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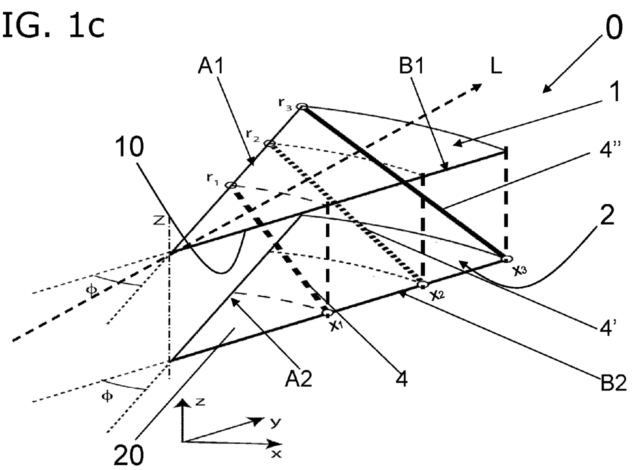
(54) UNIT CELL OF PHONONIC CRYSTAL WITH SPACE-SAVING GEOMETRY

(57) A Unit cell (0) of an artificial phononic crystal for building of artificial phononic metamaterials, especially applicable in the field of railroad and tramway protection and for railway track components for reduction of mechanical vibrations, is disclosed, with sufficient vibration attenuation abilities needs an optimized space-saving geometry. This is reached by each metal strut (4, 4', 4"...) is connected to a connection point (A) at the underside (10) on a first straight line (A1) at an radius (r1, ..rn) from a rotation axis (Z) protruding to the connection points (B') at the upper side (20) on a second straight line (B2) at the same corresponding radius (r1, ..rn) from the rotation axis (Z), while projection in x-y plane of first straight line (A1) and second straight line (B2) of each metal strut (4, 4', 4"...) includes a intersection angle (ϕ) defined by length of metal strut (4, 4', 4"...) and radius (r1, ..rn) and distances between rotation axis (Z) and connection points (A, B') of each metal strut (4, 4', 4"...) in x-y plane are equal, and each metal strut (4, 4', 4"...) is individually rotated around rotation axis (Z) such that, the longitudinal extension of each metal strut (4, 4', 4"...) is oriented to be tangential to the associated radius (r1, ..rn) in projection in the x-y plane.

FIG. 1c



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Description

TECHNICAL FIELD

[0001] The present invention describes a unit cell of an artificial phononic crystal for building of artificial phononic metamaterials, especially applicable in the field of railroad and tramway protection and for railway track components for reduction of mechanical vibrations, wherein the unit cell is comprising a first elongated plate with an underside and a second elongated plate with an upper side, both plates, comprising a polygonal ground plan extending parallel to each other in a longitudinal direction L, wherein both elongated plates, are distanced in a z-direction by a fixed height with a plurality of metal struts, fixed at connection points at the underside of the first elongated plate and protruding to connection points at the upper side of the second elongated plate, a phononic crystal comprising an array of a multiplicity of unit cell and a railway track component.

STATE OF THE ART

[0002] The main challenge related to the design of phononic crystals and acoustic metamaterials is to find the geometry of a unit cell that allows for an appropriate combination of broad low-frequency bandgaps, low mass density, high quasi-static stiffness and small size of the unit cells. Such phononic crystals are used in mechanical engineering or in building structures, for example in suspension of an engine in a vehicle chassis, the foundation of buildings in earthquake zones, etc., wherein particularly good damping at low frequencies is desirable.

[0003] In the case of phononic crystals, these four properties are strictly related: for a given topology of the crystal: lower frequency bandgaps can be obtained by increasing its mass density and characteristic length or by decreasing its quasi-static stiffness. Local resonators, even if they allow for subwavelength bandgaps, are also subject to similar conflicting requirements: relatively heavy resonators and large filling ratios/volume fractions are still needed for low-frequency and wide bandgaps.

[0004] The introduction of inertia amplification mechanisms in structured materials may help in overcoming this conflicting relation between mass density, stiffness, characteristic length and frequency. The concept of metamaterials based on phononic crystals, human-made artificial macroscopic crystals, has opened the way to the development of novel materials with advantageous properties that result from the macroscopic arrangement of their building blocks.

[0005] In EP3239973 we described a one-dimensional, in the sense of the possible direction of wave propagation, phononic crystal that exploits rotational inertia as a means to improve the performance of phononic crystals and in which the inertial elements where characterized by a axial symmetry, being shaped as disks or toroids. A vibration in vertical direction is translated into rotation of a heavy torus in the horizontal plane of the phonoic crystal. As can be seen in Figure 1 according to this prior art, the design of artificial phononic crystals or acoustic or artificial phononic metamaterials comprising such artificial phononic crystals should have a geometry of a unit cell that allows for an appropriate combination of broad low-frequency band gaps, low mass density, high quasi-static stiffness and small size of the unit cells. A multiplicity of unit cells builds the artificial phononic crystal with an array of unit cells. With the unit cell respectively a phononic crystal, comprising a multiplicity of unit cells could be reached featuring an inertia amplification mechanism based on rotational inertia, where the rotation occurs in a x-y-plane perpendicular to a wave propagation direction z. The wave propagation direction z or principal direction z is defined, along which the unit cell required to exhibit strong attenuation capabilities while offering high quasi-static stiffness and small characteristic length. The wave propagation is indicated in principal direction z from the "IN" to "OUT"-marking through the unit cell respectively the phononic crystal.

[0006] The unit cell comprises at least one building block and a multiplicity of mechanical connections. In particular the building block is a discoid or toroid in particular a torus with circular cross section or a toroid with square cross section, forming a ring. The building block could also be formed like a toroidal polyhedron. As shown in the figures, the building block is formed in particular in form of a torus or a ring with a central opening. The building block is extending in the x-y-plane, in a plane in particular perpendicular to principal direction z, while the principal direction z runs through the central opening. The principal direction z of the unit cell equals the later wave propagation direction and vibration attenuation direction.

[0007] Artificial phononic crystals for building metamaterial structure suitable for mechanical vibration isolation, comprising a multiplicity of unit cells allowed for the coupling of longitudinal motion along the z-axis, which is the main axis of the phononic crystal into a rotary motion around the same axis, allowing to exploit the moment of inertia of the disk in lieu of the mass term in a mass-spring chain type of phononic crystals.

[0008] The stringent requirements derived from high performance applications that impose specifications with regards to available constructed space and properties like total mass, stiffness and dynamic response require more flexibility with respect to the geometry of the phononic crystals to better exploit the available space, with consequences for the shape of the inertia elements and the placement of the struts. The geometrical constraints of the PnCs considered so far, it is not possible to fully benefit from rotational inertia coupling, under realistic conditions, leaving a vast portion of the design space unexploited. In applications, for example attenuation of vibrations and shockwaves in railroads, there is no sufficient space available for the known geometry of the described phononic crystals and resulting artificial phononic metamaterial.

DESCRIPTION OF THE INVENTION

[0009] The object of the present invention is to create a unit cell of an artificial phononic crystal for building of an artificial phononic metamaterial, like railway track components, like tracks or switches or power tools with sufficient vibration attenuation and inertia amplification abilities, showing an optimized space-saving geometry of the unit cell and the phononic crystal.

[0010] Due to the used materials and the construction of the unit cells a more lightweight phononic metamaterial, usable for building phononic structures for different applications, with a desired quasi-static stiffness could be achieved.

[0011] The unit cells, artificial phononic crystals respective resulting lightweight phononic metamaterials are optimized for applications in the field of railroad and tramway protection, because a special geometry for smaller spaces was found.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] Further understanding of various aspects of the invention can be obtained by reference to the following detailed description in conjunction with the associated drawings, which are described briefly below.

[0013] It should be noted that in the differently described embodiments, the same parts are provided with the same reference symbols or the same component names, the disclosures contained in the entire description being able to be applied analogously to the same parts with the same reference symbols or the same component symbols.

[0014] The subject matter of the invention is described below in conjunction with the attached drawings.

Figure 1a shows a schematic side view of a unit cell, comprising a first and second elongated plate and multiplicity of connected struts, while

Figure 1b shows a perspective view of the unit cell of Figure 1a, rotated with first elongated plate at the bottom, while

Figure 1c shows a schematic section of an upper first elongated plate and a lower second elongated plate, only with indicated struts, indicated with solid line and dotted lines.

Figure 1d shows a schematic view of a larger section of upper first elongated plate and lower second elongated plate, showing the rotational symmetry of the entire arrangement, introducing rotation angle β, while

Figure 1e shows a schematic view of first and second elongated plates connected by struts at different radii around a rotation axis while the unit cell is forcibly actuated.

Figure 1f shows a schematic view on a first elongated plate with different metal struts in projection on the elongated plate at different radii from the axis of rotation Z along a straight line L

Figure 2 shows another unit cell, comprising five elongated plates with distributed rotated struts in a schematic side view.

Figure 3 shows a perspective of a phononic crystal as array of unit cells, with a corresponding number of struts, here with five elongated plates, which are connected at first, third and fifth elongated plates.

DESCRIPTION

[0015] The simplest unit cell 0, forming an artificial phononic crystal for building of artificial phononic metamaterials, especially applicable in the field of railroad and tramway protection and for railway track components for reduction of mechanical vibrations, is shown in Figure 1a. The strict geometric requirements imposed by applications such as the vibration isolation in railway track components, like tracks or switches or power tools has led to the new unit cells 0 and phononic crystals in which the necessary functions are further refined, with respect to our previous designs.

[0016] The unit cell 0 comprises a first elongated plate 1 with a polygonal ground plan and a underside 10 and a second elongated plate 2 with a polygonal ground plan and an upper side 20. Preferably both ground plans of both plates 1, 2 are rectangular and both elongated plates 1, 2 are extending parallel to each other in a longitudinal direction L in direction of elongation. Such elongated plates 1, 2 are distanced with a plurality of metal struts 4, 4', 4", ..., which are fixed between the lower side 10 of the first elongated plate 1 and the upper side 20 of the second elongated plate 2 in a number of fastening sections X, X', X".... The constant distance h between the two elongated plates 1, 2 in their course is marked with the double arrow.

[0017] The fastening sections X, X', X".... are placed in different distances from a rotation axis Z, perpendicular to the elongated plates 1, 2 and distributed in the longitudinal direction L of the elongated plates 1, 2.

[0018] The metal struts 4, 4', 4"... are fixed in upper distances r1 to r4 from rotation axis Z at the lower side 10 of the first elongated plate 1 with upper fastening points, projecting to the second elongated plate 2 and are fixed in lower distances x1 to x4 from rotation axis Z at the upper side 20 of the second elongated plate 2 with lower fastening points. Therewith the metal struts 4, 4', 4"... are double-sided fixed in their own fastening sections (X, X', X"...) to lower side 10 and upper side 20 of both plates 1, 2, distributed along the longitudinal extension of the elongated plates 1, 2. The plurality of metal struts 4, 4', 4", ..., with their force/displacement constant, are providing spacing and vibrational damping, due to the used material. But the orientation of the struts 4, 4', 4", ..., is important.

[0019] For the sake of simplicity additional weights, often attached to elongated plates 1, 2 are not shown in the schematic figures, but are described in more detail at the end. Most preferred the fastening sections X, X', X"... are equidistantly distributed along the elongated plates 1, 2 along the longitudinal direction L, starting at the rotation axis Z.

[0020] All metal struts 4, 4', 4"... are at least partially fixed with their upper fastening points at r1 to rn and their lower fastening points at elongated plates 1, 2, 3, 1', 2' as described here. The metal struts 4, 4', 4"... are fixed with torque-free joints, optionally with joints partially transmitting torque or are welded or clamped at the undersides 10 or upper sides 20 of the associated elongated plates.

[0021] Our novel design of unit cells 0 with linear-rotational coupling that better exploit the available built space, while preserving the advantages of exploiting coupling of linear and rotational motion, shows a special arrangement of the metal struts 4, 4', 4"...

[0022] As shown in Figure 1b, the arrangement of each strut 4 between the underside 10 of the first plate 1 and the upper side 20 of the second elongated plate 2, is based on the rotation axis Z, defining origin of a first straight line A1 and a second straight line B1 in a first plane of the first elongated plate 1, both lines A1, B1 including an intersection angle ϕ in the plane of the first elongated plate 1. The first strut 4 is connected in the distance r1 directly or indirectly to the underside 10 of the first elongated plate 1, on intersection between circle segment with radius r1 between A1 and B1 and line A1 at point r1. The placement and the alignment or orientation of the metal struts 4, 4', 4"... in space relative to the other components is done accordingly, as explained with reference to Figure 1c.

[0023] In the plane of the first elongated plate 1, the first straight line A1 and the second straight line B1, including an intersection angle ϕ, with different upper distances r1, r2, r3 are indicated (Fig. 1c), while both lines A1, B1 intersect in the rotation axis Z and define the plane of different circle segment lines with distances r1, r2, r3.

[0024] In the plane of the second elongated plate 2, a third straight line A2, parallel distanced in z direction to first straight line A1 and a fourth second straight line B2, parallel distanced in z direction to second straight line B1, both A2, B2 including the same intersection angle ϕ, with identical lower distances x1, x2, x3 are indicated, while both lines A2, B2 start and intersect in the rotation axis Z and forming the plane of identical circle segment lines with distances x1, x2, x3, where x1 = r1, x2 = r2, x3 = r3, representing pairwise associated distances ((r1, x1), ... (rn, xn)) of each metal strut 4, 4', 4"....

[0025] The first metal strut 4 is projecting, from upper fastening point of the first metal strut 4 at r1 on first straight line A1 to the strut's lower fastening point x1 on the fourth straight line B2. The upper distance r1 of upper fastening point of metal strut 4 is placed on the first circle segment line with distance r1. The strut's lower fastening point x1 and therewith the end of the metal strut 4 is lying on straight line B2 and the lower second circle segment line with distance x1 in the lower plane of the second elongated plate 2. The fastening points r1 and x1 have identical distance from axis Z.

[0026] Starting from rotation axis Z, first straight line A1, second straight line B1 as well as the upper distances r1, ... rn and the corresponding circle segments are in a plane, distanced in direction of the rotation axis Z to the third straight line A2, fourth straight line B2, the lower distances x1, ... xn and the corresponding circle segments.

[0027] Figure 1c shows the projecting lines (r1, x1), (r2, x2) and (r3, x3) with omitted struts, while strut's upper fastening points (r1, r2, r3,...rn) are ending on first straight line A1 and the strut's lower fastening points are ending on the fourth straight line B2. The startpoints and endpoints of each metal strut 4, 4', 4"... are associated pairs ((r1, x1), ... (rn, xn)), wherein each point r1, ...rn have the same distance from the rotation axis Z along the first straight line A1 and each point x1, ... xn have the same distance from the rotation axis Z along the fourth straight line B2. The intersection angle ϕ is identical for all metal struts 4, 4', 4"... within the unit cell 0 and the lengths of the metal struts (4, 4', 4"...) are increasing with their distances rn from the rotation axis Z.

[0028] The main axis of rotation Z of the entire arrangement is perpendicular to the first and second elongated plates 1, 2. Two straight lines A1 and B1 lying in the upper plate 1 intersect in the Z-axis and form the angle ϕ. In Z-parallel projection, the corresponding straight lines A2 and B2 are located on the lower plate 2 and also intersect in the Z-axis with the angle ϕ. If the anchor point of the strut 4 with the upper plate 1 is now on the straight line A1 at a distance r1 from the Z-axis, then the anchor point of the strut 4 is located at the lower plate 2 at the same distance r1 from the Z-axis on the straight line B2. This rule applies accordingly to any distance r1, r2, r3, ... of the metal struts 4, 4', 4", ... from the Z-axis.

[0029] The structure is further generalized by rotating each strut 4, 4', 4" ... around the z-axis by an individual angle $\beta 1$, $\beta 2$, $\beta 3$..., keeping all other values (rn, xn, ϕ) constant. The strut's upper fastening points (r1, r2, r3,...rn) may therefore form a line of arbitrary shape.

[0030] Each metal strut 4, 4', 4", ... can be moved from its starting position to another position on the radius r1 by rotation around the Z-axis by an angle β. A different rotation angle $\beta 1$, $\beta 2$, $\beta 3$ can be selected for each metal strut 4, 4', 4". The length of each metal strut 4, 4', 4", ... is adjusted to the distance h between the first and second plate 1, 2 depending on the distance between rn to xn and the orientation after rotation around the Z-axis.

[0031] The rotation angles $\beta 1$, $\beta 2$, $\beta 3$ etc. can be chosen so that the anchor points of the metal struta 4, 4', 4", ... on the upper plate 1 lie on a line which does not form a straight line intersecting the Z-axis, but any polygonal line. In particular, all the upper anchor points of the metal struts 4, 4', 4", ... can lie on a straight line L not intersecting the Z-axis as shown in Figure 1d.

[0032] The positions of the lower anchor points of the metal struts 4, 4', 4", ... are again obtained by projecting the straight line L, which can also be a polygonal line, Z-parallel onto the lower plate and then rotating it by the angle ϕ around the Z-axis.

[0033] The schematic representation in Figure 1e shows three elastic links (diagonal dashed/solid lines between two sectors of a circle, like 'pizza' slices. The sectors of a circle represent at least parts of the first elongated plate 1 and the second elongated plate 2, which are connected by the struts 4, 4', 4". The struts 4, 4', 4" are affixed to the top and bottom elements 1, 2 at different positions (r1, r2, r3), along the radius of the circle. The arrows at Δz and $\Delta\psi$ indicate the kinematic coupling introduced by the struts 4, 4', 4" at distances r1, r2, r3. The small arrows at first elongated plate 1, qualitatively indicate the displacement of three points, corresponding to rotational deflection Δ_ψ at different positions. Essential for understanding is the rotational symmetry around the Z-axis, which applies both to the construction (angle ϕ and β) and to the operation of the arrangement (angle $\Delta\psi$). In operation, the upper plate 1 is lowered and raised in the Z-direction, which is translated via the metal struts 4, 4', 4", ... into a rotation of the lower plate 2 around the Z-axis by an angle Δ_ψ.

[0034] When the distance between the two layers 1, 2 (spanned by ABC and A'B'C', respectively) is varied, a rotation of ABC relative to A'B'C' happens. This is the foundation of the mode of action of the phononic crystals 5 with rotational inertia. At a known distance from the axis of rotation Z, (e.g. r2) This relationship can be considered identical for all three metal struts 4, 4', 4", ... , for sufficiently small values of Δz and Δ_ψ, respectively. All metal struts 4, 4', 4", ... with the same geometry (length and angle α to the xy plane and radial position ri) describe the same coupling of linear to rotational motion, independently of their position along A. In the geometry represented in the figure 1e, the three metal struts 4, 4', 4", ... are affixed along one radius of the first plate 1 and one of the second plate 2. All points on each radius describe the same angular motion Δ_ψ, if the distance between the two plates 1, 2 is changed by Δz. With the angle between the two radial lines CA and C'B' about the axis of rotation z defined as ϕ, the distance in the xy plane between the two points of connection of the metal struts 4, 4', 4", ... with the two plates 1,2 becomes 2ri sin $\phi/2$, with i = 1...3, in the case shown in the figure. Thus, the tilting angles αi of the elastic links can be described as αi = arctan h/(2ri sin ϕ/2), where h is the length of the line CC'.

[0035] A Projection along the z-axis of the elongated plates 1, 2 with connecting metal struts 4, 4', 4", ... is depicted in figure 1f. The metal struts 4, 4', 4", ... are shown as projections in the x-y plane. Their length increases with the radius r1 to r6 of the half circle drawn. In order to be located under a straight line or longitudinal axis L, such as a rail, the metal struts 4, 4', 4", ... are rotated around C to intersect the horizontal. It is to note that the metal struts 4, 4', 4", ... are always oriented to be tangential to the circles that share C as the center, where the axis of rotation intersects the x-y plane. The direction of the in-plane motion of the elongated plates 1, 2 is given by the tangential orientation of the metal struts 4, 4', 4", ...

[0036] The length of the projection of the metal struts 4, 4', 4", ... in the x-y plane is proportional to their distance from C, while their projection along z is constant at h, see figure 1f, leading to a variable inclination. In order to position the metal struts 4, 4', 4", ... along a straight line, they are rotated round the axis of rotation that intersects the x-y plane in C, until they come to intersect the horizontal. This rotation enforces the correct coupling of the motion in the x-y plane, such that all metal struts 4, 4', 4", ... couple the relative displacement into the same rotational motion (same ratio dψ/dz of rotation per unit deformation along z axis). This identity is only valid for small deformation in z direction. All metal struts 4, 4', 4", ... are distributed in direction of the longitudinal extension of the elongated plates (1, 2).

[0037] Instead of arranging the metal struts 4, 4', 4", ... in projection in the x-y plane along a straight line L, a curve can also be laid through the different radii, as indicated by the dashed line. The metal struts 4, 4', 4", ... are then positioned tangentially aligned at the intersections between the curve and the radii, what is not depicted here.

[0038] The unit cell 0 can also comprise an additional third elongated plate 3 with an additional multiplicity of metal struts 4, 4', 4"..., double-sided fixed in their own fastening sections X, X', X"..., distributed along the longitudinal extension of the elongated plates 1, 2, 3 as described above and welded between second elongated plate 2 and third elongated plate 3.

[0039] As depicted in Figure 2, a unit cell 0' or a phononic crystal 5, comprising an array of a multiplicity of unit cells 0, with more than the first elongated plate 1, the second elongated plate 2 and a third elongated plate 3, divided by a multiplicity of metal struts 4, 4', 4"..., double-sided fixed in their own fastening sections X, X', X"..., distributed along the longitudinal extension of the elongated plates 1, 2, 3, can be build. Here five elongated plates 1, 2, 3, 2', 1' with fastening sections X, X', X", X''' and connected metal struts 4, 4', 4", 4''', oriented as explained above at undersides 10 and upper sides 20 are placed, facing each other, fixed in rotated orientation of the principal directions. The phononic crystal 5 can comprise four unit cells 0 as described above.

[0040] A phononic crystal 5 comprising an array of two unit cells 0' with a total of three elongated plates 1, 2, 3 can be produced, wherein the first elongated plate 1 and the third elongated plate 3 of a first unit cell 0 are connected via connecting plates 50 to the first elongated plate 1' and the third elongated plate 3' of a second unit cell 0'. Both neighbouring unit cells 0, 0' are spaced perpendicular to their longitudinal direction L, also defined by the rotation axis Z.

[0041] As shown in Figure 3, two unit cells 0, 0', each with five elongated plates 1, 2, 3, 1', 2' are build, with rotation axis Z and their longitudinal directions L running parallel to each other, wherein each first, third and fifth elongated plate 1, 3, 2' of both unit cells 0, 0' is connected via connecting plates 50 at each other. The connecting plates 50 are laterally spacing both unit cells 0, 0' perpendicular to the longitudinal direction L.

[0042] Or the first, third and fifth elongated plates 1, 3, 2' of both unit cells 0, 0' are forming common plates of each unit cells 0, 0' and therewith reach a lateral spacing of both unit cells 0, 0' perpendicular to the longitudinal direction L of each unit cell 0, 0'.

[0043] For improving damping properties, at both peripheral areas of the first elongated plate 1, an additional weight can be attached, most preferred in form of a lateral frame element.

[0044] Such disclosed unit cells 0, 0' can form railway track components, most preferred wherein the unit cells 0, 0' are laterally spaced by at least one connecting plate 50, most preferred by two interconnecting plates 50.

[0045] In all the described embodiments of the unit cell 0, the metal struts 4, 4', 4"... in particular consisting of armouring iron.

[0046] In an adapted version with different damping characteristics the metal struts 4, 4', 4"... consist of metal bands, most preferred at least partly twisted in their course in principal direction. Such metal bands 4, 4', 4"...will be welded either directly onto the plates 1, 2, 3, 1', 2' or on surfaces of truncated cones or polyhedron frustums. The metal bands 4, 4', 4"... are acting more like spring elements and show other damping behaviour.

[0047] Depending on the desired damping properties, additional weights should be attached to the elongated plates 1, 2, 3, 1', 2'. We used not shown cuboid or block-like or brick-like lateral frame elements as additional weights, located at both end sections of the unit cell 0.

[0048] The stiffness of the whole unit cell 3 and the attenuated frequency range are adjusted to the individual application by an appropriate choice of parameters, such as length of unit cell 0, length of the struts 4, 4', 4"..., additional weights respectively of lateral frame elements and their mass distribution along the longitudinal direction L and the density of materials used. All elements of the unit cell 0 can be made of metals and/or polymer, in particular polyamide or materials which can be used in additive manufacturing techniques.

[0049] The first application of the phononic crystals 5 is the attenuation of vibrations and shockwaves in railroads, where due to the considerable loads and forces the phononic crystals 5 has to feature a mass of hundreds of kilograms accommodated in the very limited space beneath two neighboring sleepers.

[0050] Further applications of the phononic crystals 5 are in aerospace, marine, transportation engineering, where there is a need to decouple a vibration source (e.g., rotating machinery, moving parts with friction) from highly vibration sensitive devices (measurement equipment, precision instruments, passengers) or environments (laboratories, offices, conference rooms, cabin interiors). Special sound transmission properties (frequency selective filtering) can also be achieved.

[0051] Given its scalability, the concept can be applied from the millimeter to the meter scale. While the properties of the materials that the phononic crystal 5 is made of, have an effect on the properties of the phononic crystal , their selection may be steered also by a number of additional application-specific requirements, such as material costs, optical (transparency) or chemical properties (e.g. corrosion resistance), environmental requirements (sustainability, recyclability) and many more.

[0052] For manufacturing of the presented unit cells 0, phononic crystals 5 and artificial phononic metamaterial structures, additive manufacturing techniques are definitely suitable solutions. Although the geometry is relatively complex, 3d printing techniques can accomplish production of different unit cells 0, with suitable sizes for manufacturing tuned phononic crystals 5 for different applications. Even mixing of printed materials is possible.

[0053] While the conventional manufacturing of these unit cells 0 and phononic crystals 5 is very appealing for large quantities of phononic crystals 5, the process can be quite labor intensive and subject to more tolerance problems than AM. However, at the present time, the industrialization of the unit cells 0 requires use of conventional manufacturing processes.

LIST OF REFERENCE NUMERALS

[0054]

0 unit cell
1 first elongated plate
10 underside of first elongated plate
A1 first straight line
B1 second straight line
r1, ..rn upper distances of upper fastening points
ϕ intersection angle
2 second elongated plate
20 upper side of second elongated plate
A2 third straight line
B2 fourth straight line
x1, ..xn lower distances of lower fastening points
3 third elongated plate
X, X', X"... fastening sections
L longitudinal direction
Z rotation axis
h distance between elongated plates in z-direction
4, 4', 4"... metal struts
5 phononic crystal / array of unit cells
50 connecting plate

Claims

1. Unit cell (0) of an artificial phononic crystal (5) for building of artificial phononic metamaterials, especially applicable in the field of railroad and tramway protection and for railway track components for reduction of mechanical vibrations,

wherein the unit cell (0) is comprising a first elongated plate (1) with an underside (10) and a second elongated plate (2) with an upper side (20), both plates (1, 2) comprising a polygonal ground plan extending parallel to each other in a longitudinal direction (L), wherein both elongated plates (1, 2) are distanced in a z-direction by a fixed height (h) with a plurality of metal struts (4, 4', 4"...) fixed at connection points (A) at the underside (10) of the first elongated plate (1) and protruding to connection points (B') at the upper side (20) of the second elongated plate (2),

characterized in that,

each metal strut (4, 4', 4"...) is connected to a connection point (A) at the underside (10) on a first straight line (A1) at an radius (r1, ..rn) from a rotation axis (Z) protruding to the connection points (B') at the upper side (20) on a second straight line (B2) at the same corresponding radius (r1, ..rn) from the rotation axis (Z), while

- projection in x-y plane of first straight line (A1) and second straight line (B2) of each metal strut (4, 4', 4"...) includes a intersection angle (ϕ) defined by length of metal strut (4, 4', 4"...) and radius (r1, ..rn),
- distances between rotation axis (Z) and connection points (A, B') of each metal strut (4, 4', 4"...) in x-y plane are equal,
- each metal strut (4, 4', 4"...) is individually rotated around rotation axis (Z) such that, the longitudinal extension of each metal strut (4, 4', 4"...) is oriented to be tangential to the associated radius (r1, ..rn) in projection in the x-y plane,
- the metal struts (4, 4', 4"...) are distributed in direction of the longitudinal extension of the elongated plates (1, 2) in projection on x-y plane along a straight line or a curve at the intersections between line/curve and different radii
- and the respective lengths of the metal struts (4, 4', 4"...) are adjusted in such a way that the above conditions are fulfilled.

2. Unit cell (0) of an artificial phononic crystal (5) according to claim 1, wherein the unit cell (0) comprises an additional third elongated plate (3) and a multiplicity of metal struts (4, 4', 4"...) double-sided fixed in their own fastening sections (X, X', X"...) distributed along the longitudinal extension of the elongated plates (1, 2, 3).

3. Unit cell (0) of an artificial phononic crystal (5) according to claim 1, wherein the unit cell (0) comprises five elongated plates (1, 2, 3, 2', 1') with fastening sections (X, X', X"...) and connected metal struts (4, 4', 4"...) oriented and connected between upper distances (r1, ..rn) of upper fastening points along first straight line (A1) and lower distances (x1, x2, x3, ...) of lower fastening points along the fourth straight line (B2) and welded to the elongated plates (1, 2, 3, 1', 2').

4. Unit cell (0) of an artificial phononic crystal (5) according to one of the preceding claims, wherein the fastening sections (X, X', X"...) are equidistantly distributed along the elongated plates (1, 2, 3, 1', 2') along the longitudinal direction (L).

5. Unit cell (0) of an artificial phononic crystal (5) according to one of the preceding claims, wherein the metal struts (4, 4', 4"...) consisting of armouring iron.

6. Unit cell (0) of an artificial phononic crystal (5) according to one of the claims 1 to 4, wherein the metal struts (4, 4', 4"...) consist of metal bands, most preferred at least partly twisted in their course in their principal direction.

7. Unit cell (0) of an artificial phononic crystal (5) according to one of the claims 1 to 6, wherein the metal struts (4, 4', 4"...) are welded, clamped or via torque-free joints or joints partially transmitting torque indirectly connected to the elongated plates (1, 2, 3, 1', 2').

8. Phononic crystal (5) comprising an array of a multiplicity of unit cells (0, 0') according to one of the preceding claims.

9. Phononic crystal (5) according to claim 8, wherein the first elongated plate (1) and the third elongated plate (3) of a first unit cell (0) are connected via connecting plates (50) to the first elongated plate (1') and the third elongated plate (3') of a second unit cell (0'), wherein both unit cells (0) are spaced perpendicular to the longitudinal direction (L).

10. Phononic crystal (5) according to claim 9, wherein two unit cells (0, 0') each with five elongated plates (1, 2, 3, 1', 2') are build, wherein each fifth elongated plate (2') of both unit cells (0') are connected via a connecting plate (50) laterally spacing both unit cells (0, 0') perpendicular to the longitudinal direction (L).

11. Phononic crystal (5) according to claim 9, wherein two unit cells (0, 0’) each with five elongated plates (1, 2, 3, 1’, 2’) are build, wherein first, third and fifth elongated plates 1, 3, 2’ of both unit cells 0, 0’ are moulded together, forming lateral spacings of both unit cells (0, 0’) perpendicular to the longitudinal directions L.

12. Phononic crystal (5) according to one of the claims 8 to 10, wherein at both peripheral areas of the first elongated plate 1 and/or the second elongated plate (2) and/or the third elongated plate (3), an additional weight is attached, most preferred in form of a lateral frame element.

13. Railway track component, comprising at least two unit cells (0) according to one of the claims 1 to 7, wherein the unit cells (0) are laterally spaced by at least two interconnecting plates (50).

FIG. 1a

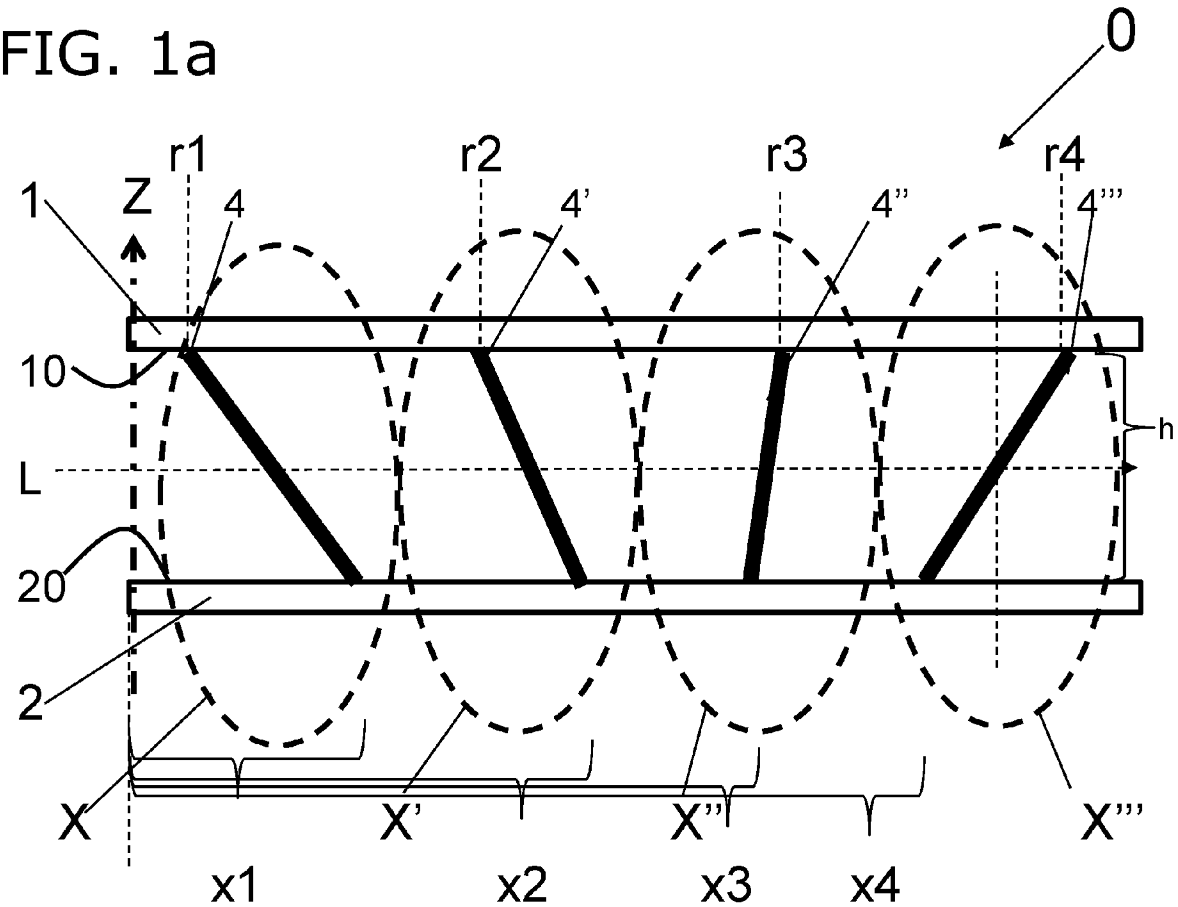

0
r1
r2
r3
r4
1
Z
4
4'
4''
4'''
10
h
L
20
2
X
X'
X''
X'''
x1
x2
x3
x4

FIG. 1b

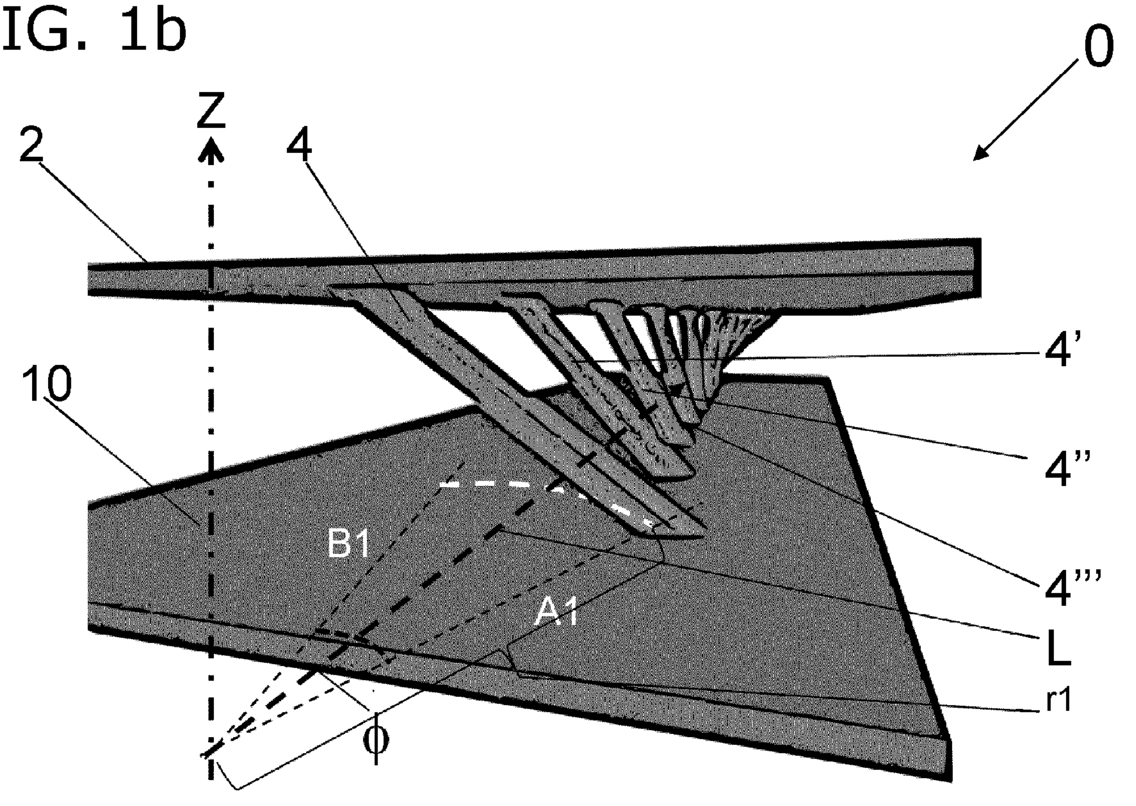

0
Z
2
4
10
4'
4''
4'''
B1
A1
L
r1
φ

FIG. 1c

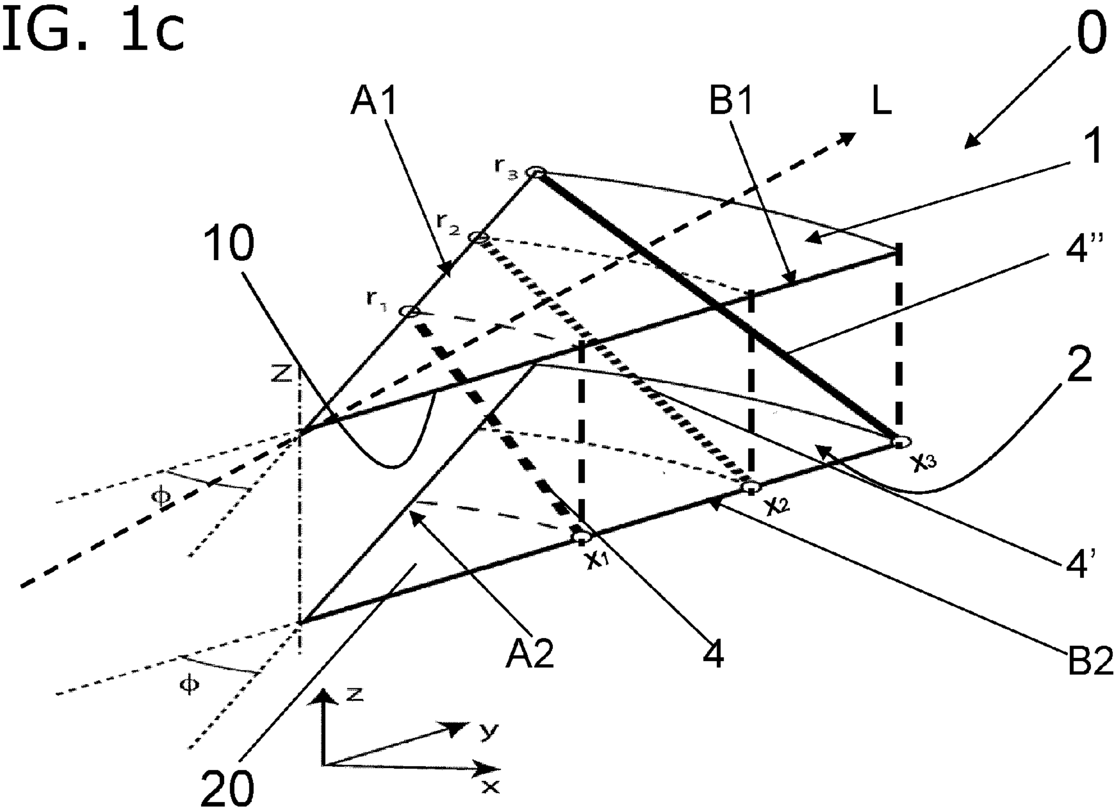


FIG. 1d

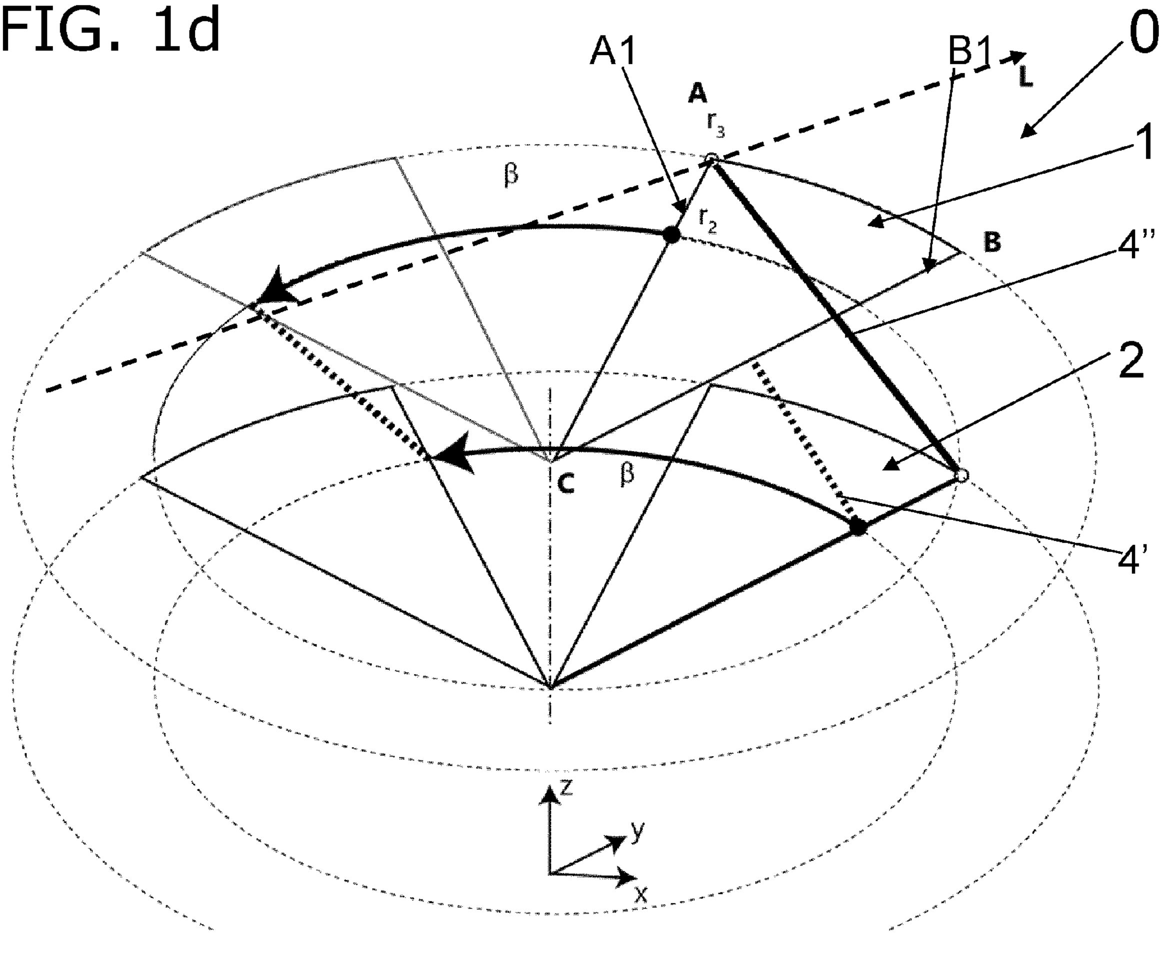


FIG. 1e

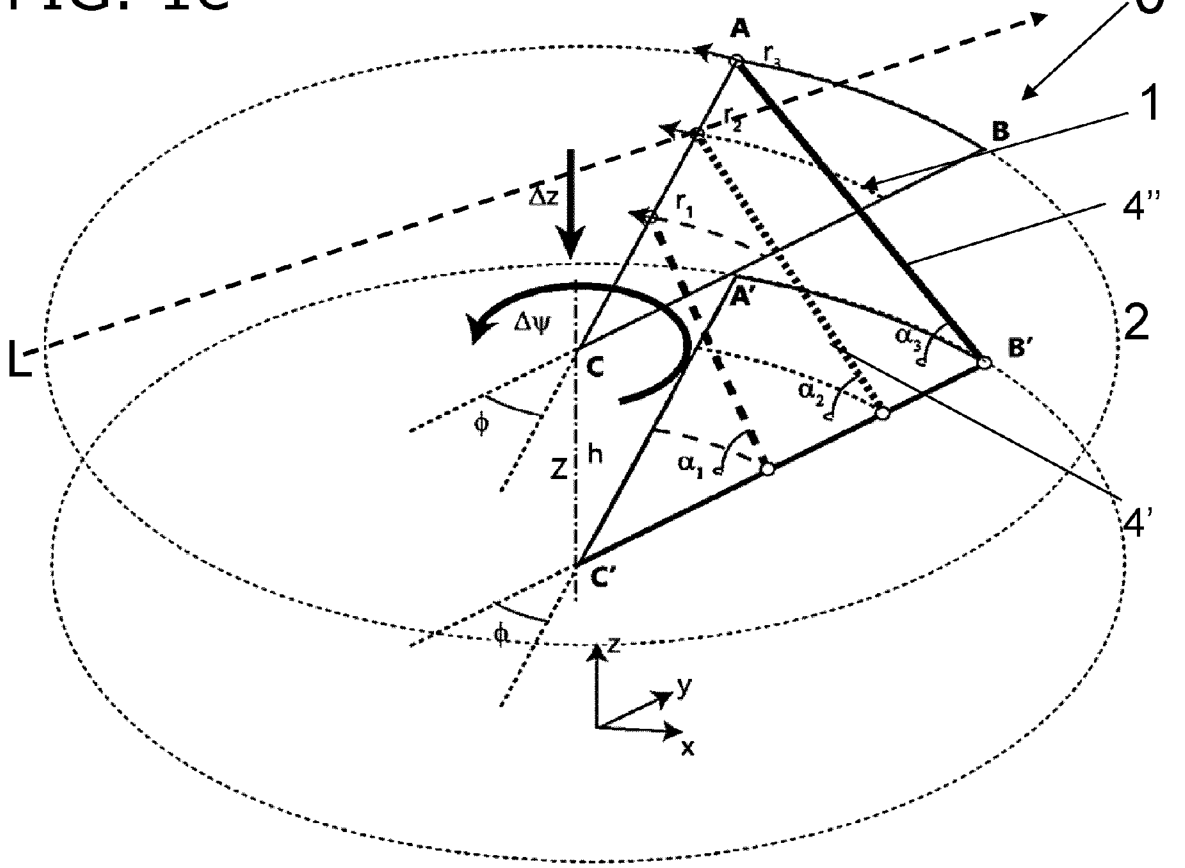

0
1
4''
2
4'
L
A
B
B'
A'
C
C'
r_3
r_2
r_1
Δz
$\Delta\psi$
α_1
α_2
α_3
ϕ
h
Z
z
y
x

FIG. 1f

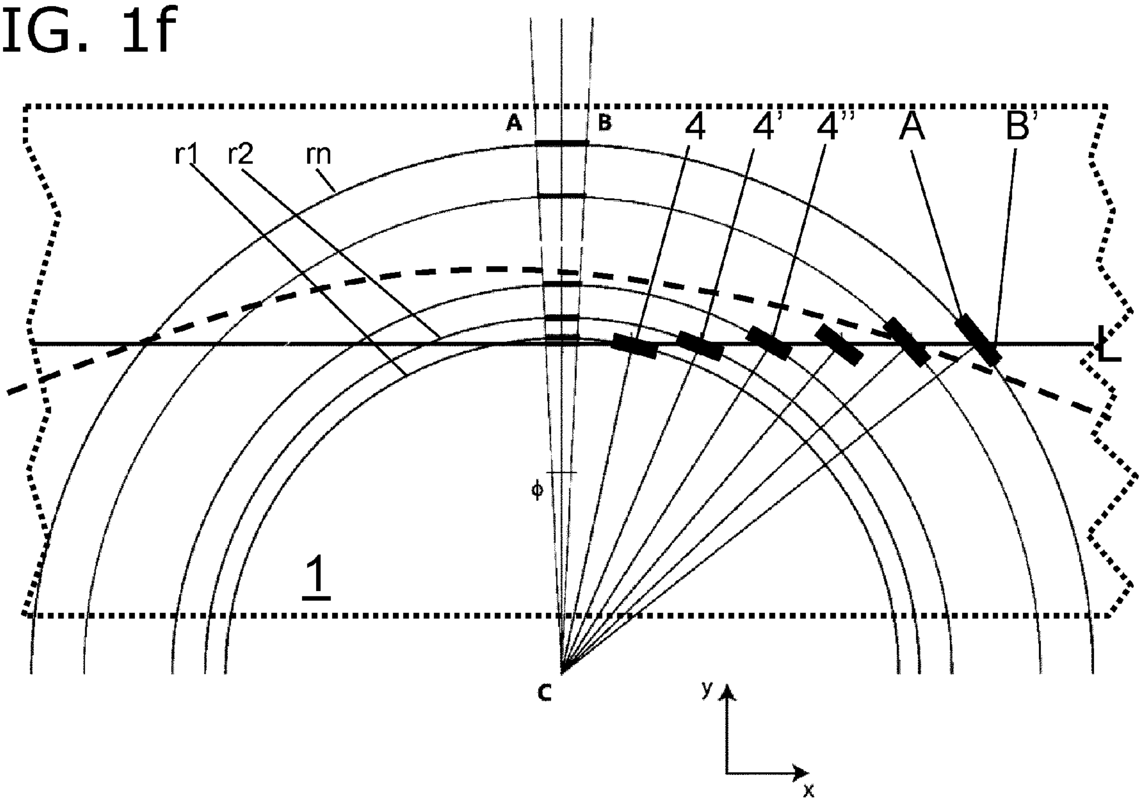

A
B
4
4'
4''
A
B'
r1
r2
rn
L
ϕ
1
C
y
x

FIG. 2

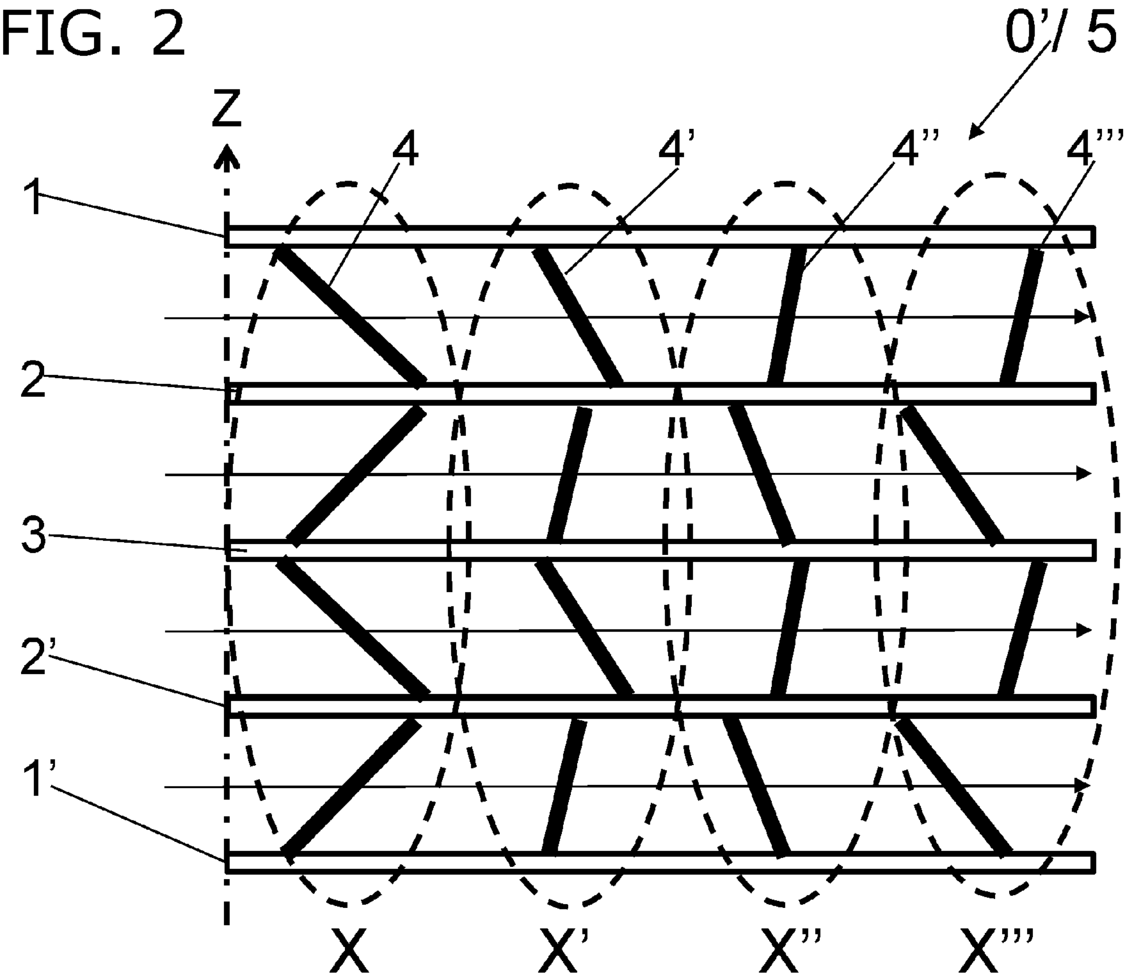
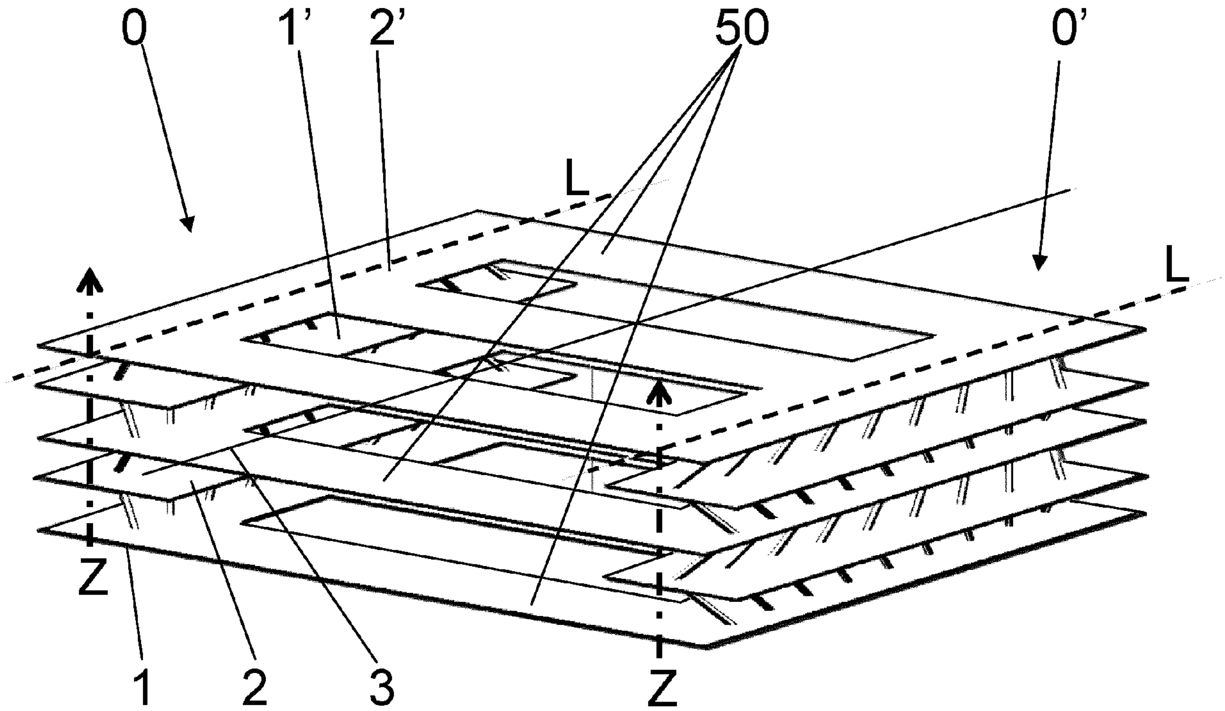


FIG. 3



EUROPEAN SEARCH REPORT

Application Number
EP 23 15 8225

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
A	FANG XIN ET AL: "Wave propagation in metamaterial lattice sandwich plates", PROCEEDINGS OF SPIE; [PROCEEDINGS OF SPIE ISSN 0277-786X VOLUME 10524], SPIE, US, vol. 9805, 1 April 2016 (2016-04-01), pages 98052R-98052R, XP060066347, DOI: 10.1117/12.2219018 ISBN: 978-1-5106-1533-5 * abstract; figures 1,4,5 * -----	1-13	INV. G10K11/172 B61G11/00 E01F8/00 F16F7/10 E01B19/00
A	ZHANG YAO ET AL: "Low-frequency vibration insulation performance of the pyramidal lattice sandwich metamaterial beam", COMPOSITE STRUCTURES, ELSEVIER SCIENCE LTD, GB, vol. 278, 24 September 2021 (2021-09-24), XP086830777, ISSN: 0263-8223, DOI: 10.1016/J.COMPSTRUCT.2021.114719 [retrieved on 2021-09-24] * abstract; figures 1,6,12,16 * -----	1-13	TECHNICAL FIELDS SEARCHED (IPC)
A	CN 114 446 274 A (UNIV XIAN JIAOTONG) 6 May 2022 (2022-05-06) * abstract; claims 1-5; figures 1a-f * -----	1-13	F16F E01F B61K B61G G10K E01B

The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
The Hague	21 July 2023	Fernandes, Paulo

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21-07-2023

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		WO 2023115632 A1	29-06-2023

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