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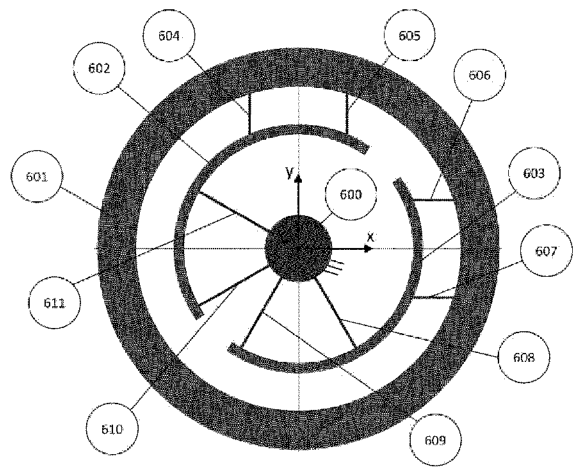
Fig.27



(57) Abstract: The mechanical oscillator according to the invention comprises an oscillating body (601), at least one rigid intermediate body (602) and a support (600). Each rigid intermediate body is connected to the support by a pair of elements (610, 611) providing rotational guidance. The elements of each pair are elastically substantially identical to each other and extend along respective axes which, in orthogonal projection onto a plane parallel to the oscillation plane of the oscillating body, cross at a point (G) and are symmetric to each other with respect to a line (x) passing between the points of junction of the first pair of elements to the rigid intermediate body. The rigid intermediate body is connected to the oscillating body by at least one further element (604, 605) providing relative guided mobility between the oscillating body and the rigid intermediate body in a direction substantially parallel to the line (x) during regular functioning of the mechanical oscillator. In a variant the pair of elements connect the rigid intermediate body to the oscillating body and the at least one first further element connects the rigid intermediate body to the support.

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[Continued on next page]

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FLEXURE PIVOT OSCILLATOR INSENSITIVE TO GRAVITY

Technical Field

[0001] The present invention relates to the field of flexure pivots. More particularly, it relates to flexure pivots which are insensitive to gravity, i.e. perform similarly independent of their orientation, and can have a linear restoring torque. Such flexure pivots are particularly suitable for use in mechanical oscillators in timepieces, however this is not the only use of such pivots.

State of the art

[0002] In the following description, references placed in square brackets refer to publications mentioned at the end of the description.

[0003] Background on mechanical watch oscillators

[0004] The time base used in all mechanical watches is a harmonic oscillator consisting of a spiral spring attached to a balance wheel having a rigid pivot rotating on jeweled bearings, see Figure 1(a). The pivoting motion on bearings causes significant friction and decreases watch autonomy as well as oscillator quality factor. Note that quality factor is believed to be the most significant indicator of chronometric performance [3].

[0005] It is well-known that flexure pivots drastically reduce friction, see [4] [5], so flexure-pivot based oscillators could improve mechanical watch time bases. In 2014, a flexure pivot was first used as mechanical watch time base, see Figure 1(b), thereby increasing quality factor to several thousands and watch autonomy by an order of magnitude to approximately 30 days [2]. This flexure pivot has a special geometry designed to minimize the effect of gravity on stiffness. This flexure pivot requires that its beams cross at a specific point and has a 3D structure which is difficult to produce.

[0006] Here, we present new flexure pivots minimizing the effect of gravity while retaining a long angular stroke and preferably a planar structure making them good candidates for mechanical watch time bases.

[0007] Oscillator flexure pivot specifications

[0008] Chronometric performance of portable timekeepers such as watches must have oscillators whose spring stiffness is insensitive to outside influences such as temperature and the orientation of the force of gravity. Since mechanical watch precision is of the order of seconds per day, we consider an effect to be negligible if it is of the order of 10 ppm (parts per million), in watchmaking terms, about a 1 s/d error.

[0009] In addition to being rotational bearings, flexure pivots provide an elastic restoring force so can be harmonic oscillators. However, their role as time bases is limited by the following factors:

[0010] Limitation 1: Spring restoring torque can be a non-linear function of rotation angle, which affects isochronism.

[0011] Limitation 2: Flexure pivot kinematics closely approximate rotational motion around a fixed axis but small translation can occur as angular rotation increases, a so-called parasitic shift.

[0012] Limitation 3: Spring stiffness can be affected by the orientation of gravity.

[0013] Limitation 4: Limited stroke and high frequency make it difficult to maintain and count oscillations using classical watch escapements.

[0014] Limitation 5: Flexure pivots may have a 3D structure making them difficult to fit into a wristwatch.

[0015] Non-linearity of beam stiffness under bending has been studied extensively [1], including flexure pivots [6], and this is also the case for parasitic shift [7].

[0016] We first focus on sensitivity to gravity as this issue has not received much attention. We will also consider stroke and admissible stress level of the beams (or blades; these terms are used interchangeably in the following) making up the flexure pivots. In addition, we will design some flexure pivots having 2D or 2.5D structure suitable for small-scale fabrication for watches.

[0017] Definition. We apply the term gravity insensitive to an oscillator if the relative change in its period caused by the effect of the orientation of gravity on its stiffness between the different vertical positions of the oscillator is of order 10 ppm. Otherwise, we will say that it is gravity sensitive.

[0018] Definition. We define stroke to be the pivot rotation angle having a maximum beam stress equal to their admissible value. The value of the admissible stress is taken to be the same for all pivots considered here. Stroke is essentially the maximum amplitude of the oscillator.

[0019] We can now define design goals for our flexure pivots.

[0020] Goal 1: Gravity insensitivity.

[0021] Goal 2: Maximum angular stroke for a given beam aspect ratio as well as admissible stress and Young's modulus (both material properties).

[0022] Goal 3: 2D or 2.5D design.

[0023] Goal 4: Linear restoring torque.

[0024] Since the main form of linear force affecting the chronometric performance of a portable timekeeper is gravity, we will use the term gravity to refer to any linear acceleration. The results of this report apply to all linear accelerations.

[0025] The aim of the invention is to at least partially attain at least one of the above-mentioned goals.

Disclosure of the invention

[0026] To this aim, the present invention provides a mechanical oscillator and a timepiece incorporating such a mechanical oscillator as defined in the appended claims.

[0027] More specifically, according to some embodiments the invention provides a mechanical oscillator comprising an oscillating body, a first rigid intermediate body and a support, the first rigid intermediate body being connected to the support by a first pair of elements providing rotational guidance, the elements of said first pair being elastically substantially identical to each other and extending along respective axes which, in orthogonal projection onto a plane parallel to the oscillation plane of the oscillating body, cross at a point and are symmetric to each other with respect to a first line passing between the points of junction of said first pair of elements to the first rigid intermediate body (and between the points of junction of said first pair of elements to the support), the first intermediate body being connected to the oscillating body by at least one first further element providing relative guided mobility between the oscillating body and the first rigid intermediate body in a direction substantially parallel to said first line during regular functioning of the mechanical oscillator.

[0028] According to other embodiments, the present invention provides a mechanical oscillator comprising an oscillating body, a first rigid intermediate body and a support, the first rigid intermediate body being connected to the oscillating body by a first pair of elements providing rotational guidance, the elements of said first pair being elastically substantially identical to each other and extending along respective axes which, in orthogonal projection onto a plane parallel to the oscillation plane of the oscillating body, cross at a point and are symmetric to each other with respect to a first line passing between the points of junction of said first pair of elements to the oscillating body (and between the points of junction of said first pair of elements to the first rigid intermediate body), the first rigid intermediate body being connected to the support by at least one first further element providing relative guided mobility between the first rigid intermediate body and the support in a direction substantially parallel to said first line during regular functioning of the mechanical oscillator.

[0029] Typically, in the present invention, the rotational motion of the oscillating body relative to the support is the main motion (first-order motion) and the motion along the first line (not necessarily a pure translation) is a second-order motion. Like the rotational motion, the motion along the first line occurs during regular functioning of the oscillator and thus occurs even in the absence of any shock disrupting the functioning of the oscillator. The at least one first further element is indeed not pre-stressed.

[0030] Typically, the oscillator according to the invention is a micromechanical oscillator. The timepiece incorporating the oscillator according to the invention may be a wristwatch or pocket watch for example.

Brief description of the drawings

[0031] Further details of the invention will appear more clearly upon reading the description below, in connection with the following figures which illustrate:

- Figure 1(a): an isometric view of a rigid pivot watch time base according to the prior art (see reference [8]).

- Figure 1(b): an isometric view of a flexure pivot watch time base (see reference [2]).
- Figures 2-12: three versions of co-strut with rigid links, ideal pivots and ideal prismatic joints.
- Figures 13: flexure versions of a rigid rod with two pivots at its ends having elastic property.
- Figures 14-19: co-struts with flexure RCC (remote center compliance) pivots.
- Figures 20-22: co-struts with cross-spring flexure pivots.
- Figures 23-26: three versions of a Horological oscillator with two co-struts arranged orthogonally sharing a common inertial rigid body (crown). Each of the co-struts has rigid links and ideal pivots.
- Figures 27-29: three versions of a Horological oscillator with two co-struts arranged orthogonally sharing a common inertial rigid body (crown). Each of the co-struts has flexure pivots.
- Figures 30-31: two equivalent versions of an oscillator with one co-strut.
- Figure 32: an oscillator with two co-struts.
- Figure 33: a graph showing the relation between the stiffness nonlinearity of the oscillator illustrated in Figure 32 and a blade length ratio.
- Figures 34 and 35: graphs showing the relation between the stiffness nonlinearity of the oscillator illustrated in Figure 32 and the half angle between RCC blades in the said oscillator.
- Figures 36-39: graphs showing the rate of an oscillator with two co-struts as a function of its angular position relative to gravity in its oscillation plane oriented vertically. Construction parameters of the oscillator are varied from Figure 36 to Figure 39.
- Figure 40: an oscillator with two co-struts, with the center of mass of its oscillating body being moved with respect to its center of rotation.
- Figures 41-42: graphs showing the rate of an oscillator with two co-struts as a function of its angular position relative to gravity in its oscillation plane oriented vertically, as well as the rate of the same

oscillator oriented horizontally. Construction parameters of the oscillator are varied from Figure 41 to Figure 42.

- Figures 43-44: two alternative designs of an oscillator with two co-struts.

Embodiments of the invention

[0032] Co-strut

[0033] Figures 2-12, 14-22 illustrate a two-degree-of-freedom oscillator that we have named a “co-strut”, which is used in our designs, as indicated below.

[0034] The co-strut comprises a first body or “oscillating body” (1701; 1801; 1901; 2401; 2501; 2601; 2701; 2801; 2901; 3001; 3101; 1101; 1201; 1301; 41; 51; 61; 71; 81; 91) with center of gravity G directly or indirectly attached to a support (1700; 1800; 1900; 2400; 2500; 2600; 2700; 2800; 2900; 3000; 3100;1100; 1200; 1300; 40; 50; 60; 70; 80; 90) by a pair of elements (1798, 1799; 1898, 1899; 1998, 1999; 2498, 2499; 2598, 2599; 2698, 2699; 2798, 2799; 2898, 2899; 2998, 2999; 3098, 3099; 3198, 3199; 1198, 1199; 1298, 1299; 1398, 1399; 43, 44; 53, 54; 63, 64; 73, 74; 83, 84; 93, 94) that can be flexible or combination of rigid and flexible, said elements (1798, 1799; 1898, 1899; 1998, 1999; 2498, 2499; 2598, 2599; 2698, 2699; 2798, 2799; 2898, 2899; 2998, 2999; 3098, 3099; 3198, 3199; 1198, 1199; 1298, 1299; 1398, 1399; 43, 44; 53, 54; 63, 64; 73, 74; 83, 84; 93, 94) being substantially identical, or at least substantially elastically identical, one with respect to the other, extending along axes that cross at point G and being situated at a mirror reflection with respect to a plane containing line (λ) which intersects the center of gravity G and the said first body (1701; 1801; 1901; 2401; 2501; 2601; 2701; 2801; 2901; 3001; 3101; 1101; 1201; 1301; 41; 51; 61; 71; 81; 91) has mobility along line (λ) in addition to its rotational mobility. The rotational motion is the main motion (first-order motion). The motion along line (λ) (not necessarily a pure translation) is a second-order motion which, like the rotational motion, occurs during regular functioning of the oscillator. The motion along line (λ) is provided by at least one further element (1705; 1805; 1905; 2410, 2411; 2510, 2511; 2610, 2611; 2710, 2711; 2810, 2811; 2910; 3010; 3110, 3111; 1105; 1205; 1305; 45; 55; 65; 75; 85; 95) connected in series with the said pair of elements through a rigid intermediate body (1702; 1802; 1902; 2402; 2502; 2602; 2702; 2802; 2902; 3002; 3102; 1102; 1202; 1302; 42; 52; 62; 72; 82; 92) of negligible mass.

[0035] Figures 5 and 9 illustrate co-struts where the said mobility of the said first body (2401; 2601) along line (λ) is provided by a parallelogram linkage (2410, 2411; 2610, 2611). The links of the said parallelogram (2410, 2411; 2610, 2611) have preferably mirror symmetry with respect to line δ perpendicular to line (λ) and passing through (G).

[0036] Figures 6 and 10 illustrate co-struts where the said mobility of the said first body (2501; 2701) along line (λ) is provided by a Watt 4-bar linkage (2510, 2511; 2710, 2711) to make the isochronism insensitive to direction of gravity and increase the resistance of the oscillator against buckling. The links of the said Watt 4-bar linkage (2510, 2511; 2710, 2711) have preferably the same distance from line (δ) perpendicular to line (λ) and passing through (G).

[0037] Figures 4, 8, 12 illustrate co-struts where the said mobility of the said first body (1901; 2801; 3101) along line (λ) is provided by a pivot (O; 2810, 2811; 3110, 3111). In Figure 12, the links (2810,2811) have preferably mirror symmetry with respect to line ψ passing through pivot point (O) and perpendicular to the line passing through (2806), (2808), (O) to make isochronism insensitive to direction of gravity.

[0038] Figures 7 and 11 illustrate co-struts where the said mobility of the said first body (2901; 3001) along line (λ) is provided by a double parallelogram linkage (2910; 3010) to make the isochronism insensitive to direction of gravity and increase the resistance of the oscillator against buckling. The links of the double parallelograms have preferably mirror symmetry with respect to line (δ) perpendicular to line (λ) and passing through (G).

[0039] The stiffness of the rotational part of such co-struts is insensitive or little sensitive to gravity for the following reason. Any external load, e.g. the force of gravity, applied to the co-strut while the co-strut oscillation plane is oriented vertically has a first component parallel to line (λ) and a second component perpendicular to line (λ). Thanks to the at least one further element (1705; 1805; 1905; 2410, 2411; 2510, 2511; 2610, 2611; 2710, 2711; 2810, 2811; 2910; 3010; 3110, 3111; 1105; 1205; 1305; 45; 55; 65; 75; 85; 95) which provides mobility along line (λ), the first component of the external load is not transmitted to the pair of elements (1798, 1799; 1898, 1899; 1998, 1999; 2498, 2499; 2598, 2599; 2698, 2699; 2798, 2799; 2898, 2899; 2998, 2999; 3098, 3099; 3198, 3199; 1198, 1199; 1298, 1299; 1398, 1399; 43, 44; 53, 54; 63, 64; 73, 74; 83, 84; 93, 94). As to the second component of the external load, it has opposite effects on the elements of the said pair, i.e. one of the elements is loaded in compression while the other is loaded in tension, thus compensating for the change of stiffness of each element.

[0040] The variants described below each incorporate two such co-struts connected in parallel to form an oscillator with one degree of freedom.

[0041] <u>Ideal-pivot oscillator #1 (see Figure 23)</u>

[0042] In this variant, the oscillator comprises eleven rigid bodies: a main rigid body (2001), two intermediate rigid bodies (2002) and (2003), two rigid links (2004) and (2005) providing rotation for intermediate body (2002) around the gravity center (G), two rigid links (2006) and (2007) providing rotation for intermediate body (2003) around the gravity center (G), two rigid links (2016) and (2017) forming a parallelogram providing mobility of intermediate body (2002) with respect to main body (2001) along the x-axis, two rigid links (2022) and (2023) forming a parallelogram providing mobility of intermediate body (2003) with respect to main body (2001) along the y-axis. The main rigid body (2001) is an oscillating body. The mass of intermediate rigid bodies (2002) and (2003) and rigid links (2004), (2005), (2006), (2007), (2016), (2017), (2022) and (2023) is negligible compared to the mass of the main rigid body (2001). Intermediate rigid body (2002) is connected to the main rigid body (2001) by a parallelogram consisting of two links parallel to the y-axis (links (2016) and (2017)), each link has two pivots at its extremities (pivots (2018), (2019), (2020), (2021)). Each of said pivots has the possibility of having elasticity providing restoring torque. The links are preferably at the same distance from the y-axis. Rigid body (2002) is connected to the ground or to a frame (or other support) (2000) by two links (2004) and (2005) remotely crossing at point G which is the pivot center of gravity. Each link has two pivots at its extremities (pivots (2008), (2009), (2010), (2011)) and each of said pivots has the possibility of having elasticity providing restoring torque. Intermediate rigid body (2003) is connected to the main rigid body (2001) by a parallelogram consisting of two links parallel to the x-axis (links (2022) and (2023)), each link has two pivots at its extremities (pivots (2024), (2025), (2026), (2027)). Each of said pivots has the possibility of having elasticity providing restoring torque. The links are preferably at the same distance from the x-axis. Rigid body (2003) is connected to the ground or to a frame (or other support) (2000) by two links (2006) and (2007) remotely crossing at point G which is the pivot center of gravity. Each link has two pivots at its extremities (pivots (2012), (2013), (2014), (2015)) and each of said pivots has the possibility of having elasticity providing restoring torque.

[0043] The pivot rotation axis is perpendicular to the x-y plane and passes through G.

[0044] This oscillator is a 2D isostatic (statically determinate) pivot. Stiffness is insensitive or little sensitive to gravity.

[0045] Ideal-pivot oscillator #2 (see Figure 24)

[0046] In this variant, the oscillator comprises eleven rigid bodies: a main rigid body (2101), two intermediate rigid bodies (2102) and (2103), two rigid links (2104) and (2105) providing rotation for main body (2101) around the gravity center (G) with respect to intermediate rigid body (2102), two rigid links (2106) and (2107) providing rotation for main body (2101) around the gravity center (G) with respect to intermediate rigid body (2103), two rigid links (2117) and (2118) forming a parallelogram providing mobility of intermediate body (2102) with respect to fixed frame (support) (2100) along the x-axis, two rigid links (2123) and (2124) forming a parallelogram providing mobility of intermediate body (2103) with respect to fixed frame (support) (2100) along the y-axis. The main rigid body (2101) is an oscillating body. The mass of intermediate rigid bodies (2102) and (2103) and rigid links (2104), (2105), (2106), (2107), (2117), (2118), (2123) and (2124) is negligible compared to the mass of the main rigid body (2101). Intermediate rigid body (2102) is connected to the main rigid body (2101) by two links symmetric with respect to the x-axis (links (2104) and (2105)), each link has two pivots at its extremities (pivots (2108), (2109), (2110), (2111)). Each of said pivots has the possibility of having elasticity providing restoring torque. Rigid body (2102) is connected to the ground or to a frame (or other support) (2100) by a parallelogram consisting of two links (2117) and (2118) parallel to the y-axis, preferably having the same distance from the y-axis. Each link has two pivots at its extremities (pivots (2119), (2120), (2121), (2122)) and each of said pivots has the possibility of having elasticity providing restoring torque. Intermediate rigid body (2103) is connected to the main rigid body (2101) by two links symmetric with respect to the y-axis (links (2106) and (2107)), each link has two pivots at its extremities (pivots (2112), (2113), (2114), (2115)). Each of said pivots has the possibility of having elasticity providing restoring torque. Rigid body (2103) is connected to the ground or to a frame (or other support) (2100) by a parallelogram consisting of two links (2123) and (2124) parallel to the x-axis, preferably having the same distance from the x-axis. Each link has two pivots at its extremities (pivots (2125), (2126), (2127), (2128)) and each of said pivots has the possibility of having elasticity providing restoring torque. The pivot rotation axis is perpendicular to the x-y plane and passes through G.

[0047] This oscillator is a 2D isostatic (statically determinate) pivot. Stiffness is insensitive or little sensitive to gravity.

[0048] <u>Ideal-pivot oscillator #3 (see Figure 25)</u>

[0049] In this variant, the oscillator comprises seven rigid bodies: a main rigid body (2201), two intermediate rigid bodies (2202) and (2203), two rigid links (2204) and (2205) providing rotation for main body (2201) around the gravity center (G) with respect to intermediate rigid body (2202), two rigid links (2206) and (2207) providing rotation for main body (2201) around the gravity center (G) with respect to intermediate rigid body (2203). The main rigid body (2201) is an oscillating body. The mass of intermediate rigid bodies (2202) and (2203) and rigid links (2204), (2205), (2206), (2207) is negligible compared to the mass of the main rigid body (2201). Intermediate rigid body (2202) is connected to the main rigid body (2201) by two links symmetric with respect to the x-axis (links (2204) and (2205)), each link has two pivots at its extremities (pivots (2210), (2211), (2212), (2213)). Each of said pivots has the possibility of having elasticity providing restoring torque. Rigid body (2202) is connected to the ground or to a frame (or other support) (2200) by pivot (2208) where the said pivot has the possibility of having elasticity providing restoring torque. Pivots (2208), (2211) and (2213) are preferably on a straight line which is preferably parallel to the y-axis. Intermediate rigid body (2203) is connected to the main rigid body (2201) by two links symmetric with respect to the y-axis (links (2206) and (2207)), each link has two pivots at its extremities (pivots (2214), (2215), (2216), (2217)). Each of said pivots has the possibility of having elasticity providing restoring torque. Rigid body (2203) is connected to the ground or to a frame (or other support) (2200) by pivot (2209) where the said pivot has the possibility of having elasticity providing restoring torque. Pivots (2209), (2215) and (2217) are preferably on a straight line which is preferably parallel to the x-axis. The pivot rotation axis is perpendicular to the x-y plane and passes through G.

[0050] This oscillator is a 2D isostatic (statically determinate) pivot. Stiffness is insensitive or little sensitive to gravity.

[0051] <u>Ideal-pivot oscillator #4 (see Figure 26)</u>

It is similar to Figure 23 where instead of parallelogram linkages, a Watt 4-bar linkage is used for each co-strut (2316-2327). This oscillator is insensitive or little sensitive to gravity, is 2D, can be isochronous, isochronism is insensitive or little sensitive to gravity, and it is more resistant to buckling compared to Figure 23.

[0052] <u>Flexure-pivot oscillator #1 (see Figure 27)</u>

[0053] This oscillator is a flexure (compliant mechanism) realization of the oscillator of Figure 23. In this variant, the oscillator comprises three rigid bodies: a main rigid body (601) and two intermediate rigid bodies (602) and (603). The main rigid body (601) is an oscillating body. The mass of intermediate rigid bodies (602) and (603) is negligible compared to the mass of the main rigid body (601). Intermediate rigid body (602) is connected to the main rigid body (601) by two blades parallel to the y-axis (blades (604) and (605)) where the blades preferably are at the same distance from the y-axis. Rigid body (602) is connected to the ground or to a frame (or other support) (600) by two blades

(610) and (611) remotely crossing at point G which is the pivot center of gravity. Blades (610) and (611) constitute an RCC pivot. Intermediate rigid body (603) is connected to the main rigid body (601) by two blades parallel to the x-axis (blades (606) and (607)) where the blades preferably are at the same distance from the x-axis. Rigid body (603) is connected to the ground or to a frame (or other support) (600) by two blades (608) and (609) remotely crossing at point G and constituting a further RCC pivot. The pivot rotation axis is perpendicular to the x-y plane and passes through G.

[0054] This oscillator is a 2D isostatic (statically determinate) flexure pivot. Gravity produces axial (tensile or compressive) load and bending moment in the flexure blades. Stiffness is insensitive or little sensitive to gravity.

[0055] Flexure-pivot oscillator #2 (see Figure 28)

[0056] This oscillator is a flexure (compliant mechanism) realization of the oscillator of Figure 24. In this variant, the oscillator comprises three rigid bodies: a main rigid body (701) and two intermediate rigid bodies (702) and (703). The main rigid body (701) is an oscillating body. The mass of intermediate rigid bodies (702) and (703) is negligible compared to the mass of the main rigid body (701). Intermediate rigid body (702) is connected to the ground or to a frame (or other support) (700) by two blades parallel to the y-axis (blades (710) and (711)). Rigid body (702) is connected to the main rigid body (701) by two blades (704) and (705) remotely crossing at point G which is the center of gravity of the pivot. Blades (704) and (705) constitute an RCC pivot. Intermediate rigid body (703) is connected to the ground or to a frame (or other support) (700) by two blades parallel to the x-axis (blades (708) and (709)). Rigid body (703) is connected to the main rigid body (701) by two blades (706) and (707) remotely crossing at point G and constituting a further RCC pivot. The pivot rotation axis is perpendicular to the x-y plane and passes through G.

[0057] This oscillator is a 2D isostatic (statically determinate) flexure pivot. Gravity produces axial (tensile or compressive) load and bending moment in the flexure blades. The out-of-plane stiffness of the pivot is provided by the width of the blades. Stiffness is insensitive or little sensitive to gravity.

[0058] Flexure-pivot oscillator #3 (see Figure 29)

[0059] This oscillator is a flexure (compliant mechanism) realization of the oscillator of Figure 25. In this variant, the oscillator comprises three rigid bodies: a main rigid body (1001) and two intermediate rigid bodies (1002) and (1003). The main rigid body (1001) is an oscillating body. The mass of intermediate rigid bodies (1002) and (1003) is negligible compared to the mass of the main rigid body (1001). Intermediate rigid body (1002) is connected to the ground or to a frame (or other support) (1000) by two blades crossing at point O_1 (blades (1004) and (1005)). Rigid body (1002) is connected to the main rigid body (1001) by two blades (1008) and (1009) remotely crossing at point G which is the center of gravity of the pivot. Blades (1008) and (1009) constitute an RCC pivot. Intermediate rigid body (1003) is connected to the ground or to a frame (or other support) (1000) by two blades crossing at point O_2 (blades (1006) and (1007)). Rigid body (1003) is connected to the main rigid body (1001) by two blades (1010) and (1011) remotely crossing at point G and constituting a further RCC pivot. The pivot rotation axis is perpendicular to the x-y plane and passes through G.

[0060] This oscillator is a 2D isostatic (statically determinate) flexure pivot. Gravity produces axial (tensile or compressive) load and bending moment in the flexure blades. The out-of-plane stiffness of the pivot is provided by the width of the blades. Stiffness is insensitive or little sensitive to gravity.

[0061] Characteristics of co-strut oscillators

[0062] 1- They are insensitive or little sensitive to gravity (the stiffness of the pivot does not change by change in orientation relative to gravity when the oscillation plane is vertical).

[0063] 2- They can be monolithically fabricated since their designs are 2D.

[0064] 3- They are statically determinate (isostatic).

[0065] 4- Their restoring torque can be linear (with respect to the rotation angle) leading to isochronous oscillations desirable for Horological applications.

[0066] The reason why we are able to achieve linear restoring torque for our co-strut oscillators can be explained as follows:

The rotational stiffness of each of element pairs (1798, 1799; 1898, 1899; 1998, 1999; 2498, 2499; 2598, 2599; 2698, 2699; 2798, 2799; 2898, 2899; 2998, 2999; 3098, 3099; 3198, 3199; 1198, 1199; 1298, 1299; 1398, 1399; 43, 44; 53, 54; 63, 64, 73, 74; 83, 84; 93, 94) has a softening tendency (negative nonlinearity). On the other hand, potential energy stored in elastic elements (2410, 2411; 2510, 2511; 2910; 3110, 3111; 2610, 2611; 2710, 2711; 3010; 2810, 2811; 1705; 1805; 1905; 1105; 1205; 1305; 45; 55; 65; 75; 85; 95) caused by parasitic motion of elements (2402; 2502; 2602; 2702; 2802; 2902; 3002; 3102; 1702; 1802; 1902; 1102; 1202; 1302; 42; 52; 62; 72; 82; 92) leads to a hardening tendency (positive nonlinearity) for the oscillator stiffness. The design can be optimized such that the softening and hardening effects cancel each other (negative and positive nonlinearities cancel each other) leading to a linear restoring torque and consequently isochronism.

It should be noted that in case of existence of a nonlinearity caused by other mechanisms than the oscillator, in particular caused by escapements, the design of the oscillator can be modified to produce a nonlinearity with the same magnitude as the said nonlinearity but opposite sign in order to reach isochronism.

[0067] Figures 30 to 35 illustrate, based on an exemplary oscillator having one or more RCCs, how the nonlinearity may be cancelled. Referring to Figure 30, the stiffness of the flexure pivot may be expressed as follows:

$$k_{RCC} = k_{RCC,0} + k_{RCC,2}\theta^2 + O(\theta^4)$$

where θ is the rotation angle of the oscillator and O designates a negligible function. The parasitic motion of the intermediate body 2 with respect to the main body 1 is:

$$d_x = \beta\theta^2 + O(\theta^4)$$

The potential energy of the flexure pivot is:

$$U_{RCC} = \frac{1}{2}k_{RCC,0}\theta^2 + \frac{1}{4}k_{RCC,2}\theta^4 + O(\theta^6)$$

The potential energy of the spring is:

$$U_p = \frac{1}{2}k_p d_x^2 = \frac{1}{2}k_p\beta^2\theta^4 + O(\theta^6)$$

The total potential energy is:

$$\begin{aligned} U &= U_{RCC} + U_p \\ &= \frac{1}{2}k_{RCC,0}\theta^2 + \frac{1}{4}\left(k_{RCC,2} + 2\beta^2 k_p\right)\theta^4 + O(\theta^6) \end{aligned}$$

The stiffness of the oscillator is:

$$k_{\text{co-strut}} = k_0(1 + \mu\theta^2) + O(\theta^4)$$

with the nominal stiffness:

$$k_0 = 2k_{RCC,0}$$

and relative stiffness nonlinearity:

$$\mu = \frac{k_{RCC,2} + 2\beta^2 k_p}{k_0}$$

The linear restoring torque condition may be written as follows:

$$k_{RCC,2} + 2\beta^2 k_p = 0$$

Referring to Figure 31, a crossing point ratio δ can be defined as follows:

$$\delta = \frac{d}{L_{RCC}}$$

As demonstrated in [9], assuming that α = 45°, where α is the half angle between the RCC blades, the stiffness coefficients of the flexure RCC pivot are:

$$k_{RCC,0} = \frac{8EI_{RCC}}{L_{RCC}}\left(3\delta^2 + 3\delta + 1\right)$$

$$k_{RCC,2} = \frac{8EI_{RCC}}{L_{RCC}}\left(3\delta^2 + 3\delta + 1\right)\mu_{RCC}$$

with:

$$\mu_{RCC} = -\left(0.08 + \delta + 1.02\delta^2\right)$$

where E is the Young's modulus and I_{RCC} is the area moment of inertia of the RCC blades.

The parasitic motion of the intermediate body 2 with respect to the main body 1 is:

$$d_x = \beta\theta^2 + O(\theta^4)$$

where (see [10]):

$$\beta = -\frac{L_{RCC}}{15\cos\alpha}\left(9\delta^2 + 9\delta + 1\right)$$

The stiffness of the parallel flexure is (see [7]):

$$k_p = \frac{24EI_p}{L_p^3} + O(\theta^2)$$

where I_p is the area moment of inertia of the parallel blades. A blade length ratio λ can be defined:

$$\lambda = \frac{L_p}{L_{RCC}}$$

The stiffness of the oscillator may be expressed as follows:

$$k_{\text{co-strut}} = k_0(1 + \mu\theta^2)$$

with:

$$k_0 = 2\frac{8EI_{RCC}}{L_{RCC}}\left(3\delta^2 + 3\delta + 1\right)$$

Therefore:

$$\mu = -\left(1.02\delta^2 + \delta + 0.08\right) + \frac{2}{75}\frac{I_p}{I_{RCC}}\frac{\left(9\delta^2 + 9\delta + 1\right)^2}{\lambda^3 \cos^2(\alpha)\ \left(3\delta^2 + 3\delta + 1\right)}$$

The linear restoring torque condition is μ = 0. This condition may be written as follows:

$$\lambda^3 = \frac{2}{75}\frac{I_p}{I_{RCC}}\frac{\left(9\delta^2 + 9\delta + 1\right)^2}{\cos^2\alpha\left(3\delta^2 + 3\delta + 1\right)(1.02\delta^2 + \delta + 0.08)}$$

Figure 33 represents the relative stiffness nonlinearity μ versus the blade length ratio λ for the oscillator shown in Figure 32. The continuous curve in Figure 33 corresponds to the relative stiffness nonlinearity μ as determined by the analytical model exposed above, assuming that all blades have a same and constant cross-section and using the following parameter values: δ = 0.15, α = 45°, $I_{RCC} = I_p$. The crosses in Figure 33 are points obtained by the finite element method (FEM) with the following parameter values: δ = 0.15, α = 42°, $I_{RCC} = I_p$. As can be seen, in both cases a value of the blade length ratio λ exists for which the nonlinearity is zero. Changing the blade length ratio λ enables to set the sign and magnitude of the restoring torque nonlinearity in order to compensate for an external isochronism defect. The angle between the RCC blades is another parameter whose value may be selected to compensate for the RCC nonlinearity or to set the sign and magnitude of the restoring torque nonlinearity in order to compensate for an external isochronism defect. By way of illustration, Figures 34 and 35 show FEM results of the relative stiffness nonlinearity μ versus the half angle α (see Figure 32) between the RCC blades, with δ = 0.15 and λ = 0.66 for Figure 34 and δ = 0.15 and λ = 2 for Figure 35.

[0068] Preferably, in the variants having parallel blades (604, 605; 708, 709) and (606, 607; 710, 711) or other spring means guiding in translation, the ratio

$$R = \frac{k_{p,0} L_R^2}{k_{R,0}}$$

is smaller than 50 and still preferably smaller than 20, where $k_{p,0}$ (expressed in N/m) is the nominal stiffness of the parallel blades or other spring means, $k_{R,0}$ (expressed in N.m/rad) is the nominal stiffness of the RCC pivot or other flexure pivot and L_R is the length of the blades of the RCC pivot or other flexure pivot. The said ratio R is also preferably greater than 0.02 and still preferably greater than 0.2.

[0069] In the variants having flexure pivots (1004, 1005) and (1006, 1007) for guiding along axes x, y, the same ratio R may be used, with the same values, by replacing $k_{p,0}$ with

$$\frac{k_{R2,0}}{(L_{R2}(1+\delta_2))^2}$$

where $k_{R2,0}$ is the nominal stiffness of these flexure pivots, L_{R2} is the blade length of these flexure pivots and δ_2 is their crossing ratio.

[0070] <u>Other embodiments</u>

[0071] According to other embodiments of the invention, the rigid intermediate bodies have a non-negligible mass and an unbalance is provided on the oscillating body to compensate for the effect of this non-negligible mass on the sensitivity of the stiffness and frequency to gravity. Figure 36 shows the rate in seconds/day of an oscillator according to the invention as a function of its angular position relative to gravity in the oscillation plane oriented vertically, with the rigid intermediate bodies having a negligible mass (considered to be zero). Figure 37 shows the rate in seconds/day of an oscillator according to the invention as a function of its angular position relative to gravity in the oscillation plane oriented vertically, with the rigid intermediate bodies having a non-negligible mass. As can be seen, the mass of the rigid intermediate bodies increases the rate variation. This defect may be compensated by moving the center of mass of the oscillating body by a distance Δ_{COM} from the center of rotation along an axis of symmetry of the oscillator in its oscillation plane, as shown in Figure 40.

[0072] Figure 38 illustrates the rate in seconds/day of an oscillator according to the invention as a function of its angular position relative to gravity in the oscillation plane oriented vertically, with the rigid intermediate bodies having a negligible mass (considered to be zero) and with the offset Δ_{COM} being equal to zero (curve with the square dots), to 11 μm (curve with the triangle-shaped dots) and to 22 μm (curve with the cross-shaped dots). One can note that a value of the offset Δ_{COM} can be found (here: 11 μm), and more generally a value of the unbalance (in nN.m) of the oscillating body can be found, where the defect caused by the non-negligible mass of the rigid intermediate bodies and the one caused by the unbalance of the oscillating body substantially cancel each other out. This is illustrated in Figure 39 which shows the rate of the same oscillator as in Figure 37 but having an offset Δ_{COM}. In general manner, the offset Δ_{COM} in the present invention is typically of at least 3 μm, preferably of at least 5 μm, still preferably of at least 7 μm.

[0073] To offset the center of mass of the oscillating body as discussed above, weights may be fastened on the oscillating body. As an alternative, material may be removed from the oscillating body, e.g. by means of a laser. As another alternative, material may be added on one side and removed on the other side so that the mass of the oscillating body remains constant.

[0074] The present invention also makes it possible to equalize the rates of the oscillator in the vertical and horizontal orientations. In Figure 41 are represented, with a curve joining square dots, the rate of the oscillator having an offset Δ_{COM} = 11 μm compensating for the defect caused by the mass of the rigid intermediate bodies as a function of its angular position relative to gravity in the oscillation plane oriented vertically and, with a dashed line, the rate of the same oscillator oriented horizontally. The inventors have found that for a given mass of the oscillating body a couple of parameters Δ_{COM} and α, where α is the half angle between the RCC blades (see Figure 32) or more generally between the elements of the/each pair of elements guiding the rotational motion of the oscillating body, may be selected to both minimize the rate variation of the oscillator in dependence upon its angular position relative to gravity in its oscillation plane oriented vertically and substantially equalize the rates of the oscillator in the vertical and horizontal orientations. This is shown in Figure 42 in which the rates in the vertical and horizontal orientations are represented for an oscillator having an offset Δ_{COM} of 9 μm and a half angle α of 19.8°. In the present invention, the half angle α between the RCC blades or more generally between the elements of the/each pair of elements guiding the rotational motion of the oscillating body is preferably of at most 21.5°, still preferably of at most 21°.

[0075] In the present invention, any element of the oscillator which is similar to Figure 13(a), can be replaced by an element which is depicted in Figure 13(b)-(g) for compliant-mechanism realization.

[0076] Preferably, the elements of each pair of elements (2304, 2305; 2498, 2499; 2598, 2599; 2898, 2899; 2998, 2999; 3198, 3199; 1798, 1799; 1198, 1199; 43, 44; 73, 74; 2004, 2005; 610, 611; 2006, 2007; 608, 609; 2698, 2699; 2798, 2799; 3098, 3099; 1898, 1899; 1998, 1999; 1298, 1299; 1398, 1399; 53, 54; 63, 64; 83, 84; 93, 94; 2104, 2105; 2204, 2205; 704, 705; 1008, 1009; 2106, 2107; 706, 707; 2206, 2207; 1010, 1011) are coplanar and each have a 2D structure, as is the case with an RCC pivot for example, so that the oscillator can have a 2D structure. The same applies to the elements which provide mobility along axes λ, x and y. The invention however does not exclude the use of non-coplanar elements such as separate crossed blades. The invention also does not exclude the use of non-coplanar pairs of elements, such as non-coplanar RCC pivots. Figure 43 shows an example of a 3D oscillator according to the invention having two co-struts in two parallel planes, the co-struts respectively having two RCC pivots. The oscillator of Figure 43 may be used when a half angle α between the blades of each RCC greater than 45° is desired or when more compactness in the oscillation plane is desired, for example.

[0077] Even when the oscillator has a 2D structure, i.e. when all elements for guidance in rotation and guidance along axes λ, x and y are coplanar, many different designs may be considered. For example, in addition to the designs depicted in Figures 27, 28, 29, 32 and 40, the oscillator may have the design shown in Figure 44, in particular if a half angle α between the blades of each RCC greater than 45° is desired.

[0078] Moreover, each blade or at least one of the blades may have a cross-section that varies along its length for e.g. a better distribution of the stresses in the blade and a longer angular stroke of the oscillator.

[0079] However, using blades all having the same constant cross-section ($I_{RCC} = I_p$) may be advantageous since this limits the effect of machining tolerances on isochronism. If e.g. the oscillator is made of silicon by an etching process such as the Deep Reactive Ion Etching, the etching defects will change the stiffness of all blades in the same manner if the blades have the same cross-section. Likewise, any silicon dioxide layer provided on the silicon oscillator will change the stiffness of all blades in the same manner if the blades have the same cross-section.

[0080] <u>List of References</u>

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Claims

1. Mechanical oscillator comprising an oscillating body (2301; 2401; 2501; 2801; 2901; 3101; 1701; 1101; 41; 71; 2001; 601), a first rigid intermediate body (2302; 2402; 2502; 2802; 2902; 3102; 1702; 1102; 42; 72; 2002; 602) and a support (2300; 2400; 2500; 2800; 2900; 3100; 1700; 1100; 40; 70; 2000; 600), the first rigid intermediate body being connected to the support by a first pair of elements (2304, 2305; 2498, 2499; 2598, 2599; 2898, 2899; 2998, 2999; 3198, 3199; 1798, 1799; 1198, 1199; 43, 44; 73, 74; 2004, 2005; 610, 611) providing rotational guidance, the elements of said first pair being elastically substantially identical to each other and extending along respective axes which, in orthogonal projection onto a plane parallel to the oscillation plane of the oscillating body, cross at a point (G) and are symmetric to each other with respect to a first line (λ; x) passing between the points (1707, 1709) of junction of said first pair of elements to the first rigid intermediate body, the first intermediate body being connected to the oscillating body by at least one first further element (2316, 2317; 2410, 2411; 2510, 2511; 2810, 2811; 2910; 3110, 3111; 1705; 1105; 45; 75; 2016, 2017; 604, 605) providing relative guided mobility between the oscillating body and the first rigid intermediate body in a direction substantially parallel to said first line (λ; x) during regular functioning of the mechanical oscillator.

2. Mechanical oscillator according to claim 1, further comprising a second rigid intermediate body (2003; 603) connected to the support (2002; 600) by a second pair of elements (2006, 2007; 608, 609) providing rotational guidance, the elements of said second pair being elastically substantially identical to each other and extending along respective axes which, in orthogonal projection onto said plane parallel to the oscillation plane of the oscillating body (2001; 601), cross at said point (G) and are symmetric to each other with respect to a second line (y) intersecting said first line (x) and passing between the points (2013, 2015) of junction of said second pair of elements (2006, 2007; 608, 609) to the second rigid intermediate body (2003; 603), the second rigid intermediate body (2003; 603) being connected to the oscillating body (2001; 601) by at least one second further element (2022, 2023; 610, 611) providing relative guided mobility between the

oscillating body (2001; 601) and the second rigid intermediate body (2003; 603) in a direction substantially parallel to said second line (y) during regular functioning of the mechanical oscillator.

3. Mechanical oscillator comprising an oscillating body (2601; 2701; 3001; 1801; 1901; 1201; 1301; 51; 61; 81; 91; 2101; 2201; 701; 1001), a first rigid intermediate body (2602; 2702; 3002; 1802; 1902; 1202; 1302; 52; 62; 82; 92; 2102; 2202; 702; 1002) and a support (2600; 2700; 3000; 1800; 1900; 1200; 1300; 50; 60; 80; 90; 2100; 2200; 700; 1000), the first rigid intermediate body being connected to the oscillating body by a first pair of elements (2698, 2699; 2798, 2799; 3098, 3099; 1898, 1899; 1998, 1999; 1298, 1299; 1398, 1399; 53, 54; 63, 64; 83, 84; 93, 94; 2104, 2105; 2204, 2205; 704, 705; 1008, 1009) providing rotational guidance, the elements of said first pair being elastically substantially identical to each other and extending along respective axes which, in orthogonal projection onto a plane parallel to the oscillation plane of the oscillating body, cross at a point (G) and are symmetric to each other with respect to a first line (λ; x) passing between the points (1807, 1809) of junction of said first pair of elements to the oscillating body, the first rigid intermediate body being connected to the support by at least one first further element (2610, 2611; 2710, 2711; 3010; 1805; 1905; 1205; 1305; 55; 65; 85; 95; 2117, 2118; 2208710, 711; 1004, 1005) providing relative guided mobility between the first rigid intermediate body and the support in a direction substantially parallel to said first line (λ; x) during regular functioning of the mechanical oscillator.

4. Mechanical oscillator according to claim 3, further comprising a second rigid intermediate body (2103; 703; 2203; 1003) connected to the oscillating body (2101; 701; 2201; 1001) by a second pair of elements (2106, 2107; 706, 707; 2206, 2207; 1010, 1011) providing rotational guidance, the elements of said second pair being elastically substantially identical to each other and extending along respective axes which, in orthogonal projection onto said plane parallel to the oscillation plane of the oscillating body (2101; 701; 2201; 1001), cross at said point (G) and are symmetric to each other with respect to a second line (y) intersecting said first line (x) and passing between the points (2112, 2114) of junction of said second pair of elements (2106, 2107; 706, 707; 2206, 2207; 1010, 1011) to the oscillating body

(2101; 701; 2201; 1001), the second rigid intermediate body (2103; 703; 2203; 1003) being connected to the support (2100; 700; 2200; 1000) by at least one second further element (2123, 2124; 708, 709; 2209; 1006, 1007) providing relative guided mobility between the oscillating body (2101; 701; 2201; 1001) and the second rigid intermediate body (2103; 703; 2203; 1003) in a direction substantially parallel to said second line (y) during regular functioning of the mechanical oscillator.

5. Mechanical oscillator according to claim 2 or 4, wherein the first and second lines (x, y) are perpendicular.

6. Mechanical oscillator according to any of claims 1 to 5, wherein the respective axes of the elements of the/each said pair of elements are coplanar.

7. Mechanical oscillator according to any of claims 1 to 6, wherein the/each said pair of elements forms an RCC pivot.

8. Mechanical oscillator according to any of claims 1 to 7, wherein the at least one first further element, respectively the at least one second further element, comprises a pair of mutually parallel elements (2316, 2317; 2410, 2411; 2510, 2511; 2910; 2016, 2017; 604, 605; 2022, 2023; 2610, 2611; 2710, 2711; 3010; 2117, 2118; 710, 711; 2123, 2124; 708, 709) which extend perpendicularly to the first line (λ; x), respectively to the second line (y).

9. Mechanical oscillator according to any of claims 1 to 8, wherein the at least one first further element, respectively the at least one second further element, forms a double parallelogram linkage (2910; 3010) or a Watt 4-bar linkage (2510, 2511; 2710, 2711).

10. Mechanical oscillator according to any of claims 1 to 7, wherein the at least one first further element, respectively the at least one second further element, forms a pivot, such as an ideal pivot (2208, 2209) or a flexure pivot comprising at least one flexible element (1004, 1005; 1006, 1007).

11. Mechanical oscillator according to any of claims 1 to 10, wherein the oscillating body is an outer part of the mechanical oscillator.

12. Mechanical oscillator according to any of claims 1 to 11, wherein the oscillating body surrounds the/each rigid intermediate body.

13. Mechanical oscillator according to any of claims 1 to 12, wherein at least some, preferably all, of said elements (43, 44; 53, 54; 63, 64; 73, 74; 83, 84; 93, 94; 604, 605, 606, 607, 608, 609, 610, 611; 704, 705, 706, 707, 708, 709, 710, 711; 1004, 1005, 1006,1007, 1008, 1009, 1010, 1011) are blades.

14. Mechanical oscillator according to any of claims 1 to 13, wherein the stiffness softening effect, i.e. negative nonlinearity, of some of said elements (1798, 1799; 1898, 1899; 1998, 1999; 1198, 1199; 1298, 1299; 1398, 1399; 43, 44; 53, 54; 63, 64, 73, 74; 83, 84; 93, 94) is canceled by the stiffness hardening, i.e. positive nonlinearity, of other of said elements (1705; 1805; 1905; 1105; 1205; 1305; 45; 55; 65; 75; 85; 95).

15. Mechanical oscillator according to any of claims 1 to 14, wherein said point (G) coincides with the center of mass of the oscillating body in orthogonal projection onto said plane parallel to the oscillation plane.

16. Mechanical oscillator according to any of claims 1 to 14, wherein in orthogonal projection onto said plane parallel to the oscillation plane the center of mass of the oscillating body is offset relative to said point in order to compensate for the effect of the mass of the rigid intermediate body(ies) on the sensitivity of the oscillator frequency to gravity.

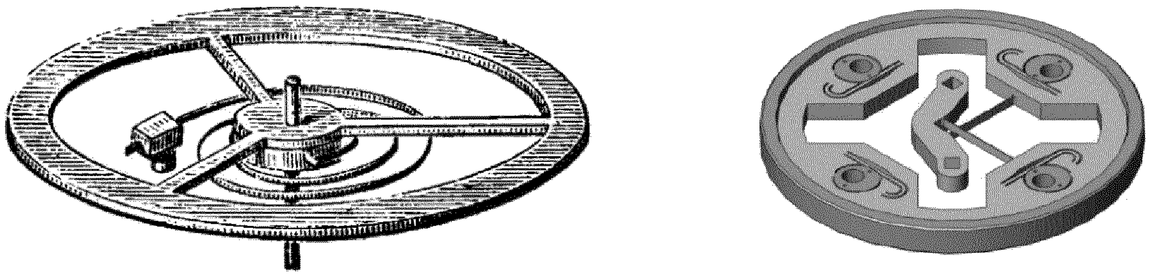
17. Mechanical oscillator according to any of claims 1 to 16, wherein the half angle (α) between the elements of the/each said pair of elements is smaller than 22.5°.

18. Mechanical oscillator according to any of claims 1 to 17, said mechanical oscillator being monolithic.

19. Timepiece comprising a mechanical oscillator according to any preceding claim.

20. Timepiece according to claim 19, wherein the combination of the stiffness softening effect, i.e. negative nonlinearity, of some of said elements (1798, 1799; 1898, 1899; 1998, 1999; 1198, 1199; 1298, 1299; 1398, 1399; 43, 44; 53, 54; 63, 64, 73, 74; 83, 84; 93, 94) and the stiffness hardening effect, i.e. positive nonlinearity, of other of said elements (1705; 1805; 1905; 1105; 1205; 1305; 45; 55; 65; 75; 85; 95) is opposite to the nonlinear effect of all of the mechanisms interacting with the oscillator, specially, the escapement.

Fig.1



(a) (b)

Fig.2

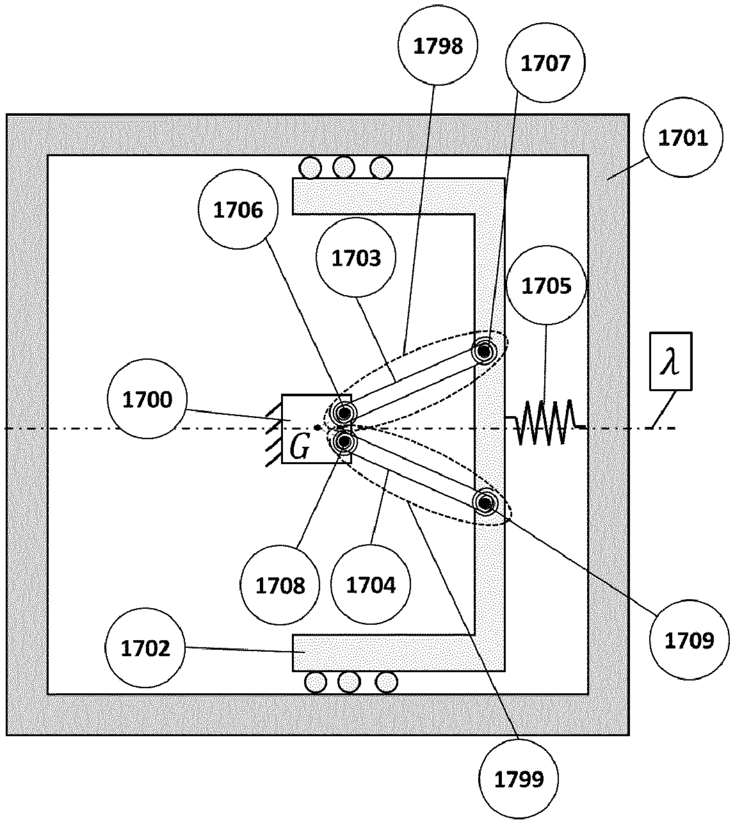

1798
1707
1701
1706
1703
1705
λ
1700
G
1708
1704
1709
1702
1799

Fig.3

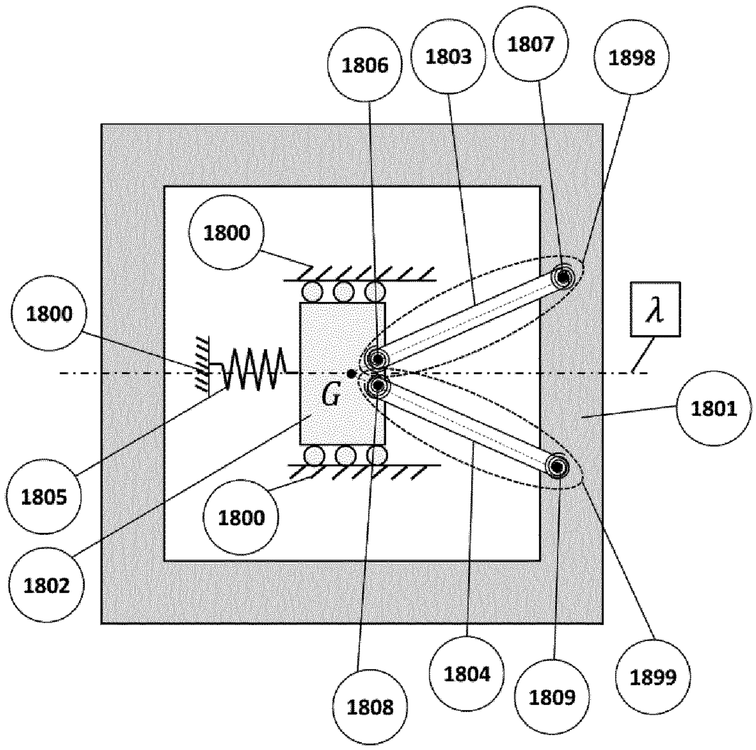

1806
1803
1807
1898
1800
1800
λ
1801
G
1805
1800
1802
1808
1804
1809
1899

Fig.4

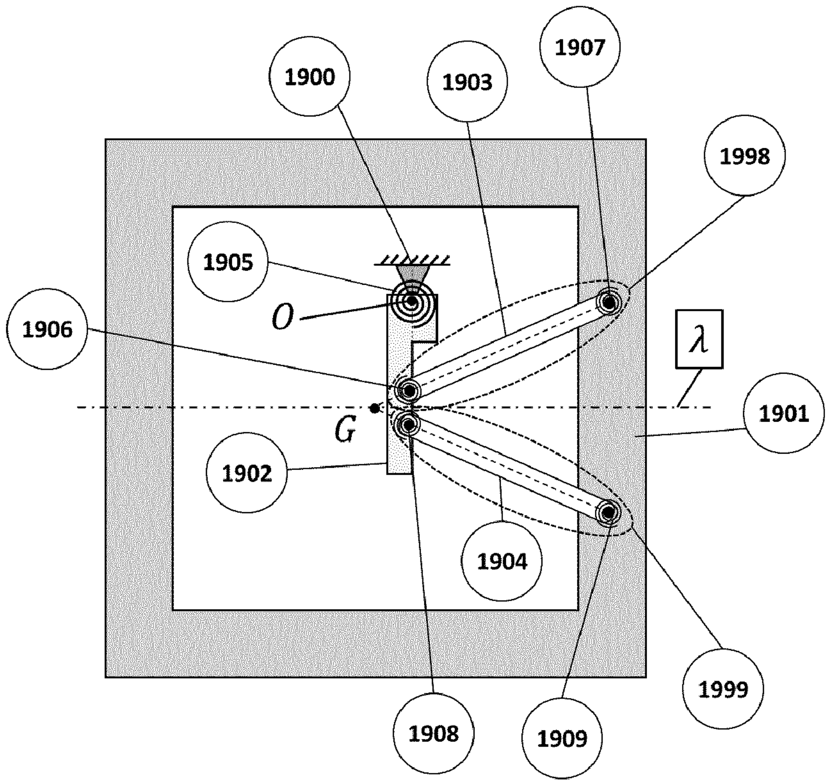

1900
1903
1907
1998
1905
O
1906
λ
1901
G
1902
1904
1999
1908
1909

Fig.5

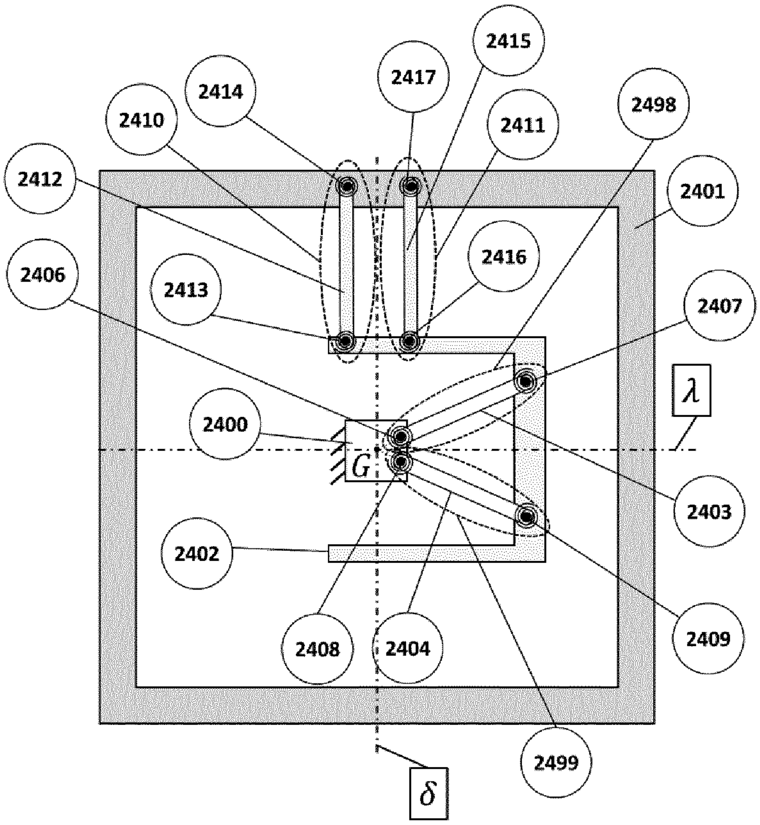
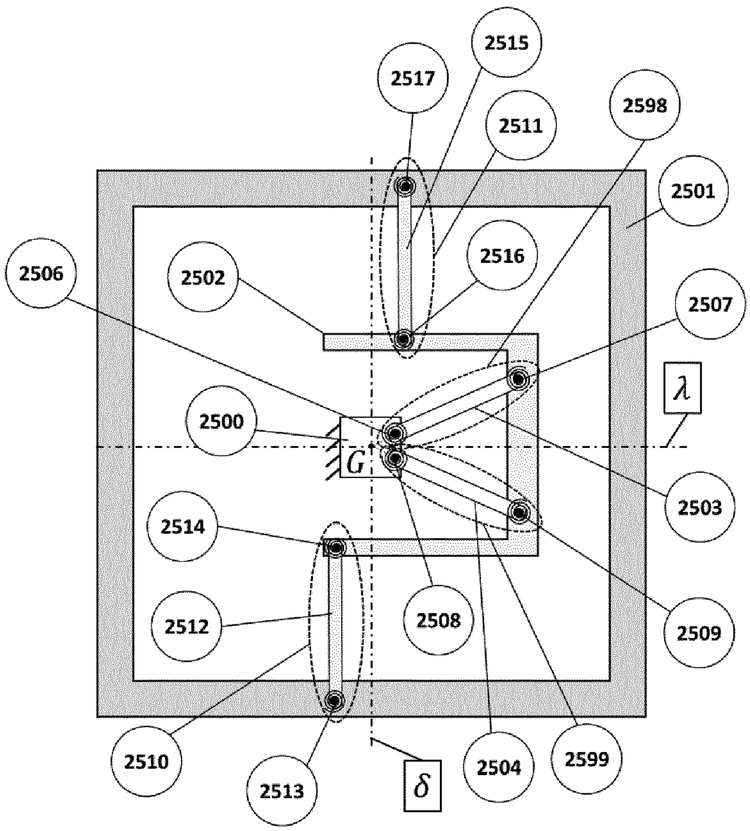

2415
2417
2414
2411
2498
2410
2412
2401
2416
2406
2413
2407
λ
2400
G
2403
2402
2409
2408
2404
2499
δ

Fig.6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2517
2511
2598
2501
2516
2506
2502
2507
λ
2500
G
2503
2514
2509
2508
2512
2510
2504
2599
2513
δ

Fig.7

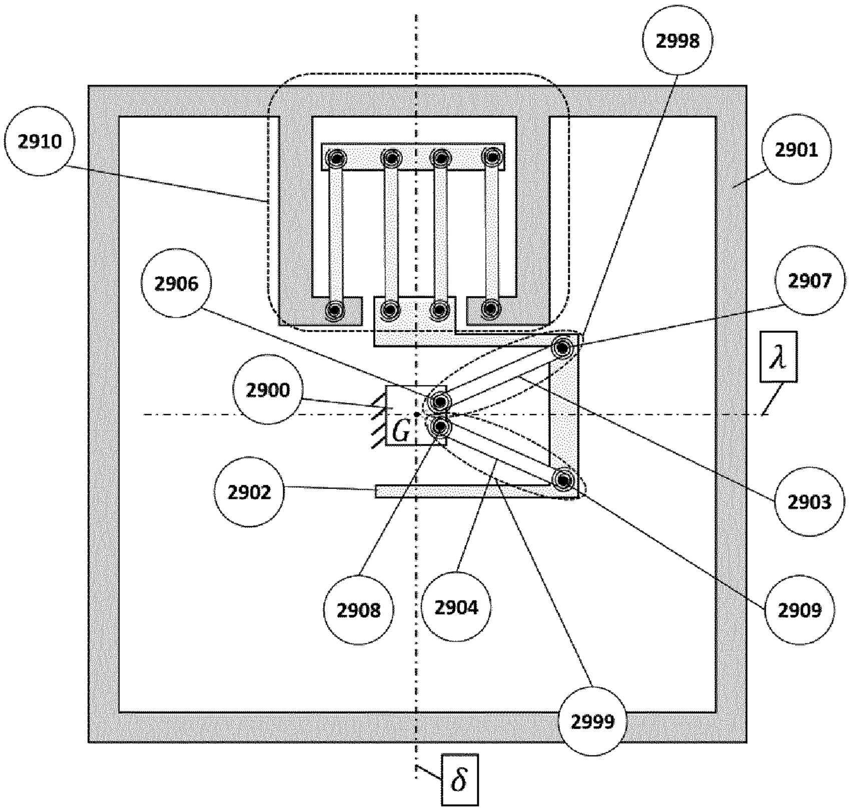
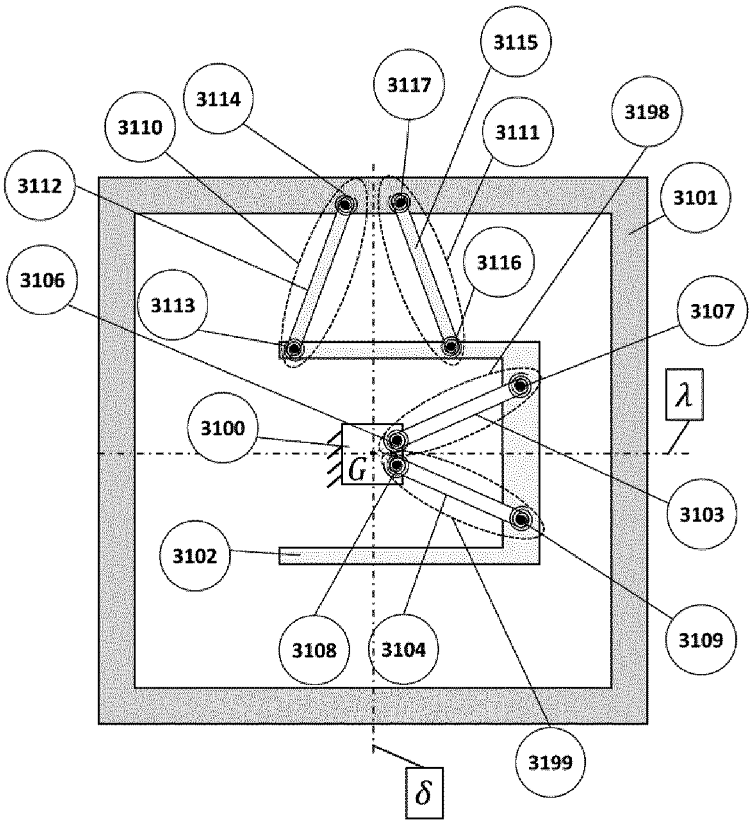

2998
2910
2901
2906
2907
λ
2900
G
2903
2902
2909
2908
2904
2999
δ

Fig.8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3114
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3110
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3198
3112
3101
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3106
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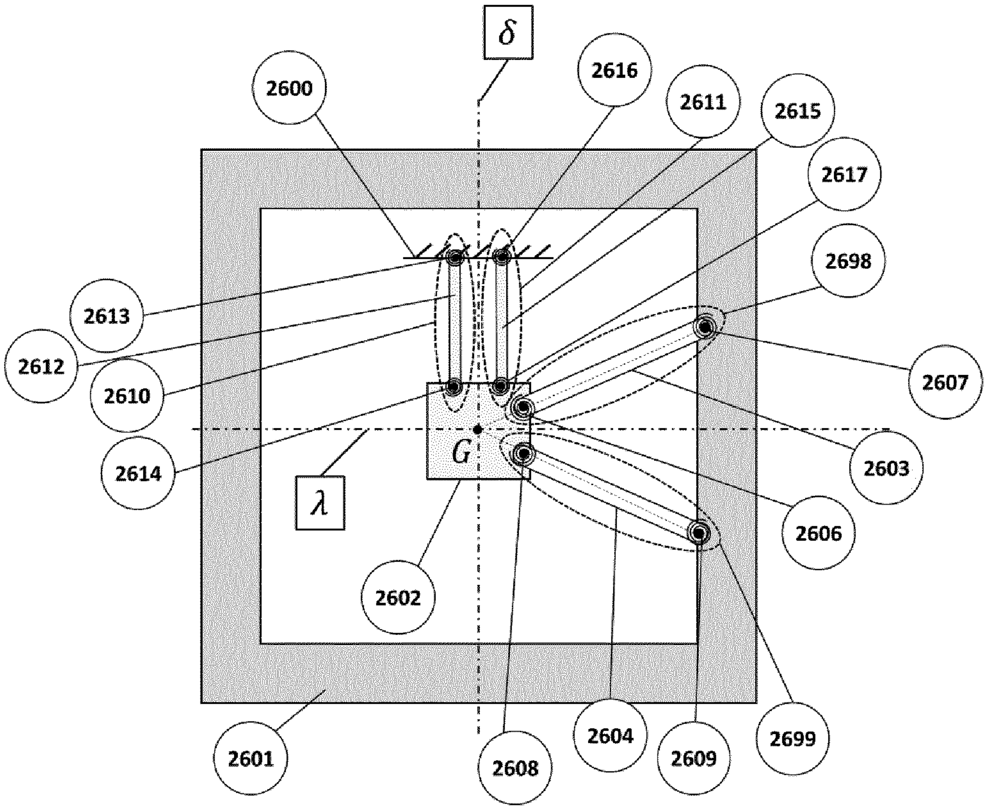
3113
λ
3100
G
3103
3102
3109
3108
3104
3199
δ

Fig.9


δ
λ
G
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2601
2602
2603
2604
2606
2607
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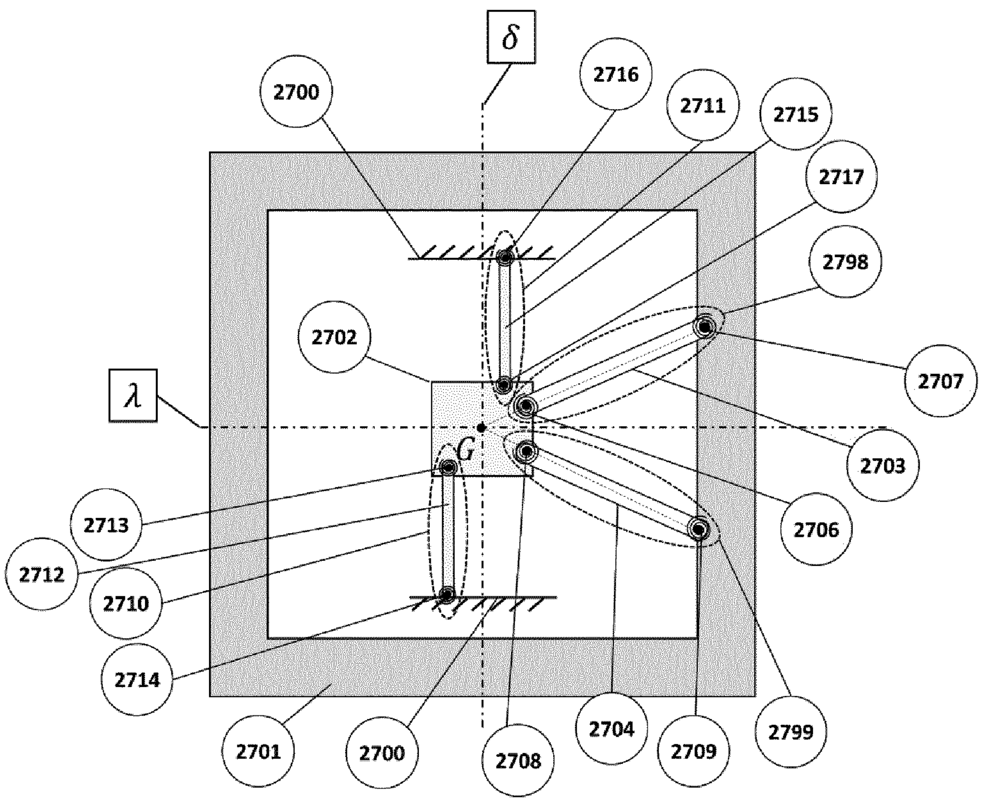
2614
2615
2616
2617
2698
2699

Fig.10


δ
λ
G
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2701
2702
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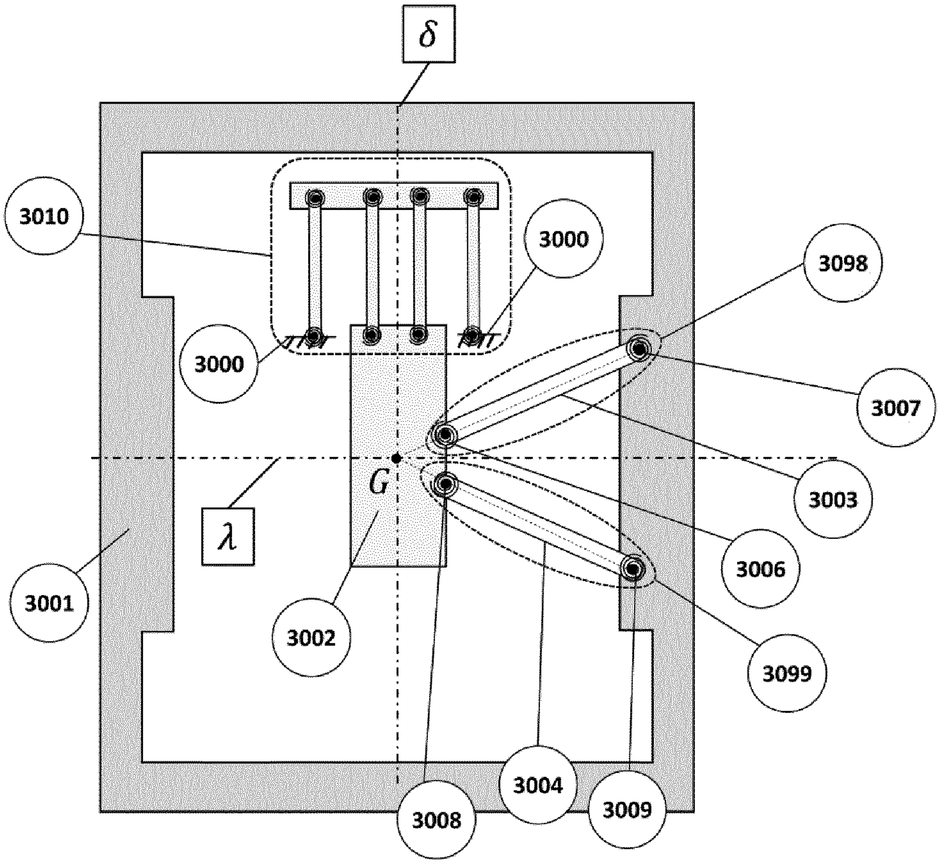
2715
2716
2717
2798
2799

Fig.11


δ
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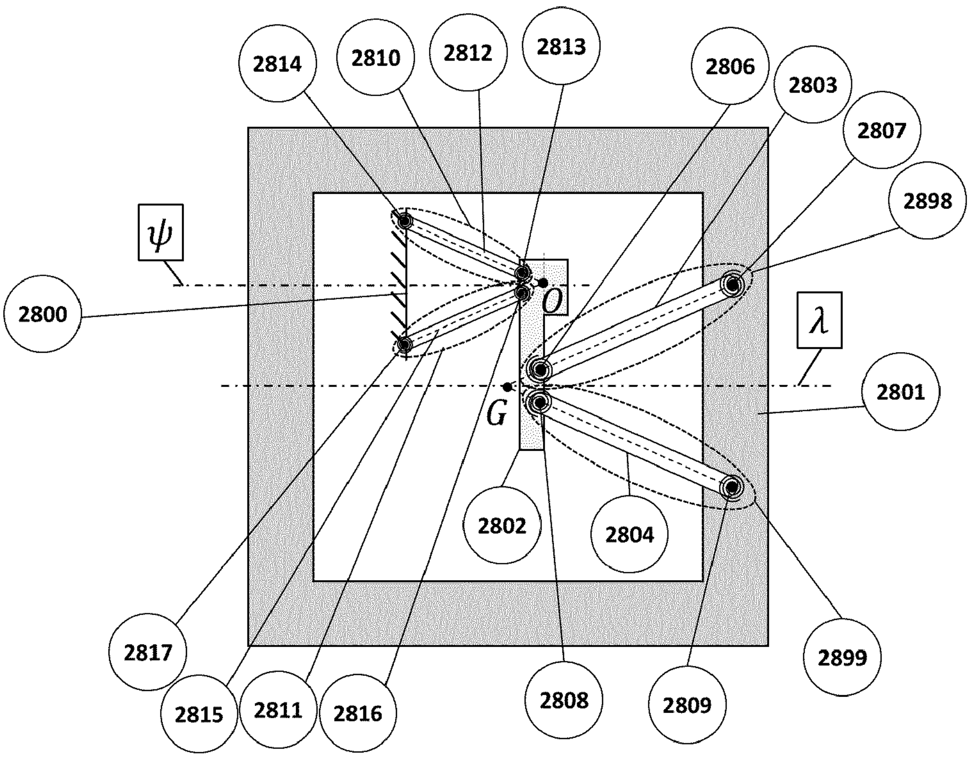
3098
3000
3007
3003
G
λ
3006
3001
3002
3099
3004
3009
3008

Fig.12


2814
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2813
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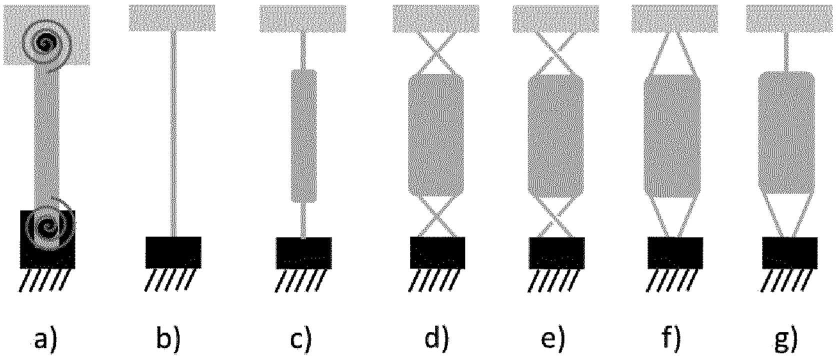
2803
2807
2898
ψ
2800
O
λ
2801
G
2802
2804
2817
2899
2815
2811
2816
2808
2809

Fig.13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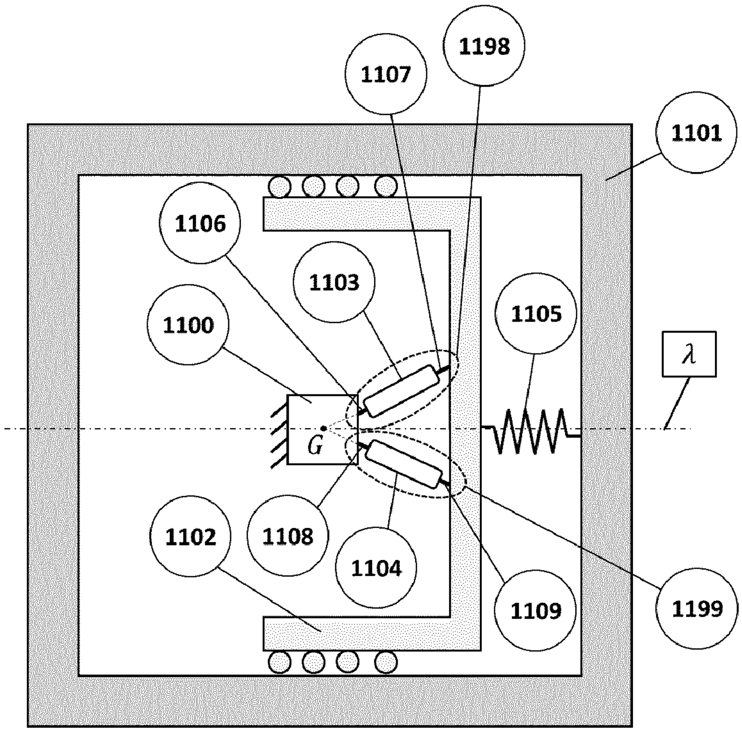
b)
c)
d)
e)
f)
g)

Fig.14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1198
1101
1106
1103
1105
1100
λ
G
1102
1108
1104
1109
1199

Fig.15

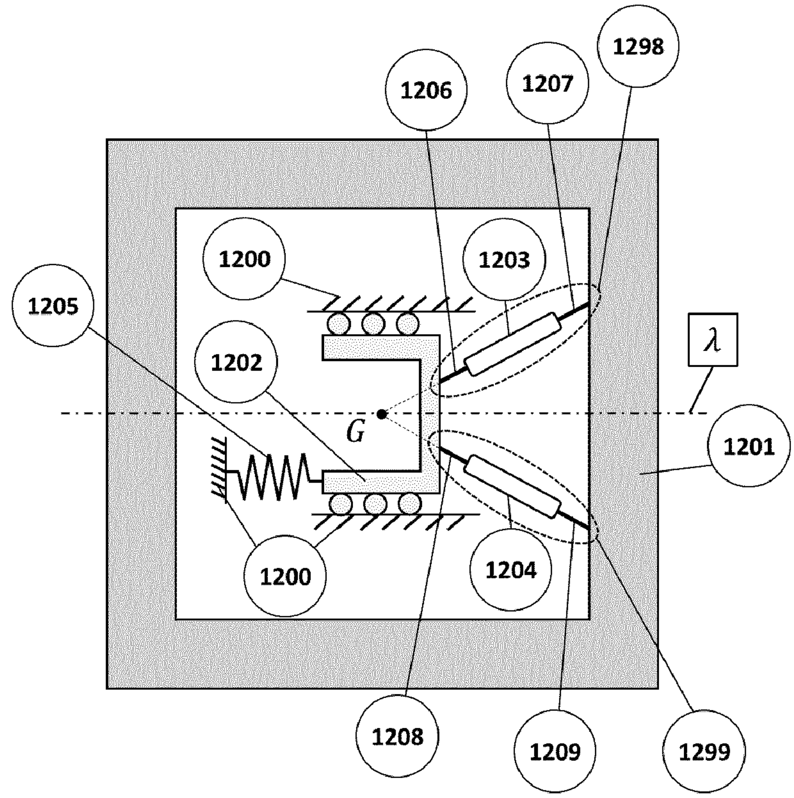
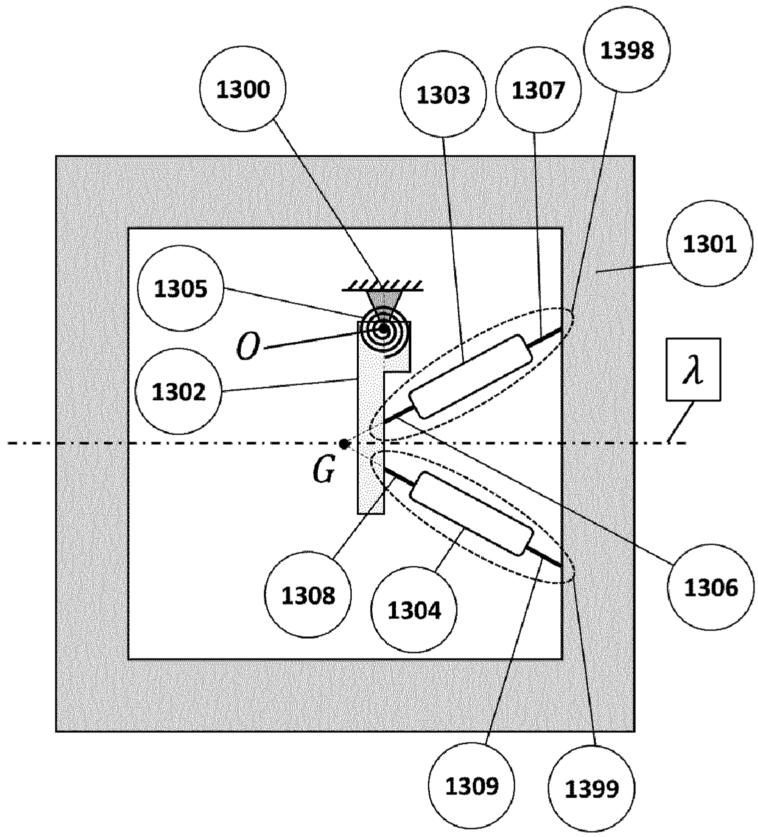

1206
1207
1298
1200
1203
1205
1202
λ
G
1201
1200
1204
1208
1209
1299

Fig.16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1398
1301
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O
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λ
G
1308
1304
1306
1309
1399

Fig.17

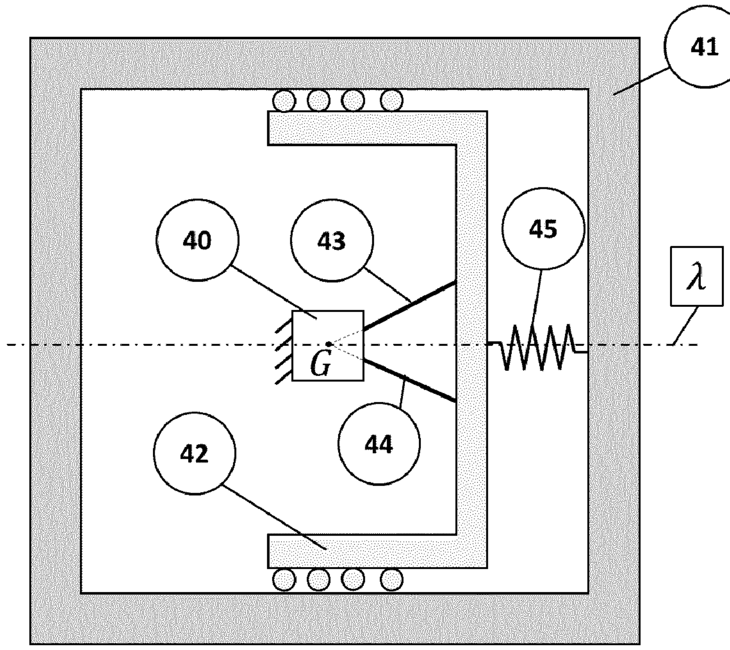


Fig.18

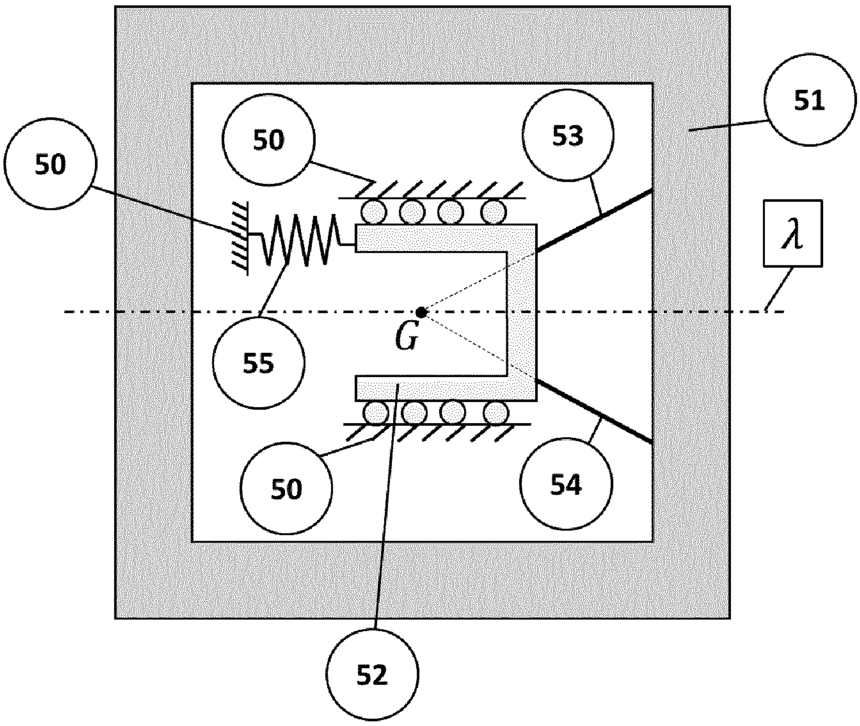


Fig.19

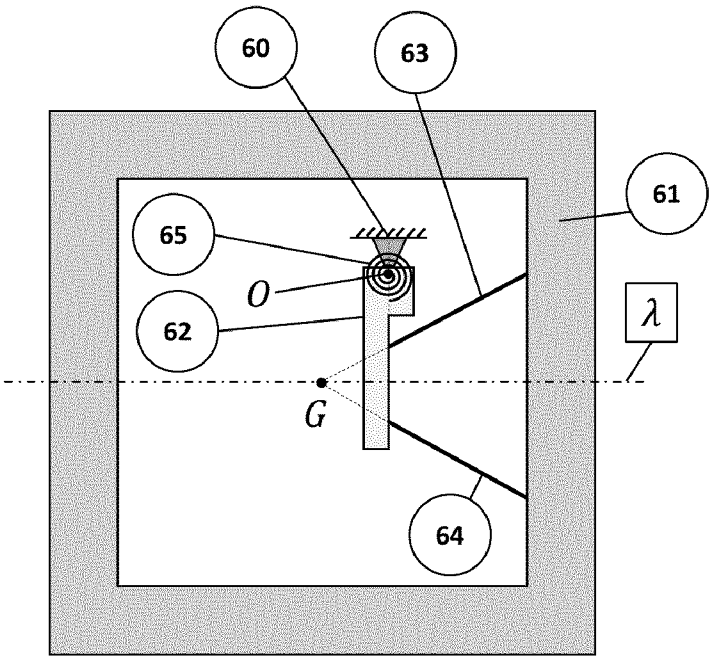


Fig.20

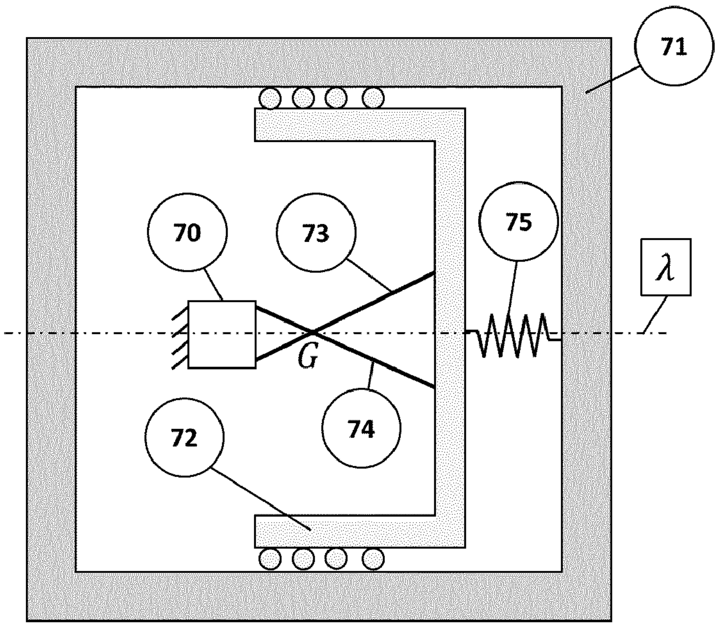


Fig.21

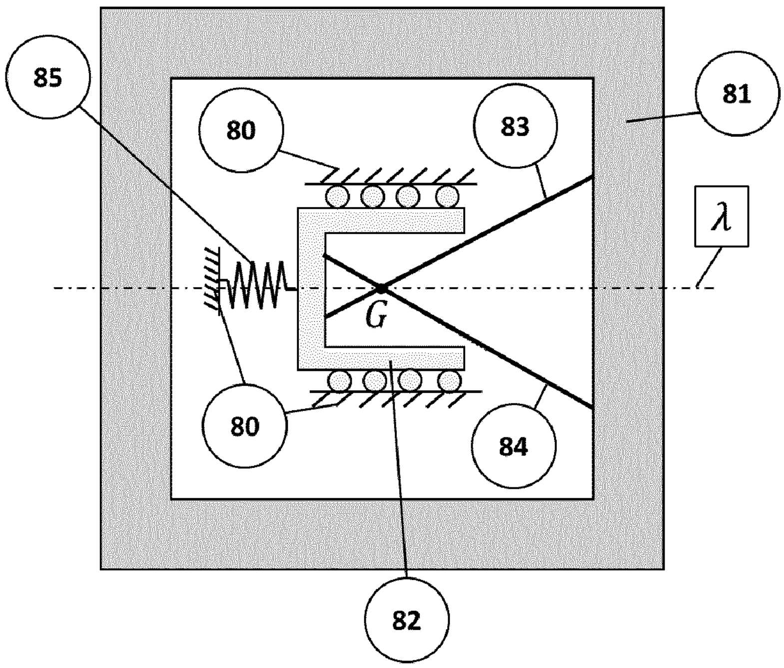


Fig.22

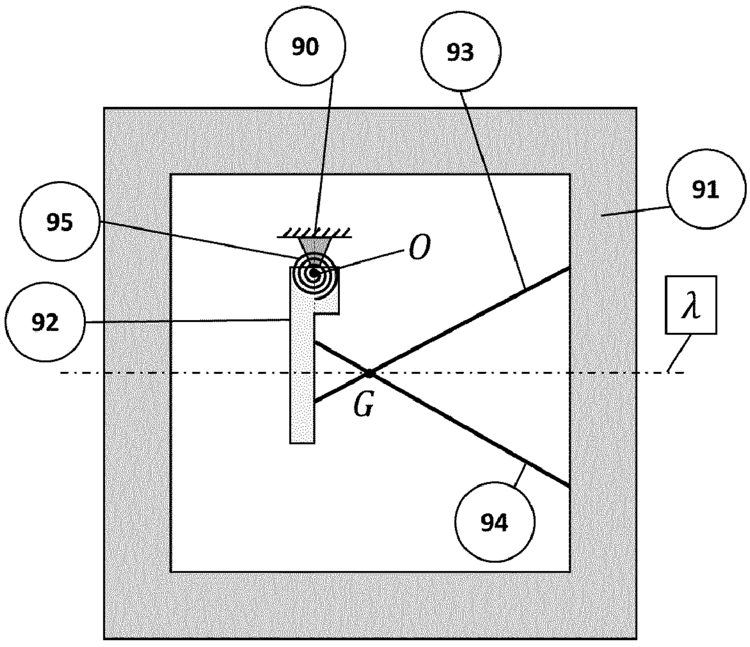
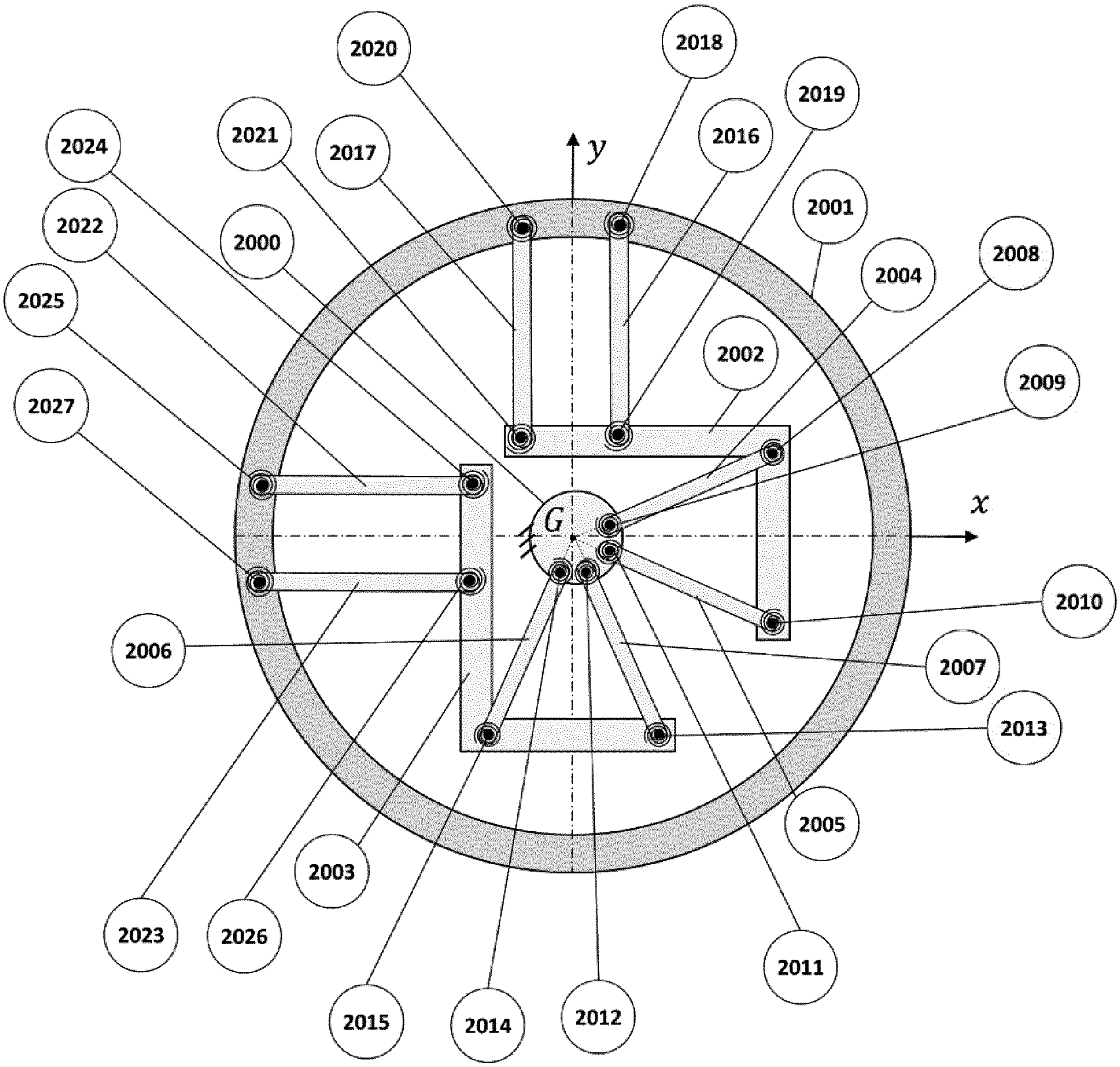


Fig.23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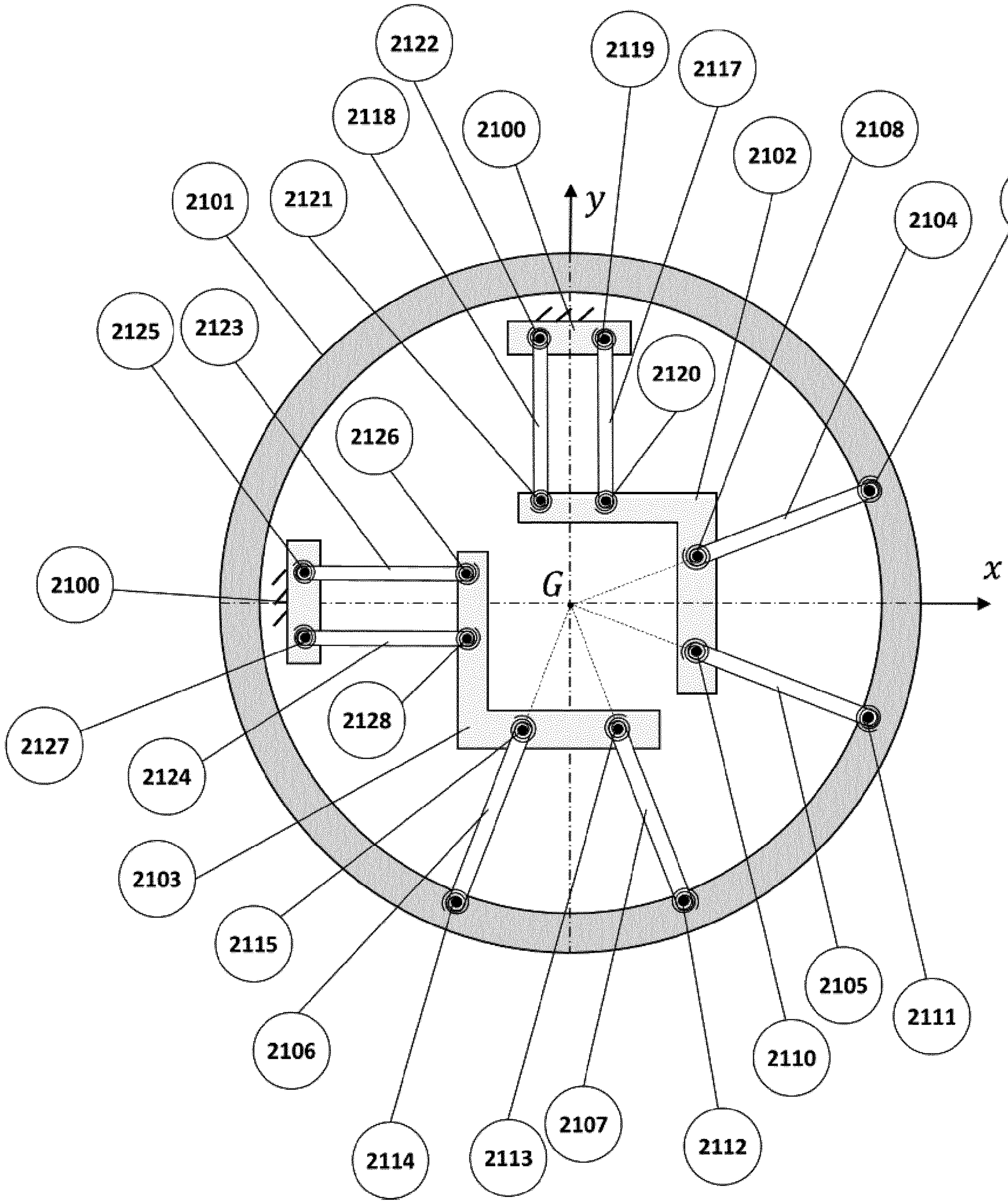
2018
2019
2024
2021
2017
2016
2001
2022
2000
2004
2008
2025
2002
2009
2027
y
x
G
2010
2006
2007
2013
2005
2003
2023
2026
2011
2015
2014
2012

Fig.24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y
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x
2100
G
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2103
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2111
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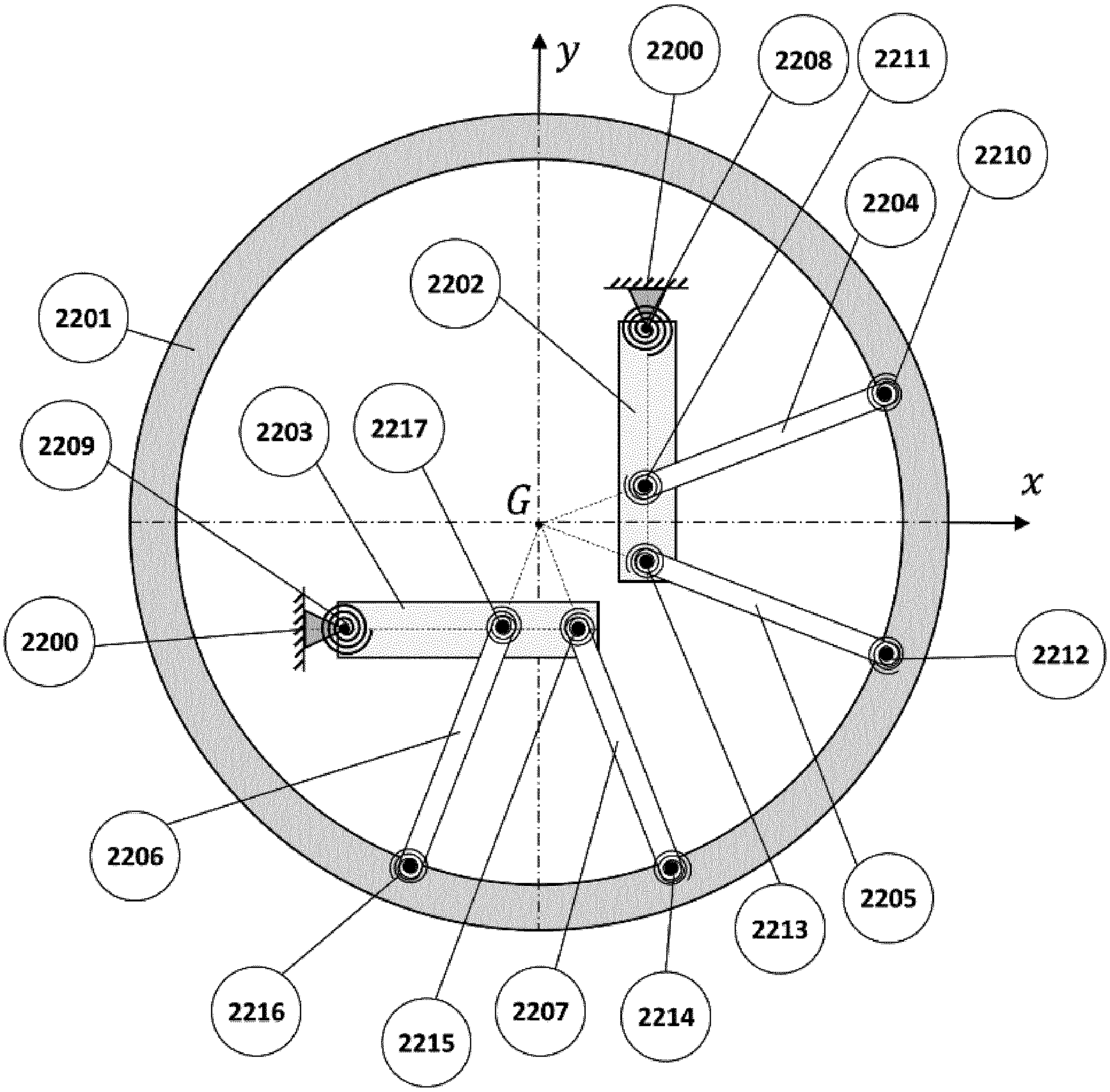
2113
2107
2112

Fig.25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x
G
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2208
2211
2210
2204
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2217
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2213
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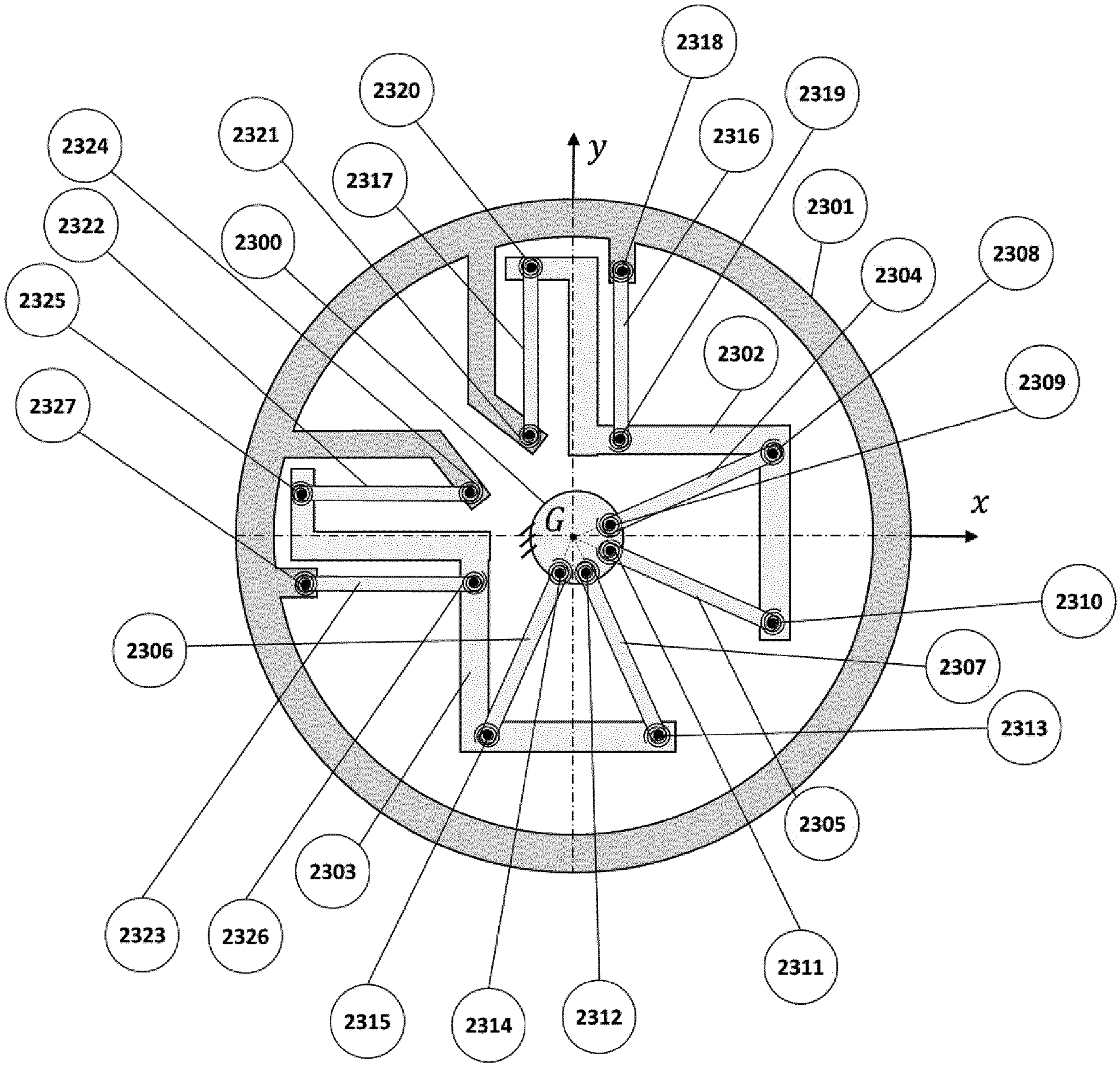
2207
2214

Fig.26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2316
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y
2301
2322
2300
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2302
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2315
2314
2312

Fig.27

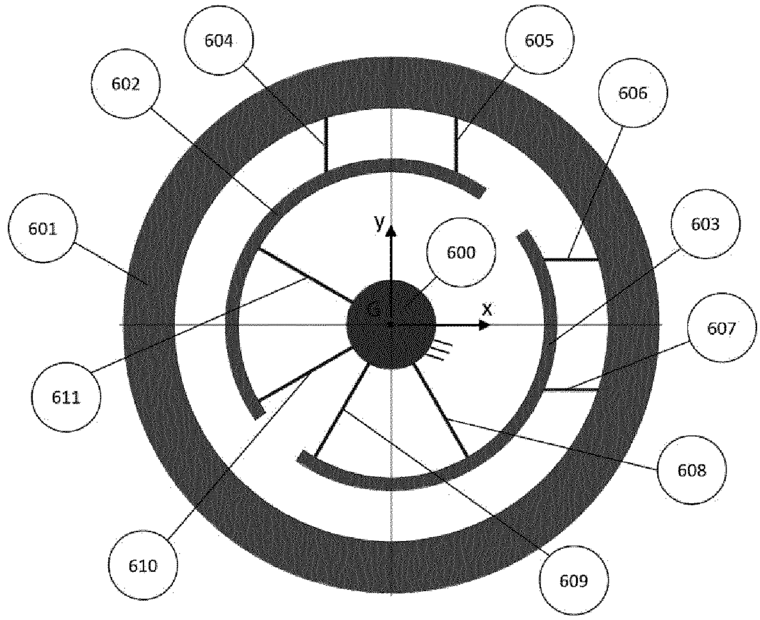
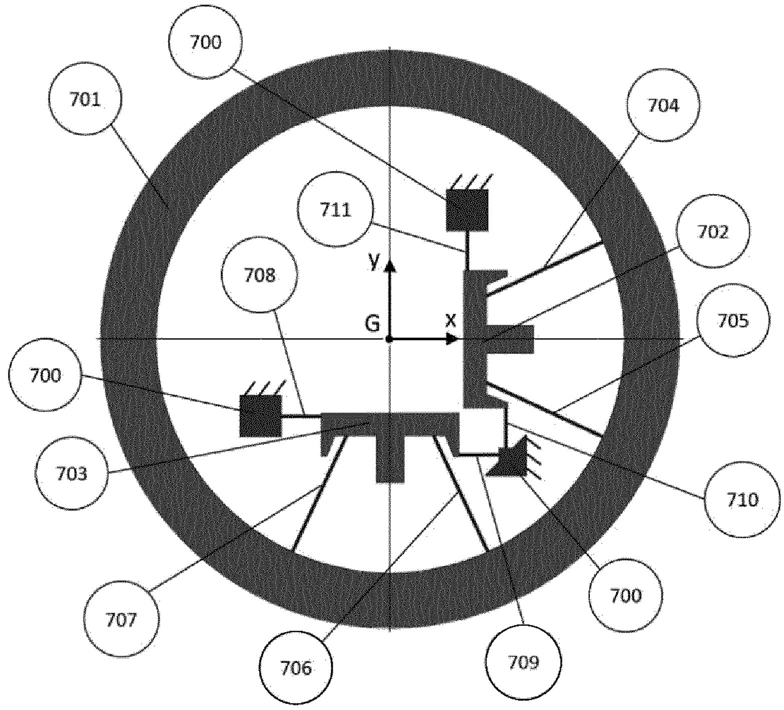

604
605
602
606
601
y
600
603
G
x
607
611
608
610
609

Fig.28


700
701
704
711
702
y
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G
x
705
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703
710
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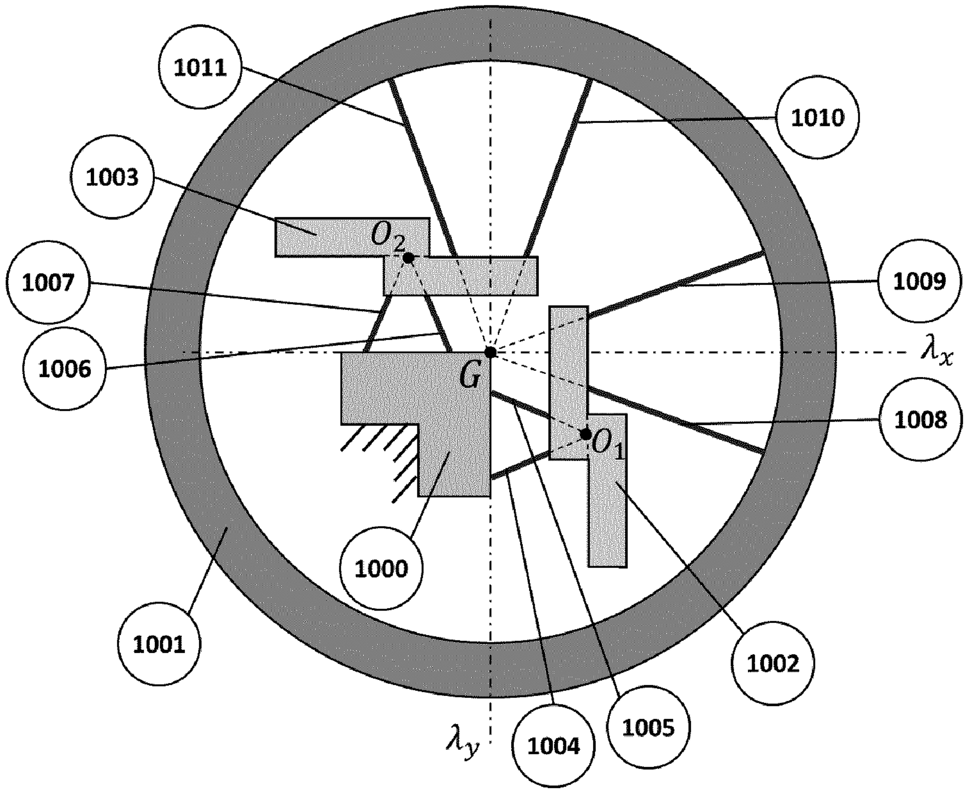
706
709

Fig.29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1010
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O_2
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1006
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λ_x
1008
O_1
1000
1001
1002
λ_y
1004
1005

Fig.30

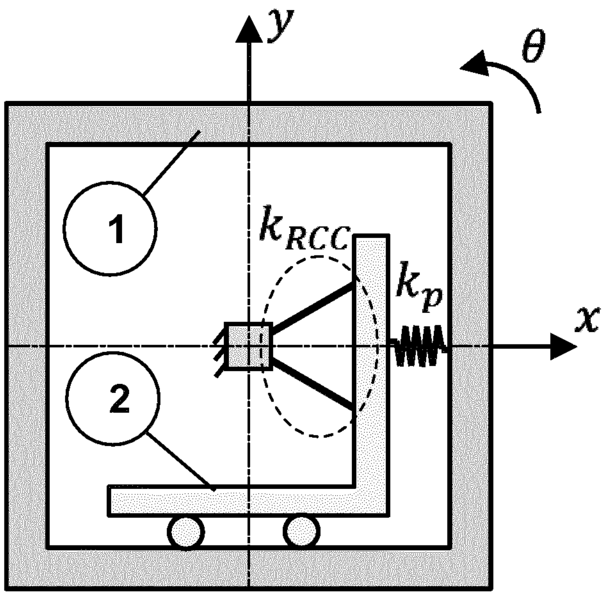


Fig.31

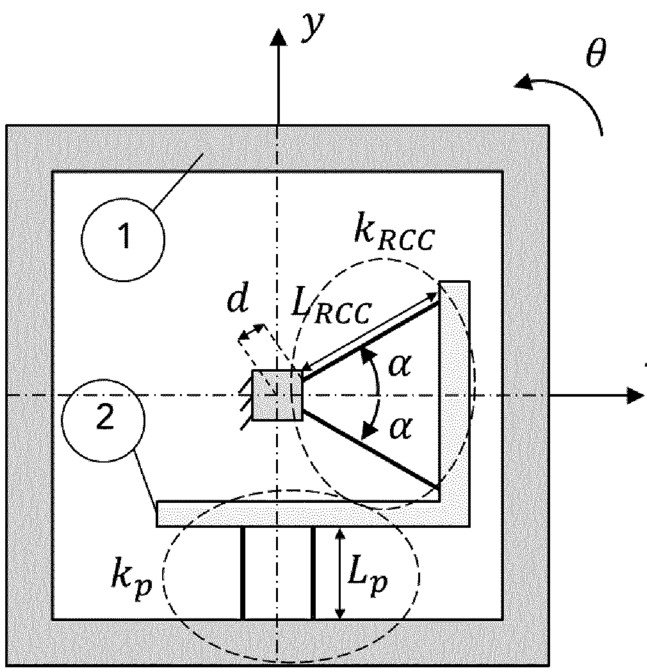


Fig.32

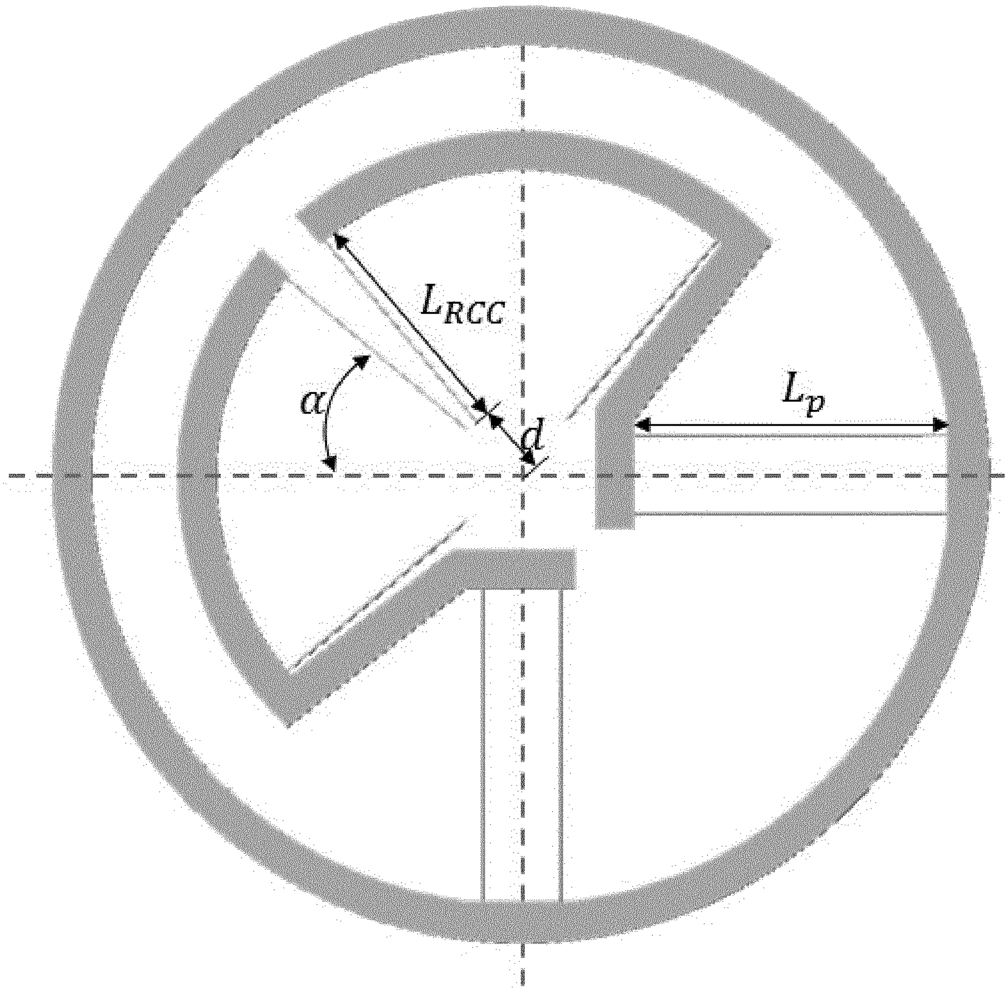


Fig.33

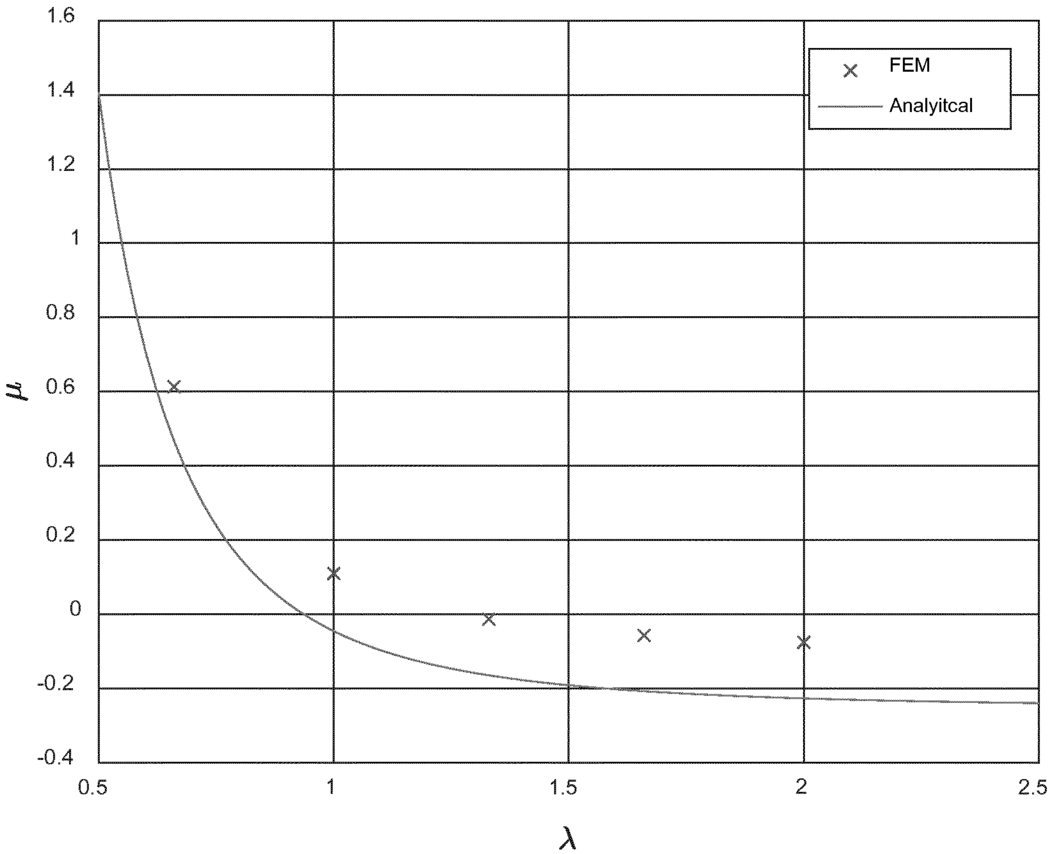
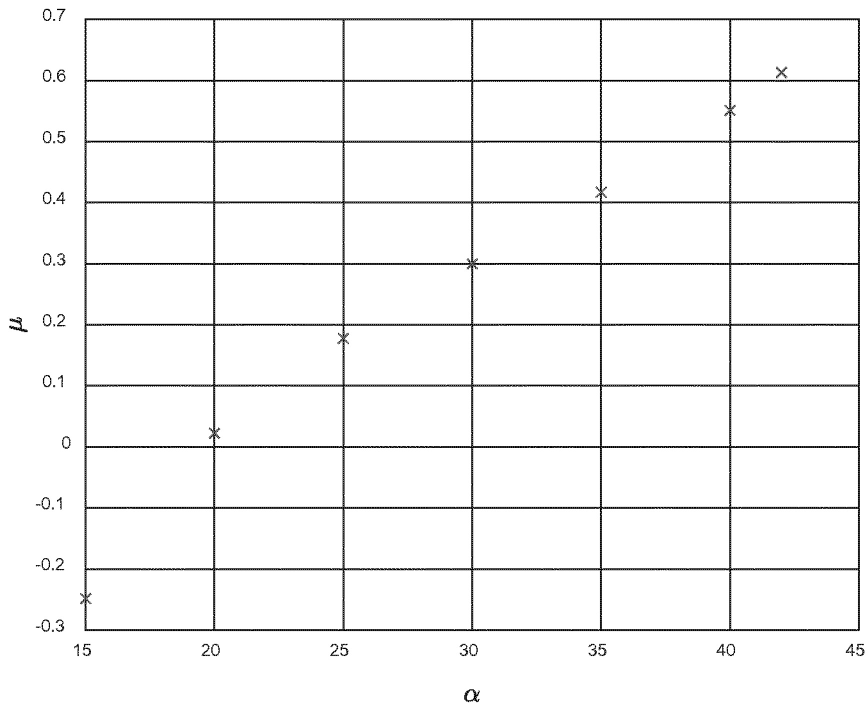


Fig.34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-0.1
-0.2
-0.3
μ
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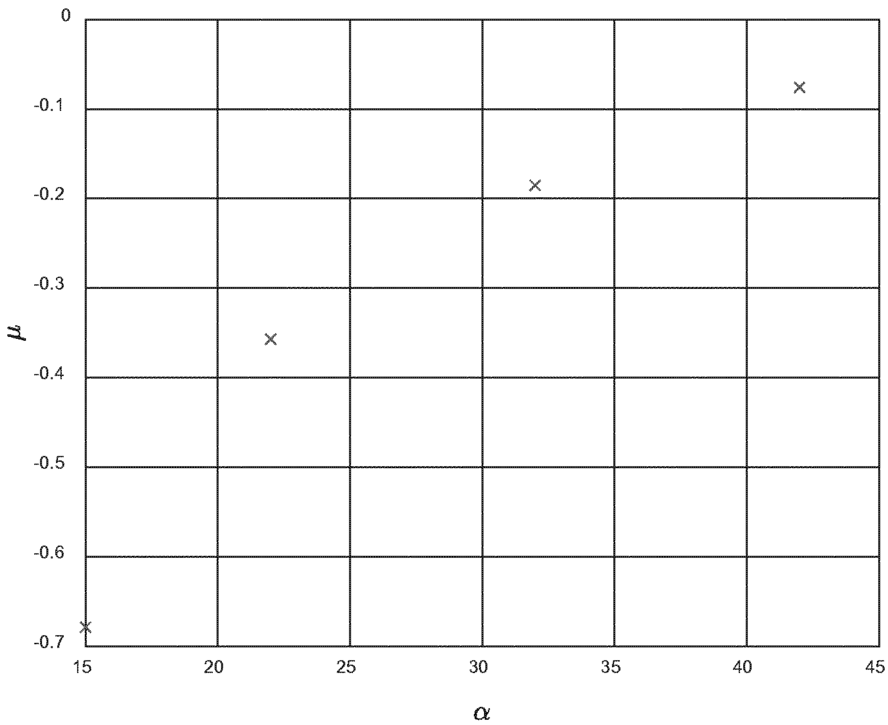
20
25
30
35
40
45
α

Fig.35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-0.6
-0.7
μ
15
20
25
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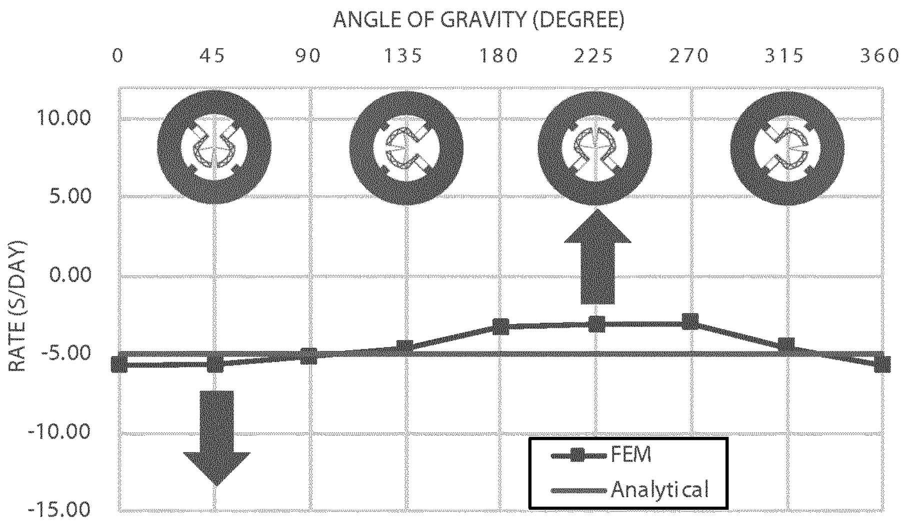
35
40
45
α

Fig.36


ANGLE OF GRAVITY (DEGREE)
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45
90
135
180
225
270
315
360
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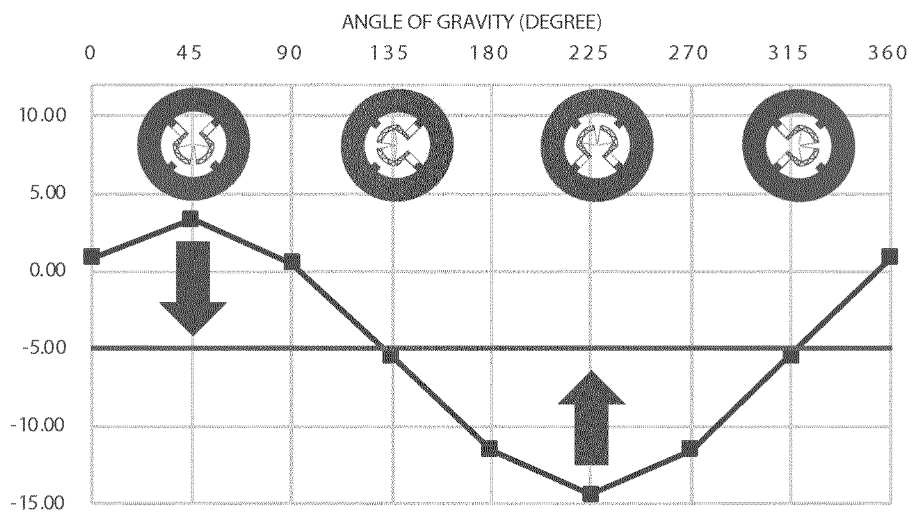
5.00
0.00
-5.00
-10.00
-15.00
RATE (S/DAY)
FEM
Analytical

Fig.37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225
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315
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5.00
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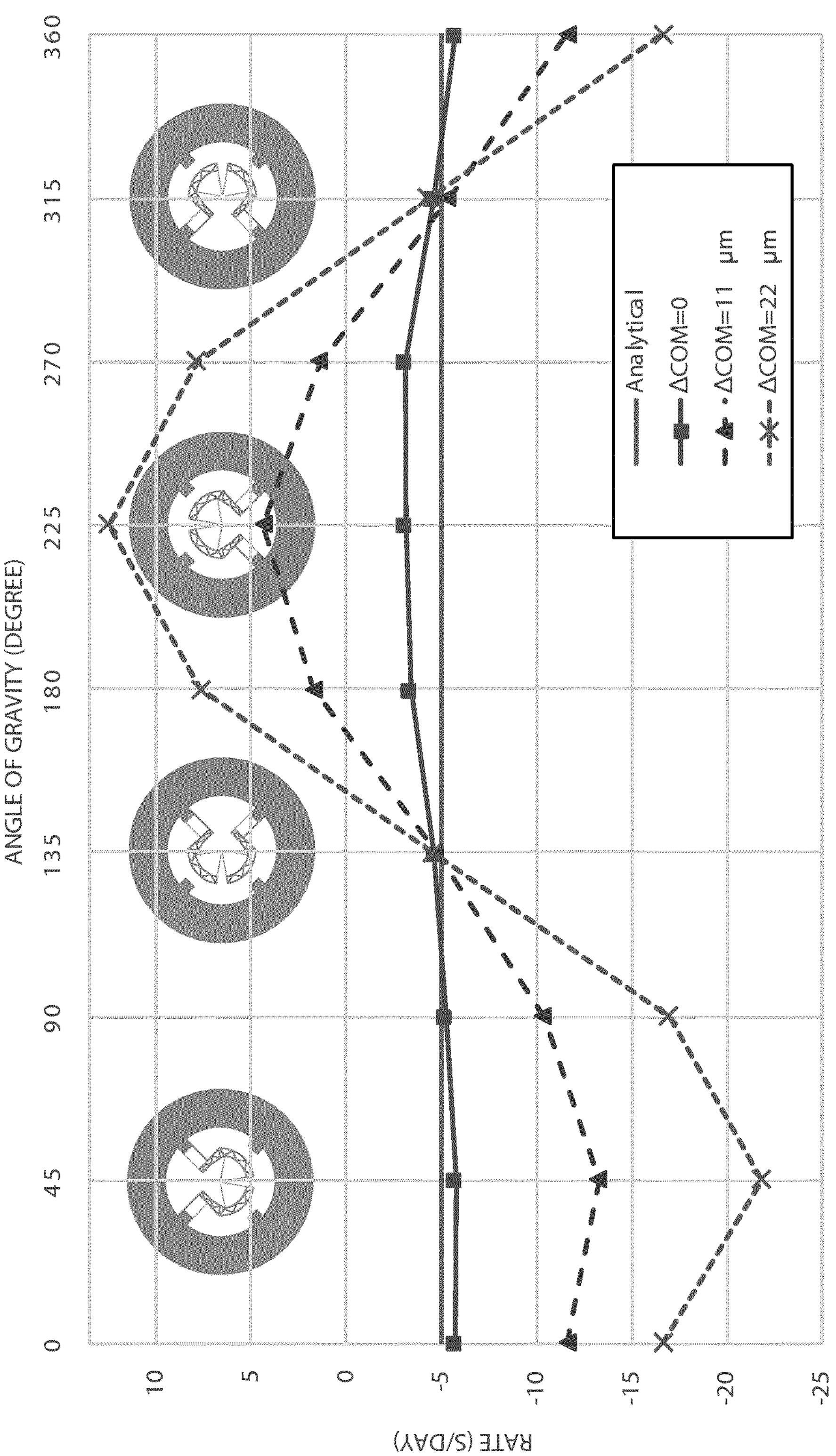
-5.00
-10.00
-15.00

Fig.38


ANGLE OF GRAVITY (DEGREE)
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45
90
135
180
225
270
315
360
RATE (S/DAY)
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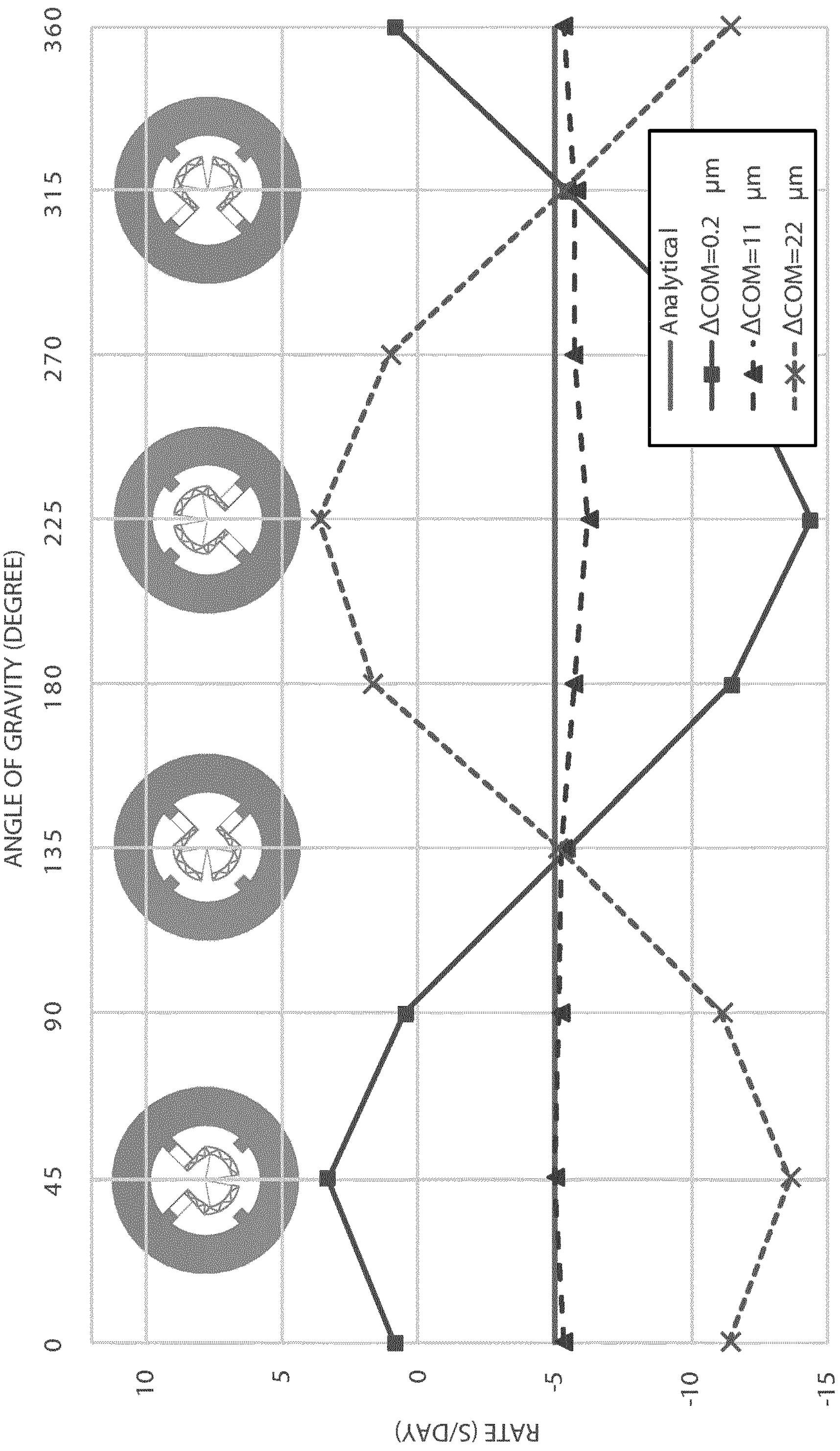
5
0
-5
-10
-15
-20
-25
Analytical
ΔCOM=0
ΔCOM=11 μm
ΔCOM=22 μm

Fig.39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90
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225
270
315
360
RATE (S/DAY)
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5
0
-5
-10
-15
Analytical
ΔCOM=0.2 μm
ΔCOM=11 μm
ΔCOM=22 μm

Fig.40

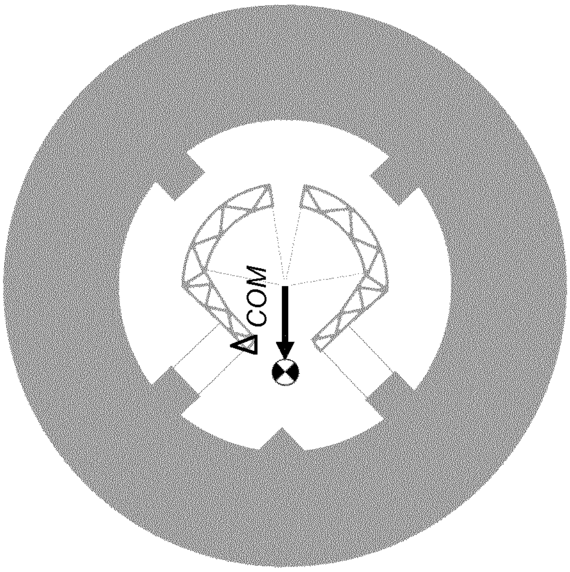


Fig.41

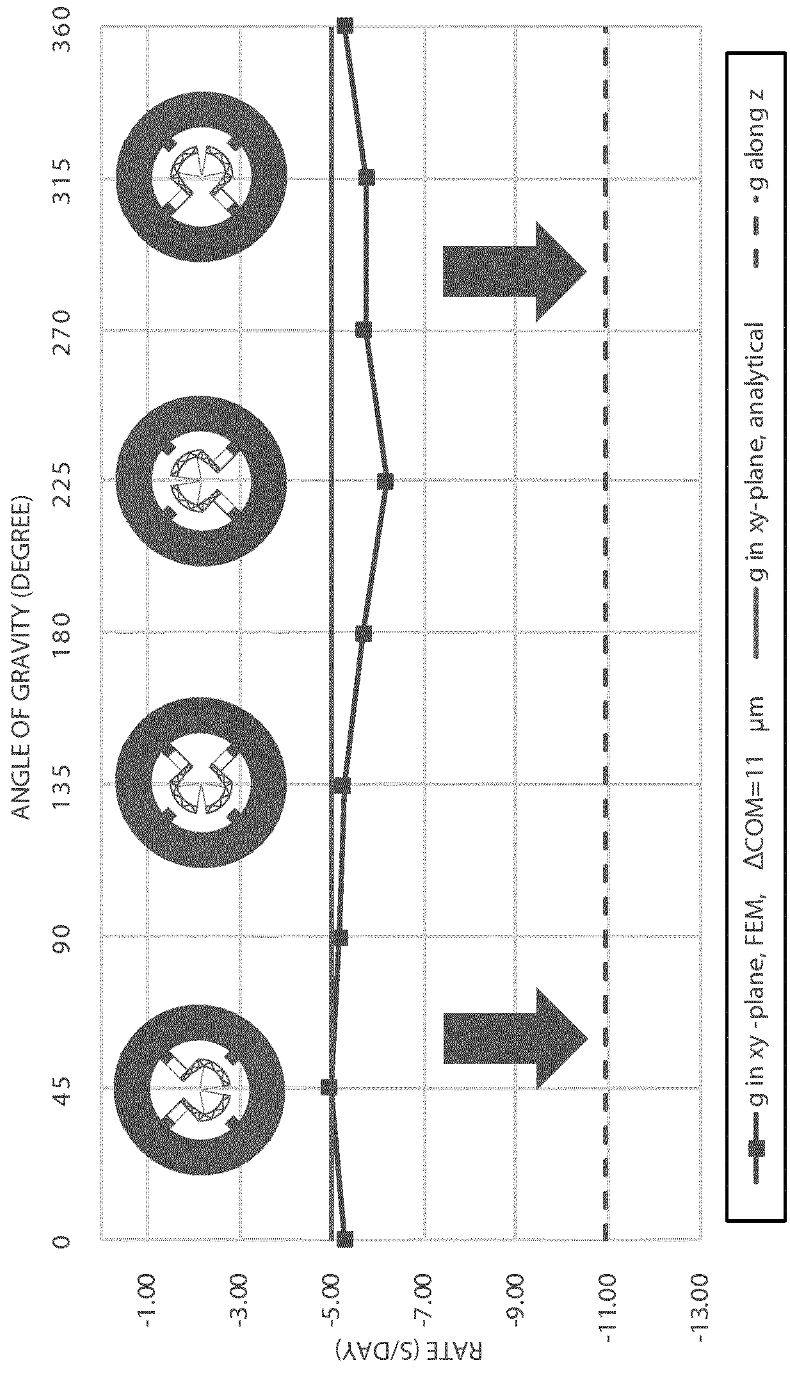

ANGLE OF GRAVITY (DEGREE)
0
45
90
135
180
225
270
315
360
RATE (S/DAY)
-1.00
-3.00
-5.00
-7.00
-9.00
-11.00
-13.00
g in xy -plane, FEM, ΔCOM=11 μm
g in xy-plane, analytical
g along z

Fig.42

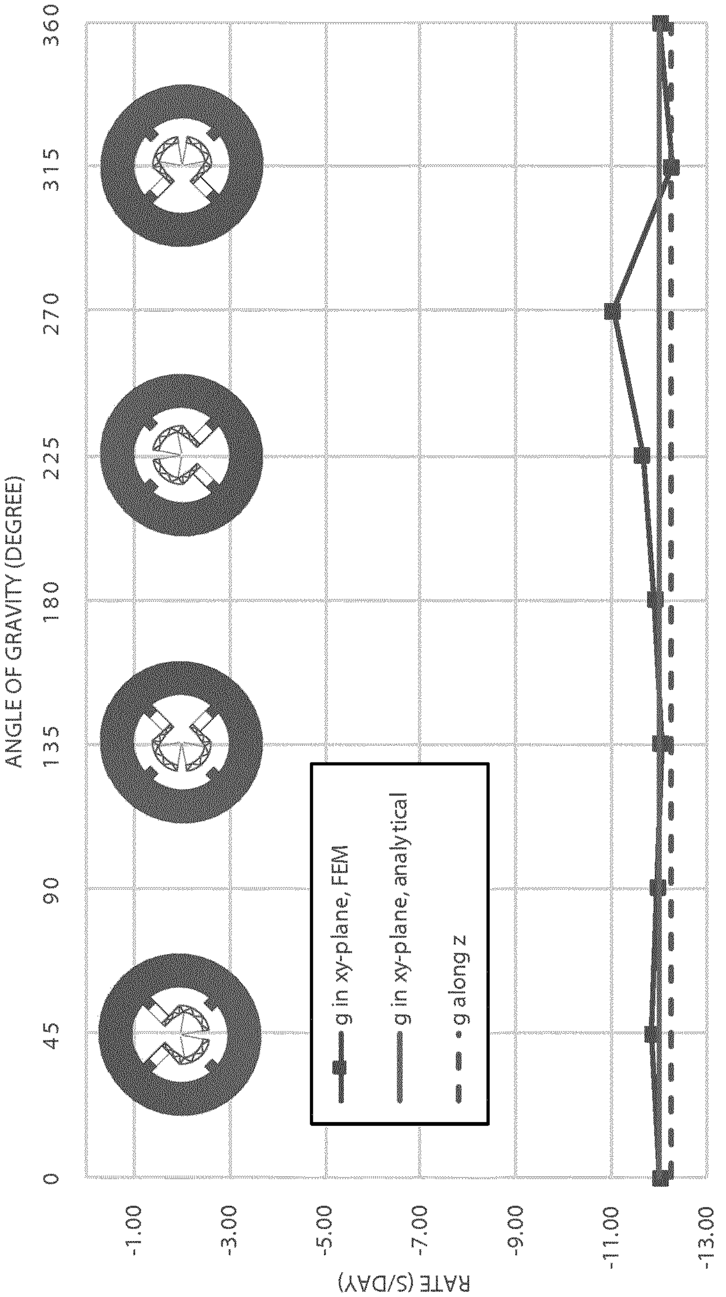

ANGLE OF GRAVITY (DEGREE)
0
45
90
135
180
225
270
315
360
RATE (S/DAY)
-1.00
-3.00
-5.00
-7.00
-9.00
-11.00
-13.00
g in xy-plane, FEM
g in xy-plane, analytical
g along z

Fig.43

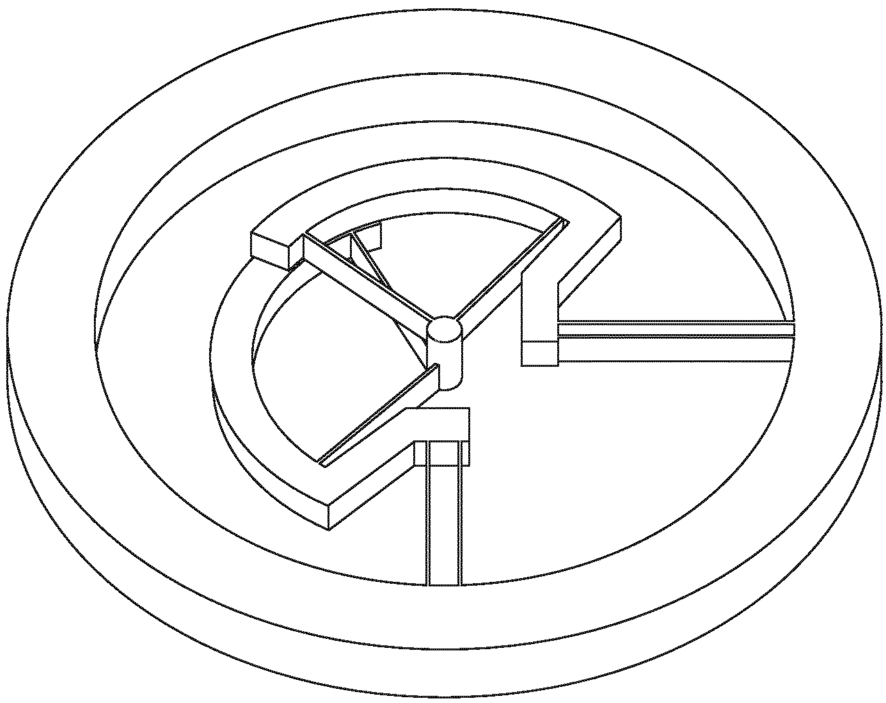
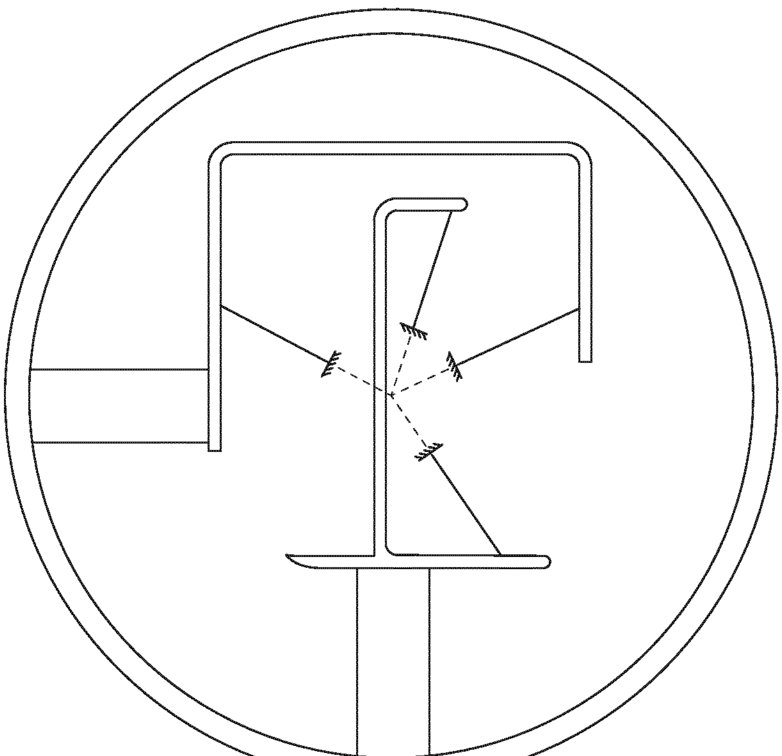


Fig.44



INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2019/068840

A. CLASSIFICATION OF SUBJECT MATTER
INV. G04B17/04 G04B17/28 G04B17/26
ADD.

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)
G04B

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.
E	EP 3 561 609 A1 (ETA SA MANUFACTURE HORLOGÈRE SUISSE) 30 October 2019 (2019-10-30) paragraphs [0045], [0050], [0051]; figure 8 -----	3,8, 10-13, 15,17,19
A	EP 3 324 247 A1 (SWATCH GROUP RES & DEV LTD [CH]) 23 May 2018 (2018-05-23) paragraph [0050]; figures 21,9,11 -----	1-20
A	EP 3 206 089 A1 (SWATCH GROUP RES & DEV LTD [CH]) 16 August 2017 (2017-08-16) page 4, lines 31-34, paragraph 29; figure 2 -----	1-20
A	EP 3 312 683 A1 (ETA SA MFT HORLOGERE SUISSE [CH]) 25 April 2018 (2018-04-25) figure 7 -----	1-20
	-/--	

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

[X] See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
1 November 2019	14/11/2019

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Cavallin, Alberto

2

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 2 273 323 A2 (MANUF ET FABRIQUE DE MONTRES ET DE CHRONOMETRES ULYSSE NARDIN LE LOCLE) 12 January 2011 (2011-01-12) figure 1	1-20

2

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2019/068840

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EP 3561609 A1	30-10-2019	CN 110389519 A	29-10-2019
		EP 3561609 A1	30-10-2019
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EP 3324247 A1	23-05-2018	CH 713138 A2	31-05-2018
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		EP 3324247 A1	23-05-2018
		JP 6453982 B2	16-01-2019
		JP 2018081094 A	24-05-2018
		US 2018136609 A1	17-05-2018
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		JP 6285584 B2	28-02-2018
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		JP 2018066738 A	26-04-2018
		RU 2017135224 A	05-04-2019
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		EP 2273323 A2	12-01-2011