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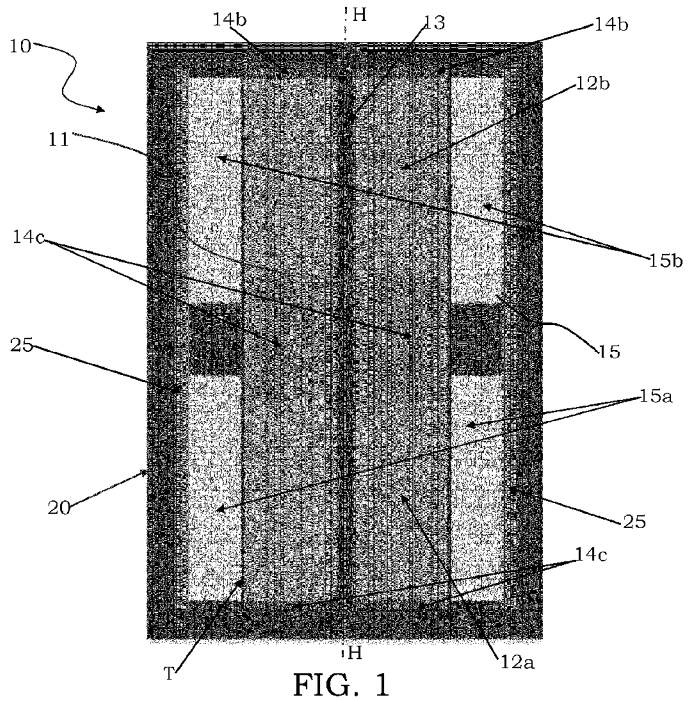

FIG. 1

(57) **Abstract:** An actuator device (10) is described, having a movable core (11) which includes at least one pair of permanent magnets (12a, 12b) which follow each other along an axis of symmetry (H-H) thereof, the movable core (11) being movable between a rest position and an extended position, at least one coil (15, 15a, 15b) which is at least partially wound around the movable core (11) and configured to generate an electromagnetic field when current flows therethrough, so as to cause the movement of the movable core (11) from the rest position to the extended position and vice versa, and a fixed element (25) which is at least partially arranged around the movable core (11); the permanent magnets (12a, 12b) and the fixed element (25) are configured to generate a magnetic force (Fm) between the movable core (11) and said fixed element (25), said magnetic force being apt to drive said movable core (11) towards the rest position when

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DESCRIPTION

Field of application

The present invention relates to an actuator device, for example a linear actuator for the opening/closing of valves. The following description is made with reference to this field of application with the only purpose of simplifying the exposition thereof.

Prior art

As it is well known, there are several types of actuators which are able to generate a linear movement. Between the various available actuators, the electromagnetic actuators are particularly widespread, as they allow, through a coil, to convert an electric signal into a linear movement due to the generation of an electromagnetic field inside the coil.

In accordance with some known solutions, linear electromagnetic actuators are manufactured, which comprise a movable core (for example of a ferromagnetic material) inside a fixed housing onto which a coil is wound, generating an internal magnetic field and the resulting translation of the movable core.

In many cases, a spring for driving the movable core in the initial rest position can be provided. However, the presence of the spring involves some drawbacks, among which the wear over time of the spring itself and the ease of breakage of the device, as well as the increase in the complexity thereof.

Moreover, there are known solutions which provide a fixed core, around which a coil is wound, and a movable component separated by an air gap where, when current is applied, the generated magnetic field causes an attraction between the two elements which tends to close the air gap. In this case too, springs for defining the balance position can be provided.

Moreover, it should be observed that, in known solutions, it is complex to obtain high forces and large air gaps.

The technical problem of the present invention is to devise an actuator device having such structural and functional features as to allow to overcome the limitations and drawbacks reported in connection with known solutions, in particular an actuator device which has a high efficiency and at the same time a simple structure.

Summary of the invention

The solution idea underlying the present invention is to manufacture a linear actuator in which the movable core is able to translate in a housing thereof and which comprises a pair of permanent magnets, and in which the arrangement of the components and the corresponding magnetic circuit are such that maintaining the movable core in the rest configuration (i.e. when no current is applied to the coils) is only ensured by a magnetic force which is generated between said movable core and a fixed magnetic component, with no need to use a spring; when a specific current is then applied to the coils, the forces due to the generated field cause a linear movement of the movable core. Moreover, the position of the permanent magnets can be adjusted with the purpose of finely adjusting the stroke of the linear actuator.

Based on this solution idea, the aforementioned technical problem is solved by an actuator device comprising a movable core including at least one pair of permanent magnets which follow each other along an axis of symmetry thereof, the movable core being movable between a rest position and an extended position, at least one coil (preferably a first coil and a second coil), which is at least partially wound around the movable core and configured to generate an electromagnetic field when current flows therethrough, so as to cause the movement of the movable core from the rest position to the extended position and vice versa, and a fixed element, which is at least partially arranged around the movable core, characterized in that the permanent magnets and the fixed element are configured to generate a magnetic force between the movable core and said fixed element (in particular an attractive force), which is exerted on the movable core for example when it is in the extended position, said magnetic force being apt to drive said movable core towards the rest position when it is in the extended position.

As mentioned, the rest position is not necessary the position in which no force is exerted, but the above magnetic force is exerted, and said position can be finely tuned, as will be disclosed in the following description.

More particularly, the invention comprises the following additional and optional features, taken individually or in combination if required.

According to an aspect of the present invention, the permanent magnets can have an axial magnetization and can be arranged with the same poles facing each other so as to generate a repulsive force therebetween, thereby resulting in magnetic field lines having a direction which is substantially orthogonal to the axis of symmetry of the permanent magnets (i.e. a radial magnetic field).

According to an aspect of the present invention, the actuator device can comprise a housing configured to house the movable core.

In an embodiment, the housing can develop along a longitudinal axis which is coincident with the axis of symmetry of the permanent magnets.

According to an aspect of the present invention, the housing can comprise an abutment surface onto which a portion (for example an end) of the movable core is adapted to abut, this abutment surface being configured to maintain the movable core in a displaced position with respect to the fixed element, the displacement being referred to the axis of symmetry of the permanent magnets, thereby defining the rest position of the movable core, wherein said rest position is different from a balance position in which no forces are exerted on said movable core.

According to an aspect of the present invention, the abutment surface can be movable and can be configured to displace the movable core along the axis of symmetry of the permanent magnets.

According to an aspect of the present invention, the actuator device can comprise a threaded element in engagement with a corresponding thread formed in the housing, said threaded element being configured to displace, by screwing/unscrewing, the position of the abutment surface in said housing and thus to adjust the position of the movable core.

According to an aspect of the present invention, the actuator device can comprise a rod in engagement with the movable core and integrally movable therewith.

According to an aspect of the present invention, the permanent magnets of the movable core can be selected among neodymium-based materials, for example NdFeB.

According to an aspect of the present invention, the fixed element can be made of a mild steel material.

According to an aspect of the present invention, the movable core can comprise a spacer arranged between the permanent magnets, said spacer being for example made of a mild steel material. The spacer is affected by the generated magnetic field lines and it magnetically interacts with the fixed element, contributing to the generation of the magnetic force which drives the movable core towards the balance, more particularly towards the rest position which does not always coincide with the balance position.

According to an aspect of the present invention, the movable core can comprise, in addition to the aforementioned spacer arranged between the permanent magnets, a first end spacer arranged at a first end of the movable core and a second end spacer arranged at a second and opposite end of the movable core; these spacers can also magnetically interact with the fixed element.

According to an aspect of the present invention, the actuator device can comprise a pair of coils (for example in series).

According to an aspect of the present invention, a first coil can be wound clockwise and a second coil can be wound counterclockwise, in such way that, when current flows therethrough, they are apt to generate a linear force so as to move the movable core along a direction which is coincident with the axis of symmetry of the permanent magnets.

The features and advantages of the actuator device of the present invention will be apparent from the following description of an exemplary embodiment thereof given by way of non-limiting example with reference to the accompanying drawings.

Brief description of the drawings

In the drawings:

- figure 1 shows a schematic section of an actuator device according to the present invention;

- figure 2 shows a sectional view of the actuator device according to an embodiment of the present invention;

- figures 3A-3B show the pattern of the magnetic field and of the magnetic flow density in the actuator device according to the present invention;

- figures 4A-4D show a diagram of the actuator device of the present invention in different operating configurations;

- figure 5 shows a graph of the force as a function of the position of a movable core of the actuator device of the present invention;

- figure 6 depicts a graph which represents the Newtons/Amperes as a function of the stroke of the movable core of the actuator device according to the present invention;

- figure 7 shows a schematic section of an actuator device according to an embodiment of the present invention; and

- figure 8 shows a graph of the force as a function of the position of the movable core of the actuator device according to the embodiment of figure 7.

Detailed description

With reference to the figures, an actuator device (hereinafter simply indicated as “actuator”) in accordance with the present invention is globally and schematically indicated with the reference number 10.

It should be noted that the figures represent schematic views and are not drawn to scale, but are instead drawn so as to emphasize the important features of the invention. Furthermore, in the figures, the different components are schematically represented and their shape can vary depending on the desired application. Moreover, it should be noted that, in the figures, identical reference numbers refer to elements which are identical in shape or function. Finally, particular expedients described in connection with an embodiment illustrated in a figure can also be used for the other embodiments illustrated in the other figures.

Moreover, it should be observed that, when sequences of process steps are illustrated, they do not necessarily follow the indicated sequence and said steps can be, in some cases, reversed.

The actuator 10 is suitable for several applications, among which the opening/closing of valves is mentioned by mere way of non-limiting example.

As illustrated in the section of figure 1, the actuator 10 comprises first of all a movable core (globally indicated with the reference 11) comprising at least one pair of permanent magnets 12a and 12b having a hollow cylindrical or discoidal shape with axial magnetization, as it will be detailed herebelow. The permanent magnets 12a and 12b develop along an axis of symmetry indicated in the present description with the reference H-H.

More particularly, as illustrated in figure 2, the permanent magnets 12a and 12b comprise an axial hole engaged by a shaft or rod (reference 13), on which the movable core 11 is thus arranged. The rod 13 is thus in engagement with the movable core 11 and is integrally movable therewith. In an embodiment, the rod 13 is made of a plastic material and there is possibly a mechanic safety stop 13s, which is also adjustable as a function of the stroke of the actuator 10.

As illustrated in the figures, the permanent magnets 12a and 12b are arranged in series and follow each other along the common axis of symmetry H-H thereof.

In an embodiment, the permanent magnets 12a and 12b of the movable core 11 are made of a neodymium-based material, as for example NdFeB, although the use of other materials is not excluded.

The movable core 11 also comprises a spacer 14c arranged between the permanent magnets 12a and 12b and made for example of a mild steel material (for example 11SMmPb30, however without being limited to a particular material).

Still more particularly, the movable core 11 comprises, in addition to the spacer 14c arranged between the permanent magnets 12a and 12b, a first end spacer 14a arranged at a first end of the movable core 11 (in particular arranged on the left according to the reference of figure 2) and a second end spacer 14b arranged at a second and opposite end of said movable core 11 (in particular arranged on the right according to the reference of figure 2).

In the embodiment illustrated in the figures, the spacers 14a, 14b and 14c and the permanent magnets 12a and 12b, which move together as a single movable component, are thus splined on the rod 13.

As it will be discussed in detail below, the movable core 11 is able to move between a rest position and an extended position (which corresponds to the force peak exerted by the actuator 10). For this purpose, the actuator 10 comprises at least one coil 15, which is at least partially wound around the movable core 11 and configured to generate an electromagnetic field when current flows therethrough, so as to cause the movement of the movable core 11 from the aforementioned rest position to the extended position, and vice versa.

More particularly, in accordance with embodiments of the present invention, the actuator 10 comprises a pair of coils, with a first coil 15a wound clockwise and a second coil 15b wound counterclockwise, in such way that, when current flows therethrough, they contribute to the generation of a linear force so as to move the movable core 11 in a linear direction, i.e. along a direction which is coincident with the axis of symmetry H-H of the permanent magnets 12a and 12b. Thereby, when current flows through the coils 15a and 15b, the permanent magnets 12a and 12b are in a magnetic field resulting from the total of the magnetic fields created by the two coils (sources).

Furthermore, there is a housing or casing 20 configured to house the movable core 11, the housing 20 developing along a longitudinal axis which is coincident with the axis of symmetry of the permanent magnets 12a and 12b. In an embodiment, the housing 20 is tubular in shape and hollow inside and it is equipped with an axial through channel to let the movable core 11 slide. The housing 20 is made of a non-magnetic material, for example a plastic material, without being limited to a specific material.

As illustrated in the example of the figures, the housing 20 is further configured to serve as a bobbin onto which the coils 15a and 15b are wound. In particular, as illustrated in figure 2, the shaft 13 has at least one end which protrudes from the housing 20, for example to connect to a load or to exert a specific force.

The terminals of the coils 15 are connected to a power supply which is able to power them with a specific voltage signal (being for example square-waved or any type of modulated signal), following which the shaft 13 performs back and forth strokes.

Furthermore, in accordance with the present invention, the actuator 10 comprises a fixed element (or fixed part) 25 arranged at least partially around the movable core 11. In the embodiment illustrated in the figures, the coils 15a and 15b are arranged between the movable core 11 and the fixed element 25, which thus serves as a cover and support thereof, said components being concentric to each other. The fixed element 25 is thus part of the fixed core of the actuator 10.

The fixed element 25 is made of a magnetic material, for example of mild steel, without being limited to a particular material, and it can have a radial thickness (i.e. along a direction which is orthogonal to the axis of symmetry H-H of the permanent magnets) of about 1 mm. Furthermore, there can be an air layer between the coils 15a and 15b and the fixed element 25, for example of about 0.2 mm. As it can be seen in the figures, the movable core 11 and the coils 15 further define an air gap T of about 1 mm between each other.

It should be observed in any case that all the indicated numerical values are only indicative and do not limit in any way the scope of the present invention.

Advantageously according to the present invention, the permanent magnets 12a and 12b, the spacer 14c and the fixed element 25 are configured to generate between said fixed element 25 and the movable core 11 a magnetic force (in particular an attractive force, indicated with the reference Fm) which is exerted on the movable core 11 when it is in a different position from the balance position thereof, i.e. when it is in a different position from the position in which, in the absence of current, no magnetic force is exerted thereon (which occurs when the movable core 11 and the fixed element 25 are centred with each other). The magnetic force Fm is thus apt to drive the movable core 11 towards the balance position, for example when the movable core 11 is in the extended position.

In other words, in accordance with the present invention, the movable core 11 and the fixed element 25 are configured to generate the aforementioned magnetic force Fm therebetween, where said movable core 11 is maintained in the initial rest position by the action of said magnetic force Fm.

As it will be detailed below, the rest position of the movable core 11 is not necessarily the balance position in which no forces act on said movable core, but it can also be a starting position in which the movable core 11 is displaced with respect to the balance position, and thus it can be a position in which the aforementioned magnetic force Fm acts.

Suitably, the permanent magnets 11 have an axial magnetization and are arranged with the same poles facing each other (i.e. with the opposite magnetization, for example with the negative pole towards the negative pole or the positive pole towards the positive pole) so as to generate a slight repulsive force therebetween, thereby resulting in magnetic field lines B having a direction which is substantially orthogonal to the axis of symmetry thereof, i.e. having a radial direction (as illustrated in figures 3A and 3B). The presence of a magnetic field flow having a radial direction allows the interaction of the latter with the fixed element 25, and thus a magnetic interaction between the movable core 11 and the fixed element 25, this interaction thereby resulting in the aforementioned magnetic force Fm which allows to drive the movable core 11.

The spacer 14c, which is made of a suitable material with magnetic properties and is arranged between the permanent magnets 12a and 12b (and thus suitably separates them, which is important since they slightly repel each other), contributes to the attraction between the movable core 11 and the fixed element 25; in particular, due to the above-described field lines generated by the configuration of the permanent magnets 12a and 12b, the spacer 14c (as well as the possible spacers 14a and 14b) magnetically interacts with the fixed element 25, thus contributing to the generation of the aforementioned attractive magnetic force Fm.

As indicated above, the spacer 14c and the possible spacers 14 and 14b are made of a magnetic material so as to contribute to the generation of the aforementioned magnetic field flow lines (generated due to the configuration of the permanent magnets) and likewise magnetically interact with the fixed components, for example they can be made of the same material of the fixed element 25.

Thereby, when current is not made to flow in the coils 15a and 15b, the movable core 11 is driven in the rest position only by the magnetic force Fm, with no need to use mechanic components like springs, thus considerably simplifying the structure of the actuator 10 and reducing the risk of breakage/wear of the components thereof.

In an embodiment, the permanent magnets are such that the aforementioned repulsive force therebetween is of about 39 N, although obviously the present invention is not limited to this value.

Furthermore, it should be observed that the number of turns of the coils 15a and 15b, which are arranged in series in the magnetic circuit, is selected between 700 and 1000, preferably between 800 and 900, in this case too without limiting to a specific number and this number can vary depending on the applications and/or circumstances.

Referring again to figure 2, in a particularly advantageous embodiment of the present invention, the housing 20 comprises thereinside an abutment surface 20b onto which a portion of the movable core 11 (for example one of the ends thereof) is adapted to abut. In particular, the housing 20 is specifically shaped to define the aforementioned abutment surface 20b, which is configured to maintain the movable core 11 in a displaced position with respect to the fixed element 25 (i.e. displaced with respect to a position in which these components are centred with respect to each other), thereby defining the rest position of the movable core. As mentioned above, in this embodiment, the rest position of the movable core 11 is thus different from the balance position in which no forces are exerted onto said movable core 11. Thereby, due to the abutment surface 20b, (with reference to the axis of symmetry H-H of the permanent magnets) the movable core 11 can be decentred with respect to the fixed element 25, wherein the movable core 11 is displaced with respect to the balance position thereof and the magnetic force Fm acts thereon.

As mentioned above, one end of the movable core 11 abuts onto the abutment surface 20b, although the present invention is not limited to this configuration and other configurations can be provided.

Suitably, the abutment surface 20b can be displaced along the axis H-H in order to displace the movable core 11, thereby adjusting the rest position of the movable core and also the stroke thereof. In particular, in an embodiment, there is a threaded element 30 in engagement with a corresponding thread formed in the housing 20 and able to be screwed/unscrewed by the user in order to finely displace the movable core 11 inside the housing 20; in this case, the abutment surface 20b corresponds to an end of the threaded element 30. Still more particularly, the threaded element 30 is configured to adjust, by screwing/unscrewing, the position of the abutment surface 20b in a direction which is parallel to the axis of symmetry H-H of the permanent magnets, thereby adjusting both the rest position and the stroke of the movable core 11.

This embodiment has the advantage that the stroke of the movable core 11 is finely adjustable, in particular selectable as a function of the position of the permanent magnets, while the magnetic force Fm always ensures the abutment of the movable core 11 in the rest position, which is adjustable as well.

As shown in figure 2, the threaded element 30 (which can be a bush), comprises a portion 30p which can be engaged by a screw for the adjustment thereof.

Figures 4A-4D show the above-described actuator 10 in different operating configurations.

Operationally, when the movable core 11 is in the rest position, it senses the driving/cogging magnetic force Fm due to the fixed element 25 when no current flows in the coils 15a and 15b (figure 4A). Based on the configuration and on the reference system adopted in figures 4A-4D, the magnetic force Fm is negative, i.e. it is directed in the negative sense of the axis y.

In the case in which the actuator 10 is vertically arranged (as illustrated in figure 4A), the movable core 11 should also be subjected to the weight force Fp due to the mass of the movable core 11 itself, which is directed in the negative sense of the axis y as well. The abutment surface 20b (not illustrated for simplicity in figures 4A-4D), acting as a mechanic stop, prevents the movable core 11 from dropping towards the minimum of the force.

Figure 4B shows the case in which the coils 15a and 15b are powered, causing the linear movement of the movable core 11. In particular, when current is made to flow in the coils, the movable core 11 senses a force Fm' (obtained as the resultant of the aforementioned magnetic force Fm and of the Lorentz force generated in this case), which is of opposite sign with respect to the magnetic force Fm which is sensed in the rest condition (i.e. it is directed in the positive sense of the axis y), the force Fm' pulling the movable core 11 towards the end of stroke (with a movement in the positive sense of the axis y). In this case, there is also a slight frictional force which is opposed to the movement of the movable core, which, for simplicity of illustration, is not depicted in the drawings, this force being anyway negligible.

As mentioned, in this case illustrated in figure 4B, because of the current which is made to flow in the coils 15a and 15b and because of the hereillustrated magnetic circuit, the linear movement of the movable core 11 is due to the Lorentz force.

More particularly, as mentioned above in connection with the case of figure 4B, the current flowing in the coils 15a and 15b in the presence of the external magnetic field created by the permanent magnets 12a and 12b generates a Lorentz force directed upwards (according to the reference of the figures) which overcomes the cogging magnetic force Fm exerted between the fixed element 25 and the movable core 11, thereby resulting in the force Fm'. This positive force (i.e. in the positive sense of the axis y) causes the linear movement of the movable core 11 towards the end of stroke.

As illustrated in figure 4C, when current is no longer made to flow in the coils 15a and 15b, the movable core 11, after reaching the end of stroke, senses again only the negative magnetic force Fm (and possibly also the weight force Fp) which brings it back to the initial rest position (with a movement in the negative sense of the axis y).

In accordance with an alternative embodiment, in the case in which there is not the abutment surface 20b (figure 4D), when current is not made to flow in the coils 15a and 15b the movable core 11 would remain in the balance position, with the possible presence of the single weight force Fp. In this case, the movable core 11 and the fixed element 25 are thus aligned/centred.

An operating example of the actuator 10 is illustrated hereafter, this example not limiting in any way the scope of the present invention. In this example, the input voltage which is applied at the terminals of the coils 15a and 15b is 12 Vdc, with a maximum power supply current of 250 mA and a maximum power of 3 W. The linear stroke of the movable core 11 is of 3.6 mm, with a total length of the actuator 10 of about 90 mm, of which about 40 mm are due to the length of the movable core 11.

Figure 5 shows a graph of the exerted force as a function of the position of the movable core 11, this graph being obtained for the actuator 10 according to the above-indicated numerical example. In this graph, which substantially depicts the force curve of the actuator 10, the curves C' represent the values obtained at zero voltage for different temperatures, while the curves C" represent the values obtained with a 12 Vdc voltage for different temperatures.

The origin (i.e. the position 0) of this graph corresponds to the balance position of the movable core 11, onto which no force of the magnetic type is exerted. As it can be noted from the shown graph, when the movable core 11 is displaced from the balance position, for example by the threaded element 30 which displaces the abutment surface 20b, the movable core 11 senses a force (in this case a negative one, always based on the reference system of the previous example), i.e. the aforementioned cogging magnetic force Fm which tends to drive it towards the balance position. In the case in which there is the abutment surface 20b, the magnetic force Fm thus helps to maintain the abutment of the movable core 11 in the rest position, without the aid of the spring. When the coils 15 are then powered, in addition to the aforementioned cogging magnetic force Fm the movable core 11 also senses a force with an opposite sense (i.e. the aforementioned Lorentz force) which causes the movement thereof, with an increase in the exerted force (note in particular the length of the curve comprised between the two vertical lines l' and l", which corresponds to the operating range of the actuator 10). Once moved, the movable core 11 thus performs a specific stroke, with a force peak of 5,78 N; after reaching the force peak, current is cut in the coils 15a and 15b and the movable core 11 tends to return to the rest position.

In this example, the displacement of the movable core 11 is of about 0.014 m, with a total stroke of about 3.6 mm; the current density is about 4.6-3.8 A/mm^2, which is a much lower value with respect to what is found in known solutions.

It is thus evident that the actuator device according to the present invention is very versatile, with the possibility of adjusting the stroke based on the construction requirements by displacing on the force curve.

The actuator 10 is also suitable to be used as bistable, because of the peculiar force curve thereof as a function of the displacement of the movable core 10, as it will be discussed herebelow.

Figure 6 depicts a graph which represents the Newtons/Amperes as a function of the stroke of the actuator 10 according to the above-indicated example. In other words, this graph shows how much current is required by the actuator 10 to exert a specific force and thus to overcome a specific resistant force. In particular, the curves D' represent the values obtained for the actuator 10 according to the present invention at different temperatures, while the curve D" represents the resistant force which must overcome the device, with reference to a traditional electromagnet according to the prior art.

The electromagnet that is used to compare the performances operates with a maximum current of 0.75 A, a power of 3 W and a power supply voltage of 12 V. The actuator 10 of the present invention has the same input voltage, power, dimensions but, advantageously, it requires a much lower current to exert a same force, thereby resulting in the curves D' illustrated in figure 6, with a considerably higher value of Newtons/Amperes.

From a dynamic point of view, it was observed that a complete working cycle, i.e. starting from the rest position up to the extended position and then again to the rest position, can be, in some circumstances, also lower than 0.20 s.

Furthermore, the fact of working with a low current density avoids overheating phenomena inside the actuator device 10. In fact, following a static thermal analysis carried out with the simulation software Flux 2D, it is possible to see how the actuator 10 according to the present invention is not subject to an excessive overheating during a working cycle; for example, by imposing an external temperature of 40 °C, the overheating which is generated by the coils 15 is approximately of 5.159 °C, and thus it is very limited.

Finally, as mentioned above, the structure of the actuator 10 can be adapted to the bistable use, with suitable both structural and power supply modifications, as schematically indicated in figure 7, which illustrates an alternative embodiment of the present invention. In this case, with respect to the configuration of figure 1, the actuator 10 includes additional spacers 14d, 14e and 14f (for example always in the form of rings) so as to modify the magnetic interaction between the movable core 11 and the fixed core, now comprising also the aforementioned spacers 14d, 14e and 14f in addition to the fixed element 25. In addition, the inclination of the spacers 14a and 14b is modified, as shown in figure 7. The size of the electromagnetic components, the magnetization of the permanent magnets 12a and 12b, the sense of the current in the coils 15a and 15b and the used materials remain instead unchanged; in general, all what was seen above for the monostable case (with a rest position), also applies to this bistable case, except for the aforementioned differences.

Figure 8 represents the force curve of the actuator 10 in the bistable case, i.e. it represents the graph of the exerted force as a function of the position of the movable core 11. The operation of the actuator 10 in the bistable version is based on the same above-seen concepts exploited for the operation thereof in the monostable version, but with some peculiarities, because now there are two stable balance positions. Still more particularly, it should be observed what follows:

- in the starting position – or initial rest position - (identified by the line P1 of figure 8), the movable core 11 is deviated from the balance position, in which the fixed core and the movable core 11 would be aligned (for example due to an initial abutment), and there is the negative preloading magnetic force Fm (with reference to the axes of the figures, as also seen above in connection with the monostable case) at zero voltage exerted between the movable core 11 and the fixed core. This zero-voltage situation is represented by the curve E’, where the preloading magnetic force Fm maintains the movable core 11 in the starting position P1 (which thus corresponds to the first stable balance point, where in this figure the point P1 was selected only for illustration purposes, for example by means of the aforementioned abutment);

- afterwards, when a positive voltage is supplied to the coils (for example 12 Vdc), the movable core 11 senses a positive force Fm’ (always according to the reference of the figures); this force is represented by the curve E” of figure 8. This force causes the movement of the movable core 11 towards the end of stroke, with a displacement from the position P1 to the position identified by the line P2. When voltage is no longer supplied (and thus taking again into account the curve E’, now at the line P2), the movable core 11 would tend, because of the nature of the force curve, to remain in said position (which thus corresponds to the second stable balance point);

- in order to pass from the position P2 to the initial position P1 the coils 15a and 15b are powered with a negative voltage: this causes the movable core 11 to sense a negative force (force curve E’” in the graph of figure 8) which brings it back in said position P1 (if required the negative voltage can be turned off at a suitable moment for voltage saving: thereby in order to return to the initial position the negative force at zero voltage is exploited);

- finally, by turning off the voltage, the reference curve is again the central force curve E’ at zero voltage, in the position P1.

The advantages of the actuator 10 in a bistable configuration are the same ones seen in the monostable case (for example low current density, possibility to adjust the stroke based on the force requirements, little overheating, compactness, high Newtons/Amperes with respect to a traditional electromagnet, and absence of springs for the operation thereof), with the addition of two stable balance positions, which can be useful in some applications, and the possible use also as a monostable actuator if the working stroke range is suitably selected.

In conclusion, the present invention thus allows to brilliantly overcome the technical problem, providing the above actuator and solving all the drawbacks of the prior art.

Advantageously, with respect to the traditional electromagnets, the here-described actuator is optimized in the arrangement of the magnets and of the magnetic circuit to allow to generate linear mechanic forces with a low current waste: compared with the traditional devices, it has a higher Newton/Ampère value with respect to known solutions, up to an order of magnitude, this due to the use of the permanent magnets.

As seen above, due to the particular adopted configuration, the use of the spring can be eliminated. The movable core remains in fact in the initial position by just exploiting the preloading magnetic force which is generated between the permanent magnets of the movable core and the fixed element. By exploiting the Lorentz force, the movable part can be made to slide in the two directions allowing the device to perform the desired stroke; moreover, the stroke can be adjusted based on the positions of the magnets.

All this is very advantageous since not only the device can be driven solely with the magnetic force, but the frictions due to the spring of known solutions are also excluded, so as to increase the usable force.

Summarizing the various advantageous features due to the illustrated configuration, there is a high force with maximum air gap, there is a current not exceeding 0.23 A (compared to the values exceeding 0.70 A of known solutions), there is a great versatility (based on the force requirements, the device stroke can be calibrated in a different manner), there is the presence of permanent magnets to have less current absorbed by the system, there is the absence of springs for the device operation, while there is a low current density (maximum density at 20°: 4.6 A/mm^2 with a current of 0.23 A, minimum density at 80° C: 3.8 A/mm^2 with a current of 0.185 A).

Furthermore, the here-described actuator device is extremely compact.

Finally, as mentioned above, in an embodiment, the actuator can also be bistable (i.e., the topology thereof is also suitable for a use as bistable), with the necessary precautions.

The actuator device of the present invention can thus be a good alternative to a traditional electromagnet, with the above-described several advantages.

Obviously, a person skilled in the art, in order to meet contingent and specific requirements, will be able to bring several modifications and variants to the above-described actuator device, all falling within the scope of protection of the invention as defined by the following claims.

CLAIMS

1. An actuator device (10) comprising:

- a movable core (11) comprising at least one pair of permanent magnets (12a, 12b) which follow each other along an axis of symmetry thereof (H-H), said movable core (11) being movable between a rest position and an extended position;

- at least one coil (15, 15a, 15b), which is at least partially wound around the movable core (11) and configured to generate an electromagnetic field when current flows therethrough, so as to cause the movement of said movable core (11) from the rest position to the extended position and vice versa; and

- a fixed element (25), which is at least partially arranged around the movable core (11),

characterized in that the permanent magnets (12a, 12b) and the fixed element (25) are configured to generate a magnetic force (Fm) between the movable core (11) and said fixed element (25), said magnetic force being apt to drive said movable core (11) towards the rest position when said movable core is in the extended position.

2. The actuator device (10) according to claim 1, wherein the permanent magnets (12a, 12b) have an axial magnetization, and wherein said permanent magnets (12a, 12b) are arranged with the same poles facing each other so as to generate therebetween a repulsive force, thereby resulting in magnetic field lines having a direction which is substantially orthogonal to the axis of symmetry (H-H) of said permanent magnets (12a, 12b).

3. The actuator device (10) according to claim 1 or 2, comprising a housing (20) configured to house the movable core (11).

4. The actuator device (10) according to claim 3, wherein the housing (20)

comprises an abutment surface (20b) onto which a portion of the movable core (11) is adapted to abut, said abutment surface (20b) being configured to maintain the movable core (11) in a displaced position with respect to the fixed element (25), thereby defining the rest position of the movable core, wherein said rest position is different from a balance position in which no forces are exerted on said movable core (11).

5. The actuator device (10) according to claim 4, wherein the abutment surface (20b) is movable and is configured to displace the movable core (11) along the axis of symmetry (H-H) of the permanent magnets (12a, 12b).

6. The actuator device (10) according to claim 5, comprising a threaded element (30) in engagement with a corresponding thread formed in the housing (20), said threaded element (30) being configured to displace, by screwing/unscrewing, the position of the abutment surface (20b) in said housing (20) and thus to adjust the position of the movable core.

7. The actuator device (10) according to any one of the previous claims, comprising a rod (13) in engagement with the movable core (11) and integrally movable therewith.

8. The actuator device (10) according to any one of the previous claims, wherein the permanent magnets (12a, 12b) of the movable core (11) are selected among neodymium-based materials, for example NdFeB.

9. The actuator device (10) according to any one of the previous claims, wherein the fixed element (25) is made of a mild steel material.

10. The actuator device (10) according to any one of the previous claims, wherein the movable core (11) comprises a spacer (14c) arranged between the permanent magnets (12a, 12b), said spacer (14c) being made for example of a mild steel material, said spacer (14c) being configured to magnetically interact with the fixed element (25).

11. The actuator device (10) according to claim 10, wherein the movable

core (11) comprises, in addition to the spacer (14c) arranged between the permanent magnets (12a, 12b), a first end spacer (14a) arranged at a first end of the movable core (11) and a second end spacer (14b) arranged at a second and opposite end of the movable core (11).

12. The actuator device (10) according to any one of the previous claims, comprising a pair of coils (15a, 15b), wherein a first coil (15a) is wound clockwise and a second coil (15b) is wound counterclockwise, in such way that, when current flows therethrough, they are apt to generate a linear force so as to move the movable core (11) along a direction which is coincident with the axis of symmetry (H-H) of the permanent magnets (12a, 12b).

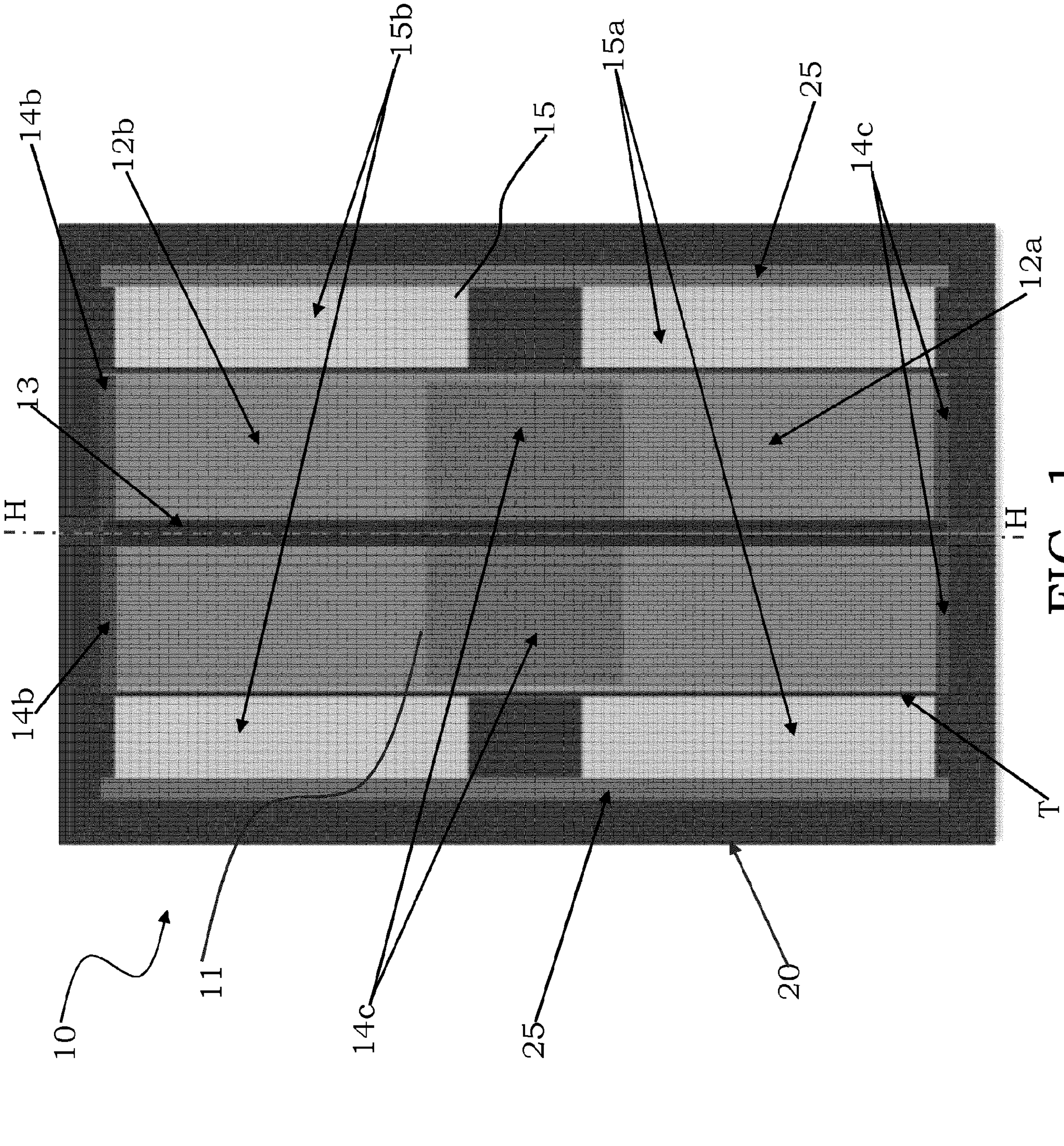
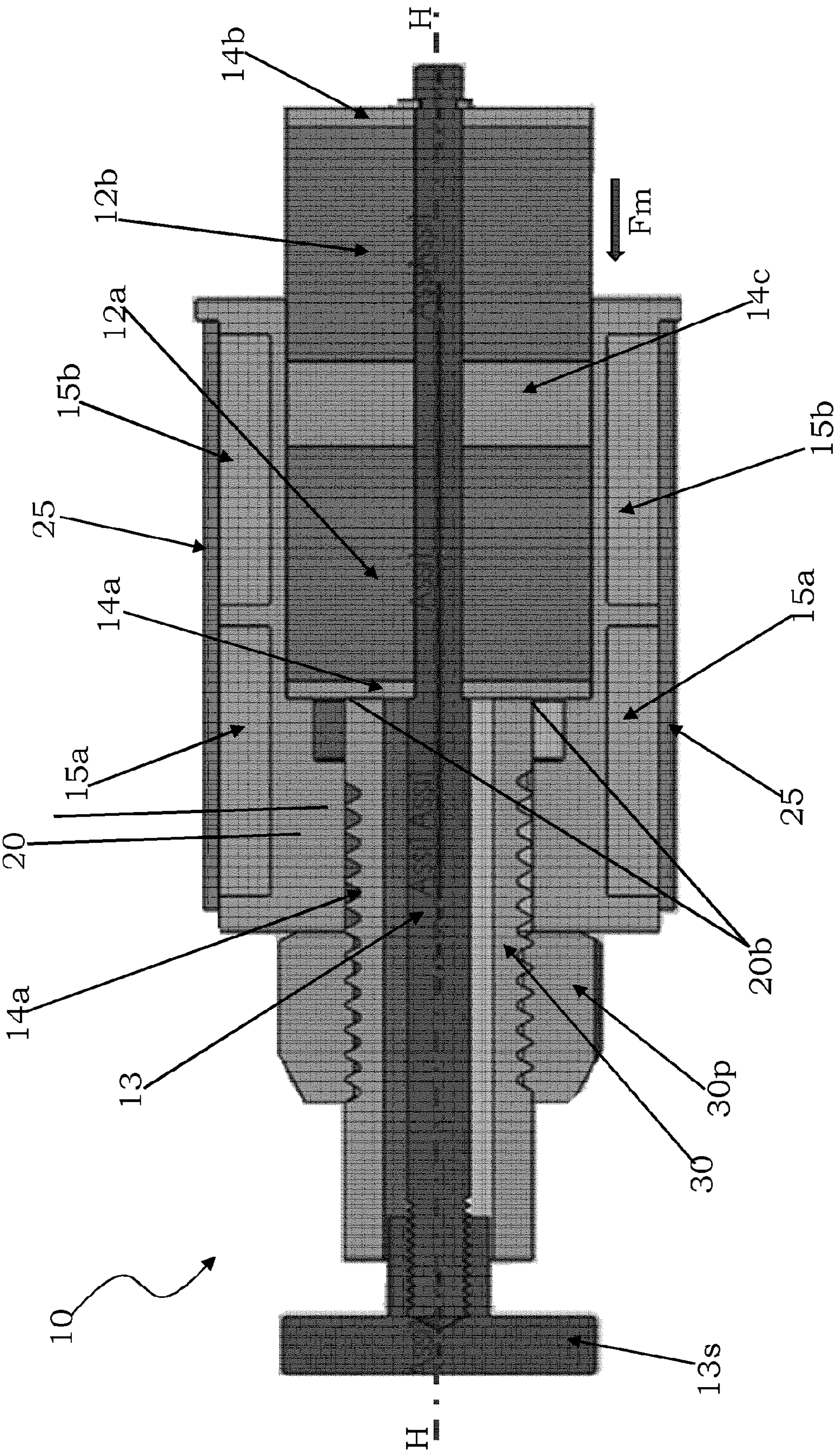


FIG. 1


H
14b
12b
Fm
12a
14c
15b
15b
25
14a
15a
15a
20
25
20b
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13
30p
30
10
13s
H

FIG. 2

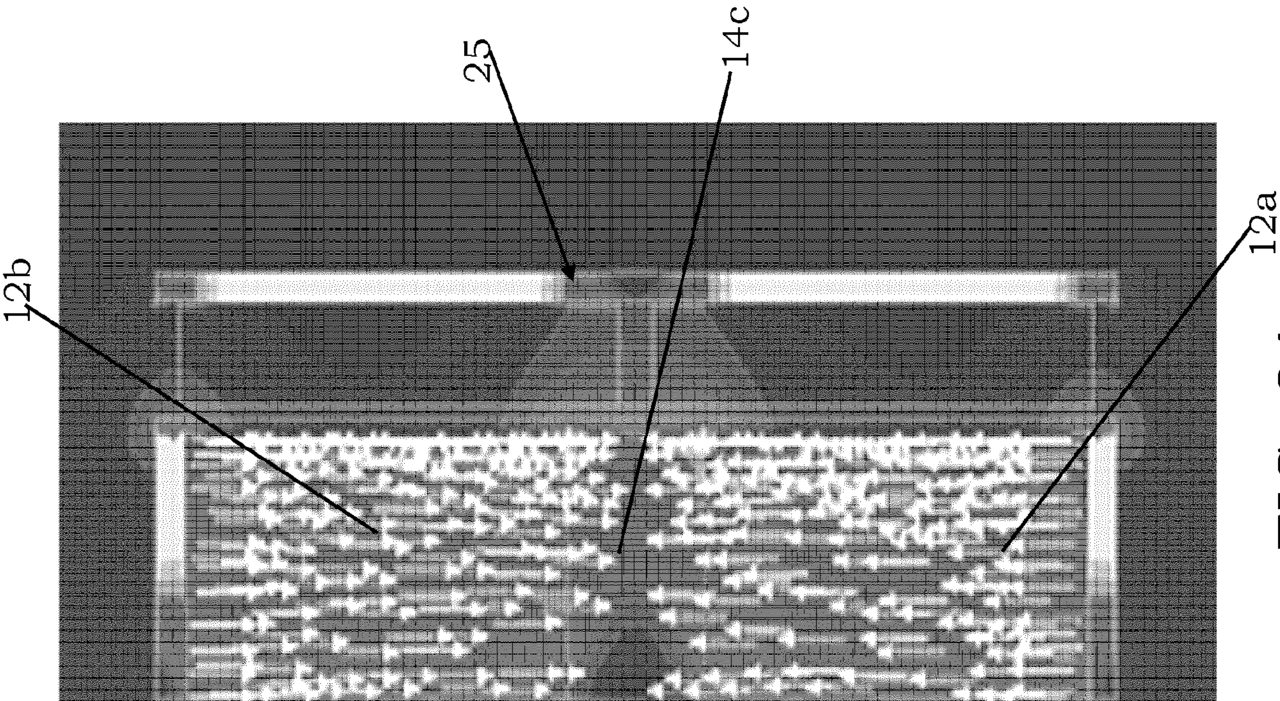


FIG. 3A

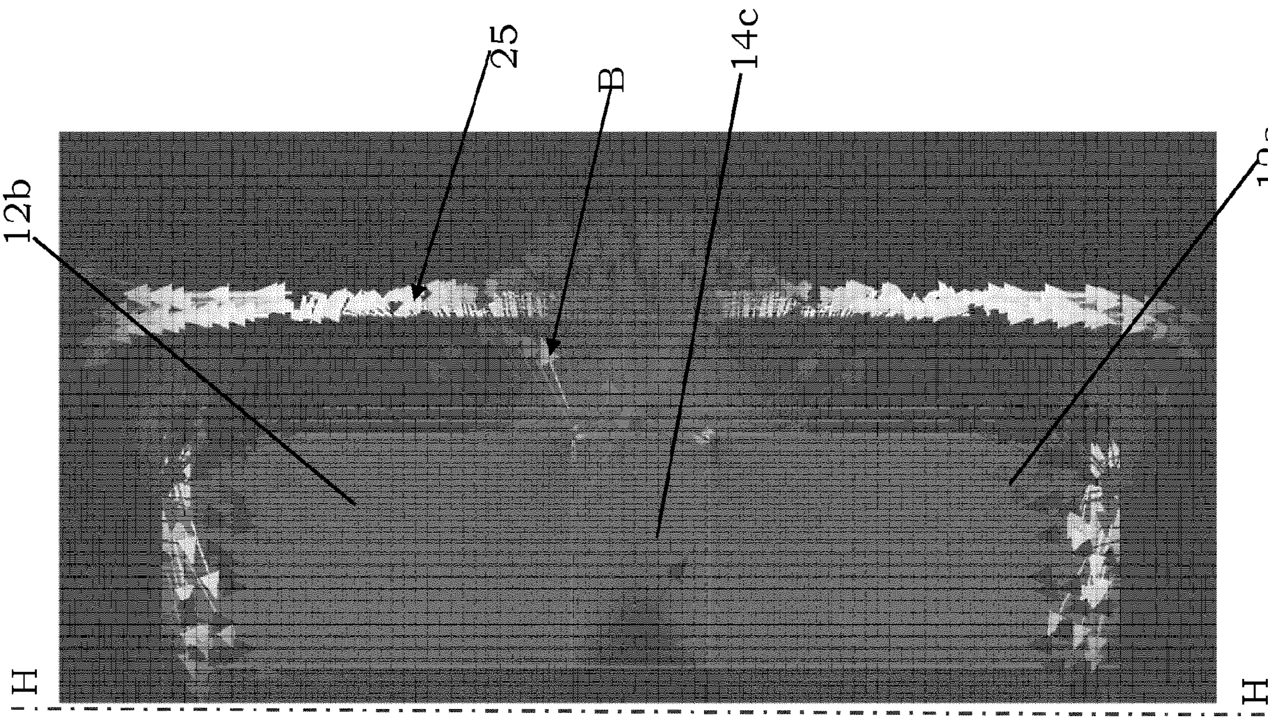


FIG. 3B

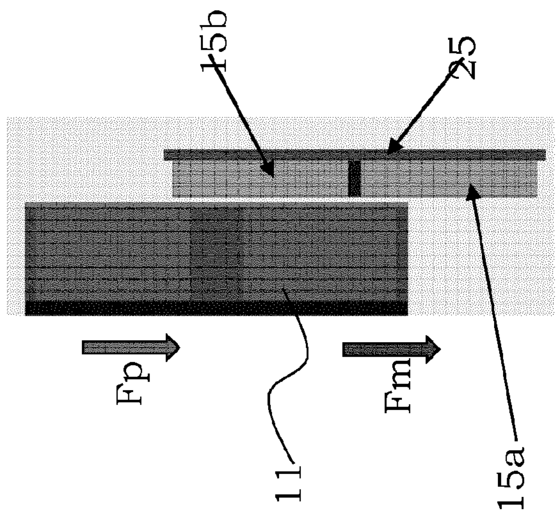


FIG. 4A

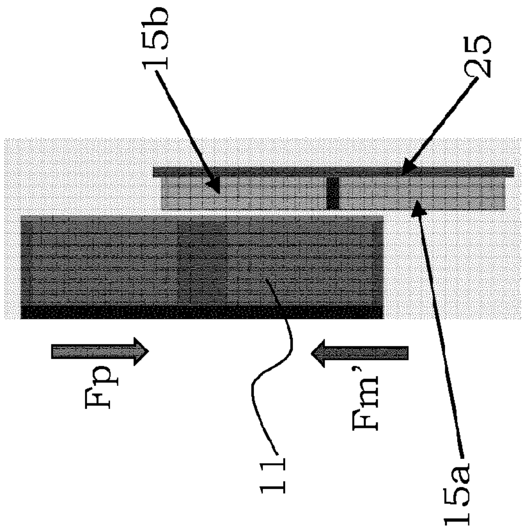


FIG. 4B

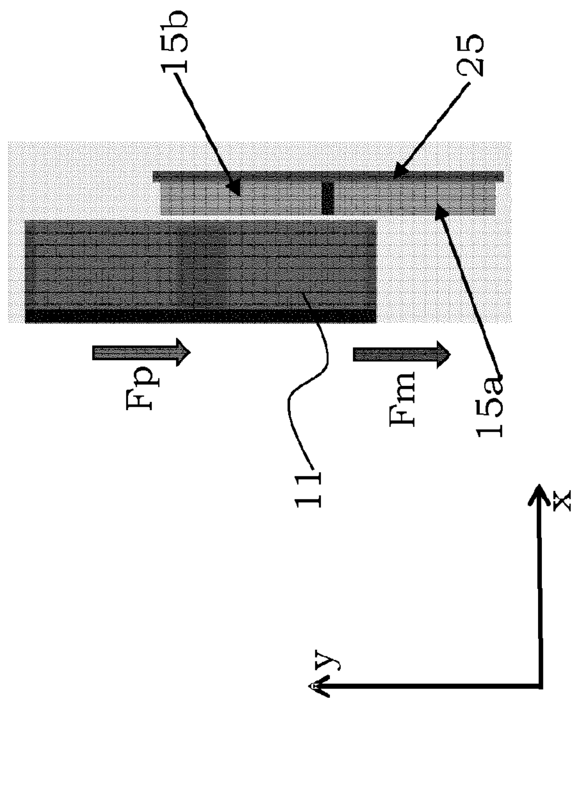


FIG. 4C

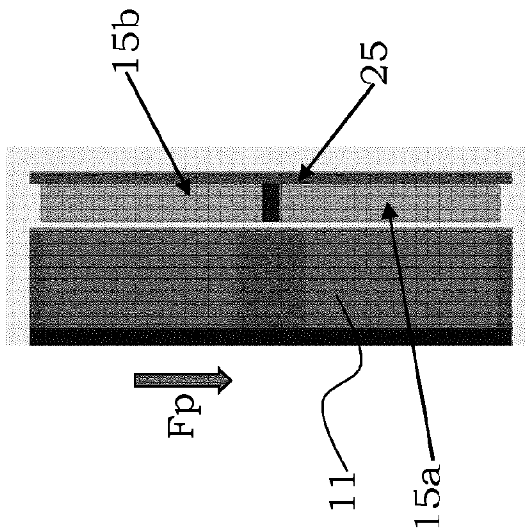
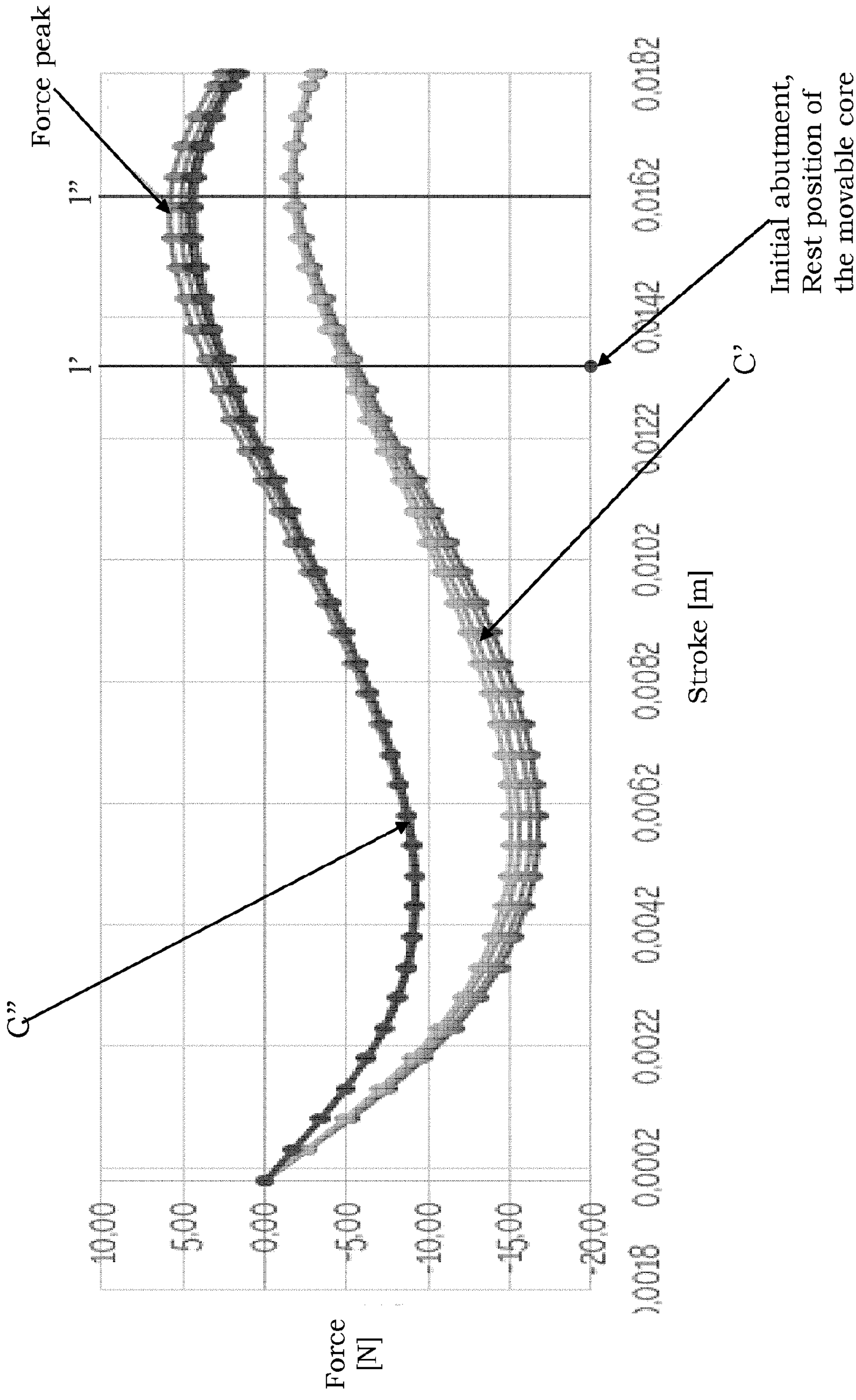


FIG. 4D

5/8


Force peak
1”
1’
Initial abutment,
Rest position of
the movable core
C’
C”
Stroke [m]
Force
[N]
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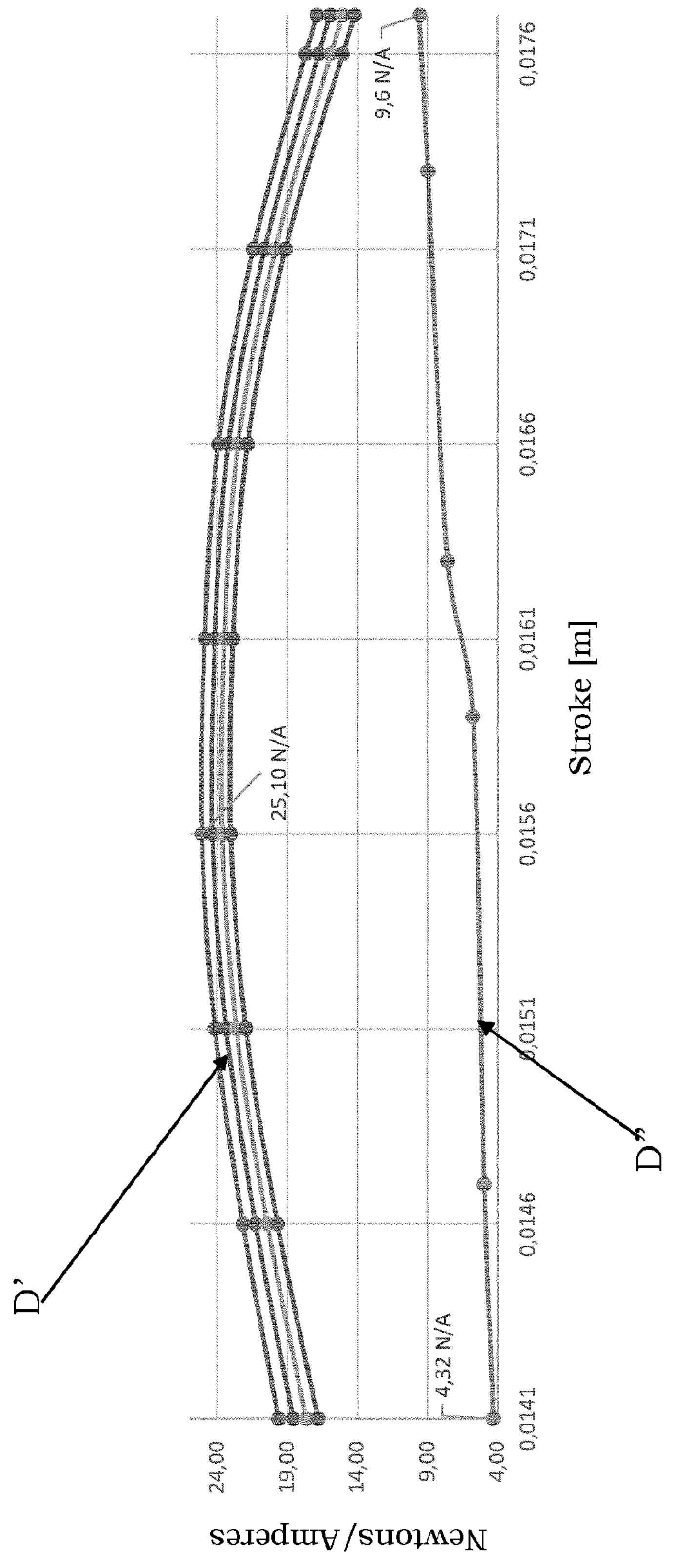
5,00
0,00
-5,00
-10,00
-15,00
-20,00
0,0002
0,0022
0,0042
0,0062
0,0082
0,0102
0,0122
0,0142
0,0162
0,0182

FIG. 5


Newtons/Amperes
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19,00
14,00
9,00
4,00
0,0141
0,0146
0,0151
0,0156
0,0161
0,0166
0,0171
0,0176
Stroke [m]
25,10 N/A
9,6 N/A
4,32 N/A
D'
D''

FIG. 6

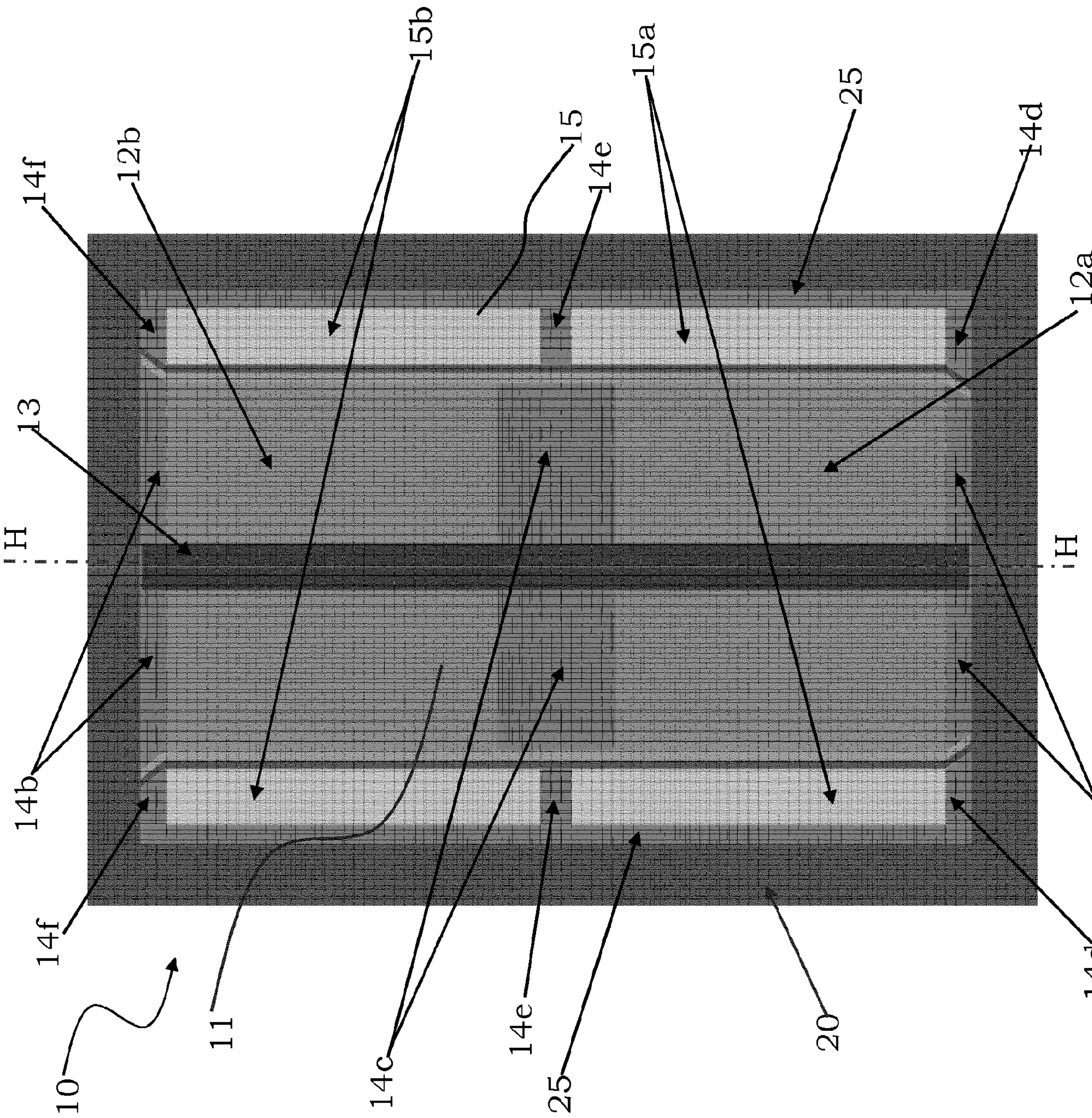
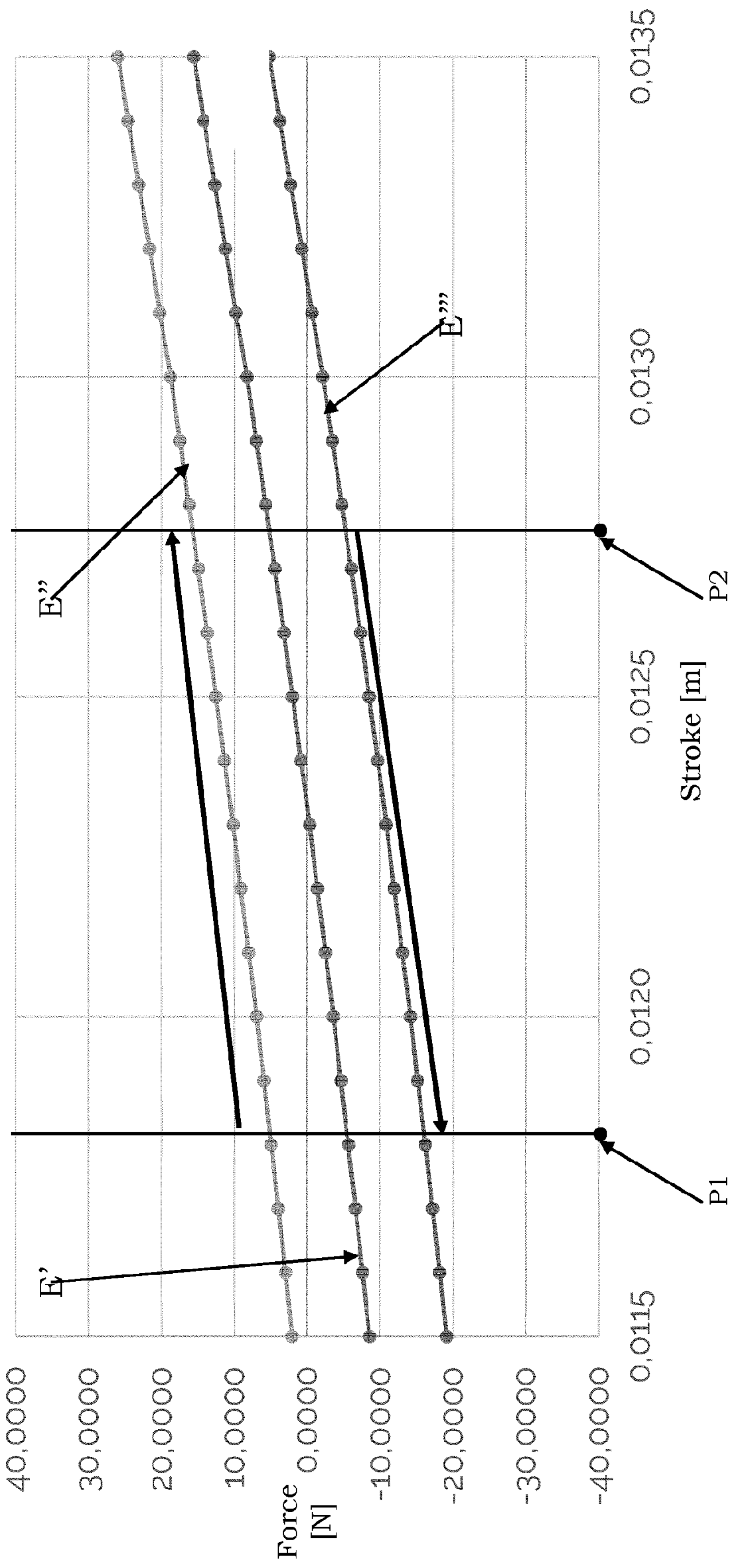

14f
12b
15b
15
14e
15a
25
14d
12a
13
H
H
14b
14f
11
10
14c
14e
25
20
14d
14a

FIG. 7



Force
[N]
40,0000
30,0000
20,0000
10,0000
0,0000
-10,0000
-20,0000
-30,0000
-40,0000
0,0115
0,0120
0,0125
0,0130
0,0135
Stroke [m]
E'
E''
E'''
P1
P2

FIG. 8

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2024/066445

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01F7/16 H01F7/08
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)
H01F

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	GB 2 052 886 A (POLAROID CORP) 28 January 1981 (1981-01-28) figures 1,2 page 3, line 46 - page 4, line 68	1-3,7, 9-12
X Y	EP 0 572 155 A1 (WESTINGHOUSE ELECTRIC CORP [US]) 1 December 1993 (1993-12-01) figures 1-3 paragraph [0049] - paragraph [0057]	1-5,7, 10,11 6,8
Y	US 2022/221026 A1 (FANGAUER PHILIPP [DE] ET AL) 14 July 2022 (2022-07-14) figure 1 column 2, line 14 - column 3, line 14	6,8

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

☒ See patent family annex.

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

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"Y" document of particular relevance;; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
27 August 2024	12/09/2024

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	Tano, Valeria

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2024/066445

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
GB 2052886	A	28-01-1981	CA	1132646	A	28-09-1982
			DE	3020852	A1	18-12-1980
			FR	2458934	A1	02-01-1981
			GB	2052886	A	28-01-1981
EP 0572155	A1	01-12-1993	EP	0572155	A1	01-12-1993
			GB	2271668	A	20-04-1994
			JP	H0638485	A	10-02-1994
			KR	930024033	A	21-12-1993
US 2022221026	A1	14-07-2022	CN	114072885	A	18-02-2022
			DE	102019112334	A1	12-11-2020
			EP	3966840	A1	16-03-2022
			US	2022221026	A1	14-07-2022
			WO	2020229347	A1	19-11-2020