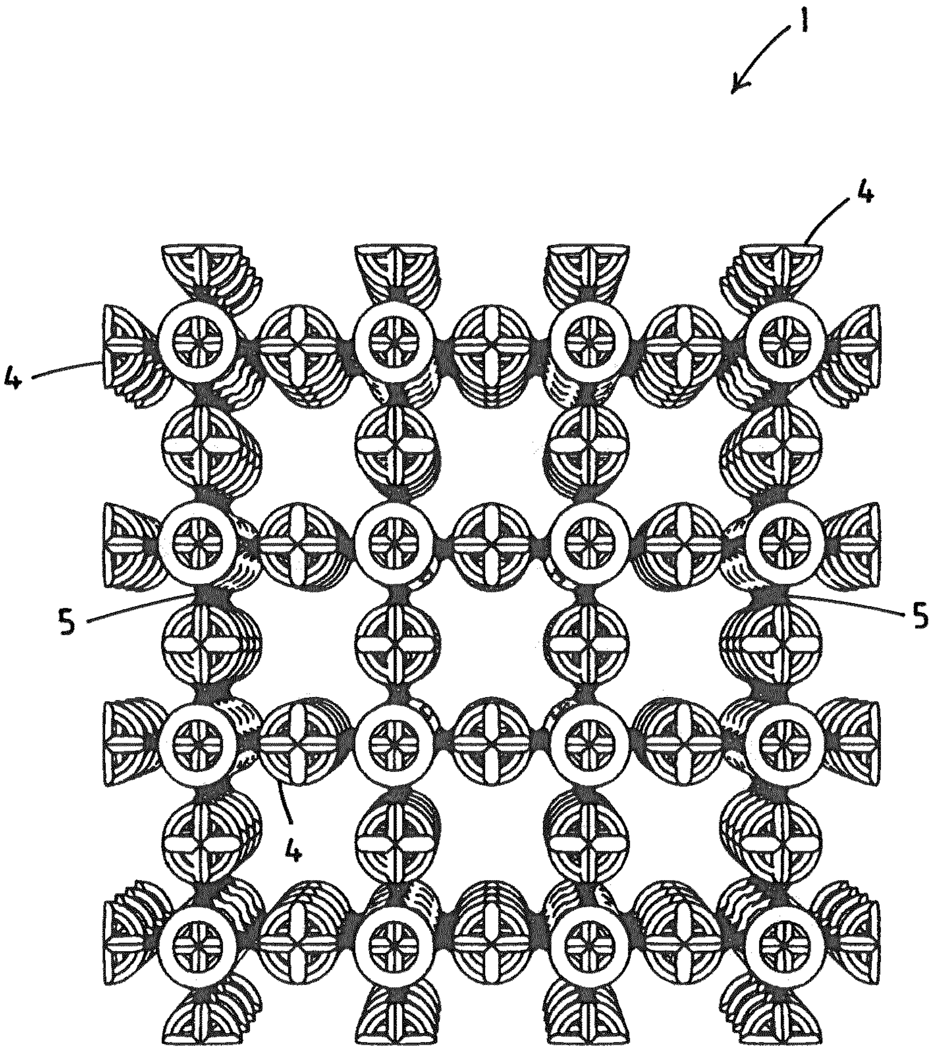

Fig.3

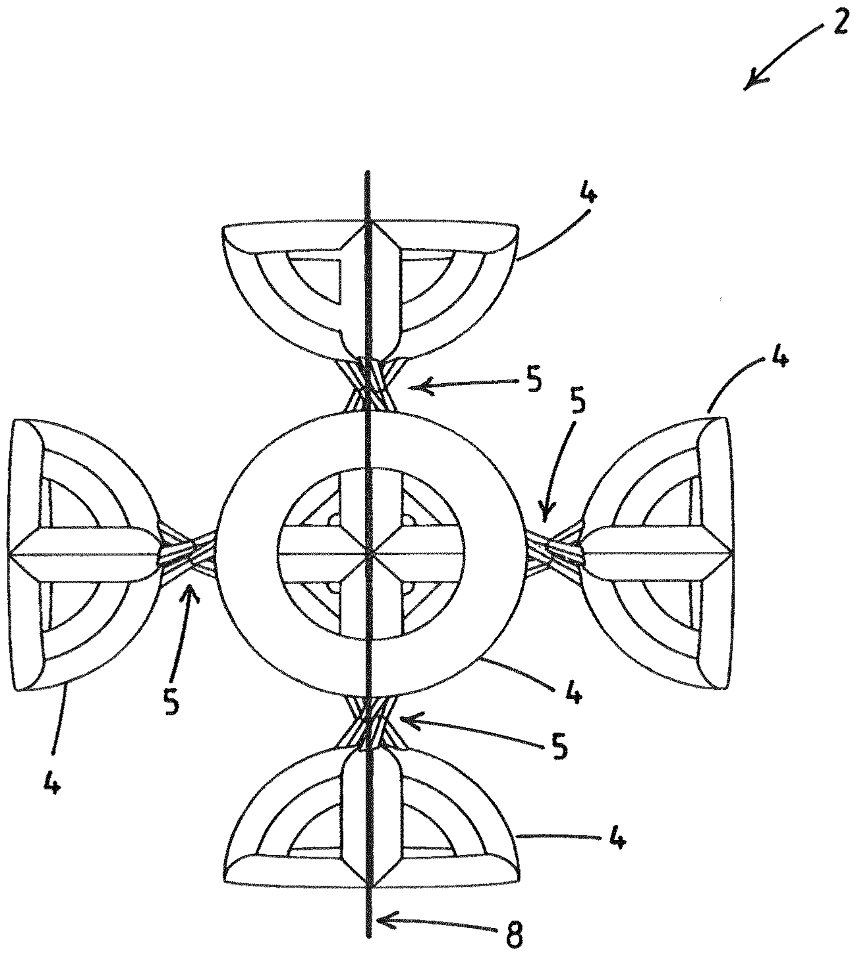

Fig. 4

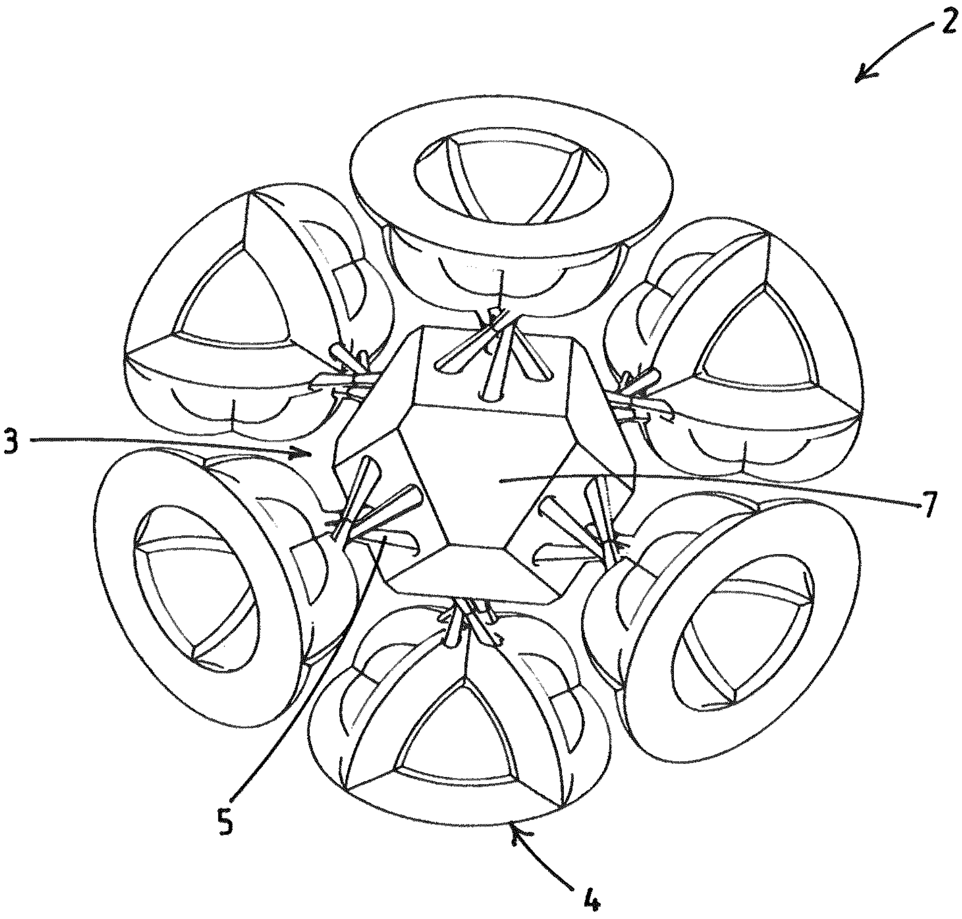

Fig. 5

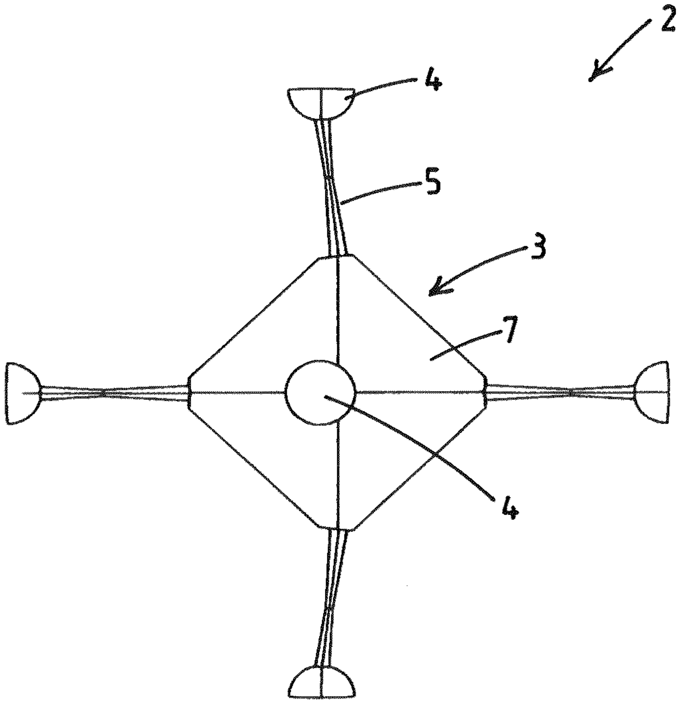

Fig. 6

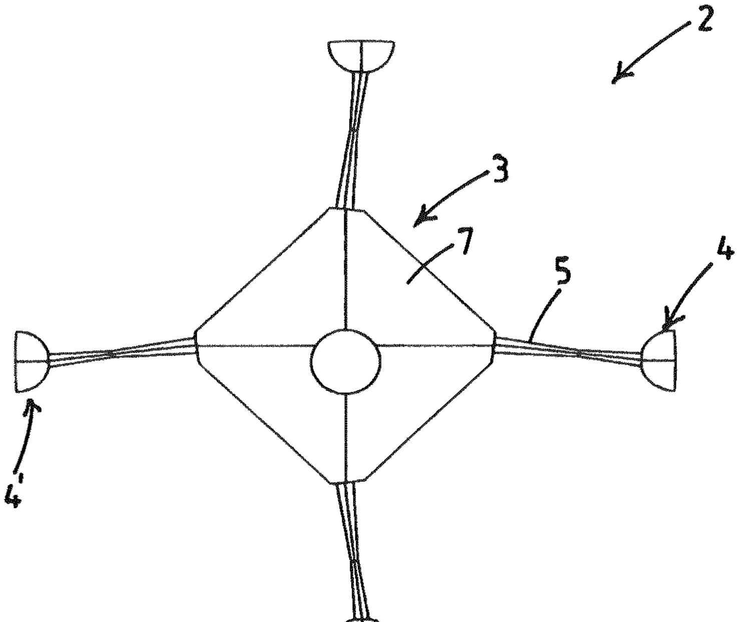

Fig. 7

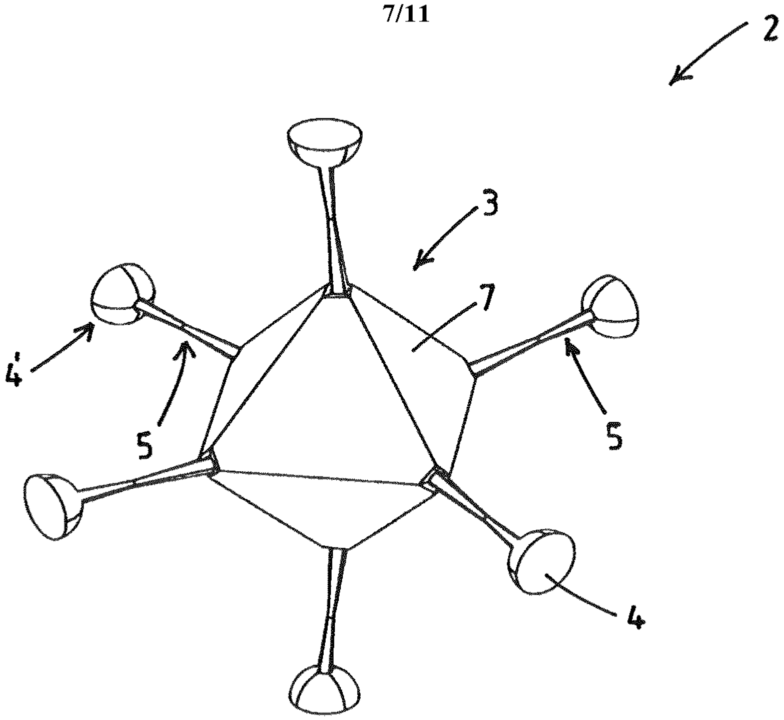

Fig. 8

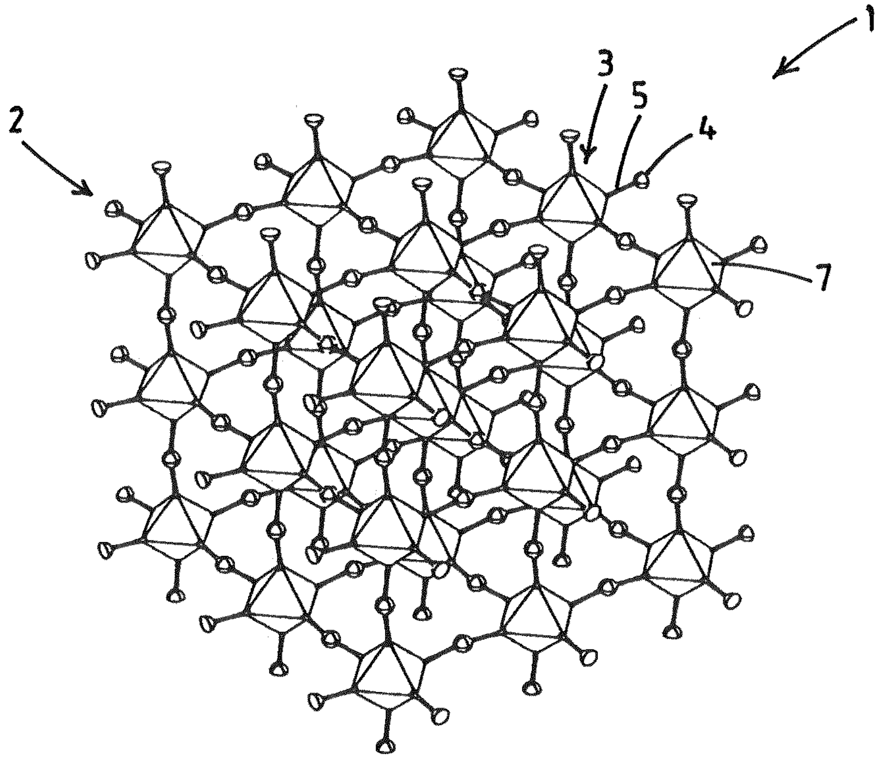

Fig. 9

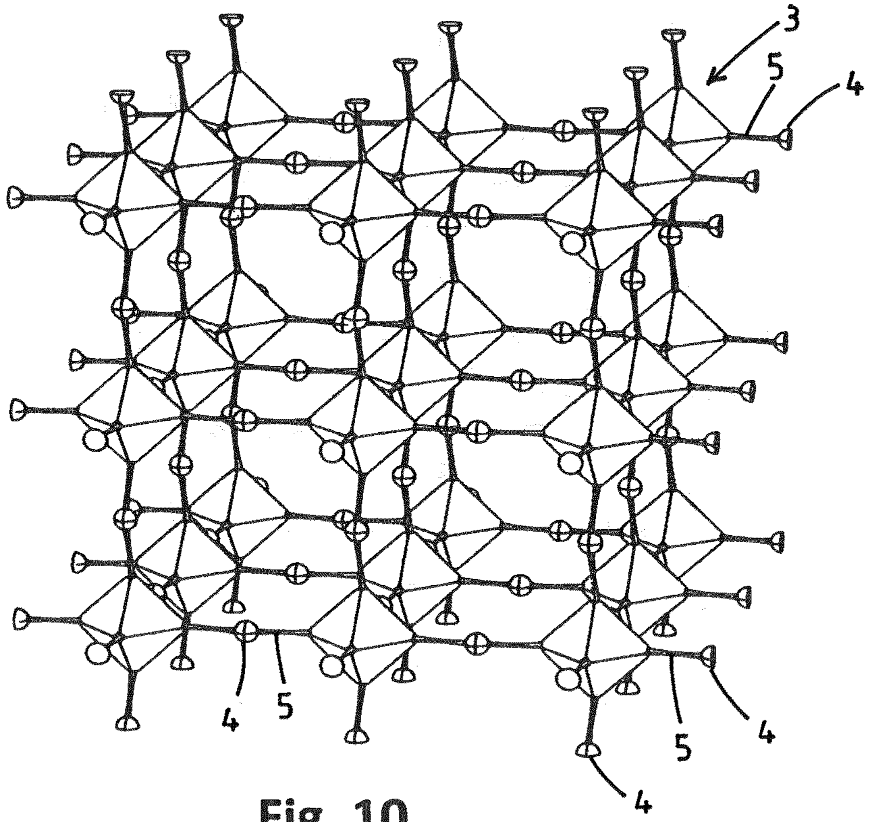

Fig. 10

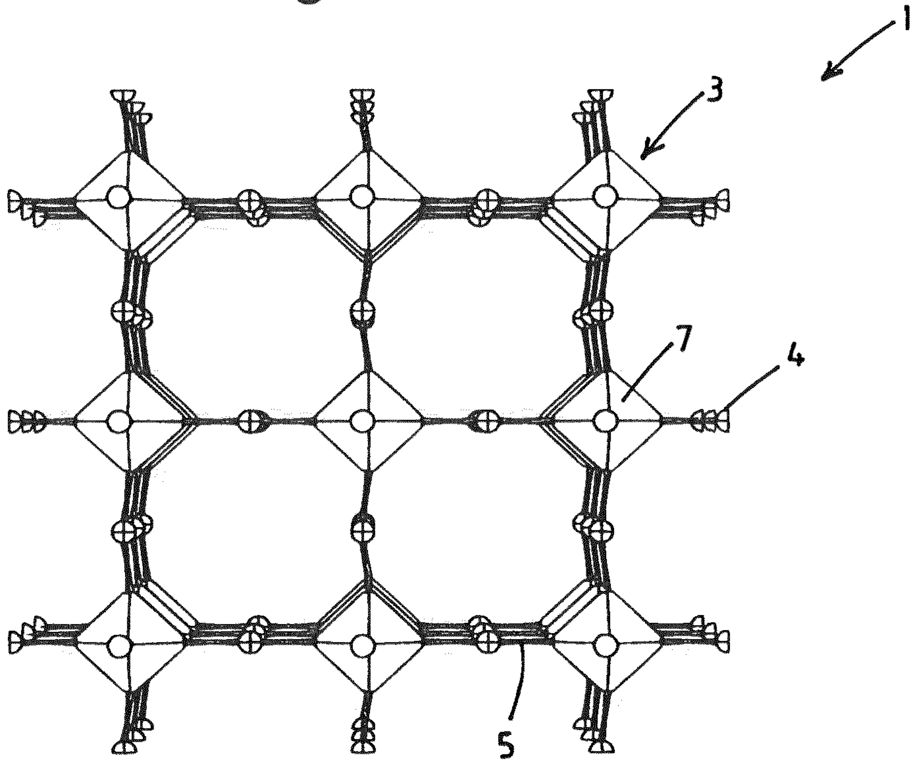

Fig. 11

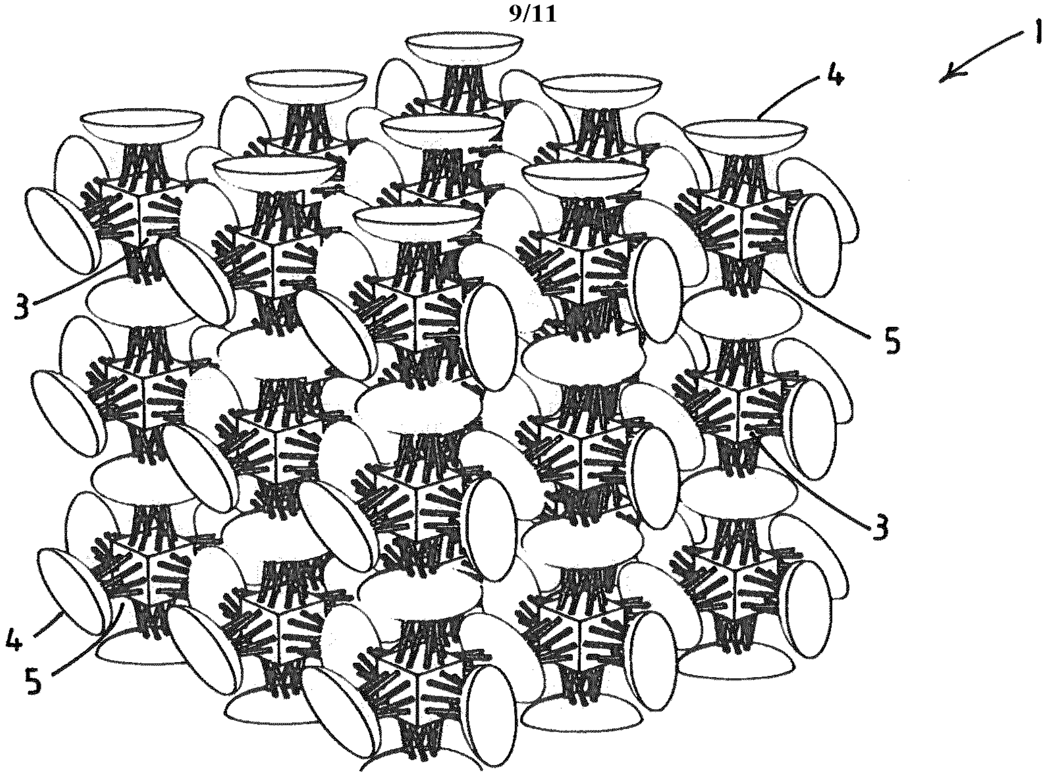

Fig. 12

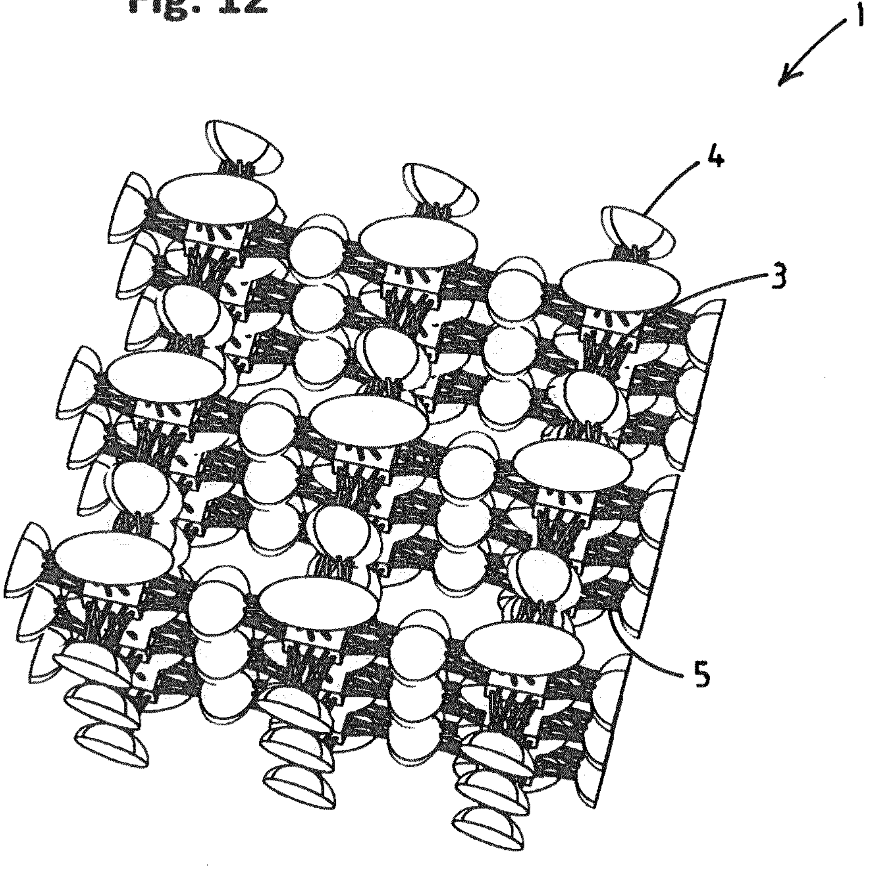

Fig. 13

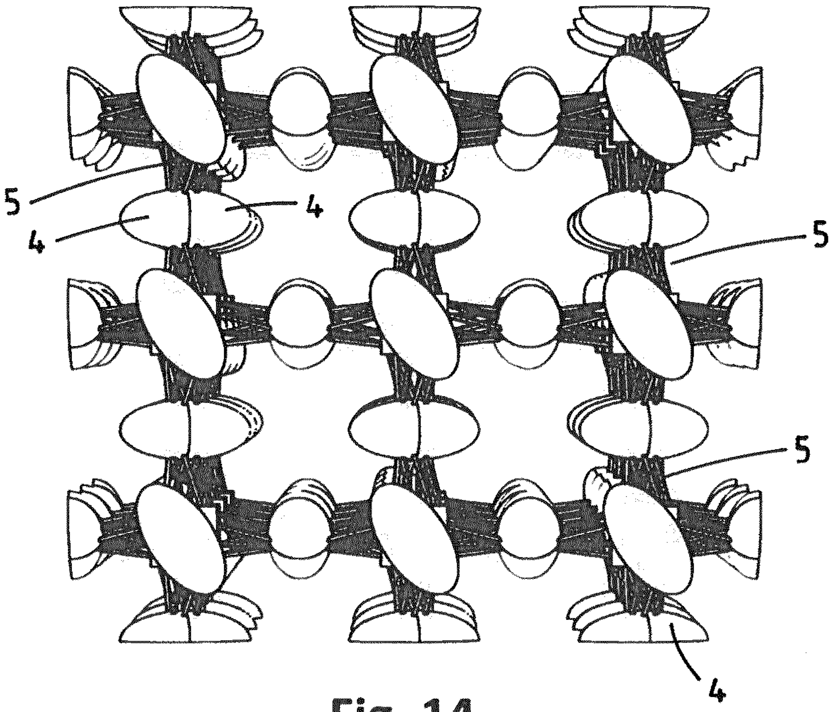

Fig. 14

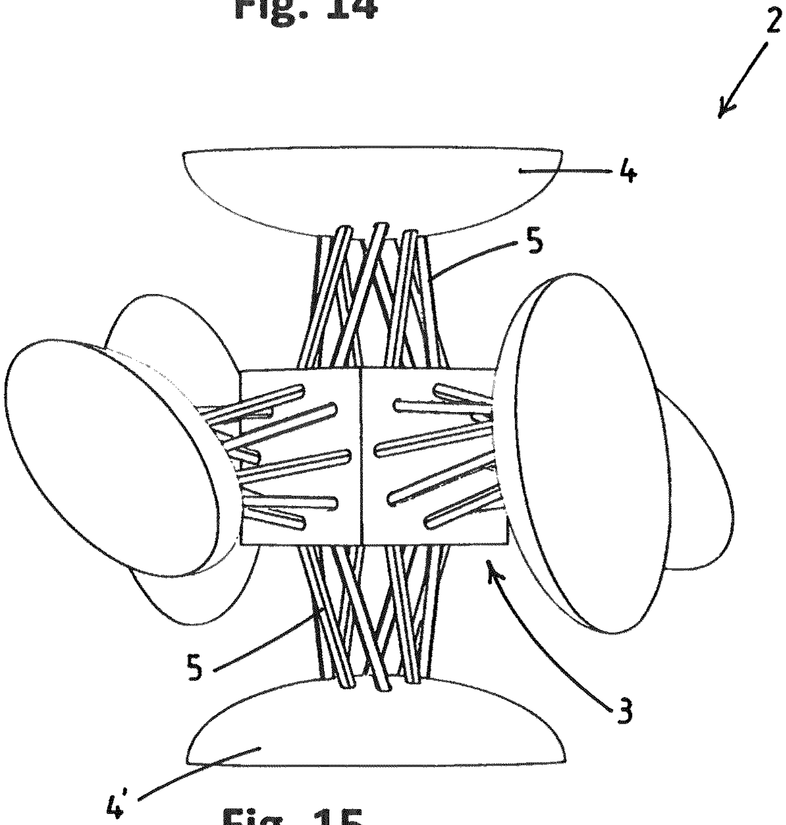

Fig. 15

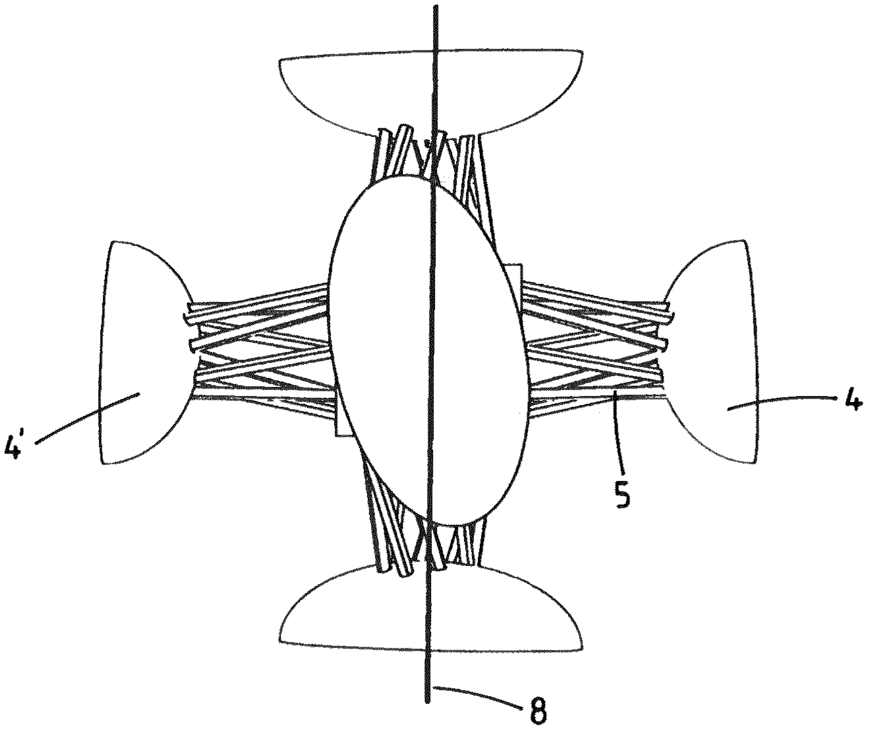

Fig. 16

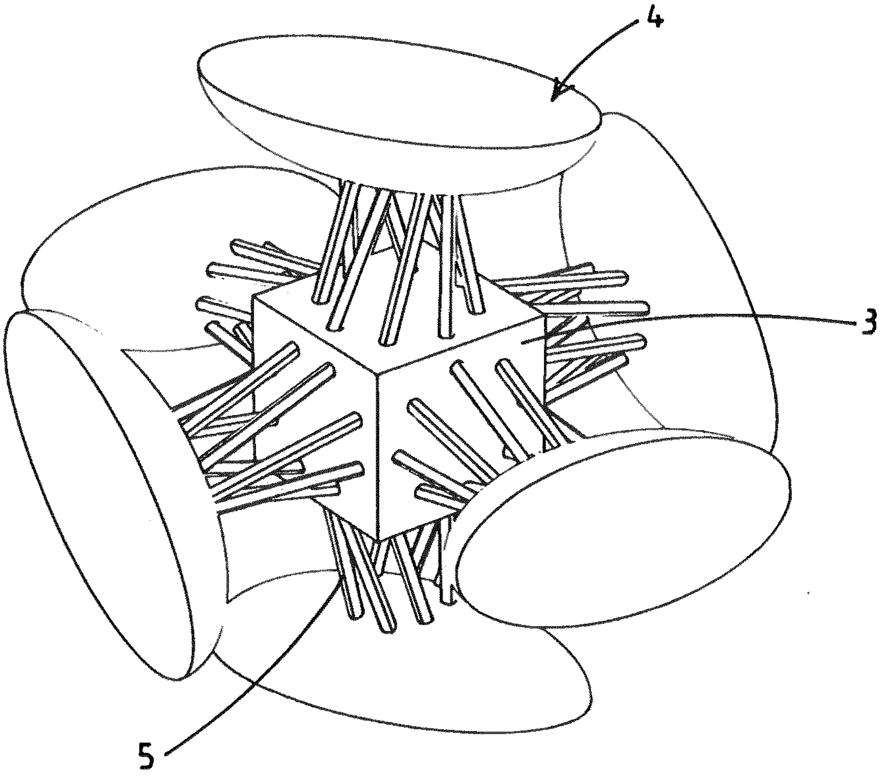

Fig. 17

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2021/059663

A. CLASSIFICATION OF SUBJECT MATTER
INV. G10K11/162
ADD. E04B1/74 E04B1/82 E04B1/84

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G10K E04B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2019/141794 A (POLITECNICO DI MILANO) 25 July 2019 (2019-07-25) claim 1; figures 1-13, 15-16 page 3, lines 18-21 page 4, lines 4-20 page 8, lines 12-25 -----	1-18
A	CN 109 036 367 A (NANJING PHOTOACOUSTIC SUPERSTRUCTURE MATERIAL RES INSTITUTE CO LTD) 18 December 2018 (2018-12-18) figures 1-2 -----	1-18
	-/--	

☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
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"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search 18 June 2021	Date of mailing of the international search report 02/07/2021
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Naujoks, Marco

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INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2021/059663

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	SCHMIED JASCHA U ET AL: "Toward structurally integrated locally resonant metamaterials for vibration attenuation", PROCEEDINGS OF SPIE; [PROCEEDINGS OF SPIE ISSN 0277-786X VOLUME 10524], SPIE, US, vol. 10164, 11 April 2017 (2017-04-11), pages 1016413-1016413, XP060090294, DOI: 10.1117/12.2260306 ISBN: 978-1-5106-1533-5 figures 4, 5 -----	1-18
A	US 2013/025961 A1 (KOH CHEONG YANG [SG] ET AL) 31 January 2013 (2013-01-31) paragraph [0051]; figure 2 -----	1-18

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2021/059663

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2019141794 A	25-07-2019		
CN 109036367 A	18-12-2018	NONE	
US 2013025961 A1	31-01-2013	US 2013025961 A1	31-01-2013
		WO 2012151472 A2	08-11-2012