(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) **World Intellectual Property Organization**
International Bureau

(43) **International Publication Date**
23 January 2025 (23.01.2025)

WIPO | PCT

(10) **International Publication Number**
WO 2025/017315 A1

(51) **International Patent Classification:**
F16F 15/10 (2006.01) ***F16F 15/18*** (2006.01) ***F16F 15/00*** (2006.01) *F16F 7/10* (2006.01) ***F16F 15/14*** (2006.01)

(21) **International Application Number:** PCT/GB2024/051893

(22) **International Filing Date:** 19 July 2024 (19.07.2024)

(25) **Filing Language:** English

(26) **Publication Language:** English

(30) **Priority Data:**
2311113.1 20 July 2023 (20.07.2023) GB
23275109.9 20 July 2023 (20.07.2023) EP

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(81) **Designated States** *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CV, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IQ, IR, IS, IT, JM, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, MG, MK, MN, MU, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

(84) **Designated States** *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, CV, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SC, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, ME, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

(54) **Title:** CONTROL ARRANGEMENT AND METHOD

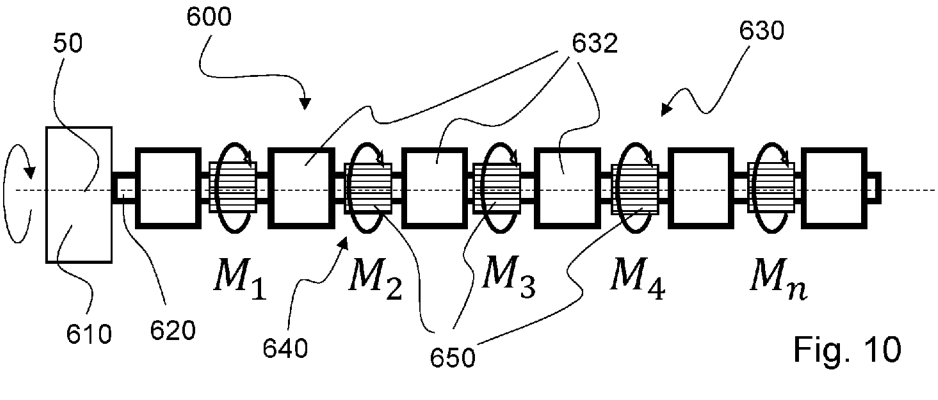

Fig. 10

(57) **Abstract:** A control arrangement (600) for controlling torsional vibration of a structure (610), the control arrangement comprising a body (620) and a control element configuration (630) providable along the body, wherein the body is couplable to the structure, wherein the control arrangement further comprises an active control apparatus (640) wherein, in use, the active control apparatus is operable to control the wave speed of torsional vibration of the body.

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Declarations under Rule 4.17:
— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

Published:
— *with international search report (Art. 21(3))*

CONTROL ARRANGEMENT AND METHOD

FIELD

The present invention relates to a control arrangement, in particular to a control arrangement for controlling torsional vibration of a structure. The present invention further relates to a method of controlling torsional vibration of a structure.

BACKGROUND

Torsional vibration is angular vibration of an object or structure. A common example is angular vibration of a shaft about its axis of rotation. Torsional vibration may be caused by speed fluctuations of various components and the twisting of sections of the object or structure during its rotation.

Excessive torsional vibration can lead to failure of components, such as shafts, couplings, fans, gears, engine dampers, and the like. Torsional vibration is often a concern in power transmission systems using rotating shafts or couplings. Torsional vibration can also result in other vibration effects or the generation of noise.

Existing control arrangements for controlling, or damping, torsional vibration include viscous dampers and tuned absorbers (otherwise known as harmonic dampers). Problems associated with such existing control arrangements include a requirement for space to incorporate the control arrangement, potential for failure or damage of the control arrangement due to the components and materials required, and insufficient control or damping of particular vibrational frequencies.

Furthermore, many conventional apparatuses do not allow for adjustable or adaptive control of torsional vibration. Instead, passive approaches have been proposed, but may have limited control over the torsional vibration, in particular reduced effectiveness in situations where frequency of torsional vibration may vary over time, or may provide limited low-frequency control.

It is one aim of the present invention, amongst others, to provide an improved control arrangement and/or address one or more of the problems discussed above, or discussed elsewhere, or to at least provide an alternative control arrangement.

SUMMARY

According to a first aspect of the present invention, there is provided a control arrangement for controlling torsional vibration of a structure, the control arrangement comprising body and a control element configuration providable along the body, wherein the body is couplable to the structure, wherein the control arrangement further comprises an active control apparatus wherein, in use, the active control apparatus is operable to control the wave speed of torsional vibration of the body.

In one example, the control arrangement is configurable to cause a decrease in wave speed of torsional vibration of the body.

In one example, the active control apparatus is operable to control the decrease in wave speed of torsional vibration of the body.

In one example, the body is couplable to, or with, the structure by being connectable to, providable in, or being part of, the structure. In one example, the body is coupled to the structure. In one example, the body is connected to, provided in, or part of, the structure.

In one example, the control element configuration comprises one or more regions of different material characteristic.

In one example, the active control apparatus is operable to control a material characteristic of one or more regions of the control element configuration.

In one example, the material characteristic is rigidity, density and/or shear modulus.

In one example, the active control apparatus and/or the control element configuration comprises a smart material or smart composite, wherein application of an electric and/or magnetic field to the smart material or smart composite causes a change in a material characteristic of the smart material or smart composite.

In one example, the control element configuration comprises a plurality of control elements. In one example, the control element configuration comprises a control element in the form of a graduated or varying material characteristic.

In one example, the control element configuration comprises a plurality of control elements. In one example, the control element configuration comprises a plurality of mass members. In one example, the control element configuration comprises spaced apart mass members.

In one example, the smart material or smart composite is provided between one or more pairs of mass members.

In one example, the smart material or smart composite is provided between one or more mass members and the body, so as to couple the one or more mass members to the body.

In one example, the active control apparatus comprises an actuator arrangement configured to apply a force to the control element configuration.

In one example, the actuator arrangement comprises one or more actuator assemblies, wherein at least one actuator assembly is arranged to provide a connection between a pair of mass members to provide a force thereto.

In one example, the actuator arrangement comprises one or more stators and one or more permanent magnets, wherein the actuator arrangement is configured to provide rotational actuation.

In one example, the actuator arrangement comprises: one or more stators connected to a first mass member of a pair of mass members; and one or more permanent magnets connected to a second mass member of the pair of mass members.

In one example, the actuator arrangement comprises: one or more stators mounted on a region of the body; and one or more permanent magnets connected to one or more mass members adjacent to the region of the body at which the one or more stators are mounted.

In one example, the actuator arrangement comprises: one or more permanent magnets mounted on a region of the body; and one or more stators connected to one or more mass members adjacent to the region of the body at which the one or more stators are mounted.

In one example, the actuator arrangement comprises: one or more stators provided remotely from the body; and one or more permanent magnets connected to one or more mass members.

In one example, the actuator arrangement comprises one or more rotary actuators provided between one or more pairs of mass members.

In one example, the actuator arrangement comprises one or more actively controllable proof-mass actuators, wherein the proof-mass actuators are attached to, or are embedded in, one or more of the mass members.

In one example, a damping material is provided between one or more pairs of mass members.

In one example, one or more of the mass members have: a disc-shaped cross section; a cross-shaped cross section; or a star-shaped cross section.

In one example, the body has a tapered cross section along at least part of its length.

In one example, in at least a subset of the mass members, a dimension of each mass member is the same as a dimension of the structure at a first end.

In one example, the body has a constant cross section along at least part of its length.

In one example, in at least a subset of the mass members, a dimension of each mass member increases along the length of the body.

In one example, the body has a first region of tapering cross section along a first part of its length and a second region of constant cross section along a second part of its length.

In one example, the structure is a shaft. In one example, the control arrangement is configured to be couplable to the shaft. In one example, the control arrangement is connectable to, providable in, on, or as part of the shaft. In one example, the control arrangement is coupled to the shaft. In one example, the control arrangement is connected to, provided in, or, or as part of the shaft.

In one example, the body is hollow.

In one example, the hollow body comprises at least a region of constant wall thickness and/or at least a region of decreasing wall thickness.

In one example, the control element configuration is provided on an inner surface and/or an outer surface of the hollow body.

According to a second aspect of the present invention, there is provided a method of controlling torsional vibration of a structure, the method comprising: providing a control arrangement comprising: a body, the body being couplable to the structure; a control element configuration; and an active control apparatus; providing the control element configuration along the body; and operating the active control apparatus to control the wave speed of torsional vibration of the body.

In one example, the method comprises causing, by the control arrangement, a decrease in wave speed of torsional vibration of the body.

In one example, the method comprises operating the active control apparatus to control the decrease in wave speed of torsional vibration of the body.

In one example, the method comprises coupling the body with the structure. In one example, the method comprises coupling the body with the structure by connecting the body and the structure, providing the body in or on the structure, or providing the body as part of the structure.

In one example, the method comprises providing a control element configuration comprising a plurality of control elements. In one example, the plurality of control elements may be mass members. In one example, the method comprises spacing the control elements, or mass members, apart along the structure.

According to a third aspect of the present invention, there is provided a vehicle comprising a control arrangement according to the first aspect of the present invention.

According to a fourth aspect of the present invention, there is provided a component, for example a damped component, comprising a control arrangement according to the first aspect of the present invention. The component may be, or comprise, the structure.

According to a further aspect of the present invention, there is provided a method of manufacturing a control arrangement according to the first aspect of the present invention. The method comprises providing: a body, the body being couplable to the structure; a control element configuration; and an active control apparatus; providing the control element configuration along a body; configuring the control arrangement to control the wave speed of torsional vibration of the body.

In one example, the method may comprise configuring the control arrangement to control a decrease in wave speed of torsional vibration of the body.

In one example, the method may comprise configuring the active control apparatus to operate to control the decrease in wave speed of torsional vibration of the body.

Features of any one aspect may be combined with features of any other aspect, as desired or as appropriate. In particular, features of the control arrangement according to the first aspect may be combined with features of the method, vehicle or structure according to the second, third and fourth aspects.

BRIEF DESCRIPTION OF THE FIGURES

Embodiments of the invention will now be described by way of example only with reference to the figures, in which:

Figure 1 shows a control arrangement;

Figure 2 shows a control arrangement;

Figure 3 shows a control arrangement comprising an active control apparatus;

Figure 4 shows a control arrangement;

Figure 5 shows a control arrangement;

Figure 6 shows a control arrangement;

Figure 7 shows a control arrangement provided with a damping material;

Figure 8(a) and (b) shows control arrangement cross sections;

Figure 9(a) to (c) shows control arrangements comprising hollow shafts;

Figure 10 shows a control arrangement comprising an active control apparatus;

Figure 11 shows a control arrangement comprising an active control apparatus;

Figure 12 shows a cross section through a mass member of a control arrangement comprising an active control apparatus;

Figure 13 shows a control arrangement comprising an active control apparatus;

Figure 14 shows control arrangements comprising an active control apparatus;

Figure 15(a) and (b) show control arrangements each comprising an active control apparatus;

Figure 16 shows a control arrangement comprising an active control apparatus;

Figure 17 shows a control arrangement comprising an active control apparatus;

Figure 18(a) and (b) show control arrangements each comprising an active control apparatus;

Figure 19 shows an example of a coupled control arrangement and structure;

Figure 20 shows an example of a coupled control arrangement and structure;

Figure 21 shows a vehicle;

Figure 22 shows a construction; and

Figure 23 shows general methodology principles.

DETAILED DESCRIPTION

In overview of the disclosure provided herein, control arrangements are described which are configured to reduce the wave speed of torsional vibration of, or in, a body. By reducing the wave speed of torsional vibration, the effect of material losses within the control arrangement is increased due to the decrease in wavelength of the torsional vibration. That is, damping as a result of structural losses increases as the wavelength of the torsional vibration decreases. In this way, energy (i.e., unwanted energy due to torsional vibration) is more efficiently and effectively dissipated. Furthermore, in this way, energy (i.e., unwanted energy due to torsional vibration) passed from a structure to the body is more efficiently and effectively dissipated.

This can be understood from a theoretical perspective. The torsional wave speed c is defined as

$$c = \sqrt{\frac{G\,J(x)}{I(x)}}$$

where G is the shear modulus, $J(x)$ is the polar moment of inertia or torsional constant, and $I(x)$ is the mass moment of inertia.

However, for a uniform cross section of the structure, $J(x) = \iint xy\,dx\,dy$ and $I(x) = \iint \rho xy\,dx\,dy$. Therefore, the torsional wave speed c reduces to

$$c = \sqrt{\frac{G}{\rho}}$$

and thus it may be understood that a change in diameter of the structure alone does not affect the wave speed of torsional vibration.

In the present disclosure, mechanisms, or approaches, to reduce the wave speed of torsional vibration include:

1. Reducing the material shear modulus G
2. Increasing the material density ρ
3. Providing a control arrangement having a non-uniform cross section that reduces the ratio of the polar moment of inertia $J(x)$ to mass moment of inertia $I(x)$ (e.g., maintains the same effective mass moment of inertia $I(x)$ but decreases in polar moment of inertia $J(x)$, or increases the effective mass moment of inertia $I(x)$ but maintains the polar moment of inertia $J(x)$)

The embodiments described herein each incorporate one or more of these mechanisms or approaches in order to cause or affect a decrease in (or, more generally, control of) wave speed of torsional vibration. The mechanisms may be combined, which may enhance the damping effect.

Control arrangements for controlling torsional vibration of a structure will be described. Vibration in the structure (to which the control arrangement is couplable, or is coupled to) is absorbed and dissipated by the control arrangement.

Comparisons may be drawn with the acoustic black hole effect. An acoustic black hole is a device or constructions configured to exhibit the acoustic black hole effect. The acoustic black hole effect involves causing the wavelength of vibration propagating along the acoustic black hole to be reduced to zero.

In the present disclosure, the structure may be any object or component, for example a shaft, coupling, fan, or gear. The structure may be any rotatable component, i.e., a component configured to rotate, or be rotated, in use. Rotation of the structure may cause, generate, or result in, torsional vibration. In the examples described herein, the structure (and a body which is coupled to the structure) is configured to rotate about an axis (e.g., a longitudinal axis, indicated as axis 50 in Figures 1 to 6, 10, 11, 13 to 17, and 19, with the direction of rotation indicated by the associated arrow). In a particularly advantageous arrangement, the control arrangement used in combination with a shaft. A shaft may be an elongate member which is configured to be rotated, in use. The control arrangement may be coupled to the shaft. A shaft may be subjected to torsional vibration and torsional forces, and thus controlling torsional vibration thereof is highly advantageous in reducing risk of damage or failure due to fatigue. A further advantage associated with application to a shaft is the reduction in level of generated noise.

In general, the structure may be any structure, object or component to which the control arrangements described herein may be coupled, or couplable, to. The structure and control arrangement may together be referred to as an assembly, vibrationally controlled assembly, or a damped structure or damped component. In an example, the control arrangement being coupled or couplable to the structure may be by virtue of the control arrangement being connected, or connectable to, the structure. For example, the control arrangement may be connected at an end of the structure, or to a surface of the structure. In a further example, the control arrangement being coupled or couplable to the structure may be by virtue of the control arrangement being providable on or in the structure. For example, the control arrangement may replace a section of the structure, for example a section or portion of the structure may be replaced with the control arrangement, and the control arrangement may act as a part of the structure. In a further example, the control arrangement being coupled or couplable to the structure may be by virtue of the control arrangement being part of the structure. For example, the body of the control arrangement (described in greater detail below) may actually be provided by the structure itself. That is, the body may be provided by a body, or body portion, of the structure. The control element configuration may be providable along the body, and in this example this means that the control element configuration is providable along the structure. Furthermore, in such an example it may be considered that the control element configuration acts to cause a decrease in wave speed of torsional vibration in the structure. This is in contrast to providing a specific, or distinct, body portion – instead, the structure itself provides the body. In relation to the above, coupling, by connecting, providing on or in, or as part of the structure, allows torsional vibration to be passed from the structure to the control arrangement, to be controlled thereat. Each of the couplings described above may be highly advantageous, as torsional vibration of the structure can propagate to the control arrangement to be controlled, thereby reducing torsional vibration, reducing noise, and/or reducing fatigue or damage to the structure. Coupling by connecting the control arrangement to the structure may be simple to construct. Coupling by providing the control arrangement on or in the structure may reduce the overall weight, save space, and improve the propagation of torsional vibration from the structure to the control arrangement. Coupling by the control arrangement being part of the structure may reduce the overall weight and save space.

Referring to the figures, various embodiments of control arrangements are shown. Each control arrangement described herein is for controlling torsional vibration of a structure. Each control arrangement comprises a control element configuration, which may comprise or be a plurality of control elements. For avoidance of doubt, and as will be described in greater detail below, control elements may include mass members or regions, or sections, of reduced shear modulus or increased material density. Control elements are providable along the body (which as above may be a distinct body of the control arrangement, or indeed a part of the structure itself). Control elements may be mountable, or mounted, along the body. Each control arrangement may be configurable to cause a decrease in wave speed of torsional vibration of the body. In other words, when the structure is subjected to, or experiences, torsional vibration, the control arrangement may cause (or “function so as to cause”) a decrease in wave speed of torsional vibration of the body. The body may be connected to, or be part of, a structure which is part of a vibrating system or is a source of vibration. For example, the structure may be a component part of an engine.

As introduction to a subset of the figures, in particular to Figures 3 and 10 to 18, various embodiments of control arrangements are shown, in which each control arrangement comprises an active control apparatus. In use, the active control apparatuses are operable to control the wave speed of torsional vibration of the body. Whilst the control arrangements of other figures may be considered to be examples of "passive" control arrangements, the control arrangements described in relation to Figures 3 and 10 to 18 may be considered to be examples of "active" control arrangements. Examples of active control apparatuses may adapt or adjust, or be adapted or adjusted, so as to control the wave speed of torsional vibration. It will be appreciated that the active control apparatus described in relation to Figure 3 and 10 to 18 may be incorporated in the control arrangements described in relation to the other figures. That is, features thereof may be combined as desired or as appropriate. In particular, the control arrangements described in relation to each of Figures 1, 2, and 4 to 9 may comprise one or more of the examples of active control apparatus described in relation to Figures 3 and 10 to 18. That is, active control apparatus are described in relation to Figures 3 and 10 to 18 may be applied to any of the control arrangements described herein. Such combinations may synergistically provide advantages in both increasing or controlling the damping effect, and enabling adjustment or adaptability to different frequencies and/or magnitudes of torsional vibration. That is, the active control apparatus described herein enable control of the level of damping.

As mentioned above, in use, the active control apparatuses are operable to control the wave speed of torsional vibration of the body. Typically, this control is to control a decrease (or a level of decrease, or reduction) in the wave speed of torsional vibration of the body. However, in other examples, control may be to maintain a wave speed of torsional vibration of the body. That is, maintaining the wave speed of torsional vibration may be to counteract the effect of external force which would otherwise cause an increase in the wave speed of torsional vibration of the body. In this sense, the active control apparatus also similarly operates to control a "decrease" in the wave speed of torsional vibration of the body. In some examples, for example for testing, it may be useful for the active control apparatus to operate to control an increase in wave speed of torsional vibration of the body. However, primarily, the active control apparatus operates to control a decrease in the wave speed of torsional vibration of the body, and the description herein focuses on this approach. It will nevertheless be appreciated by the skilled person from the disclosure herein that each active control apparatus may also be operable to maintain or increase the wave speed of torsional vibration of the body.

Referring to Figure 1, a first embodiment of a control arrangement 100 is shown. The control arrangement 100 is for controlling torsional vibration of a structure 110. The control arrangement 100 comprises a body 120. The body 120 is coupled to the structure 110. In this example, the body 120 is coupled to the structure 110 by being connected at an end of the structure 110. The control arrangement 100 comprises a control element configuration 130, which may otherwise be referred to as a control element arrangement 130. The control element configuration 130 may act to cause a decrease in wave speed of torsional vibration in the body 120. The control element configuration 110 is provided along the body 120. As mentioned above (and also relevant to Figures 2 to 6 and 10 to 19), the structure 110 and body 120 are configured to rotate about axis 50 in the direction of the associated arrow. Rotation results in the generation of torsional vibration which it is desired to control.

In the first embodiment (and also in the second embodiment described below), the control element configuration 130 comprises one or more regions of different material characteristic. That is, each region may have a different material characteristic, and/or within a region the material characteristic may be graded or graduated or gradually varying. The term “material characteristic” is used to refer to a characteristic of the material from which the control element configuration 130 and/or body 120 is formed, where for example the characteristic may be rigidity, density and/or shear modulus. Such characteristics are suited to causing a decrease in wave speed of torsional vibration of the body 120 when employed in the manner described herein.

In the first embodiment, the material shear modulus G is graduated, or “graded”, along the length of the body 120. Here, the shear modulus gradually reduces along the length of the body 120. This is an example of the first mechanism described above to reduce the wave speed of torsional vibration of the body 120. The control element configuration 130 may be provided on or in the body 120. That is, the body 120 itself may be formed so as to provide the control element configuration 130 – in other words, the body 120 may have a gradually reducing shear modulus along its length, thereby providing the control element configuration 130.

The control element configuration 130 may comprise a stack of discs of different materials, having gradually reducing shear modulus. Alternatively, or additionally, additive manufacture may be used to provide the graduated shear modulus of the control element configuration 130. In an example, the control element configuration 130 may comprise a variation from PMMA/acrylic (e.g., as a material of relatively higher shear modulus) to a thermoplastic elastomer/rubber (e.g., as a material of relatively lower shear modulus).

Gradually reducing the shear modulus is advantageous in reducing the wave speed of torsional vibration, and thus providing damping. However, a problem associated with this approach may be undesired or impractical levels of flexibility of the control element configuration 130 and/or body 120.

Referring to Figure 2, a second embodiment of a control arrangement 200 is shown. The control arrangement 200 is for controlling torsional vibration of a structure 210. The control arrangement 200 comprises a body 220. The body 220 is coupled to the structure 210. In this example, the body 220 is coupled to the structure 210 by being connected at an end of the structure 210. The control arrangement 200 comprises a control element configuration 230. The control element configuration 230 is provided along the body 220. In the second embodiment, the material density ρ is graduated, or “graded”, along the length of the structure. Here, the density gradually increases along the length of the body 220. This is an example of the second mechanism described above to reduce the wave speed of torsional vibration. The control element configuration 230 may be provided on or in the body 220. That is, the body 220 itself may be formed so as to provide the control element configuration 230 – in other words, the body 220 may have a gradually increasing density along its length, thereby providing the control element configuration 230.

The control element configuration 230 may comprise a series or stack of discs of different materials, having gradually increasing density. Alternatively, or additionally, additive manufacture may be used to provide the graduated density of the control element configuration 230. In an example, the control element configuration 230 may comprise a variation from carbon fibre (e.g., as a material of relatively lower density) to tungsten (e.g., as a material of relatively higher density).

Gradually increasing the density is advantageous in reducing the wave speed of torsional vibration, and thus providing damping. However, a problem associated with this approach is that it may only be possible to achieve a relatively small change in density with practical materials for the control element configuration 230 and/or body 220. Level of control of torsional vibration may thereby be less than necessary or desired.

In relation to Figures 1 and 2 described above, variation in shear modulus or density, as the aforementioned material characteristic, is described. In a further example, the material characteristic may be rigidity. The rigidity may be graduated to interact with the torsional vibration to cause a decrease in the wave speed thereof.

Referring to Figure 3, a third embodiment of a control arrangement 300 is shown. The control arrangement 300 is for controlling torsional vibration of a structure 310. The control arrangement 300 comprises a body 320. The body 320 is coupled to the structure 310. In this example, the body 320 is coupled to the structure 310 by being connected at an end of the structure 310. The control arrangement 300 comprises a control element configuration 330. The control element configuration 330 is provided along the body 220. In the third embodiment, the control arrangement 300 comprises an active control apparatus 340. In use, the active control apparatus 340 is operable to control the wave speed (e.g., the decrease in wave speed) of torsional vibration of the body 320.

In the third embodiment, the active control apparatus 340 is operable to control the material characteristic of one or more regions of the control element configuration 330. In this way, the control element configuration 330 can be configured, or controlled, so as to comprise one or more regions of different material characteristic, and/or within a region the material characteristic may be graded or graduated or gradually varying. The term “material characteristic” may be used to refer to a characteristic of the material from which the control element configuration 330 and/or body 320 is formed. Additionally, or alternatively, in some examples, the control element configuration 330 may be taken to comprise the active control apparatus 340, and thus the term “material characteristic” may also encompass characteristics, or states, of the active control apparatus 340. For example, the characteristic may be rigidity, density and/or shear modulus.

Such characteristics are suited to causing a decrease in wave speed of torsional vibration of the body 120 when employed in the manner described herein.

In greater detail, the active control apparatus 340 is operable to control a material characteristic of one or more regions of the control element configuration 330. In the third embodiment, the material characteristic may be rigidity, density and/or shear modulus.

Control arrangements 300 according to the third embodiment are highly advantageous, as they enable precise or accurate control of the wave speed, and damping, of torsional vibration of the body 320. Furthermore, a low-profile and/or compact control arrangement 300 is thereby provided.

The active control apparatus 340 of the third embodiment may take a number of different forms, and exemplary constructions thereof are described below.

In a first exemplary construction of the third embodiment of the control apparatus 300, the material shear modulus G can be controlled by the active control apparatus 340. The control element configuration 330 is formed from a smart material or smart composite. A smart material or smart composite is a material or composite material configured to change material characteristic, or effective material characteristic, under application of an one or more stimuli, such as an electric and/or magnetic field. Examples of smart materials and smart composites include electroactive polymers, piezoelectric materials, electrorheological material (e.g., electrorheological elastomers), and magnetorheological materials (e.g., such as magnetorheological elastomers). It also includes composite structures with the aforementioned smart technologies embedded into traditional materials such that a localised change in effective material characteristic can be configured. An example of this would be an elastomer with embedded piezoelectric actuators or electroactive polymers. The active control apparatus 340 may be configured to apply one or more stimuli, including, but not limited to, an electric and/or magnetic field (as appropriate) to the smart material or composite, thereby to cause or induce a change in the material characteristic or deformation of the smart material or smart composite. The active control apparatus 340 may be provided within, or embedded in, the control element configuration 330. In an example, the control element configuration 330 is formed of a magnetorheological elastomer, and the active control apparatus 340 comprises one or more electromagnets 342a – d. The electromagnets 342a – d are embedded within the control element configuration 330.

In this way, the material shear modulus can be graduated, “graded”, or varied, along the length of the body 320, by appropriate operation of the active control apparatus 340. Here, the active control apparatus 340 may be operated such that the shear modulus gradually reduces along the length of the body 320. This is an example of the first mechanism described above to reduce the wave speed of torsional vibration of the body 320. The control element configuration 330 may be provided on or in the body 320. That is, the body 320 itself may be formed so as to provide the control element configuration 330 – in other words, the body 320 may be formed from a smart material or smart composite, thereby providing the control element configuration 330.

In a second exemplary construction of the third embodiment of the control apparatus 300, the material density ρ can be controlled by the active control apparatus 340, so as to graduate, or grade, the material density along the length of the structure. The active control apparatus 340 may be operable to cause an increase in density along the length of the body 340. For example, the control element configuration 330 may comprise one or more internal volumes, or chambers. The active control apparatus 340 may comprise a fluid supply assembly, configured to supply fluid into the chambers, thereby to adjust or control the density along the length of the structure. This is an example of the second mechanism described above to reduce the wave speed of torsional vibration.

In a third exemplary construction of the third embodiment of the control apparatus 300, the material rigidity can be controlled by the active control apparatus 340 so as to graduate, or grade, the material rigidity along the length of the structure. The rigidity may be graduated to interact with the torsional vibration to cause a decrease in the wave speed thereof. The control element configuration 330 is formed from a smart material or smart composite. A smart material or smart composite is a material or composite material configured to change material characteristic, or effective material characteristic, under application of one or more stimuli, such as an electric and/or magnetic field. Examples of smart materials and smart composites include electroactive polymers, piezoelectric materials, electrorheological materials (e.g., electrorheological elastomers), and magnetorheological materials (e.g., such as magnetorheological elastomers). It also includes composite structures with the aforementioned smart technologies embedded into traditional materials such that a localised change in effective material characteristic can be configured. An example of this would be an elastomer with embedded piezoelectric actuators or electroactive polymers. The active control apparatus 340 may be configured to apply one or more stimuli, including, but not limited to, an electric and/or magnetic field (as appropriate) to the smart material or composite, thereby to cause or induce a change in the material characteristic or deformation of the smart material or composite. The active control apparatus 340 may be provided within, or embedded in, the control element configuration 330. In an example, the control element configuration 330 is formed of a magnetorheological elastomer, and the active control apparatus 340 comprises one or more electromagnets 342a – d. The electromagnets 342a – d are embedded within the control element configuration 330.

In this way, the material rigidity can be graduated, “graded”, or varied, along the length of the body 320, by appropriate operation of the active control apparatus 340. Here, the active control apparatus 340 may be operated such that the rigidity gradually reduces along the length of the body 320. This is an example of the first mechanism described above to reduce the wave speed of torsional vibration of the body 320. The control element configuration 330 may be provided on or in the body 320. That is, the body 320 itself may be formed so as to provide the control element configuration 330 – in other words, the body 320 may be formed from a smart material or smart composite, thereby providing the control element configuration 330.

Referring to Figure 4, a fourth embodiment of a control arrangement 400 is shown. The control arrangement 400 is for controlling torsional vibration of a structure 410. The control arrangement 400 comprises a body 420. The body 420 is coupled to the structure 410. In this example, the body 420 is coupled to the structure 410 by being connected at an end of the structure 410. The control arrangement 400 comprises a control element configuration 430. The control element configuration 430 comprises a plurality of control elements 432. The control elements 432 are in the form of mass members. The control elements 432 may be in the form of solid discs. The plurality of control elements 432 are provided along the body 420. The control element configuration 430 comprises spaced apart control elements 432, which may be in the form of mass members. In the third embodiment, a non-uniform cross section is provided by the control arrangement 400 when provided on the body 420, due to the provision of the spaced apart control elements 432. In this way, the outer diameter varies along the length of the body 420 between the diameter of the control elements 432 and the diameter of the body 420 itself. In other words, the cross section across the length of the body 420 varies along its length due to the provision of spaced apart control elements 432. In this example, the body 420 is tapered thereby reducing the polar moment of inertia $J(x)$, and the control elements 432 each have the same radius as the body 420 (or the structure 410) at its widest point thereby maintaining the same effective mass moment of inertia $I(x)$. That is, a dimension of each control element 432 (or mass member) is the same as a dimension of the body 420 (or the structure 410) at a first end (e.g., its widest end). This approach is an example of the third mechanism described above to reduce the wave speed of torsional vibration. In this mechanism, it is considered that the spaced apart control elements 432 (or the step change in diameter as a result of the control elements 432 being provided on the body 420) presents an impedance to a vibration wavefront propagating through the body 420, which results in reflections causing interference (e.g., both constructive and deconstructive interference). In this way, the energy of the vibration wavefront is concentrated or “trapped” at frequency dependent locations and is damped thereat. This is known as rainbow trapping. In this way, vibrations may be damped by the control arrangement 400.

In this way, a significant reduction in wave speed of torsional vibration is possible. Furthermore, a reduction in total mass of the control arrangement is achieved. A further advantage is that the control arrangement 400 of the fourth embodiment maintains the same maximum radius as the body 420 (or of the structure 410), and as a result not additional space is required compared with that of a body 420 (or structure 410) of constant radius.

Referring to Figure 5, a fifth embodiment of a control arrangement 500 is shown. The control arrangement 500 is for controlling torsional vibration of a structure 510. The control arrangement 500 comprises a body 520. The body 520 is coupled to the structure 510. In this example, the body 520 is coupled to the structure 510 by being connected at an end of the structure 510. The control arrangement 500 comprises a control element configuration 530. The control element configuration 530 comprises a plurality of control elements 532. The control elements 532 are in the form of mass members. The control elements 532 may be in the form of solid discs. The plurality of control elements 532 are provided along the body 520. The control element configuration 530 comprises spaced apart control elements 532, which may be in the form of mass members. In the fifth embodiment, the control arrangement 500 has a non-uniform cross section as a result of the provision of the control elements 532. That is, the cross section across the length of the body 520 varies along its length due to the provision of spaced apart control elements 532. In this example, the body 520 has a constant diameter along its length (in contrast with the tapered diameter of the body 420 in the fourth embodiment). The control elements 532 increase in radius along the length of the body 520. That is, the control elements 532 are arranged along the body 520 to provide a series of control elements 532 that progressively increase in diameter. That is, a dimension of each control element 532 (or mass member) increases along the length of the body 520. The polar moment of inertia $J(x)$ is constant due to the constant diameter of the body 520, whereas the increasing diameter of the control elements 532 results in an increase in the effective mass moment of inertia $I(x)$. This approach is an example of the third mechanism described above to reduce the wave speed of torsional vibration. In this mechanism, it is considered that the spaced apart control elements 532 (or the step change in diameter provided by the control elements 532) presents an impedance to a vibration wavefront propagating through the body 520, which results in reflections causing interference (e.g., both constructive and deconstructive interference). In this way, the energy of the vibration wavefront is concentrated or “trapped” at frequency dependent locations and is damped thereat. This is known as rainbow trapping. In this way, vibrations may be damped by the control arrangement 500.

In this way, a significant reduction in wave speed of torsional vibration is possible. Whilst there may be a greater requirement for space to accommodate the control arrangement 500 and an overall greater mass may result, such an arrangement is advantageous in maintaining strength and stiffness of the body 520, which reduces the risk of failure of the body 520, for example due to fatigue.

The control arrangement of the fourth and fifth embodiments described above may be combined. Referring to Figure 6, an example of such a combined approach is shown. In this example, the body 620 has a tapered cross section along at least a part of its length (e.g., a first part of its length l_1), and a constant cross section along at least a part of its length (e.g., a second part of its length l_2). Along the first part of its length l_1, the body 620 tapers to a practical minimum radius, which may be governed by the required strength and/or stiffness of the body 620. As above, in this length part or region, this results in a reduction the polar moment of inertia $J(x)$. Along the first part of its length l_1, the control elements 632 each have the same radius as the body 620 at its widest point thereby maintaining the same effective mass moment of inertia $I(x)$ in this length part or region. That is, in a subset of the control elements 632 (i.e., those in the region l_1), a dimension of each control element is the same as a dimension of the body 620 (or the structure 610) at a first end. Along the second part of its length l_2, the body 620 has a constant diameter. The control elements 632 increase in radius along the second part of the length l_2 of the body 620. That is, the control elements 632 are arranged along the second part of the length l_2 of the body 620 to provide a series of control elements 632 that progressively increase in diameter. In other words, in a subset of the control elements 632 (i.e., those in region l_2), a dimension of each control element 632 increases along the length of the body 620. In this length part or region, the polar moment of inertia $J(x)$ is constant due to the constant diameter of the body 620, whereas the increasing diameter of the control elements 632 results in an increase in the effective mass moment of inertia $I(x)$.

Advantageously, by such a construction, the body 620 is not required to taper to a small diameter, such that strength and stiffness of the body 620 can be maintained, which reduces the risk of failure of the body 620, for example due to fatigue.

Applicable to all embodiments and examples described above, a damping material may be employed to increase the damping effect of the control arrangement. Referring to Figure 7, a damping material 450 is shown provided on a control arrangement 400 according to the fourth embodiment. However, as above, the damping material 450 may be applied in other embodiments described herein in a corresponding manner, as will be appreciated by the skilled person from the present disclosure. The damping material 450 is provided between one or more pairs of control elements 432, which may mean between one or more pairs of mass members. The damping material 450 is provided in gaps 414 between adjacent control elements 432. The damping material 450 constrains adjacent control elements 432, thereby increasing torsional stiffness which reduces the wave speed. As a result, the damping material 450 advantageously increases the damping effect significantly. The amount of damping material 450 can be chosen, or adjusted, to control the amount of damping – in particular, the depth of fill of the gaps 414 can be chosen, or adjusted. The damping material 450 may be a viscoelastic material.

Whilst in some of the embodiments described above the control elements may be in the form of mass member discs (e.g., of disc-shaped or circular-shaped cross section), alternative cross sections are possible and indeed may be advantageous. In Figure 8(a) and 8(b), a cross section of a control arrangement 400 and body 420 is shown. Referring to Figure 8(a), a cross-shaped mass member cross section is shown. Each cross-shaped mass member may comprise a plurality of (e.g., four) mass sub-members 432a, 432b, and so on. Referring to Figure 8(b), a star-shaped mass member cross section is shown. Each star-shaped mass member may comprise a plurality of (e.g., eight) mass sub-members 432a, 432b, and so on. Such cross sections may be advantageous in reducing the mass of the control arrangement 400. In a highly advantageous construction not illustrated in the figures, the control arrangement 400 may be provided in a fluid bath – that is, the control elements 432 may be immersed in the fluid bath. The cross-shaped and star-shaped cross section of control elements 432 is highly advantageous in this scenario, as when provided in the fluid bath the damping effect is increased. This is due to the increase in surface area, and resistance to vibration of the control elements 432 by the fluid of the fluid bath. In this way, the damping effect can be increased without increasing the torsional stiffness (which would occur when a damping material 450 is provided to constrain the control elements 432, as described above). The fluid in the fluid bath may be oil, or other viscous fluid. The control arrangement 400 may comprise the fluid bath.

Figure 9 shows three examples of control arrangements 900 and hollow bodies 920a, 920b, 920c to which the present invention may be applied. In highly advantageous examples, the hollow bodies may be hollow structures, such as hollow shafts. Torsional stiffness of a hollow shaft is dependent on the wall thickness, so in examples of the present invention the wall thickness may be reduced instead of, or in addition to, the outer diameter of the body as in the examples described above.

Referring to Figure 9(a), a hollow body 920a of constant wall thickness is shown. A control element configuration 930 is provided on the body 920a.

Referring to Figure 9(b), a hollow body 920b of tapering (e.g., decreasing) wall thickness is shown. A control element configuration 930 is provided within the body 920b. Advantageously, the control elements 932 are thus protected from damage by being provided within the hollow body 920b. It will also be noted that the hollow body 920b has a constant outer diameter.

Referring to Figure 9(c), a hollow body 920c of tapering (e.g., decreasing) wall thickness is shown. A control element configuration 930 is provided on the outer surface of the body 920c.

Turning now to Figures 10 to 18, as introduced above, various embodiments of control arrangements comprising active control apparatus are shown and will be described with reference thereto. It will be appreciated that the features thereof may be incorporated in any of the other embodiments of the control arrangements as described herein. In particular, each of the control arrangements comprising active control apparatus as shown in Figures 10 to 18 also comprise spaced apart mass members, and it will thus be apparent to the skilled person from the present disclosure how the following teaching may be applied to the control arrangements of other embodiments described herein which also comprise spaced apart mass members. In this regard, only features of the respective active control apparatus will be described below in relation to Figures 10 to 18, to avoid repetition. Corresponding numerals will be used to indicate features corresponding to embodiments previously described.

Referring to Figure 10, a sixth embodiment of a control arrangement 600 is shown. The control arrangement 600 is for controlling torsional vibration of a structure 610. The control arrangement 600 comprises a body 620 coupled to the structure 610. In this example, the body 620 is coupled to the structure 610 by being connected at an end of the structure 610. The control arrangement 600 comprises a control element configuration 630. The control element configuration 630 comprises a plurality of control elements 632. The control elements 632 are in the form of mass members.

The control arrangement 600 comprises an active control apparatus 640. In use, the active control apparatus 640 is operable to control the wave speed (e.g., the decrease in wave speed) of torsional vibration of the body 620. The active control apparatus 640 comprises an actuator arrangement 650. The actuator arrangement 650 is configured to control stiffness along the length of the body 620. In an example, the actuator arrangement 650 may replace the mass members, and the actuators themselves may instead provide the mass members.

The active control apparatus 640 integrates active moments. In the present example, the actuator arrangement 650 is configured to apply a series of active moments M_1 *to* M_n. The actuator arrangement 650 may comprises one or more electric motors, servomotors, piezoelectric actuators, and/or electroactive polymers.

Control arrangements 600 according to the sixth embodiment are highly advantageous, as they enable precise or accurate control of the wave speed, and damping, of torsional vibration of the body 620. The ability to adapt or adjust operation to control varying frequencies of torsional vibration over time, or provide improved low-frequency control, is facilitated by the active control apparatus 640.

Referring to Figure 11, a seventh embodiment of a control arrangement 700 is shown. It will be appreciated that the control arrangement 700 has structural similarities to that of the control arrangement 400 of the fourth embodiment, as shown in Figures 4 and 7. The control arrangement 700 is for controlling torsional vibration of a structure 710. The control arrangement 700 comprises a body 720 coupled to the structure 710. In this example, the body 720 is coupled to the structure 710 by being connected at an end of the structure 710. The control arrangement 700 comprises a control element configuration 730. The control element configuration 730 comprises a plurality of control elements 732. The control elements 732 are in the form of mass members.

The control arrangement 700 comprises an active control apparatus 740. In use, the active control apparatus 740 is operable to control the wave speed (e.g., the decrease in wave speed) of torsional vibration of the body 720.

The active control apparatus 740 comprises a smart material or smart composite. Smart materials and smart composites are described above. The active control apparatus 740 may be configured to apply one or more stimuli, including, but not limited to, an electric and/or magnetic field (as appropriate) to the smart material or composite, thereby to cause or induce a change in the material characteristic, or effective material characteristic, of the smart material or composite. Additionally, or alternatively, external or remote apparatus or componentry may be configured to apply one or more stimuli, such as an electric and/or magnetic field (as appropriate), to the smart material or composite, thereby to cause or induce a change in the material characteristic of the smart material or composite.

The smart material or composite may be provided between one or more pairs of mass members 732. The smart material or composite may be provided in gaps 714 between adjacent pairs of mass members 732. In some examples, the smart material or composite may be arranged to encapsulate the mass members 732.

In this way, stiffness can be actively increased and decreased, thereby to control the wave speed (e.g., the decrease in wave speed) of torsional vibration of the body 720. Furthermore, control arrangements 700 according to the seventh embodiment are highly advantageous, as they enable precise or accurate control of the wave speed, and damping, of torsional vibration of the body 720. The ability to adapt or adjust operation to control varying frequencies of torsional vibration over time, or provide improved low-frequency control, is facilitated by the active control apparatus 740.

Referring to Figure 12, an eighth embodiment of a control arrangement 800 is shown in cross section. The control arrangement 800 is for controlling torsional vibration of a structure (not shown). The control arrangement 800 comprises a body 820 coupled to the structure. The control arrangement 800 comprises a control element configuration 830, comprising a plurality of control elements 832 in the form of mass members, of which one mass member 832a is shown.

The control arrangement 800 comprises an active control apparatus 840. The active control apparatus 840 comprises a smart material or smart composite. Smart materials and composites are described above. The active control apparatus 840 may be configured to apply one or more stimuli, including, but not limited to, an electric and/or magnetic field (as appropriate) to the smart material or composite, thereby to cause or induce a change in the material characteristic, or effective material characteristic, of the smart material or composite. Additionally, or alternatively, external or remote apparatus or componentry may be configured to apply the stimuli to the smart material or composite, thereby to cause or induce a change in the material characteristic, or effective material characteristic, of the smart material or composite. The smart material or composite is provided between one or more mass members 832 and the body 820, so as to couple the one or more mass members 832 and the body 820. As can be seen from Figure 12, the mass member 832a is coupled, or connected, to the body 820 by the smart material or composite. The smart material or composite may be provided to surround a region of the body 820, and the mass member 832a may be mounted thereon.

By appropriate application of an electric and/or magnetic field to the smart material or composite, the stiffness of connection between mass member 832a and the body 810 is controllable. In this way, stiffness can be adjusted or adapted by appropriate control of material characteristic of the smart material or composite. A reduced stiffness is obtainable. Furthermore, control arrangements 800 according to the eighth embodiment are highly advantageous, as they enable precise or accurate control of the wave speed, and damping, of torsional vibration of the body 820. The ability to adapt or adjust operation to control varying frequencies of torsional vibration over time, or provide improved low-frequency control, is facilitated by the active control apparatus 840.

Referring to Figure 13, a control arrangement 1500 is shown, as an introduction to Figures 14 to 18. The control arrangement 1500 comprises an active control apparatus 1540. The active control apparatus 1540 integrates active moments. Integration of active moments may be achieved in various ways, examples of which are shown and described in relation to Figures 14 to 18. Active control of stiffness along length of the body 1520 is facilitated.

Referring to Figure 14, a ninth embodiment of a control arrangement 900 is shown. The control arrangement 900 is for controlling torsional vibration of a structure 910. The control arrangement 900 comprises a body 920 coupled to the structure 910. In this example, the body 920 is coupled to the structure 910 by being connected at an end of the structure 910. The control arrangement 900 comprises a control element configuration 930. The control element configuration 930 comprises a plurality of control elements 932. The control elements 932 are in the form of mass members.

The control arrangement 900 comprises an active control apparatus 940. The active control apparatus 940 integrates active moments. The active control apparatus 940 comprises an actuator arrangement 950. The actuator arrangement 950 is configured to apply a force to the control element configuration 930. The actuator arrangement 950 comprises one or more actuator assemblies 950a – c. At least one actuator assembly 950a – c is arranged to provide a connection between a pair of mass members 932 to provide a force thereto. In the illustrated example, the actuator arrangement 950 comprises a plurality of actuator assemblies 950a - c, each providing connection between adjacent pairs of mass members 932.

The one or more actuator assemblies 950a – c may be configured to provide linear actuation – that is, the actuator assemblies 950a – c may be linear actuators. The actuator assemblies 950a – c may be arranged to apply force perpendicular to the axis of rotation 50 of the body 920. Suitable actuators may include hydraulic, electrodynamic, electromagnetic and/or piezoelectric actuators. By the present construction, an active moment is presented between adjacent mass members 932.

Control arrangements 900 according to the ninth embodiment are highly advantageous, as they enable precise or accurate control of the wave speed, and damping, of torsional vibration of the body 920. The ability to adapt or adjust operation to control varying frequencies of torsional vibration over time, or provide improved low-frequency control, is facilitated by the active control apparatus 940.

Figure 15 shows two examples of a tenth embodiment of a control arrangement 1000. The control arrangement 1000 comprises an active control apparatus 1040. The active control apparatus 1040 comprises an actuator arrangement 1050 incorporating one or more electromagnets comprising one or more coils (e.g., stators) 1052 and one or more permanent magnets 1054. In this way, each active control apparatus 1040 integrates active moments. The control arrangement 1000 is for controlling torsional vibration of a structure 1010. The control arrangement 1000 comprises a body 1020 coupled to the structure 1010.

In this example, the body 1020 is coupled to the structure 1010 by being connected at an end of the structure 1010. The control arrangement 1000 comprises a control element configuration 1030. The control element configuration 1030 comprises a plurality of control elements 1032. The control elements 1032 are in the form of mass members.

Referring to Figure 15(a), a first example of the control arrangement 1000 is shown. One or more stators 1052 are mounted on, or otherwise connected to, a first control element 1032a. One or more permanent magnets 1054 are mounted on, or otherwise connected to, a second control element 1032b. The first control element 1032a and second control element 1032b may be adjacent, and may thereby be said to be a corresponding pair of control elements 1032. That is, a pair of mass members 1032 may be two adjacent mass members. The stators 1052 and permanent magnets 1054 may be provided in sets. For avoidance of doubt, the stators 1052 rotate with the body 1020.

In this way, the actuator arrangement 1050, in use, applies rotational actuation. Active control of stiffness along length of the body 1052 is facilitated.

Referring to Figure 15(b), a second example of the control arrangement 1000 is shown. The stators 1052 or magnets 1054 may be mounted on a region of the body 1020 between a pair of mass members 1032. The other of the stators or magnets 1054 may be mounted on, coupled to, attached to, or otherwise connected to, one or more mass members adjacent said region of the body 1020. In the example illustrated in the figure, the magnets 1054 are mounted on the mass members 1032a, 1032b, and the stators 1052 are provided in a region of the body 1020 between the mass members 1032a, 1032b. For avoidance of doubt, the stators 1052 rotate with the body 1020. As above, a pair of mass members 1032 may be two adjacent mass members.

In this way, the actuator arrangement 1050, in use, applies rotational actuation. Active control of stiffness along length of the body 1052 is facilitated. Furthermore, control arrangements 1000 according to the tenth embodiment are highly advantageous, as they enable precise or accurate control of the wave speed, and damping, of torsional vibration of the body 1020. The ability to adapt or adjust operation to control varying frequencies of torsional vibration over time, or provide improved low-frequency control, is facilitated by the active control apparatus 1040.

Referring to Figure 16, an eleventh embodiment of a control arrangement 1100 is shown. The control arrangement 1100 is for controlling torsional vibration of a structure 1110. The control arrangement 1100 comprises a body 1120 coupled to the structure 1110. In this example, the body 1120 is coupled to the structure 1110 by being connected at an end of the structure 1110. The control arrangement 1100 comprises a control element configuration 1130. The control element configuration 1130 comprises a plurality of control elements 1132. The control elements 1132 are in the form of mass members.

The control arrangement 1100 comprises an active control apparatus 1140 comprising an actuator arrangement 1150 incorporating one or more electromagnets comprising one or more coils (e.g., stators) 1152 and one or more permanent magnets 1154. In this way, each active control apparatus thereof integrates active moments. The one or more stators 1152 are provided remote from the body 1120. That is, the stators 1152 are not attached to the body 1120, such that the stators 1152 do not rotate with the body 1120. The stators 1152 may be mounted around, and proximal to, the control elements 1132. The one or more magnets 1154 are mounted on, or otherwise connected to, the control elements 1132. Alternatively, or additionally, one or more magnets 1154 may be mounted on, or otherwise connected to, the body 1120.

In this way, the actuator arrangement 1150, in use, applies rotational actuation. Active control of stiffness along length of the body 1120 is facilitated. Furthermore, the actuator arrangement 1150 is at least in part provided remotely from the body 1120 and control element configuration 1130, thereby simplifying construction.

Referring to Figure 17, a twelfth embodiment of a control arrangement 1200 is shown. The control arrangement 1200 is for controlling torsional vibration of a structure 1210. The control arrangement 1200 comprises a body 1220 coupled to the structure 1210. In this example, the body 1220 is coupled to the structure 1210 by being connected at an end of the structure 1210. The control arrangement 1200 comprises a control element configuration 1230. The control element configuration 1230 comprises a plurality of control elements 1232. The control elements 1232 are in the form of mass members.

The control arrangement 1200 comprises an active control apparatus 1240. The active control apparatus 1240 integrates active moments. The active control apparatus 1240 comprises an actuator arrangement 1250 incorporating one or more rotary actuators 1252. One or more of the rotary actuators 1252 may be provided between the mass members 1232. One or more of the rotary actuators 1252 may be provided to connect to one or more mass members 1232. One or more of the rotary actuators may be provided between one or more of the mass members 1232 and the body 1220 (in a similar manner to that described in relation to Figure 12). The one or more rotary actuators may comprise one or more hydraulic, pneumatic, piezoelectric, and/or electrodynamic actuators.

In this way, the actuator arrangement 1250, in use, applies rotational actuation. Active control of stiffness along length of the body 1220 is facilitated. Furthermore, the actuator arrangement 1250 is at least in part provided remotely from the body 1220 and control element configuration 1230, thereby simplifying construction.

Referring to Figure 18, a thirteenth embodiment of a control arrangement 1300 is shown in cross section. The control arrangement 1300 is for controlling torsional vibration of a structure (not shown). The control arrangement 1300 comprises a body 1320 coupled to the structure. The control arrangement 1300 comprises a control element configuration 1330, comprising a plurality of control elements 1332 in the form of mass members, of which one mass member 1332a is shown.

The control arrangement 1300 comprises an active control apparatus 1340. The active control apparatus 1340 integrates active moments. The active control apparatus 1340 comprises one or more proof-mass actuators 1342, which may be referred to as actively controllable proof-mass actuators 1342. The proof-mass actuators 1342 are attached to, or are embedded in, one or more of the mass members 1332. The proof-mass actuators may be electrodynamic and/or piezoelectric. Each proof-mass actuator 1342 is configured to, in use, exert an inertial rotational force.

In the example illustrated in Figure 18(a), a permanent magnet mass 1344 may be caused to move by operation of stator coils 1346, thereby exerting an inertial rotational force. In the example illustrated in Figure 18(b), a permanent magnet mass 1344 may be mounted at an end of a deflectable arm. Operation of stator coils 1346 may cause deflection of the permanent magnetic mass, thereby to exert an inertial rotational force.

Control arrangements 1300 according to the thirteenth embodiment are highly advantageous, as they enable precise or accurate control of the wave speed, and damping, of torsional vibration of the body 1320. The ability to adapt or adjust operation to control varying frequencies of torsional vibration over time, or provide improved low-frequency control, is facilitated by the active control apparatus 1340.

As described above, the control arrangement being coupled or couplable to the structure in various ways. In the examples shown in Figures 1 to 6, 10 and 11, and 13 to 17, the control arrangement is coupled to the structure by being connected at an end of the structure. Figures 19 and 20 illustrated further ways in which the control arrangement may be coupled or couplable to the structure. Whilst in Figures 19 and 20 the control arrangement 500 of the fifth embodiment is shown, it will be appreciated that the manner of coupling described here in relation to Figures 19 and 20 may be applied to any of the control arrangements described herein.

Referring to Figure 19, the control arrangement 500 is coupled or couplable to the structure 510 by being provided or providable on or in the structure. In Figure 19, the control arrangement replaces a section of the structure 510. For example, a section or portion of the structure 510 may be replaced with the control arrangement 500, and the control arrangement may act as a part of the structure 510. The body 520 may be connected in, or between sections of, the structure 510, and may be connected to ends of the structure 510 as shown in the figure.

Referring to Figure 20, the control arrangement 500 is coupled or couplable to the structure 510 by virtue of the control arrangement 500 being part of the structure 510. For example, as shown in Figure 20, the body 520 of the control arrangement 500 is provided by the structure 510 itself. That is, no body 520 is provided that is distinct or separate to the structure 510.

Referring to Figure 21, a vehicle 2100 is schematically shown. The vehicle 2100 comprises a control arrangement 100, according to any of the embodiments described herein. The vehicle 2100 may be a land-based vehicle, watercraft, or aircraft. The vehicle, or a component thereof, may comprise, or be, the body and/or structure.

Referring to Figure 22, a construction 2200 is schematically shown. The construction 2200 comprises a control arrangement 100, according to any of the embodiments described herein. The construction 2200 may be a building, infrastructure, construction, or the like. The structure, or a component thereof, may comprise, or be, the body and/or structure.

Referring to Figure 23, a method of controlling torsional vibration of a structure. Step S2310 comprises providing a control arrangement comprising a body, the body being couplable to the structure; a control element configuration; and an active control apparatus. Step S2320 comprises providing the control element configuration along the body. Step S2330 comprises operating the active control apparatus to control the wave speed of torsional vibration of the body. Step S2330 may comprise operating the active control apparatus to control the decrease in wave speed of torsional vibration of the body. A further optional step may comprise causing, by the control arrangement, a decrease in wave speed of torsional vibration of the body.

CLAIMS

1. A control arrangement (100, 200, 300 – 1300) for controlling torsional vibration of a structure (110, 210, 310 – 1210), the control arrangement comprising a body (120, 220, 320 – 1320) and a control element configuration (130, 230, 330 – 1330) providable along the body, wherein the body is couplable to the structure, wherein the control arrangement further comprises an active control apparatus (340, 640, 740 – 1340, 1540) wherein, in use, the active control apparatus is operable to control the wave speed of torsional vibration of the body.

2. The control arrangement (100, 200, 300 – 1300) according to claim 1, wherein the active control apparatus (340, 640, 740 – 1340, 1540) is operable to control a material characteristic of one or more regions of the control element configuration.

3. The control arrangement (100, 200, 300 – 1300) according to claim 2, wherein the material characteristic is rigidity, density and/or shear modulus.

4. The control arrangement (100, 200, 300 – 1300) according to any one of the preceding claims, wherein the active control apparatus (340, 640, 740 – 1340, 1540) and/or the control element configuration (130, 230, 330 – 1330) comprises a smart material or smart composite, wherein application of an electric and/or magnetic field to the smart material or smart composite causes a change in a material characteristic of the smart material or smart composite.

5. The control arrangement (100, 200, 300 – 1300) according to any one of the preceding claims, wherein the control element configuration comprises spaced apart mass members (432, 532, 632 – 1332).

6. The control arrangement (100, 200, 300 – 1300) according to claim 5 when dependent on claim 4, wherein the smart material or smart composite is provided between one or more pairs of mass members.

7. The control arrangement (100, 200, 300 – 1300) according to claim 5 or 6, when dependent on claim 4, wherein the smart material or smart composite is provided between one or more mass members (832a) and the body (820), so as to couple the one or more mass members to the body.

8. The control arrangement (100, 200, 300 – 1300) according to any one of the preceding claims, wherein the active control apparatus (340, 640, 740 – 1340, 1540) comprises an actuator arrangement (650, 950, 1050, 1150, 1250) configured to apply a force to the control element configuration.

9. The control arrangement (100, 200, 300 – 1300) according to claim 8, when dependent directly or indirectly on claim 5, wherein the actuator arrangement comprises one or more actuator assemblies (950a – c), wherein at least one actuator assembly is arranged to provide a connection between a pair of mass members to provide a force thereto.

10. The control arrangement (100, 200, 300 – 1300) according to claim 8, when dependent directly or indirectly on claim 5, wherein the actuator arrangement comprises:

one or more stators (1052, 1152, 1346); and

one or more permanent magnets (1054, 1154, 1344),

wherein the actuator arrangement is configured to provide rotational actuation.

11. The control arrangement (100, 200, 300 – 1300) according to claim 8, when dependent directly or indirectly on claim 5, wherein the actuator arrangement comprises:

one or more stators (1152) provided remotely from the body (1120); and one or more permanent magnets (1154) connected to one or more mass members (1132).

12. The control arrangement (100, 200, 300 – 1300) according to claim 8, wherein the actuator arrangement (650, 950, 1050, 1150, 1250) comprises one or more rotary actuators provided between one or more pairs of mass members.

13. The control arrangement (100, 200, 300 – 1300) according to claim 8, when dependent directly or indirectly on claim 5, wherein the actuator arrangement comprises one or more actively controllable proof-mass actuators (1342), wherein the proof-mass actuators are attached to, or are embedded in, one or more of the mass members (1332).

14. The control arrangement (100, 200, 300 – 1300) according to any one of the preceding claims, wherein the structure is a shaft.

15. A method of controlling torsional vibration of a structure, the method comprising:

providing a control arrangement comprising:

a body, the body being couplable to the structure;

a control element configuration; and

an active control apparatus;

providing the control element configuration along the body; and

operating the active control apparatus to control the wave speed of torsional vibration of the body.

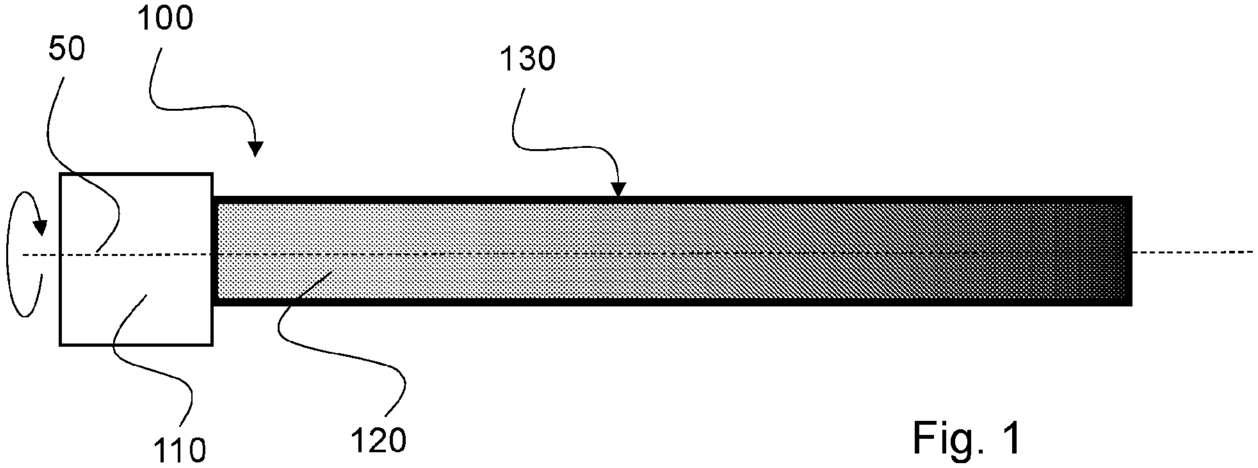


Fig. 1

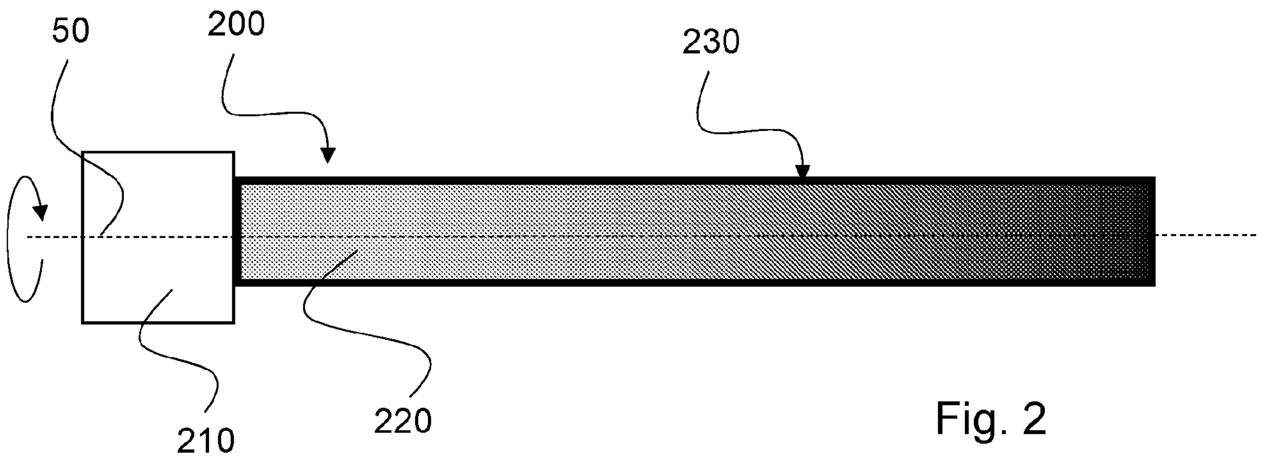


Fig. 2

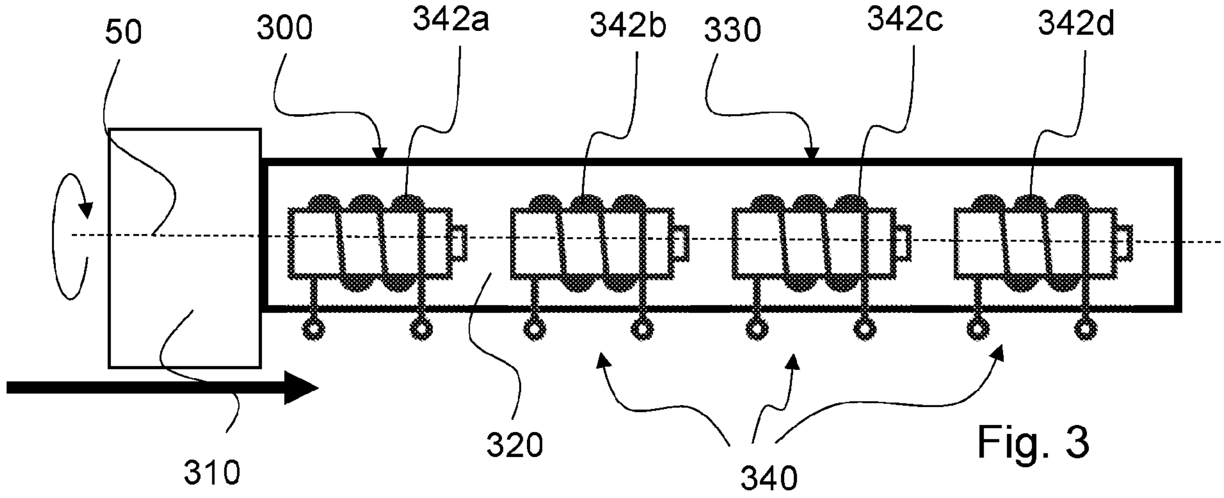

50
300
342a
342b
330
342c
342d
310
320
340

Fig. 3

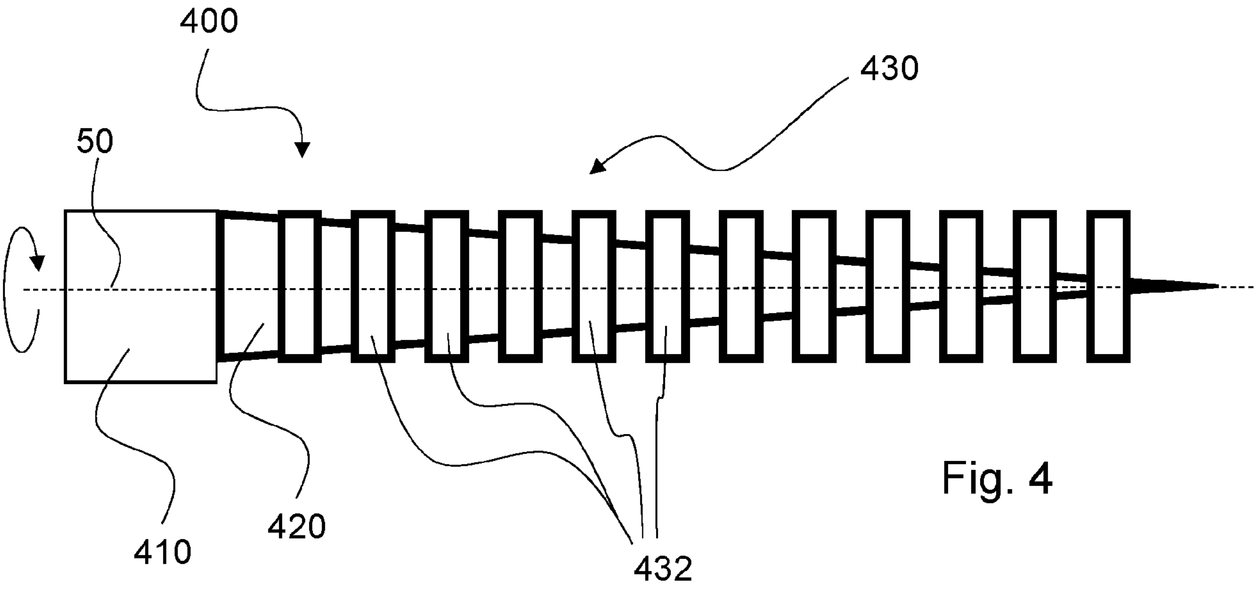

400
430
50
410
420
432

Fig. 4

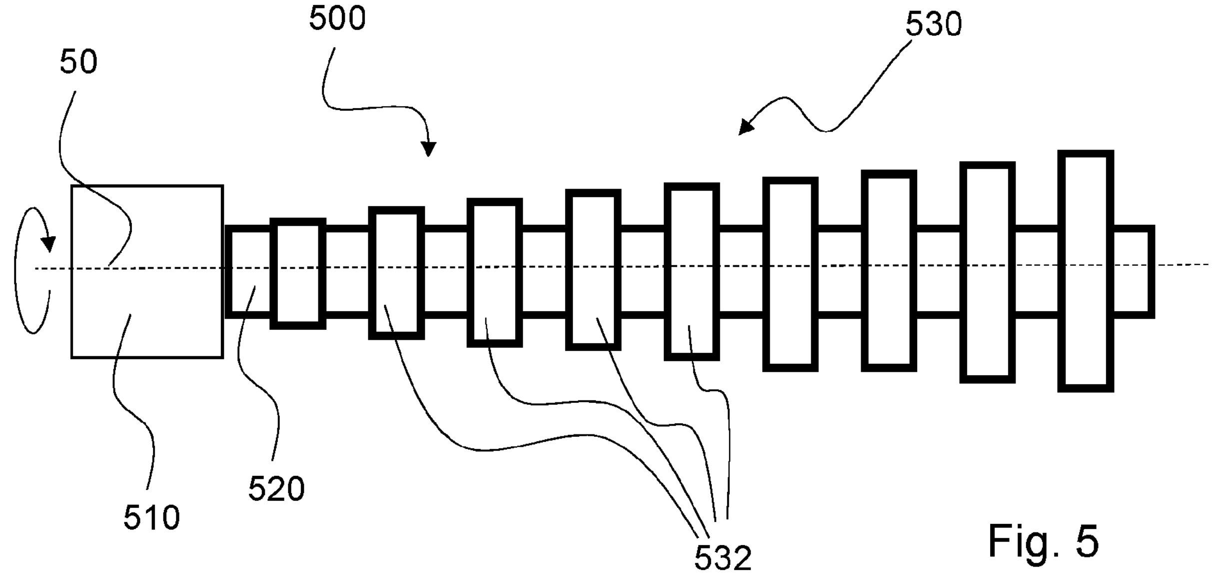


Fig. 5

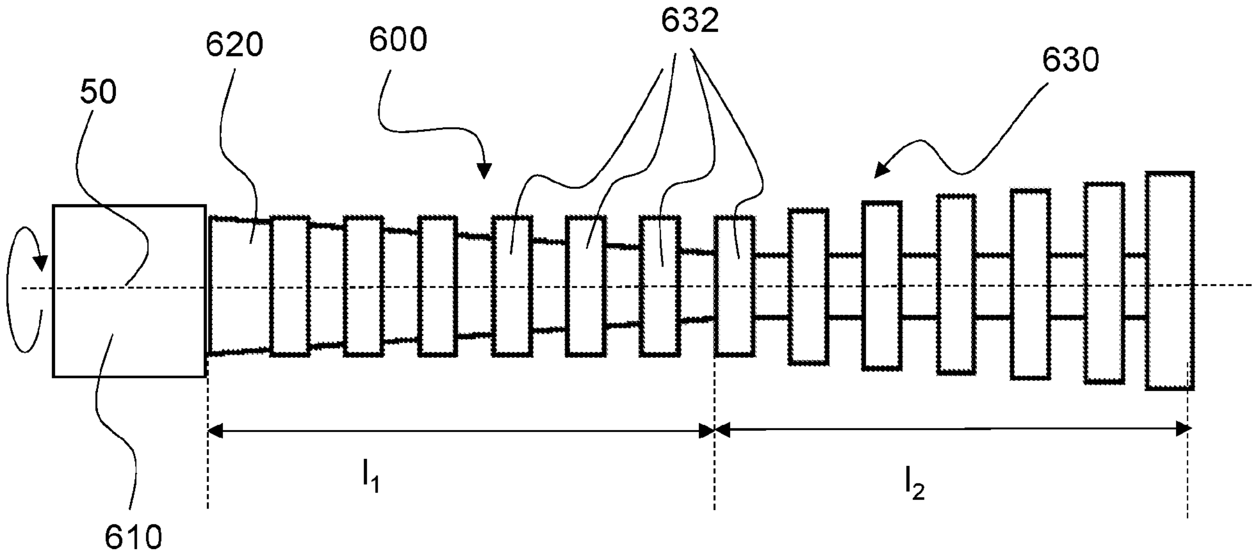


Fig. 6

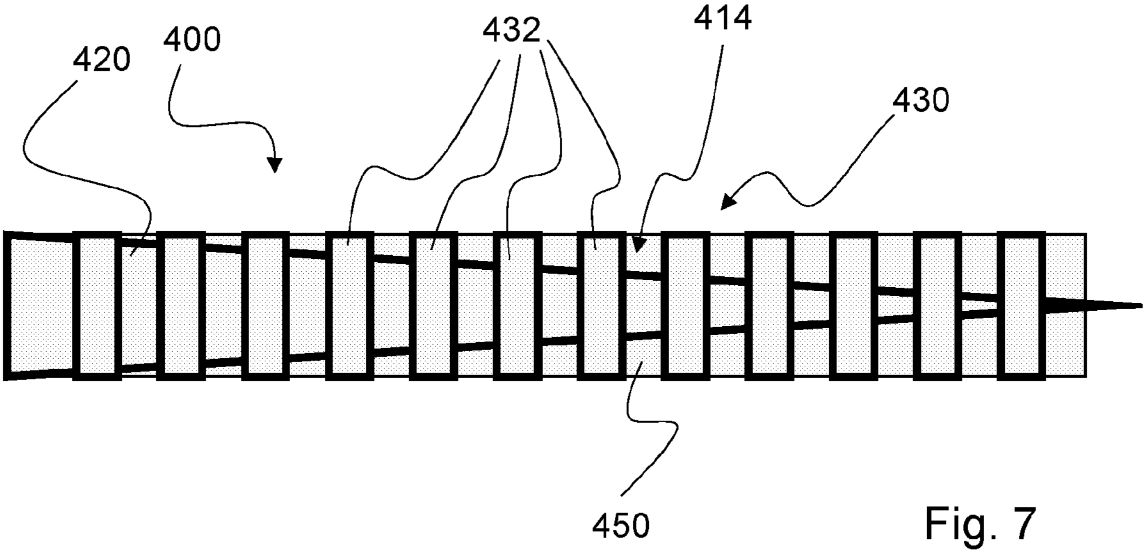


Fig. 7

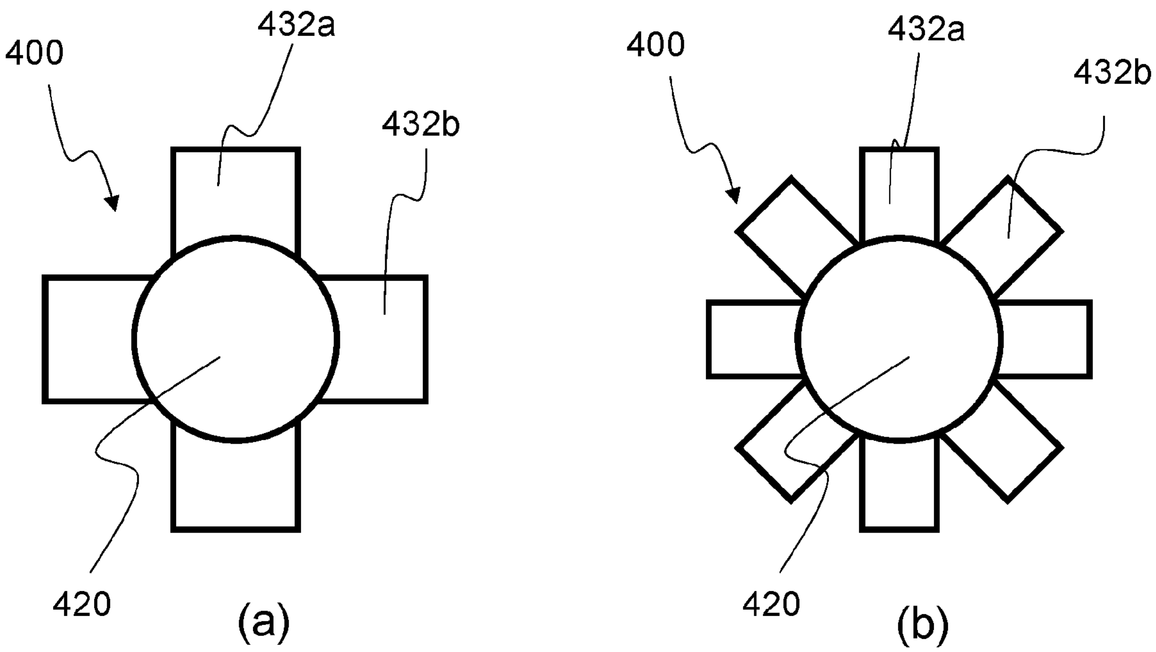
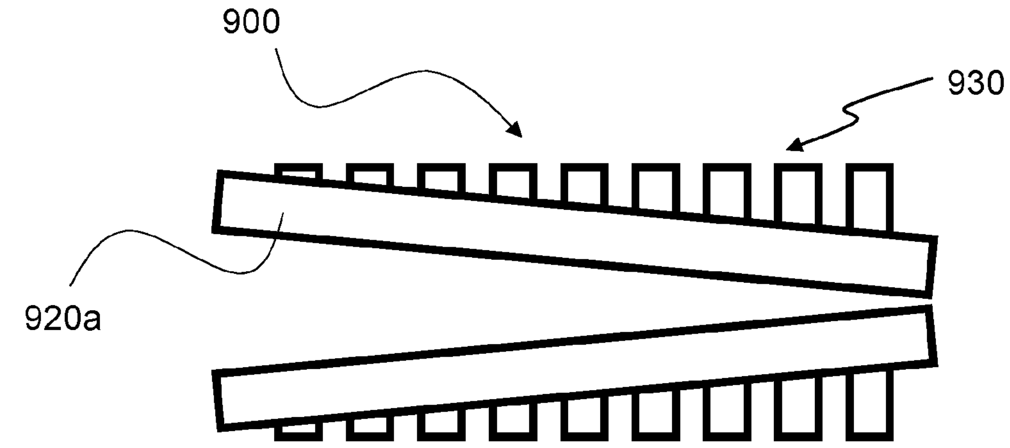
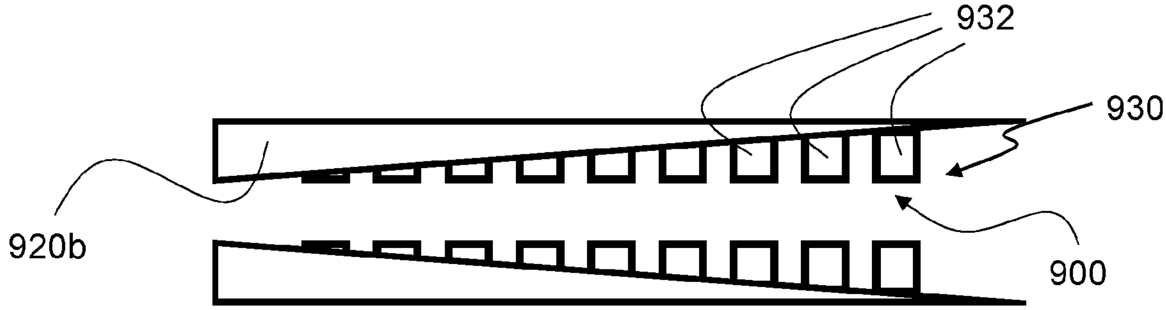


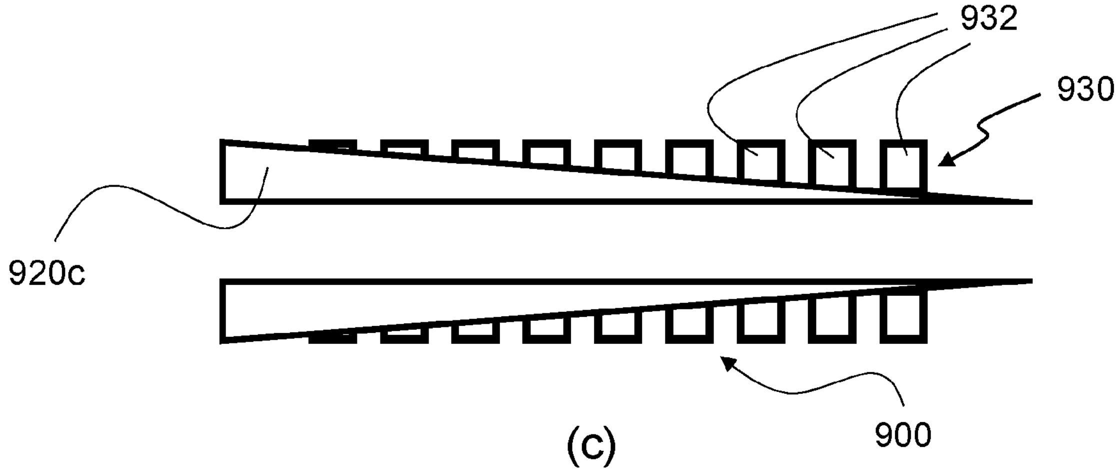
Fig. 8



(a)



(b)



(c)

Fig. 9

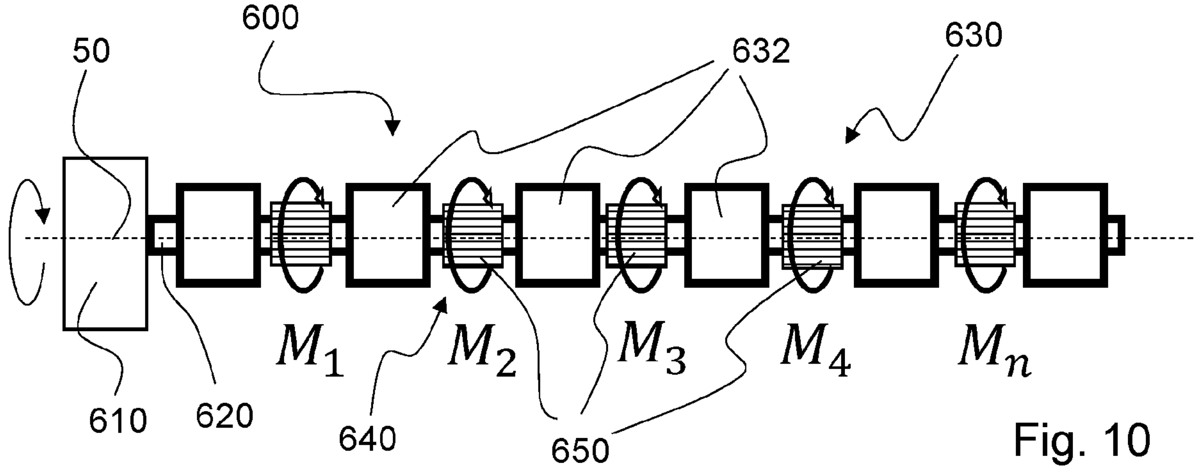


Fig. 10

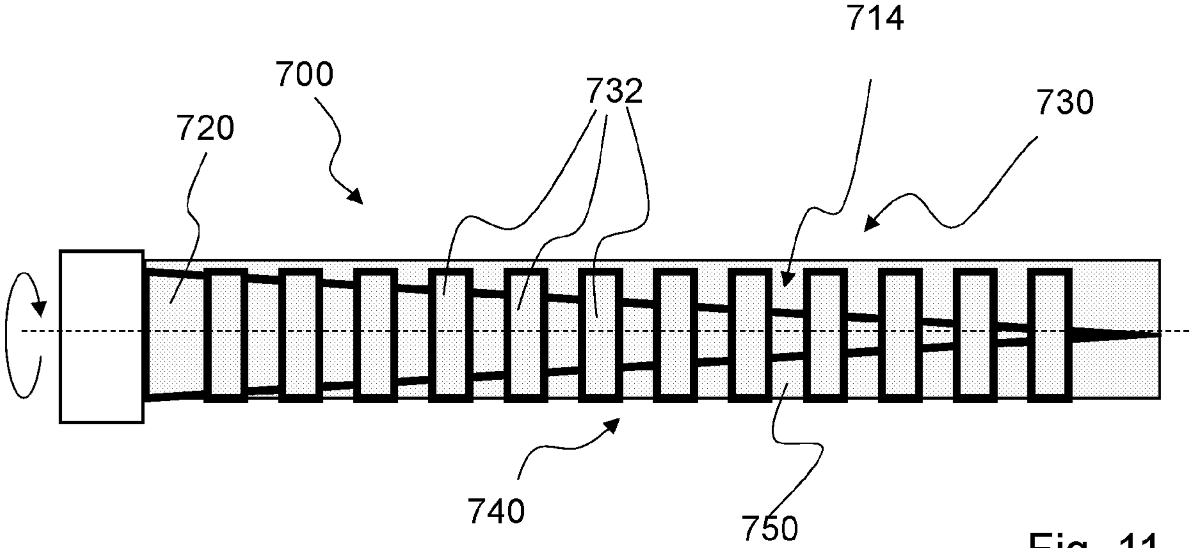


Fig. 11

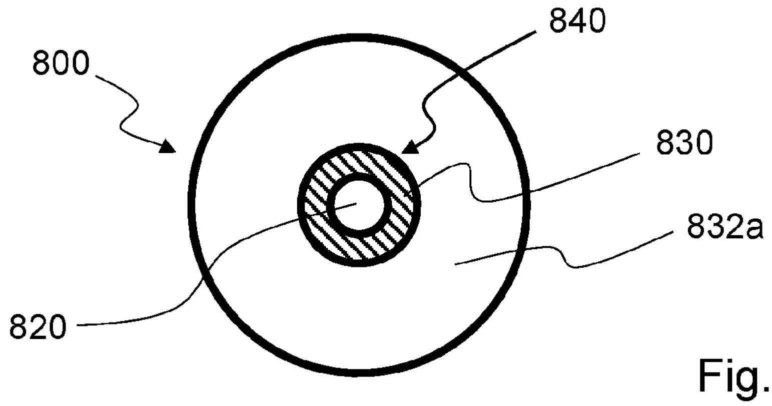


Fig. 12

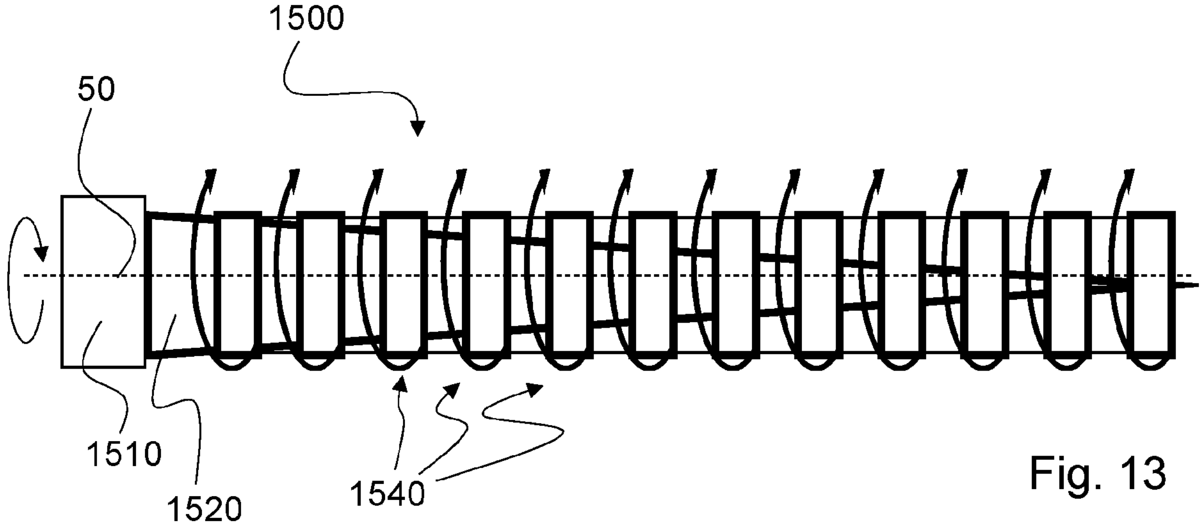

1500
50
1510
1520
1540

Fig. 13

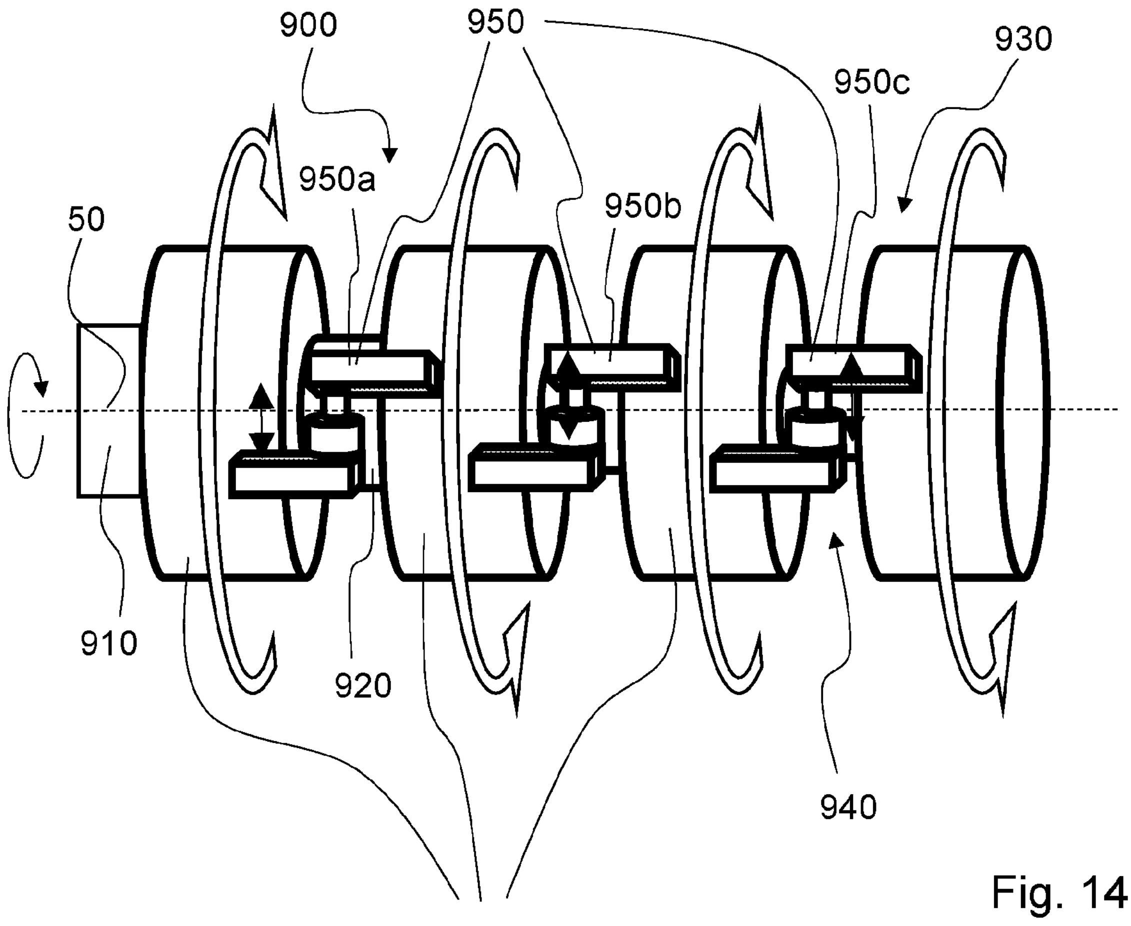

900
950
930
950c
950a
950b
50
910
920
940
932

Fig. 14

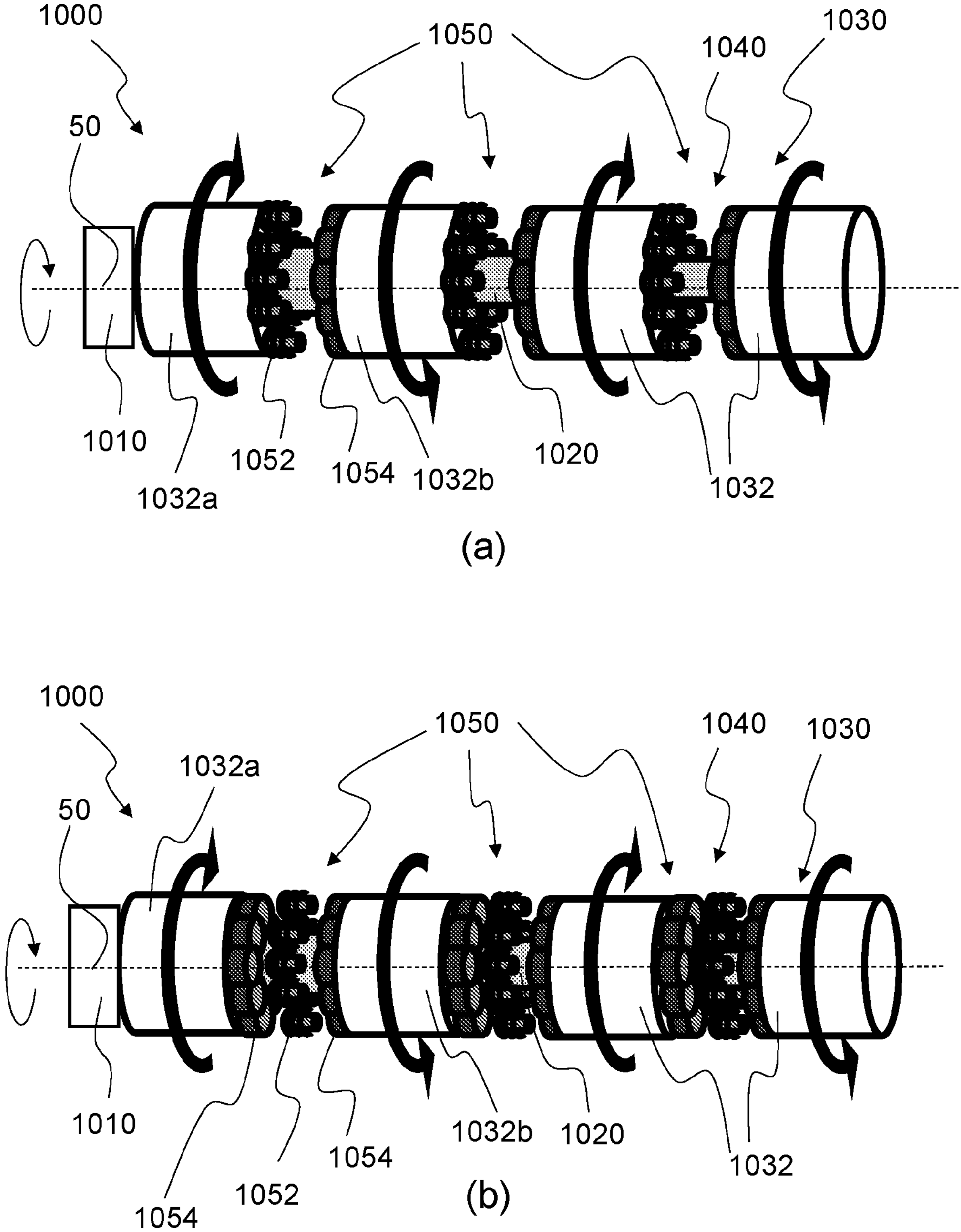

1000
1050
1040
1030
50
1010
1032a
1052
1054
1032b
1020
1032
(a)
1000
1050
1040
1030
1032a
50
1010
1054
1052
1054
1032b
1020
1032
(b)

Fig. 15

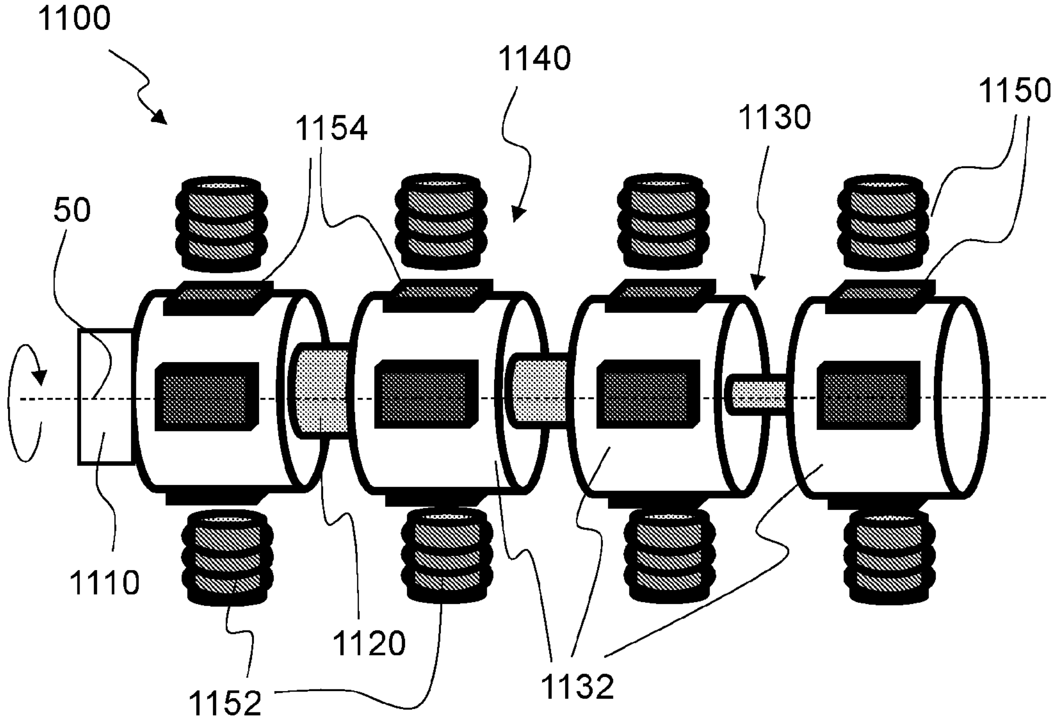

1100
1140
1154
1130
1150
50
1110
1120
1152
1132

Fig. 16

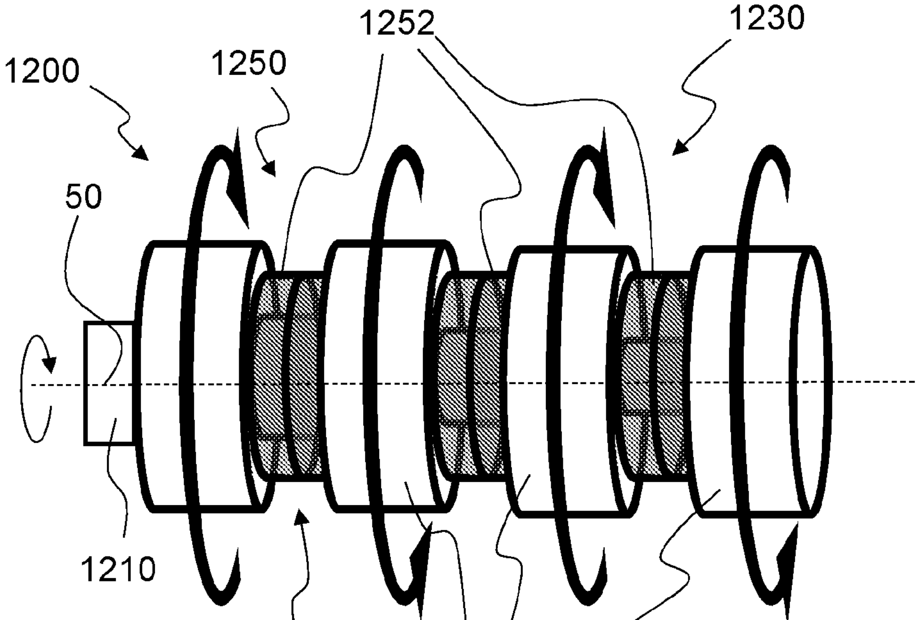
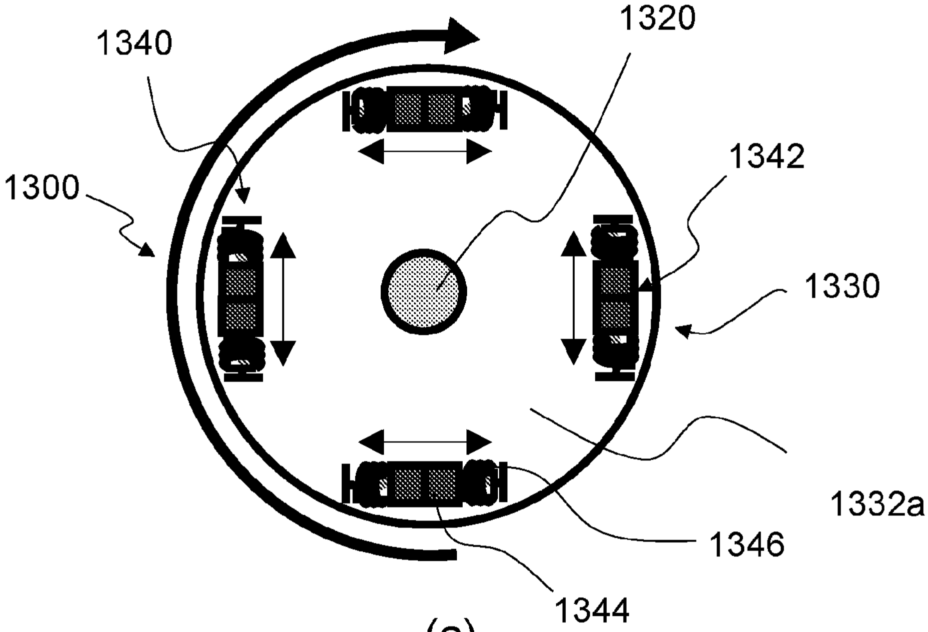
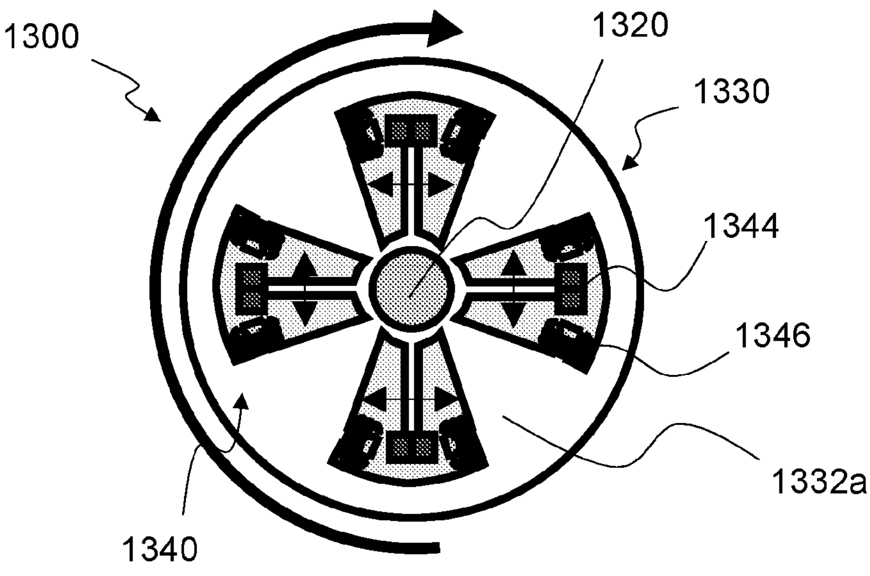

1252
1230
1200
1250
50
1210
1240
1232

Fig. 17


1340
1320
1300
1342
1330
1332a
1346
1344

(a)


1300
1320
1330
1344
1346
1332a
1340

(b)

Fig. 18

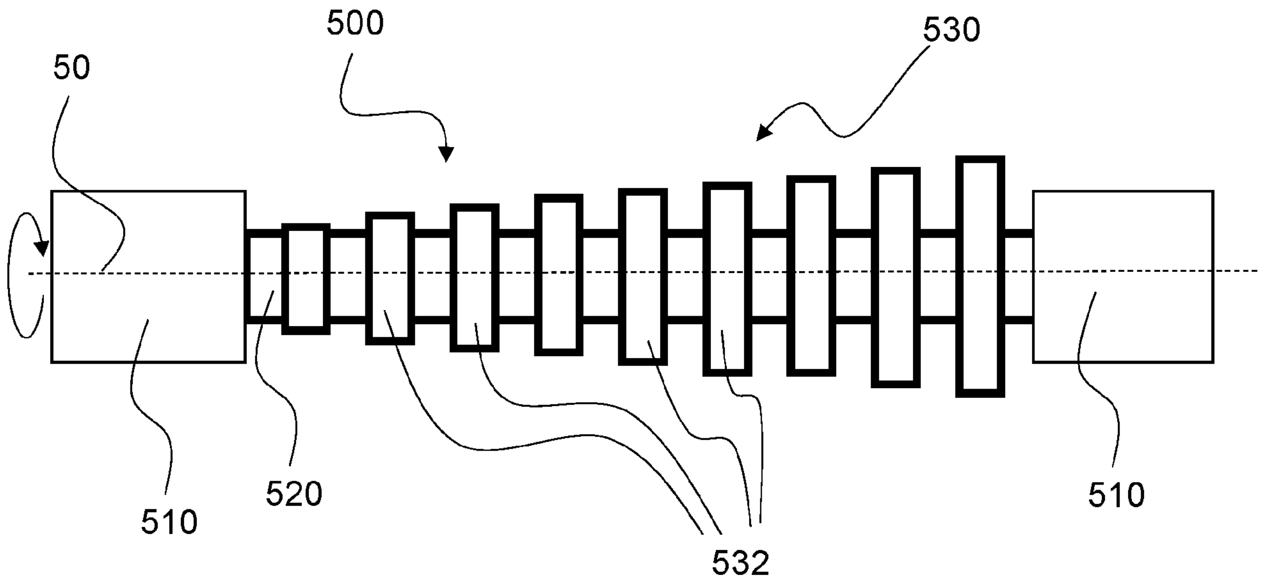


Fig. 19

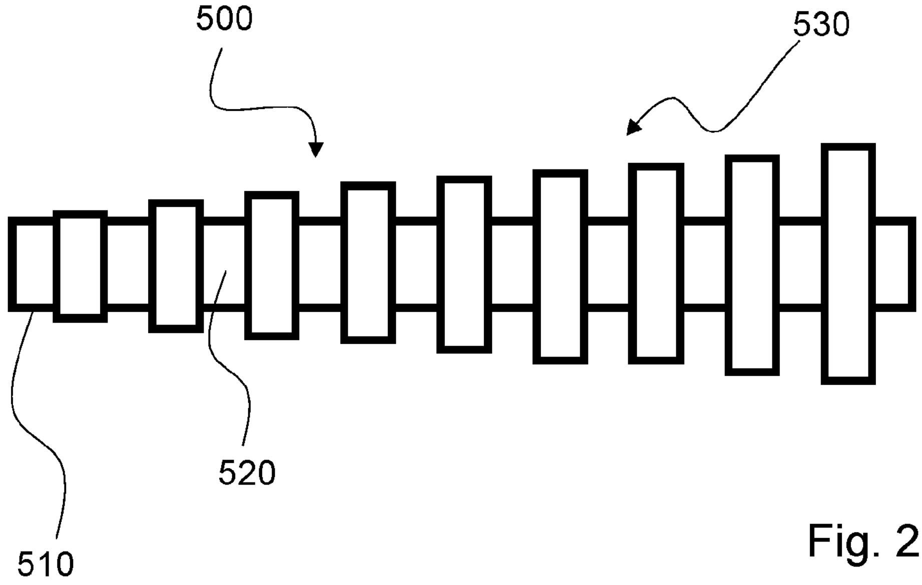


Fig. 20

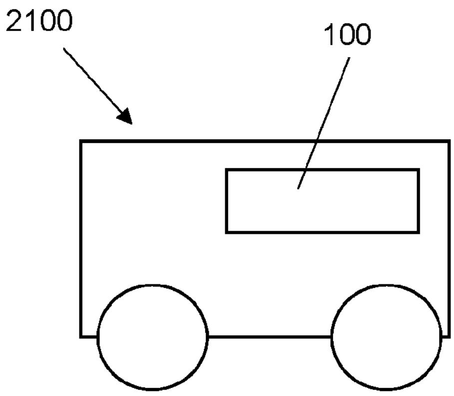


Fig. 21

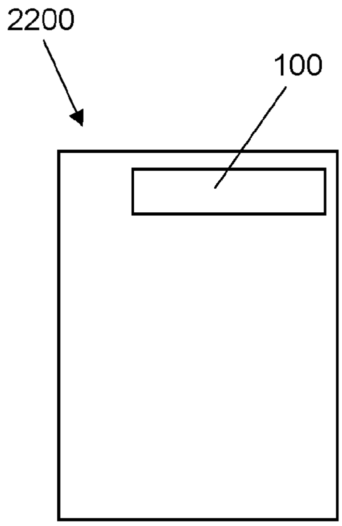


Fig. 22

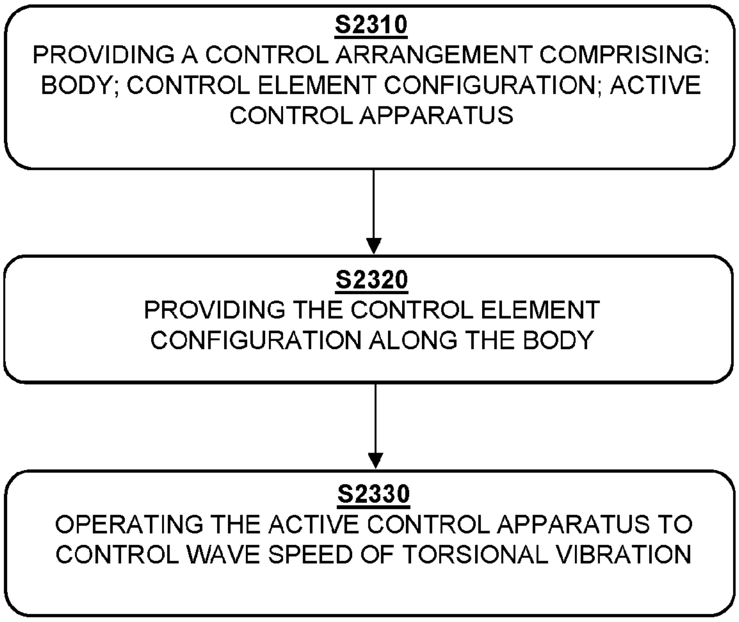


Fig. 23

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2024/051893

A. CLASSIFICATION OF SUBJECT MATTER
INV. F16F15/10 F16F15/00 F16F15/14 F16F15/18
ADD. F16F7/10

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)
F16F

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.
X	EP 2 910 813 B1 (MAN TRUCK & BUS SE [DE]) 17 July 2019 (2019-07-17)	1,2,5,8, 10,11, 13-15
A	paragraph [0051]; claim 1; figures	3,4,6,7, 9,12

X	DE 10 2006 041417 B3 (WINKLHOFER & SOEHNE GMBH [DE]) 3 April 2008 (2008-04-03)	1-8,14, 15
A	claims 1, 4-6, 14, 15; figures	9-13

X	CA 2 316 757 A1 (DANA CORP [US]) 28 February 2001 (2001-02-28) page 5, lines 11-18; figures	1-4,15

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance;; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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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
15 October 2024	05/11/2024

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	Huyge, Kevin

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

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