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(54) Title: HIGH-ASPECT-RATIO HOMOPOLAR MAGNETIC ACTUATOR

(57) Abstract: A homopolar magnetic actuator is configured to exert controllable radial forces on a body adapted to rotate around an axis. The actuator comprises at least three radial magnetic pole assemblies distributed at some distances from each other along the axis, each including a plurality of poles adjacent to an actuator target on the body. Permanent magnets are used to induce bias magnetic fluxes in the assemblies with polarities alternating from assembly to assembly but remaining the same around the rotational axis. Having several small bias fluxes distributed between several pole assemblies instead of a large single bias flux facilitates designing an actuator with a high aspect ratio. A control coil around each pole can induce a control magnetic flux in the poles. These control fluxes affect magnetic flux distribution around the actuator target, resulting in magnetic forces exerted on the target.

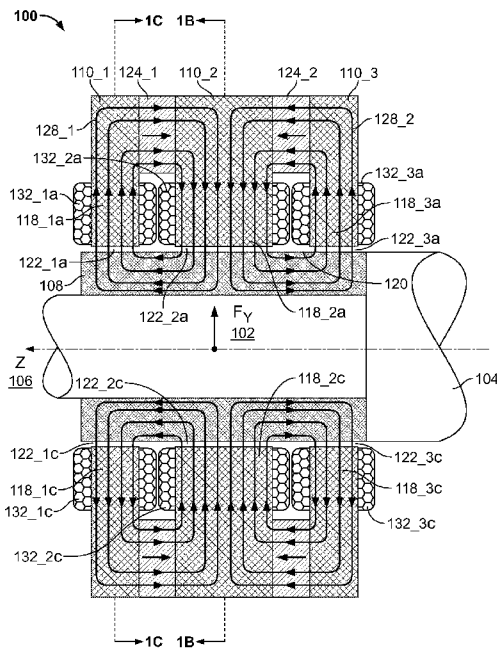


FIG. 1A

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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))*
- *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

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## High-Aspect-Ratio Homopolar Magnetic Actuator

### **CLAIM OF PRIORITY**

5           This disclosure claims priority to U.S. Provisional Patent Application Serial No. 61/104,215, filed October 9, 2008, the entire contents of which are hereby incorporated by reference.

### **BACKGROUND**

10           This disclosure is directed to homopolar magnetic actuators. Actuators for active magnetic bearings (AMBs) can be divided into two broad categories: heteropolar and homopolar. The division is based on the polarities of magnetic poles placed around the rotor: if in the absence of the radial loading the magnetic polarity  
15 stays the same all the way around the rotor at any given axial position, then the actuator is called homopolar; otherwise, it is heteropolar. Homopolar magnetic actuators have several important advantages over heteropolar actuators, including low rotational losses and ease of using permanent magnets to generate a portion of the total magnetic field needed to support the rotor, thus reducing power consumption, number  
20 of terminal wires, and the actuator negative stiffness. However, they exhibit a relatively small aspect ratio which cannot be changed much at the design stage. The latter drawback often complicates integration of homopolar radial magnetic actuators into machines where the aspect ratio of the available envelope cannot be changed easily. In contrast, the aspect ratio of the heteropolar radial magnetic actuator can be  
25 easily adjusted at the design stage.

### **SUMMARY**

          An electromagnetic actuator may include a body having a rotational axis and at least three radial magnetic pole assemblies, each circumferentially arranged around the  
30 rotational axis, separated therefrom by radial gaps, and distributed along the rotational axis at fixed distances from each other. Each radial magnetic pole assembly may include a plurality of radial poles adjacent and spaced apart from a lateral facing surface of the body and can be configured to communicate magnetic flux with the lateral facing surface of the body. The body and the plurality of radial poles of each  
35 radial magnetic pole assembly may be magnetically coupled to each other and define a

radial magnetic control circuit. Further, an excitation coil around each of the plurality of radial poles can be configured to produce control magnetic flux in the radial magnetic control circuits. A plurality of magnetic elements is distributed with alternating polarities along the rotational axis, each of which can reside between adjacent radial magnetic pole assemblies. The plurality of magnetic elements can be configured to produce bias magnetic flux flowing radially within each radial magnetic pole assembly and axially in the body between adjacent radial magnetic pole assemblies. In some instances, the magnetic elements may be permanent magnets.

A method for exerting a radial force on a body configured to rotate about a rotational axis can involve communicating a first bias magnetic flux between a first radial pole assembly, the body, and a second radial pole assembly, the first radial pole assembly adjacent the second radial pole assembly. The first and second radial pole assemblies may be spaced apart from one another along the rotational axis, each of the first and second radial pole assemblies being circumferentially arranged around the rotational axis, and separated from the body by an air gap. The first magnetic bias flux may propagate through the body in a direction parallel to the rotational axis. The method may further include communicating a second bias magnetic flux between the second radial pole assembly, the body, and a third radial pole assembly. The second and third radial pole assemblies may be spaced apart from one another along the rotational axis. The second and third radial pole assemblies may each be circumferentially arranged around the rotational axis and may be separated from the body by an air gap. The second bias magnetic flux may propagate through the body in a direction parallel to the rotational axis and opposite from the first bias magnetic flux. In addition, the method can include communicating a first radial control magnetic flux between the first radial pole assembly and the body, where the first radial control magnetic flux can propagate between a first radial pole of the first pole assembly, the body, and a second pole of the first pole assembly, and the first radial control magnetic flux can propagate in a radial direction orthogonal to the rotational axis. The method can also include communicating a second radial control magnetic flux between the second radial pole assembly and the body, the second radial control magnetic flux propagating between a first radial pole of the second pole assembly, the body, and a second pole of the second pole assembly. The second radial control magnetic flux can

propagate in a radial direction orthogonal to the rotational axis and opposite from the first radial control magnetic flux. The method can additionally include communicating a third radial control magnetic flux between the third radial pole assembly and the body. The third radial control magnetic flux may propagate between a first radial pole of the third pole assembly, the body, and a second pole of the third pole assembly. 5 The third radial control magnetic flux may propagate in a radial direction orthogonal to the rotational axis opposite from the second radial control magnetic flux.

An electric machine system can include a body having a rotational axis configured to move relative to a base. The system can also include an electromagnetic 10 actuator sub-assembly coupled to the base that may include three radial pole assemblies, each circumferentially arranged around the rotational axis, separated from the body by radial gaps, and distributed along the rotational axis at fixed distances from each other. Each radial magnetic pole assembly may include a plurality of radial poles adjacent a lateral facing surface of the body and may be adapted to communicate 15 magnetic flux with the lateral facing surface of the body. The body and the plurality of radial poles within each pole assembly may be magnetically coupled and define a plurality of radial magnetic control circuits. The plurality of radial poles may be adapted to communicate magnetic fluxes with the lateral facing surface of the body. A control coil may be around each of the radial poles and configured to produce control 20 magnetic flux in the radial magnetic control circuits. A plurality of magnetic elements may be distributed with alternating polarities along the rotational axis, each of which can reside between adjacent radial magnetic pole assemblies. The magnetic elements may be configured to produce bias magnetic fluxes flowing radially within each radial magnetic pole assembly and axially in the body between adjacent radial magnetic pole 25 assemblies. The system may have one or more position sensors configured to sense the position of the body, and may also include at least one control electronics package configured to control the magnetic flux in the radial magnetic control circuits.

In instances, the electromagnetic actuator may include first and second end radial magnetic pole assemblies, each residing at opposite ends of the electromagnetic 30 actuator. The actuator may also include a first end pole circumferentially arranged around the rotational axis, separated from the body by radial gaps and adjacent the first end radial magnetic pole assembly that may be configured to produce bias magnetic

flux flowing radially within the first end pole in a direction opposite to the bias magnetic flux in the first end radial magnetic pole assembly. A second end pole circumferentially arranged around the rotational axis may be separated from the body by radial gaps and adjacent the second end radial magnetic pole assembly. A second end magnetic element may be configured to produce bias magnetic flux flowing  
5 radially within the second end pole in a direction opposite to the bias magnetic flux in the second end radial magnetic pole assembly.

In instances, the actuator body may include a low reluctance target, the target adapted to communicate magnetic flux. In instances, the control magnetic flux is  
10 changed in response to a controllable current. The control magnetic flux can be adjusted to affect a total flux in the radial air gaps. The excitation coil around each of the plurality of radial poles may be energizable with a control current to produce distinct control fluxes in each of the radial magnetic control circuits of the respective radial magnetic pole assemblies.

In embodiments, the actuator can communicate a first, second, and third radial control magnetic flux by energizing control coils around radial poles of the first, second, and third radial pole assemblies with control currents. Varying the control current can affect a total magnetic flux distribution in the air gaps between the first, second, and third radial pole assemblies and the body. In some embodiments, the  
20 electric machine system has a body that may be coupled to a driven load, the driven load comprising at least one of a flywheel, a compressor, a generator, or an expander. The body may be coupled to a driver, where the driver may include at least one of a motor, an engine, or a turbine. In some instances, the body may be a rotor and the base may be a stator of an electric machine. In embodiments, the electronic control  
25 package may be configured to control the magnetic flux in the radial magnetic control circuits by energizing the control coil around each of the plurality of radial poles with a control current. The electronic control package may further be configured to energize the control coils around each of the plurality of radial poles with a control current to produce distinct control fluxes in the radial magnetic control circuits of the  
30 respective radial magnetic pole assemblies.

## DESCRIPTION OF DRAWINGS

FIG. 1A is a side cross-sectional schematic of an embodiment of the high-aspect-ratio homopolar actuator.

5 FIG. 1B is an axial cross-sectional schematic of the high-aspect-ratio homopolar actuator of FIG. 1A taken along view 1B-1B.

FIG. 1C is an axial cross-sectional schematic of the high-aspect-ratio homopolar actuator for FIG. 1A taken along view 1C-1C.

10 FIG. 2A is an axial cross-sectional schematic of an example heteropolar actuator showing a bias flux distribution.

FIG. 2B is an axial cross-sectional schematic of the heteropolar actuator of FIG. 2A showing the pole polarity distribution pattern.

FIG. 2C is an axial cross-sectional schematic of another example heteropolar actuator showing an alternative pole polarity distribution pattern.

15 FIG. 2D is an axial cross-sectional schematic of the heteropolar actuator of FIGS. 2A-B showing the generation of a radial force in the +Y direction.

FIG. 3 is a side cross-sectional schematic of an example low-aspect-ratio homopolar actuator.

20 FIG. 4A is a side cross-sectional schematic of an embodiment of a high-aspect-ratio homopolar actuator with a plurality of radial magnetic pole assemblies.

FIG. 4B is an axial cross-sectional schematic of the high-aspect-ratio homopolar actuator of FIG. 4A taken along view 4B-4B.

FIG. 4C is an axial cross-sectional schematic of the high-aspect-ratio homopolar actuator of FIG. 4A taken along view 4C-4C.

25 FIG. 5A is a side cross-sectional schematic showing an embodiment of a high-aspect-ratio homopolar actuator with end poles used to terminate a chain of the radial magnetic pole assemblies.

FIG. 5B is an axial cross-sectional schematic of the high-aspect-ratio homopolar actuator of FIG. 5A taken along view 5B-5B.

30 FIG. 5C is an axial cross-sectional schematic of the high-aspect-ratio homopolar actuator of FIG. 5A taken along view 5C-5C.

FIG. 6 is a side cross-sectional schematic illustrating an embodiment of the high-aspect-ratio homopolar actuator adapted to an electric machine system in accordance with the present disclosure.

FIG. 7 is a side cross-sectional schematic of an example heteropolar actuator showing the dimensions for calculating the aspect ratio.

FIG. 8 is a side cross-sectional schematic of an example low-aspect-ratio homopolar actuator showing the dimensions for calculating the aspect ratio.

### DETAILED DESCRIPTION

FIG. 1A is a side cross-sectional schematic of an embodiment of a high-aspect-ratio homopolar actuator 100 that serves to exert controllable radial forces 102 on a body 104 having a rotational axis Z 106 and including an actuator target 108. The actuator may include three radial magnetic pole assemblies 110\_1, 110\_2, and 110\_3 distributed along the rotational axis 106 at some distances from each other. Each radial magnetic pole assembly includes a plurality of radial poles adjacent the lateral facing surface 120 of the body 104 and separated from it by radial gaps. For example, FIG. 1B shows that the radial magnetic pole assembly 110\_2 includes a plurality of radial poles 118\_2a through 118\_2d adjacent the lateral facing surface 120 of the body 104 and separated from it by radial gaps 122\_2a through 122\_2d. Radial magnetic poles 118\_2a through 118\_2d are adapted to communicate magnetic fluxes with the lateral facing surface 120 of the body 104 through radial gaps 122\_2a-122\_2d. The body 104 (more specifically the actuator target 108) and the plurality of radial poles 118\_2a through 118\_2d within the pole assembly 110\_2 are magnetically coupled and define a plurality of radial magnetic control circuits.

Similarly, FIG. 1C, which is an axial cross-sectional schematic of the high-aspect-ratio homopolar actuator for FIG. 1A taken along view 1C-1C, shows that the radial magnetic pole assembly 110\_1 has four radial magnetic poles 118\_1a through 118\_1d adjacent the lateral facing surface 120 of the body 104 and separated from it by radial gaps 122\_1a through 122\_1d.

Axially magnetized permanent magnets 124\_1 and 124\_2 installed between the radial magnetic pole assemblies 110\_1, 110\_2 and 110\_3 can induce bias magnetic fluxes 128\_1 and 128\_2 flowing radially within each radial magnetic pole assembly



and axially within the actuator target 108, which is a part of the body 104, between any two neighboring radial magnetic pole assemblies so that directions of radial bias magnetic fluxes within radial magnetic pole assemblies and directions of the axial magnetic fluxes between neighboring radial magnetic pole assemblies alternate in the axial direction. Magnets 124\_1 and 124\_2 may be, for example, neodymium iron boron magnets or samarium cobalt magnets, though are not limited as such. Magnets 124\_1 and 124\_2 may be axially magnetized permanent magnets or radially magnetized permanent magnets. More specifically, the bias flux 128\_1 induced by the magnet 124\_1 flows radially outwards in the radial magnetic pole assembly 110\_1, radially inwards in the magnetic pole assembly 110\_2, and axially in the positive Z direction when flowing from the radial magnetic pole assembly 110\_2 to the radial magnetic pole assembly 110\_1 within the actuator target 108. The bias flux 128\_2 induced by the magnet 124\_2 flows radially outwards in the radial magnetic pole assembly 110\_3, radially inwards in the magnetic pole 110\_2, and axially in the negative Z direction when flowing from the radial magnetic pole assembly 110\_2 to the radial magnetic pole assembly 110\_3 within the actuator target 108. Note that directions of the axial bias fluxes within the actuator target 108 alternate along the rotational axis: the bias flux 128\_1 flows in the positive Z direction, whereas the subsequent bias flux 128\_2 flows in the negative Z direction. Similarly, the directions of the radial bias fluxes also alternate from pole assembly to pole assembly along the rotational axis: the bias flux 128\_1 flows outwards in the pole assembly 110\_1 then bias fluxes 128\_1 and 128\_2 flow together radially inwards in the pole assembly 110\_2, and the bias flux 128\_2 flows again radially outwards in the pole assembly 110\_3. This is equivalent to saying that magnetic poles of the assemblies alternate along the rotational axis: South-North-South for the subsequent assemblies 110\_1, 110\_2 and 110\_3.

Because the radial magnetic pole assembly 110\_2 accommodates two magnetic bias fluxes 128\_1 and 128\_2, it may be two times wider in the axial direction than either the first or the last radial magnetic pole assemblies 110\_1 and 110\_2 respectively, each of which accommodates only one bias flux: 128\_1 and 128\_2 respectively.

Each radial magnetic pole 118\_1a through 118\_1d, 118\_2a through 118\_2d or 118\_3a through 118\_3d is equipped with a control coil 132\_1a through 132\_1d, 132\_2a through 132\_2d, or 132\_3a through 132\_3d, respectively. The coils are adapted to produce magnetic fluxes in the plurality of radial magnetic control circuits defined by the actuator target 108, which is a part of the body 104, and the plurality of radial poles within each pole assembly magnetically coupled to the actuator target 108. Mechanism of producing radial forces by different radial pole assemblies 110\_1, 110\_2 or 110\_3 is essentially identical except for polarities of the control currents, which would be the same for the assemblies 110\_1 and 110\_3 but opposite for the assembly 110\_2 due to different directions of the bias fluxes within the assembly. FIG. 1B illustrates mechanism of producing radial force in the radial magnetic pole assembly 110\_2.

When the body 104 is centrally positioned and there are no currents in the radial control windings 132\_2a through 132\_2d, the bias flux densities under each pole 118\_2a through 118\_2d are equal because of the symmetrical nature of the system. Therefore, there is no radial force produced on the body 104. By energizing some of the radial control windings, 132\_2a through 132\_2d, the flux distribution may be altered so as to develop a radial force 102. For example, FIG. 1B shows windings 132\_2a and 132\_2c energized with control currents 134\_2a and 134\_2c, respectively. These currents produce radial control flux 136\_2. The excitation coils maybe individually energized, energized in unison, or some combination thereof to produce a control magnetic flux that produces a radial force 102 on the body 104 of sufficient magnitude and direction, as well as location relative to the body.

In the radial air gap 122\_2a, control flux 136\_2 adds to the magnetic bias fluxes 128\_1 and 128\_2, whereas in the radial air gap 122\_2c, radial control fluxes 136\_2 subtracts from the magnetic bias fluxes 128\_1 and 128\_2. Due to the higher resulting net magnetic flux density in the radial air gap 122\_2a compared to the radial air gap 122\_2c, radial electromagnetic force  $F_Y$  102\_2 acts on the actuator target 108 and, consequently, on the body 104. In FIG. 1B this force  $F_Y$  102\_2 is directed upward.

Continuing with FIG.1B, the portion of the electromagnetic force  $F_Y$  102\_2 exerted on actuator target 108 by the upper pole 118\_2a associated with winding

132\_2a can be calculated as  $F_{rad1} = \frac{1}{2\mu_0} (B_{0rad} + B_{1rad})^2 \cdot A_{rad}$ , where  $B_{0rad}$  is the density of the combined bias fluxes 128\_1 and 128\_2 in radial gap 122\_2a,  $B_{1rad}$  is the density of the radial control flux 136\_2 in the radial gap 122\_2a, and  $A_{rad}$  is the projection of the pole surface adjacent to the radial air gap 122\_2a on a plane normal to the pole axis (Y axis as illustrated in FIG. 1B).

Similarly, the electromagnetic force exerted on actuator target 108 by the lower poles 118\_2c associated with winding 134\_2b can be calculated as:

$$F_{rad2} = \frac{1}{2\mu_0} (B_{0rad} - B_{1rad})^2 \cdot A_{rad}.$$

The net radial force exerted on actuator target 108 by the radial magnetic pole assembly 110\_2 will then be:

$$F_{rad} = F_{rad1} - F_{rad2} = \frac{A_{rad}}{2\mu_0} \left\{ (B_{0rad} + B_{1rad})^2 - (B_{0rad} - B_{1rad})^2 \right\} = 2 \frac{A_{rad}}{\mu_0} B_{0rad} B_{1rad}$$

If radial control currents 134\_2a and 134\_2b are equal to a radial control current  $I_{rad}$ , the radial control magnetic flux density  $B_{1rad}$  will be proportional to the radial control current  $I_{rad}$ , and, consequently, the radial force  $F_{rad}$  will be proportional to  $I_{rad}$ . Although illustrated and described above in the Y direction, the same features apply in the X direction. Therefore, this implementation allows the electromagnetic actuator 100 to produce bidirectional electromagnetic forces along two radial axes, designated in FIG. 1B as X 180 and Y 182.

FIG. 1C illustrates generating a radial force 102\_1 in the radial magnetic pole assembly 110\_1. The difference from FIG. 1B is that directions of the radial control currents 134\_1a and 134\_1b may be reversed compared to the currents 134\_2a and 134\_2b in FIG. 1B in order to have force 102\_1 directed in the same way as the force 102\_2 in FIG. 1B because the direction of the bias flux 128\_1 in the radial magnetic pole assembly 110\_1 is opposite to the direction of the bias flux in the radial magnetic pole assembly 110\_2. The control current directions in the magnetic pole assembly 110\_3 would be identical to these in the magnetic pole assembly 110\_1 shown on FIG. 1A because the bias fluxes directions are identical.

The actuator target 108 can be composed of electrical steel laminations electrically isolated from each other and stacked together in the axial direction in order

to minimize eddy currents that can be induced if the body 104 rotates about its axis 106.

As can be learned from FIGS. 1A through 1C the bias flux polarity in this design does not change around the rotor circumference at any given axial position. In particular, FIG. 1B shows that the combined bias flux 128\_1 and 128\_2 is directed inwards in every pole 118\_2a through 118\_2d of the radial magnetic pole assembly 110\_2. Similarly, FIG. 1C shows that the bias flux 128\_1 is directed outward in every pole 118\_1a through 118\_1d of the radial magnetic pole assembly 110\_1. The bias flux distribution in the radial magnetic pole assembly 110\_3 is identical to the assembly 110\_1. In certain instances, having the same bias flux polarity around the circumference of the actuator target at any given axial position results in lower rotational losses than in, for example, heteropolar actuators. As an example for comparison, FIG. 2A illustrates the structure and operational principle of a heteropolar actuator 200, discussed here with no intention of admitting to the prior art.

The heteropolar actuator 200 shown in FIG. 2A consists of an actuator target 202 mounted on the rotor and a stator element 206 having a plurality of pole members 214 located in proximity to the actuator target 202 and separated from it by an air gap 208. Pole members 214a and 214b that face the actuator target 202 are separated from each other by slots with electrical coils 212 around each pole 214. The coils 212 may be energized with constant bias currents to produce bias fluxes 220 flowing between two adjacent poles (e.g., poles 214a and 214b). The bias fluxes are needed to maintain linear relationships between forces and control currents injected in the coils in addition to the bias currents.

Since the magnetic field lines are closed, if the bias flux 220 enters the actuator target 202 at some point, it exits it at another point. In the heteropolar actuators shown in FIGS. 2A–D, where the magnetic flux lines are contained in the same radial plane, the polarity of the pole members 214 may vary along the rotor circumference. Depending on the mutual orientation of the bias currents in the neighboring winding, different patterns of the pole polarities are possible. FIGS. 2B–C show two such patterns with the patterns shown in FIG. 2B corresponding the bias flux directions shown in FIG. 2A. When a rotor supported by a heteropolar bearing spins, it sees alternating polarities of the magnetic field. Even though the actuator target 202

mounted on the rotor could be made laminated, there still will be eddy currents induced in it, resulting in noticeable rotational losses. In addition to eddy currents, remagnetization of the rotor material exposed to alternating magnetic field will further increase the rotational losses.

5           In addition to lower rotational losses, homopolar actuator designs such as shown in FIG. 1A have an advantage of an easy integration of permanent magnets into the design which can be used to generate bias magnetic fields instead of current-carrying coils used in FIGS. 2A-C. The use of permanent magnets may minimize the resistive losses associated with the current in a coil. In addition, fewer terminal wires  
10 would be needed compared to the heteropolar design of FIGS. 2A-C if the latter uses a separate coil to generate a bias flux or a power rating of an external source of the current in the control coil would be smaller compared to one of the heteropolar design of FIGS. 2A-C if the latter uses a single coil to generate both the bias and the control fluxes. The reduction of wires and/or current source power rating may simplify the  
15 actuator construction and improve reliability. The use of permanent magnet bias may also result in a smaller and nearly constant negative stiffness (*i.e.*, the rate at which the destabilizing pulling radial force, which is unavoidable in the presence of a bias field, changes with the rotor offset from the equilibrium position).

FIG. 3 shows a conventional homopolar radial magnetic actuator that includes  
20 two radial magnetic pole assemblies 310\_1 and 310\_2 similar to the radial magnetic pole assemblies 110\_1, 110\_2 and 110\_3 in FIG. 1A and a magnet 324 used to generate bias magnetic field 328. A mechanism of producing radial force by radial magnetic pole assemblies 310\_1 and 310\_2 is identical to producing force with radial magnetic pole assemblies 110\_1, 110\_2 and 110\_3 in FIGS. 1A-C. In both actuators shown in  
25 FIG. 3 and FIGS. 1A-C, the polarity of the bias magnetic flux does not change around the rotor circumference at any given axial position. The high-aspect-ratio actuator shown in FIGS. 1A through 1C would be shorter axially than two separate actuators of FIG. 3, would have fewer wire terminals since the control coils 132\_2a through 132\_2d of the radial magnetic poles each replace two control coils such as 332\_1a that  
30 would be needed if two separate actuators shown in FIG. 3 were used, and also would produce a more energy efficient design since resistance of any of the control coils

132\_2a and 132\_2c would be less than the combine resistance of two individual control coils it would replace.

Furthermore, an arrangement shown in FIGs. 1A through 1C opens a way for stacking up any number of radial magnetic pole assemblies, such as 110\_2, in a single unit with magnetic polarities of the bias fields alternating from assembly to assembly, as shown in FIGs. 4A through 4C. The actuator 400 shown in FIGs. 4A through 4C has a plurality of radial magnetic pole assemblies 410\_1 through 410\_6 distributed along the rotational axis 406 at some distances from each other. Each radial magnetic pole assembly includes a plurality of radial poles. For example, the radial magnetic pole assembly 410\_2 includes radial magnetic poles 418\_2a through 418\_2d adjacent the lateral facing surface 420 of the body 404 and separated from it by radial gaps 422\_2a through 422\_2d. More details are given in FIG. 4B, which is an axial cross-sectional schematic of the high-aspect-ratio homopolar actuator of FIG. 4A taken along view 4B-4B. Radial magnetic poles 418\_2a through 418\_2d are adapted to communicate magnetic fluxes with the lateral facing surface 420 of the body 404 through radial gaps 422\_2a-422\_2d. The body 404 and the plurality of radial poles 418\_2a through 418\_2d within the pole assembly 410\_2 are magnetically coupled and define a plurality of radial magnetic control circuits.

Similarly, FIG. 4C, which is an axial cross-sectional schematic of the high-aspect-ratio homopolar actuator of FIG. 4A taken along view 4C-4C, shows that the radial magnetic pole assembly 410\_1 has four radial magnetic poles 418\_1a through 418\_1d adjacent the lateral facing surface 420 of the body 404 and separated from it by radial gaps 422\_1a through 422\_1d.

Returning to FIG. 4A, axially magnetized permanent magnets 424\_1 through 424\_5 installed between the radial magnetic pole assemblies 410\_1 through 410\_6 serve as magnetic means inducing bias magnetic fluxes 428\_1 through 428\_5 flowing radially within each radial magnetic pole assembly and axially within the actuator target 408, which is a part of the body 404, between any two neighboring radial magnetic pole assemblies so that directions of radial bias magnetic fluxes within radial magnetic pole assemblies and directions of the axial magnetic fluxes between neighboring radial magnetic pole assemblies alternate in the axial direction. For example, the bias flux 428\_1 induced by the magnet 424\_1 flows radially inwards in

the radial magnetic pole assembly 410\_1, radially outwards in the magnetic pole assembly 410\_2, and axially in the negative Z direction when flowing from the radial magnetic pole assembly 410\_1 to the radial magnetic pole assembly 410\_2 within the actuator target 408. The bias flux 428\_2 induced by the magnet 424\_2 flows radially  
5 inwards in the radial magnetic pole assembly 410\_3, radially outwards in the magnetic pole assembly 410\_2, and axially in the positive Z direction when flowing from the radial magnetic pole assembly 410\_3 to the radial magnetic pole assembly 410\_2 within the actuator target 408. Note that the direction of the axial bias flux within the actuator target 408 alternates along the rotational axis: the bias flux 428\_1 flows in the  
10 negative Z direction, the bias flux 428\_2 flows in the positive Z direction, the bias flux 428\_3 flows again in the negative Z direction, and so on. Similarly, the directions of the radial bias fluxes also alternate from pole assembly to pole assembly along the rotational axis: the bias flux 428\_1 flows inwards in the pole assembly 410\_1, the bias fluxes 428\_1 and 428\_2 flow radially outwards in the pole assembly 410\_2, the bias  
15 fluxes 428\_2 and 428\_3 flow again radially inwards in the next pole assembly 410\_3, and so on. This is equivalent to saying that magnetic poles of the assemblies alternate along the rotational axis: North-South- North and so on for the subsequent radial pole assemblies 410\_1, 410\_2, 410\_3 and so on.

Each radial magnetic pole (e.g., radial magnetic poles 418\_1a-418\_1d and 418\_2a-  
20 418\_2d) is equipped with a control coil (e.g., coil 432\_1a-432\_1d and 432\_2a-432\_2d, respectively). The coils are adapted to produce magnetic fluxes in the plurality of radial magnetic control circuits defined by the actuator target 408, which is a part of the body 404, and the plurality of radial poles within each pole assembly magnetically coupled to the actuator target 408. Mechanism of producing radial forces  
25 by different radial pole assemblies 410\_1 through 410\_6 is essentially identical except for polarities of the control currents, which would be identical for every other assembly, but opposite for the adjacent assemblies. Control windings 432\_1a-432\_6d around each radial magnetic pole 418\_1a-418\_6d can produce control magnetic flux through the poles, as discussed further below. Though not shown in FIG. 4A, it is to  
30 be understood that a radial magnetic pole coinciding with 418\_6d and a winding around it coinciding with 432\_6d are contemplated in a similar manner as the radial

poles and windings discussed in FIGS. 4B–C. For example, FIG. 4B illustrates mechanism of producing radial force in the radial magnetic pole assembly 410\_2.

When the body 404 is centrally positioned and there are no currents in the radial control windings 432\_2a through 432\_2d, the bias flux densities under each pole 5 418\_2a through 418\_2d are equal because of the symmetrical nature of the system. Therefore, there is no radial force produced on the body 404. By energizing some of the radial control windings 432\_2a through 432\_2d, the flux distribution may be altered so as to develop a radial force. For example, FIG. 4B shows windings 432\_2a and 432\_2c energized with control currents 434\_2a and 434\_2c, respectively. These 10 currents produce radial control flux 436\_2.

In the radial air gap 422\_2a control flux 436\_2 adds to the magnetic bias fluxes 428\_1 and 428\_2 (shown on FIG. 4A), whereas in the radial air gap 422\_2c radial control flux 436\_2 subtracts from the magnetic bias fluxes 428\_1 and 428\_2. Due to the higher resulting net magnetic flux density in the radial air gap 422\_2a compared to 15 the radial air gap 422\_2c, radial electromagnetic force  $F_Y$  402\_2 acts on the actuator target 408 and, consequently, on the body 404. In FIG. 4B, this force  $F_Y$  402\_2 is directed upward.

FIG. 4C illustrates generating a radial force 402\_1 in the radial magnetic pole assembly 410\_1. The difference from FIG. 4B is that direction of the radial control 20 currents 434\_1a and 434\_1c may be reversed compared to the currents 434\_2a and 434\_2c in FIG. 4B in order to have force 402\_1 directed in the same way as the force 402\_2 in FIG. 4B because the direction of the bias flux 428\_1 in the radial magnetic pole assembly 410\_1 is opposite to the direction of the bias flux in the radial magnetic pole assembly 410\_2. The control current direction in magnetic pole assemblies 25 410\_3 and 410\_5 in FIG. 4A would be identical to these in the magnetic pole assembly 410\_1 because the bias fluxes directions are identical. Similarly, the control current directions in magnetic pole assemblies 410\_4 and 410\_6 would be identical to these in the magnetic pole assembly 410\_2.

Using the arrangement shown in FIGS. 4A through 4C allows one to overcome 30 a drawback of the design shown in FIG. 3, such as a low aspect ratio of the actuator target and of the overall actuator envelope. The definitions of the actuator aspect ratios are clarified by FIGS. 7 and 8 for the heteropolar and homopolar actuators



respectively: the actuator target aspect ratio is defined as  $L_t/(OD_t-ID_t)$  and the overall actuator envelope aspect ratio is defined as  $L/(OD-ID_t)$ . The main factors responsible for low aspect ratios in the homopolar radial magnetic actuator design shown in FIG. 3 are a) a large pole area of the magnet 324 is needed to generate sufficient bias magnetic flux 328, and b) a large cross-sectional area of the actuator target defined as  $\frac{\pi}{4}(OD_i^2 - ID_i^2)$  is needed to carry bias magnetic flux 328 axially between the radial magnetic pole assemblies 310\_1 and 310\_2. The first factor results in a large assembly outer diameter (OD), whereas the second factor is responsible for a low target ID (ID<sub>t</sub>). In contrast, in the heteropolar magnetic actuator 200 shown in FIGS. 2A through 2D, there are no axial magnetic fluxes, both control fluxes 222 and bias fluxes 220 are tangential and divided into small portions along the circumference, each portion of the flux running only a short distance between two neighboring poles (*e.g.*, poles 214a and 214b). By changing the number of poles in a heteropolar actuator, its aspect ratios can be adjusted, and, in particular, it can be made very high. In contrast, the aspect ratios of the homopolar radial actuator 300 cannot be changed much and typically are relatively low. The fixed aspect ratio of the homopolar actuator 300 often makes its integration into a machine difficult because the aspect ratio of the envelope available for the actuator may not be changed. Furthermore, having an optimal aspect ratio of the actuator target is very important in rotating machinery since it affects dynamics of the rotor on which the actuator target is mounted. In contrast to the actuator 300 shown in FIG. 3, the aspect ratio of the actuator 400 shown in FIGS. 4A through 4C can be adjusted by changing the number of the radial magnetic pole assemblies. In this case, similar to heteropolar actuator 200, the entire bias flux needed to achieve the required load capacity in the actuator 400 shown in FIGS. 4A-C is divided into a series of smaller fluxes 428\_1 through 428\_5 running only a short distance between two neighboring radial pole assemblies (*e.g.*, assemblies 410\_1 and 410\_2). The difference is that in the heteropolar actuator 200, the fluxes are divided in the circumferential direction, which results in alternating polarities of the poles in this direction and causes rotational losses as discussed above, whereas in the design 400 in FIGS. 4A through 4C, poles alternate in the axial direction while preserving the homopolar structure in the tangential direction with associated low rotational losses.

In some applications, it might be beneficial to terminate a chain of radial magnetic pole assemblies with non-laminated, soft-magnetic end-poles having no slots and no windings, as illustrated in FIGs. 5A through 5C. The radial magnetic pole assemblies 510\_2 through 510\_5 shown in FIG. 5A through 5C are similar to the radial magnetic pole assemblies 410\_1 through 410\_6 in FIGs. 4A through 4C. Each of the radial magnetic pole assemblies 510\_2 through 510\_5 includes a plurality of radial poles, adjacent the lateral facing surface 520 of the body 504 and separated from it by radial gaps. For example, the magnetic pole assembly 510\_2 includes radial magnetic poles 518\_2a through 518\_2d adjacent the lateral facing surface 520 of the body 504 and separated from it by radial gaps 522\_2a through 522\_2d (also shown in FIG. 5B). More details are given in FIG. 5B, which is an axial cross-sectional schematic of the high-aspect-ratio homopolar actuator for FIG. 5A taken along view 5B-5B. Radial magnetic poles 518\_2a through 518\_2d are adapted to communicate magnetic fluxes with the lateral facing surface 520 of the body 504 through radial gaps 522\_2a-522\_2d. The body 504 and the plurality of radial poles 518\_2a through 518\_2d within the pole assembly 510\_2 are magnetically coupled and define a plurality of radial magnetic control circuits.

Referring to FIG. 5A, axially magnetized permanent magnets 524\_2 through 524\_4 installed between the radial magnetic pole assemblies 510\_2 through 510\_5 serve as magnetic means inducing bias magnetic fluxes 528\_2 through 528\_4 flowing radially within each radial magnetic pole assembly and axially between any two neighboring radial magnetic pole assemblies within the actuator target 508, which is a part of the body 504, so that directions of radial bias magnetic fluxes within radial magnetic pole assemblies and directions of the axial magnetic fluxes between neighboring radial magnetic pole assemblies alternate in the axial direction. For example, the bias flux 528\_2 induced by the magnet 524\_2 flows radially inwards in the radial magnetic pole assembly 510\_2, radially outwards in the magnetic pole assembly 510\_3, and axially in the negative Z direction when flowing from the radial magnetic pole assembly 510\_2 to the radial magnetic pole assembly 510\_3 within the actuator target 508. The bias flux 528\_3 induced by the magnet 524\_3 flows radially inwards in the radial magnetic pole assembly 510\_4, radially outwards in the magnetic pole assembly 510\_3, and axially in the positive Z direction when flowing from the

radial magnetic pole assembly 510\_4 to the radial magnetic pole assembly 510\_3 within the actuator target 508. Note that the direction of the axial bias flux within the actuator target 508 alternates along the rotational axis: the bias flux 528\_2 flows in the negative Z direction, the bias flux 528\_3 flows in the positive Z direction, the bias flux 528\_4 flows again in the negative Z direction and so on. Similarly, the directions of the radial bias fluxes also alternate from pole assembly to pole assembly along the rotational axis: the bias flux 528\_2 flows inwards in the pole assembly 510\_2, the bias fluxes 528\_2 and 528\_3 flow radially outwards in the pole assembly 510\_3, the bias fluxes 528\_3 and 528\_4 flow again radially inwards in the next pole assembly 510\_4, and so on. In other words, the magnetic poles of the assemblies alternate along the rotational axis: North-South-North, and so on, for the subsequent radial pole assemblies 510\_2, 510\_3, 510\_4, etc. Control windings (e.g., 532\_1a-532\_6d in FIG. 5A) around each radial magnetic pole 518\_1a-518\_6d can produce control magnetic flux through the poles, as discussed further below. Though not shown in FIG. 5A, it is to be understood that a radial magnetic pole coinciding with 518\_6d and a winding around it coinciding with 532\_6d are contemplated in a similar manner as the radial poles and windings discussed in FIGS. 5B-C.

Referring to FIG. 5B, each radial magnetic pole 518\_2a through 518\_5d within radial magnetic pole assemblies 510\_2 through 510\_5 is equipped with a control coil 532\_2a through 532\_5d, respectively. These coils are adapted to produce magnetic fluxes in the plurality of radial magnetic control circuits defined by the actuator target 508, which is a part of the body 504, and the plurality of radial poles within each pole assembly magnetically coupled to the actuator target 508. Mechanism of producing radial forces by different radial pole assemblies 510\_2 through 510\_5 shown in FIG. 5A is essentially identical except for polarities of the control currents, which would be identical for the every other assembly but opposite for the adjacent assemblies. For example, FIG. 5B illustrates mechanism of producing radial force in the radial magnetic pole assembly 510\_2.

When the body 504 is centrally positioned and there are no currents in the radial control windings 532\_2a through 532\_2d, the bias flux densities under each pole 518\_2a through 518\_2d are equal because of the symmetrical nature of the system. Therefore, there is no radial force produced on the body 504. By energizing some of

the radial control windings, for example 532\_2a and 532\_2c, the flux distribution may be altered so as to develop a radial force. For example, FIG. 5B shows windings 532\_2a and 532\_2c energized with control currents 534\_2a and 534\_2c, respectively. These currents produce radial control flux 536\_2.

5 In the radial air gap 522\_2a control flux 536\_2 adds to the magnetic bias fluxes 528\_1 (shown in FIG. 5A) and 528\_2, whereas in the radial air gap 522\_2c radial control fluxes 536\_2 subtracts from the magnetic bias fluxes 528\_1 and 528\_2. Due to the higher resulting net magnetic flux density in the radial air gap 522\_2a compared to the radial air gap 522\_2c, radial electromagnetic force  $F_Y$  502\_2 acts on the actuator target 508 and, consequently, on the object 504. In FIG. 5B this force  $F_Y$  502\_2 is directed upward.

In addition to radial magnetic pole assemblies 510\_2 through 510\_5 the actuator 500 shown in FIG. 5A through 5C also includes the first end pole 510\_1 and the second end pole 501\_6, each circumferentially arranged around the rotational axis  
15 506. For example, each of the first end pole 510\_1 and the second end pole 501\_6 may be concentric to the rotational axis. The first end pole 510\_1 is installed next to the first end radial magnetic pole assembly 510\_2 and separated from it by some distance. Similarly, the second end pole 510\_6 is installed next to the second end radial magnetic assembly 510\_5 and separated from it by some distance. A permanent magnet 524\_1 induces bias flux 528\_1 which flows radially in the first end pole 510\_1 in the direction opposite to the direction of fluxes 528\_1 and 528\_2 in the neighboring radial magnetic pole assembly 510\_2 and into a portion of the body 504 across air gap 522\_1. Similarly, a permanent magnet 524\_5, induces bias flux 528\_5 which flows radially in the second end pole 510\_6 in the direction opposite the direction of fluxes  
20 528\_4 and 528\_5 in the neighboring radial magnetic pole assembly 510\_5.

FIG. 5C illustrates a construction and a function of first end pole 510\_1. A construction and a function of the second end pole 510\_6 shown on FIG. 5A are identical. Since these poles do not have a plurality of poles and control winding, there are no control fluxes in them and they cannot be used to produce a controllable force  
30 on the body 504. However, they serve as return paths for the bias magnetic fluxes 528\_1 and 528\_5. Further, the region 503 of the body 504 adjacent the end poles

510\_1 and 510\_6 may be of non-laminated, soft magnetic material, while the actuator target 508 may be stacked laminations.

In some aspects, the high-aspect-ratio homopolar actuator of the present disclosure (for example, actuator 400 of FIG. 4A, or, alternatively, actuator 500 of FIG. 5A) may be utilized as part of an Active Magnetic Actuator (AMB) system to support an object without a mechanical contact. FIG. 6 is a side cross sectional schematic of an example of using an AMB system in an electric rotational machine 600. The rotational electric machine 600 can be, for example, an electric compressor consisting of an electric motor 602 driving an impeller 604 mounted directly on the motor shaft 606. The electric motor 602 has a rotor 608 and a stator 610. Alternatively the impeller 604 can be driven by a flow of gas or liquid and spin the rotor 608 attach to it through the shaft 606. In this case the motor 602 can be used as a generator which would convert the mechanical energy of the rotor 608 into electricity. In embodiments, the rotor 608 of the electric machine 600 can be supported radially and axially without mechanical contact by means of front and rear radial AMBs 612 and 614. The front AMB 612 provides an axial suspension of the entire rotor 608 and a radial suspension of the front end of the rotor, whereas the rear AMB 614 provides only radial suspension of the rear end of the rotor 608. When the AMBs 612 and 614 are not working, the rotor rests on the mechanical backup bearings 616 and 618. The front backup bearing 616 provides the axial support of the entire rotor 608 and a radial support of the rotor front end, whereas the rear backup bearing 618 provides only radial support of the rear end of the rotor 608. There are sufficient radial clearances between the inner diameters of the mechanical backup bearings 616, 618, and the outer diameters of the rotor portions interfacing with those bearings to allow the rotor 608 to be positioned radially without touching the backup bearings 616, 618 when the AMBs 612 and 614 are activated. Similarly, there are sufficient axial clearances between the backup bearings 616, 618 and the portions of the rotor 608 interfacing with those bearings to allow the rotor 608 to be positioned axially without touching the backup bearings 616 and 618 when the AMBs 612 and 614 are activated.

The front AMB 612 consists of an electromagnetic actuator 620, radial position sensors 622, axial position sensor 624, and control electronics 640. The electromagnetic actuator 620 is capable of exerting radial and axial forces on the

actuator target 626 firmly mounted on the rotor 608. The axial force is the force in the direction of Z-axis 628 and the radial forces are forces in the direction of X-axis 630 (directed into the page) and the direction of Y-axis 632. The actuator has three sets of coils corresponding to each of the axes and the forces are produced when the  
5 corresponding coils are energized with control currents produced by control electronics 640. The position of the front end of the rotor in space is constantly monitored by non-contact position sensors 622 and 624. The non-contact position sensors 622 monitor radial position of the rotor whereas the position sensor 624 monitors the axial position of the rotor.

10 Signals from the position sensors 622 and 624 are input into the control electronics 640, which generates currents in the control coils of the electromagnetic actuator 620 whenever it finds that the rotor is deflected from the desired position such that these currents produce forces pushing the rotor back to the desired position.

The rear AMB 614 consists of a high-aspect-ratio electromagnetic actuator 634  
15 consistent with the present disclosure, radial non-contact position sensors 636, and control electronics 640. Because it features a higher ratio between the length and the diameter than a conventional radial homopolar actuator, it can be placed under the motor endturns 638. This reduces length of the machine 600 and improves its rotordynamics. Rear AMB 614 functions identical to the front AMB 620 except that it  
20 does not control the axial position of the rotor 608 because this function is already performed by the front AMB 612. Correspondingly, the high-aspect-ratio actuator 634 may not be able to produce controllable axial force and there may be no axial position sensor. The radial portion of the front AMB actuator 620 is shown of a conventional homopolar type similar to the one presented in FIG. 3. The complete actuator 620 can  
25 exert both axial and radial forces on the actuator target 626.

**WHAT IS CLAIMED IS:**

1. An electromagnetic actuator comprising:
  - a body having a rotational axis;
  - 5 at least three radial magnetic pole assemblies, each circumferentially arranged around the rotational axis, separated from the body by radial gaps, and distributed along the rotational axis at fixed distances from each other, each radial magnetic pole assembly comprising:
    - a plurality of radial poles adjacent and spaced apart from a lateral
    - 10 facing surface of the body and configured to communicate magnetic flux with the lateral facing surface of the body, and
    - the plurality of radial poles of the respective radial magnetic pole assembly and the body magnetically coupled and defining a radial magnetic control circuit;
    - 15 an excitation coil around each of the plurality of radial poles configured to produce control magnetic flux in the radial magnetic control circuits; and
    - a plurality of magnetic elements distributed with alternating polarities along the rotational axis, each of the magnetic elements residing between adjacent radial magnetic pole assemblies and configured to produce bias magnetic fluxes flowing
    - 20 radially within each adjacent radial magnetic pole assembly and axially in the body between adjacent radial magnetic pole assemblies.

2. The actuator of claim 1 wherein two of the at least three radial magnetic pole assemblies are first and second end radial magnetic pole assemblies, the first and second end radial magnetic poles assemblies residing at opposite ends of the electromagnetic actuator of claim 1, the actuator further comprising:

5 a first end pole circumferentially arranged around the rotational axis, separated from the body by radial gaps and adjacent the first end radial magnetic pole assembly; and

10 a first end magnetic element configured to produce bias magnetic flux flowing radially within the first end pole in a direction opposite to the bias magnetic flux in the first end radial magnetic pole assembly.

3. The actuator of claim 2 further comprising:

15 a second end pole circumferentially arranged around the rotational axis, separated from the body by radial gaps and adjacent the second end radial magnetic pole assembly; and

20 a second end magnetic element configured to produce bias magnetic flux flowing radially within the second end pole in a direction opposite to the bias magnetic flux in the second end radial magnetic pole assembly.

4. The actuator of claim 1 wherein the body comprises a low reluctance target, the target adapted to communicate magnetic flux.

5. The actuator of claim 1 wherein the magnetic fluxes entering the lateral surface of the body exert radial forces on the body.

6. The actuator of claim 5 wherein the radial forces are proportional to the magnetic fluxes in the radial magnetic control circuits.

30 7. The actuator of claim 1 wherein the magnetic element comprises a permanent magnet.



8. The actuator of claim 7 wherein the permanent magnet comprises at least one of a neodymium iron boron magnet or a samarium cobalt magnet.

9. The actuator of claim 7 wherein the permanent magnet comprises at least one  
5 of an axially magnetized permanent magnet or a radially magnetized permanent magnet.

10. The actuator of claim 1 wherein the control magnetic flux is produced by a control current in the excitation coil, the control current controllable to affect a total  
10 magnetic flux in the control magnetic circuit.

11. The actuator of claim 1 wherein the excitation coil around each of the plurality of radial poles is energizable with a control current to produce distinct control fluxes in the radial magnetic control circuits of the respective radial magnetic pole assemblies.

12. A method for exerting a radial force on a body, the body configured to rotate about a rotational axis, the method comprising:

communicating a first bias magnetic flux between a first radial pole assembly, the body, and a second radial pole assembly, the first and second radial pole assemblies spaced apart from one another along the rotational axis, the first and second radial pole assemblies each circumferentially arranged around the rotational axis, and the first and second radial pole assemblies separated from the body by an air gap, the first bias magnetic flux propagating through the body in a direction parallel to the rotational axis;

communicating a second bias magnetic flux between the second radial pole assembly, the body, and a third radial pole assembly, the second and third radial pole assemblies spaced apart from one another along the rotational axis, the second and third radial pole assemblies each circumferentially arranged around the rotational axis, and the second and third radial pole assemblies separated from the body by an air gap, the second radial bias magnetic flux propagating through the body in a direction parallel to the rotational axis and opposite from the first bias magnetic flux;

communicating a first radial control magnetic flux between the first radial pole assembly and the body, the first radial control magnetic flux propagating between a first radial pole of the first pole assembly, the body, and a second pole of the first pole assembly, the first radial control magnetic flux propagating in a radial direction orthogonal to the rotational axis;

communicating a second radial control magnetic flux between the second radial pole assembly and the body, the second radial control magnetic flux propagating between a first radial pole of the second pole assembly, the body, and a second pole of the second pole assembly, the second radial control magnetic flux propagating in a radial direction orthogonal to the rotational axis opposite from the first radial control magnetic flux; and

communicating a third radial control magnetic flux between the third radial pole assembly and the body, the third radial control magnetic flux propagating between a first radial pole of the third pole assembly, the body, and a second pole of the third pole assembly, the third radial control magnetic flux propagating in a radial direction orthogonal to the rotational axis opposite from the second radial control magnetic flux.

13. The method of claim 12 wherein communicating a first, second, and third radial control magnetic flux further comprises:

energizing a control coil around each of the first and second radial poles of the first, second, and third radial pole assemblies with a control current.

5

14. The method of claim 12 further comprising varying the control current to affect a total magnetic flux in the air gaps between the first, second, and third radial pole assemblies and the body.

15. A system comprising:

a body having a rotational axis configured to move relative to a base;

an electromagnetic actuator sub-assembly coupled to the base comprising:

10 three radial magnetic pole assemblies, each circumferentially arranged around the rotational axis, separated from the body by radial gaps, and distributed along the rotational axis at fixed distances from each other, each radial magnetic pole assembly comprising:

15 a plurality of radial poles adjacent and spaced apart from a lateral facing surface of the body and configured to communicate magnetic flux with the lateral facing surface of the body, and

the plurality of radial poles of the respective radial magnetic pole assembly and the body magnetically coupled and defining a radial magnetic control circuit,

20 a control coil around each of the plurality of radial poles configured to produce control magnetic flux in the radial magnetic control circuits, and

25 a plurality of magnetic elements distributed with alternating polarities along the rotational axis, each of the magnetic elements residing between adjacent radial magnetic pole assemblies and configured to produce bias magnetic fluxes flowing radially within each adjacent radial magnetic pole assembly and axially in the body between adjacent radial magnetic pole assemblies;

one or more position sensors configured to sense a position of the body; and

at least one control electronics package configured to control the magnetic flux in the radial magnetic control circuits.

16. The system of claim 15 wherein the body is coupled to a driven load, the driven load comprising at least one of a flywheel, a compressor, a generator, or an expander.

5

17. The system of claim 15 wherein the body is coupled to a driver, the driver comprising at least one of a motor, an engine, or a turbine.

18. The system of claim 15 wherein the body is a rotor and the base is a stator of  
10 an electric machine.

19. The system of claim 15 wherein the electronic control package is configured to control the magnetic flux in the radial magnetic control circuits by energizing the control coil around each of the plurality of radial poles with a control current.

15

20. The system of claim 19 wherein the electronic control package is further configured to energize the control coils around each of the plurality of radial poles with a control current to produce distinct control fluxes in the radial magnetic control circuits of the respective radial magnetic pole assemblies.

20

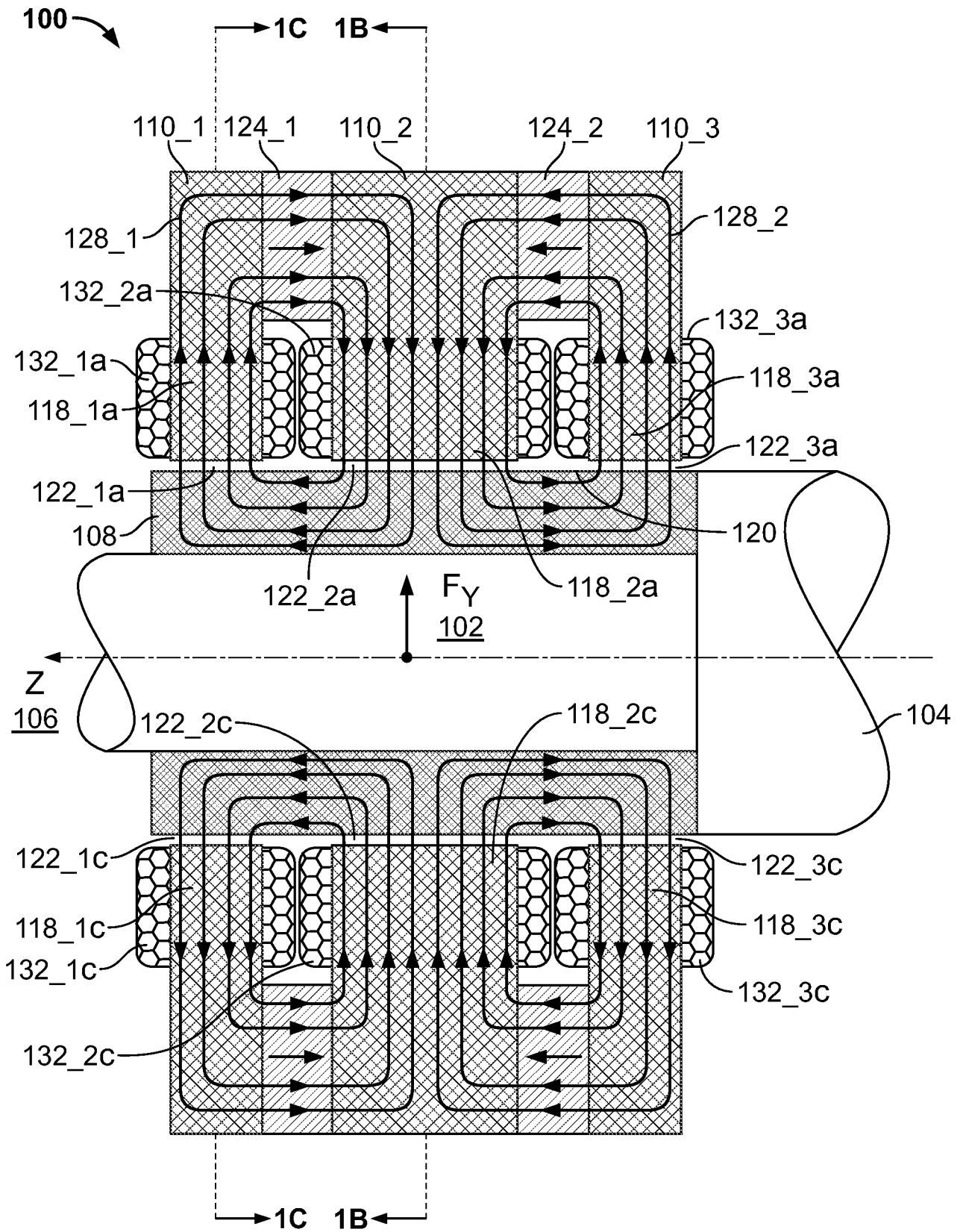
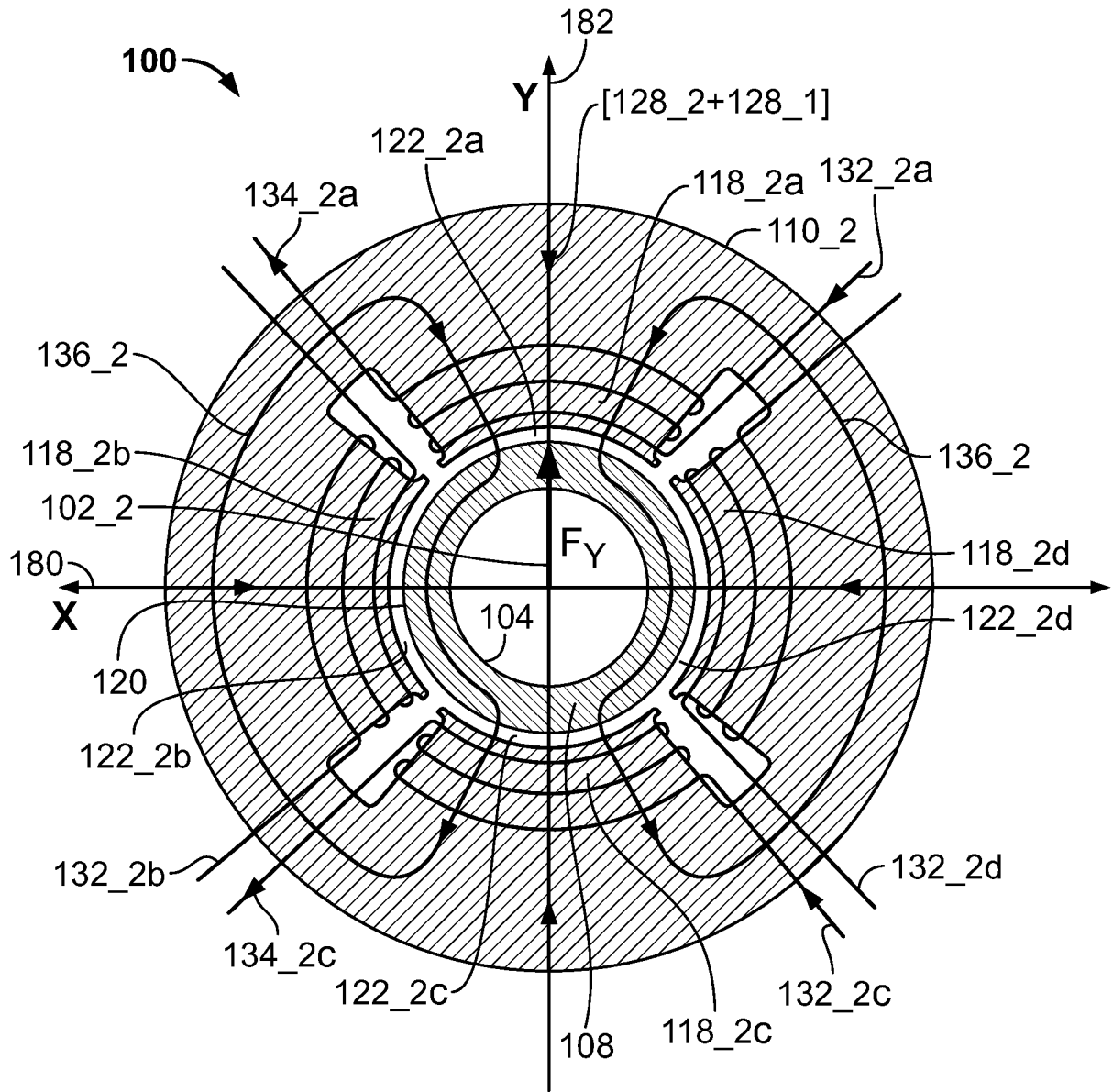


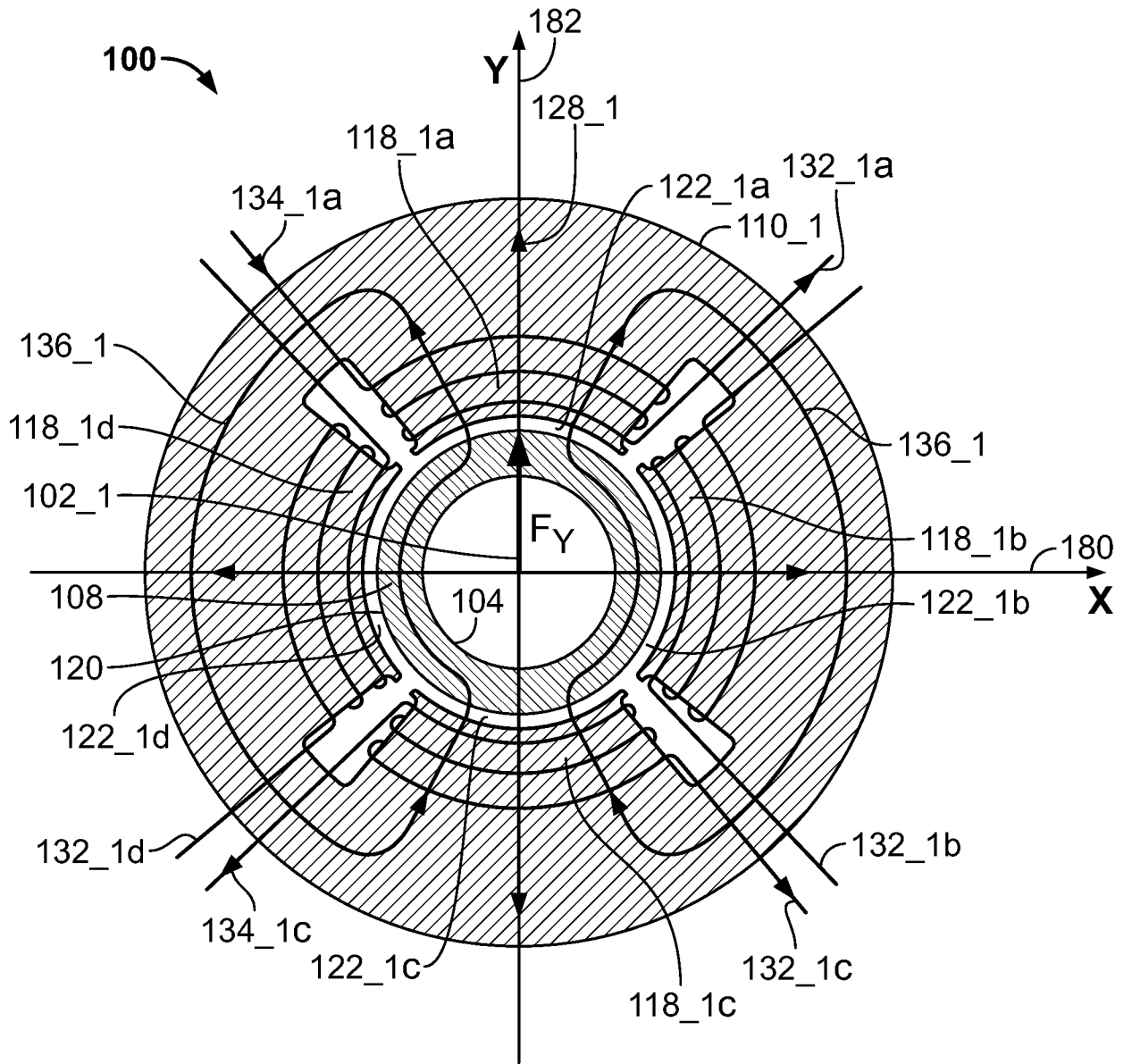
FIG. 1A

VIEW 1B-1B



**FIG. 1B**

VIEW 1C-1C



**FIG. 1C**

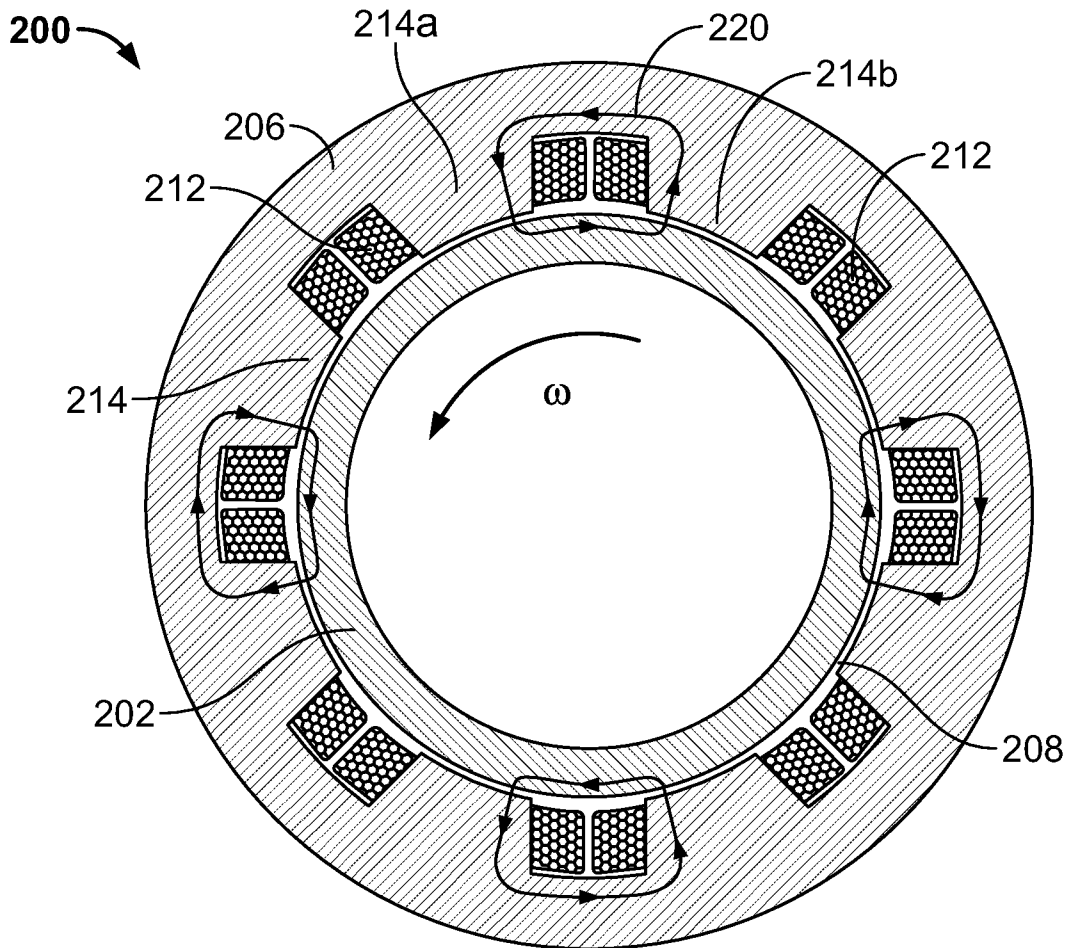


FIG. 2A



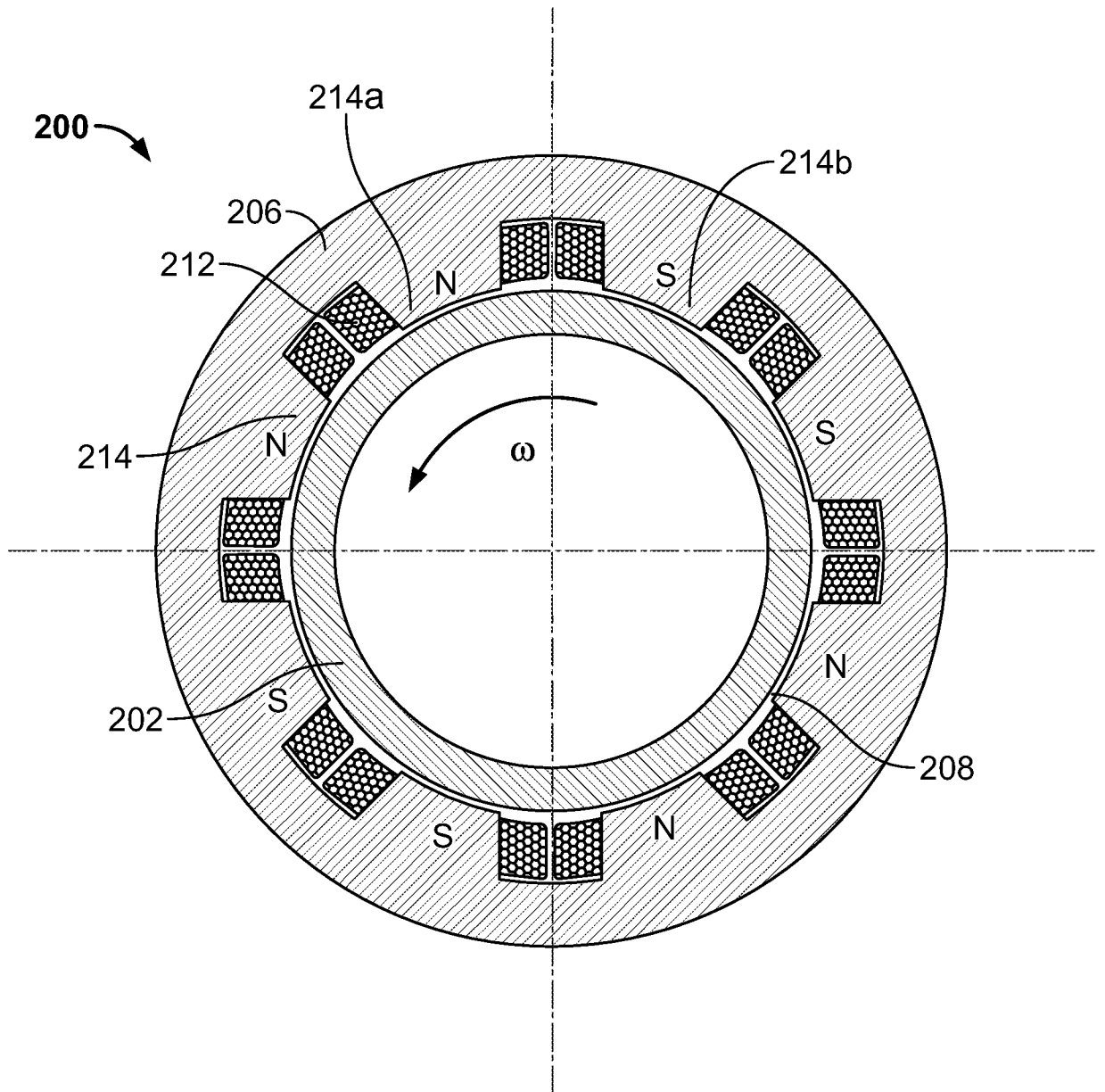


FIG. 2B

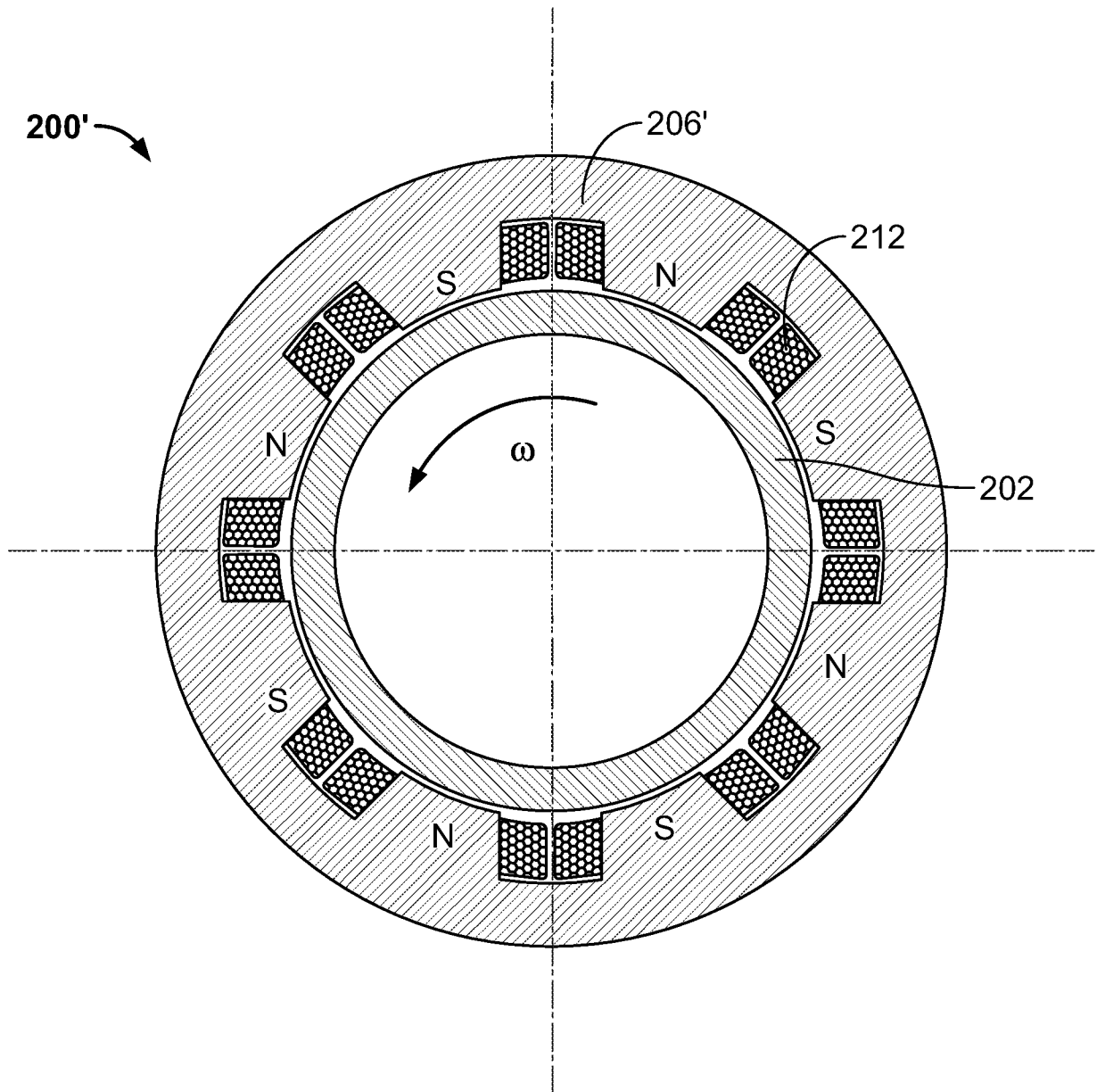


FIG. 2C

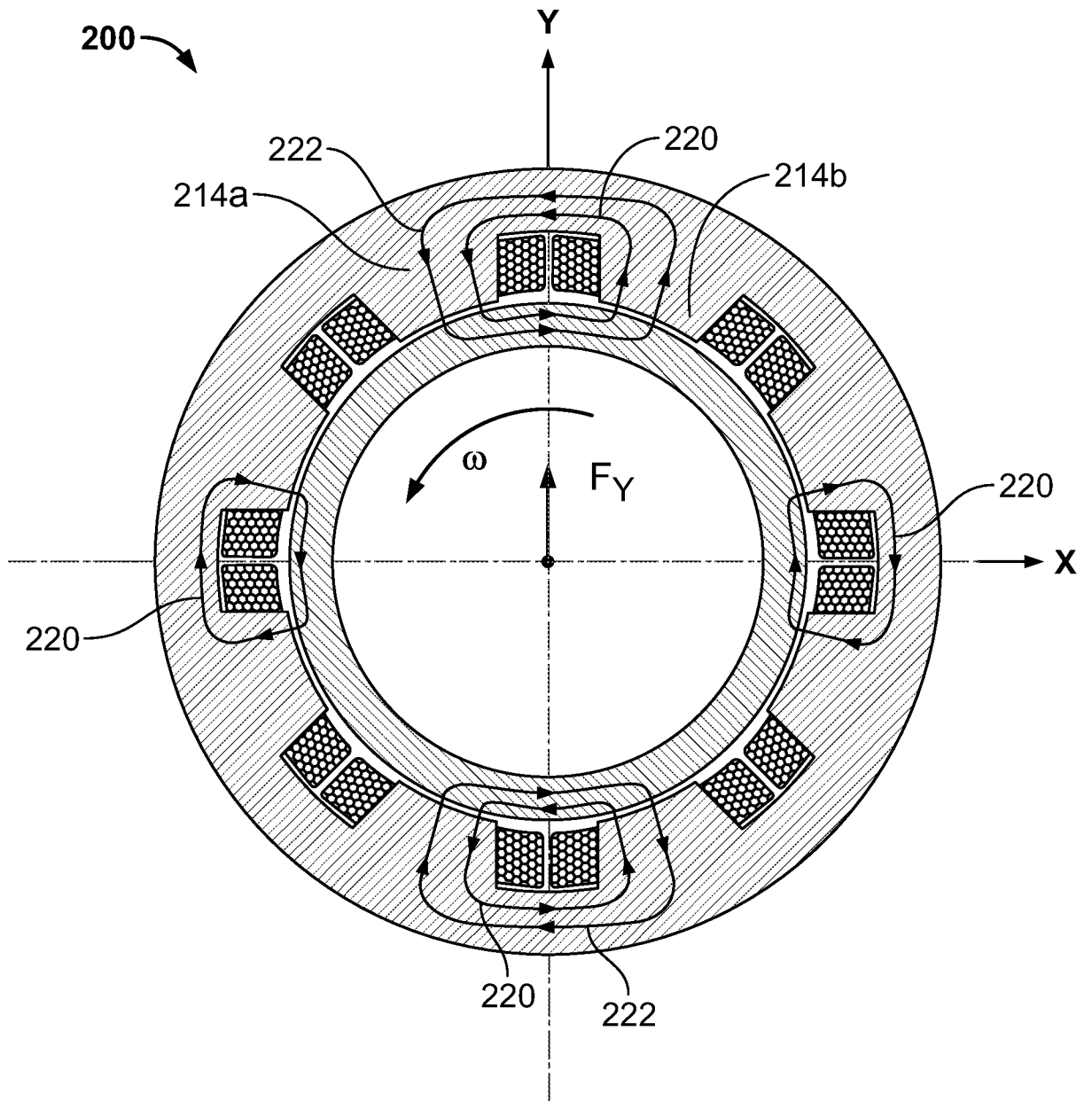


FIG. 2D

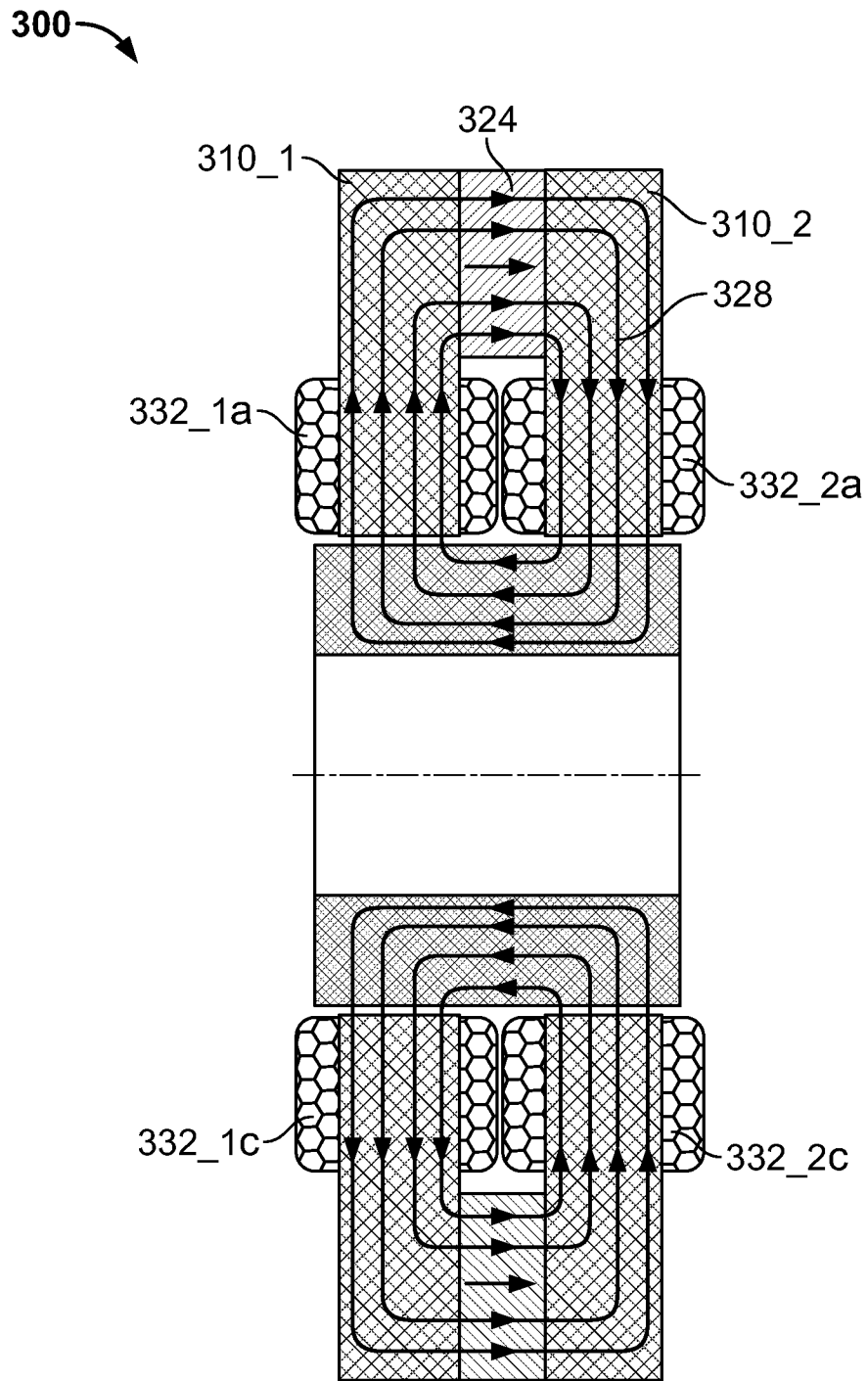
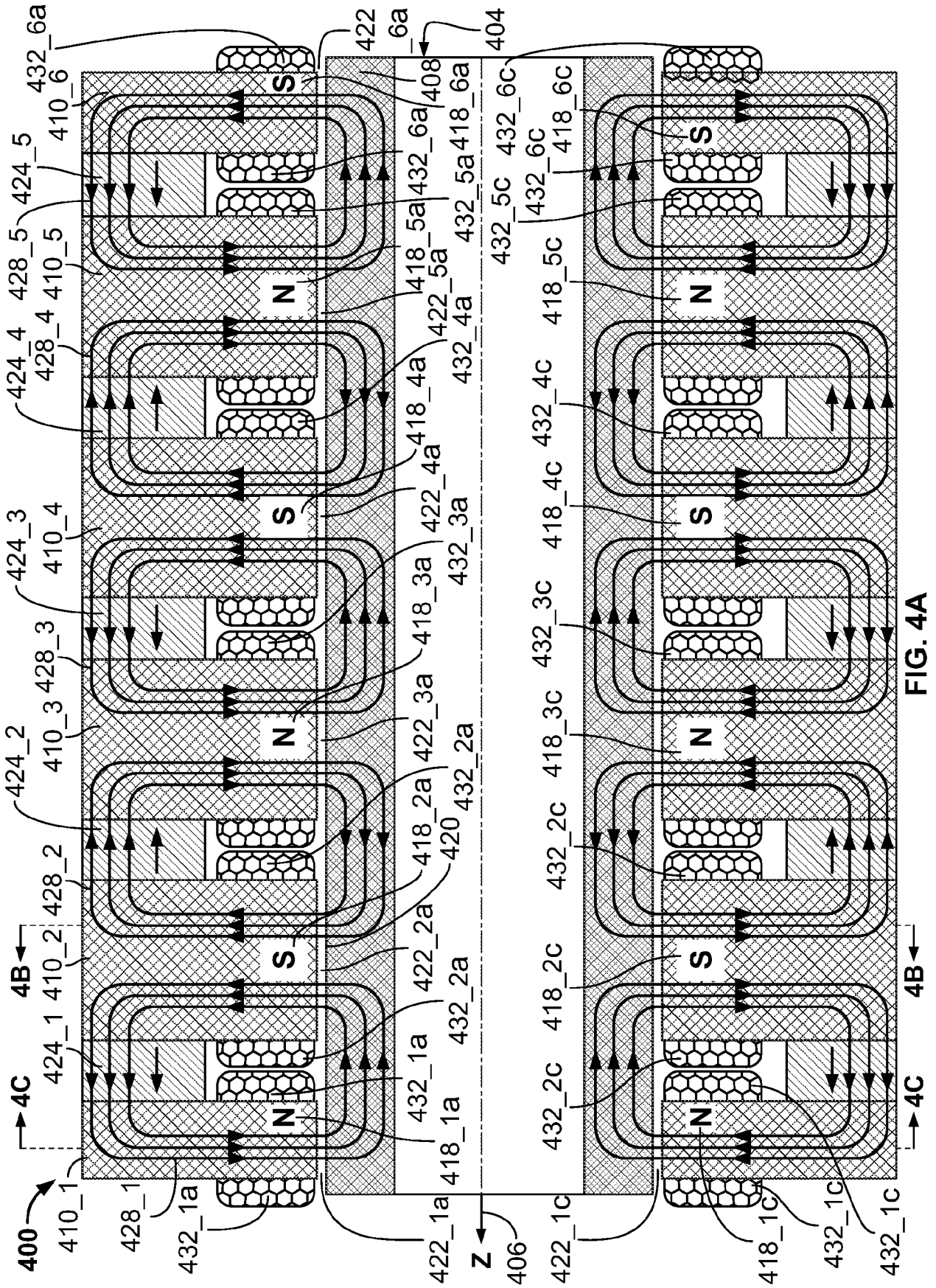
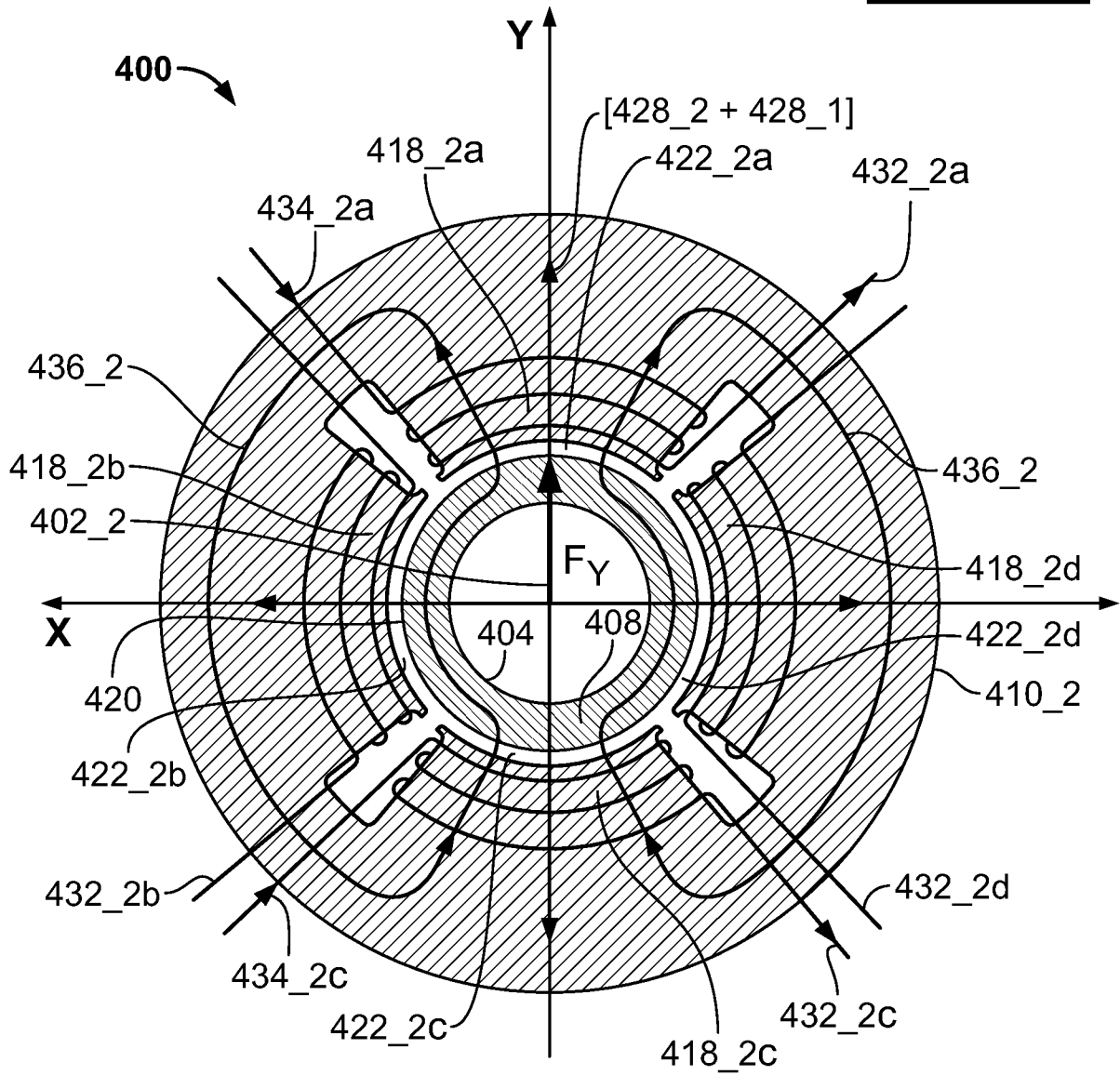


FIG. 3

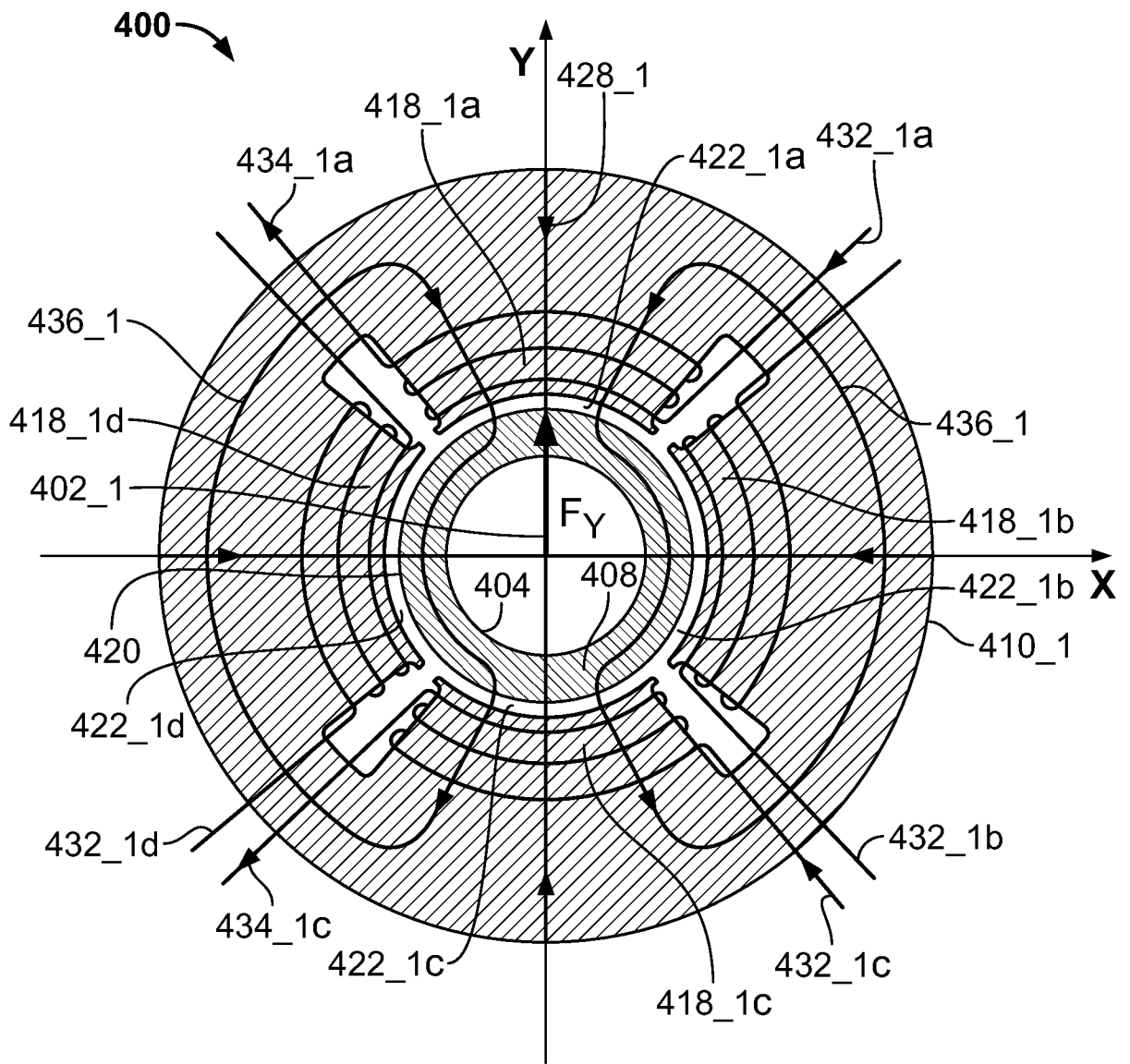


VIEW 4B-4B



**FIG. 4B**

VIEW 4C-4C



**FIG. 4C**

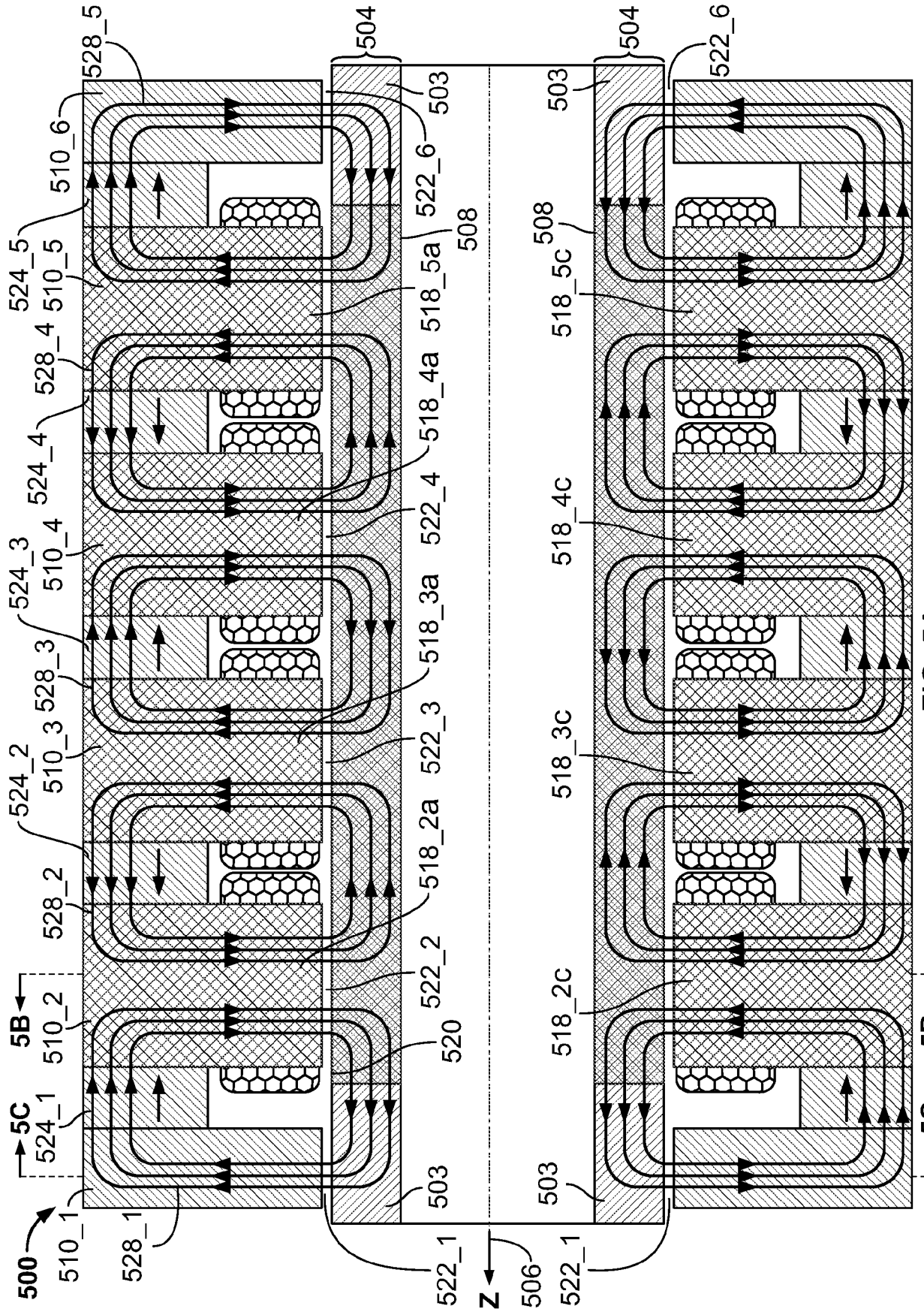
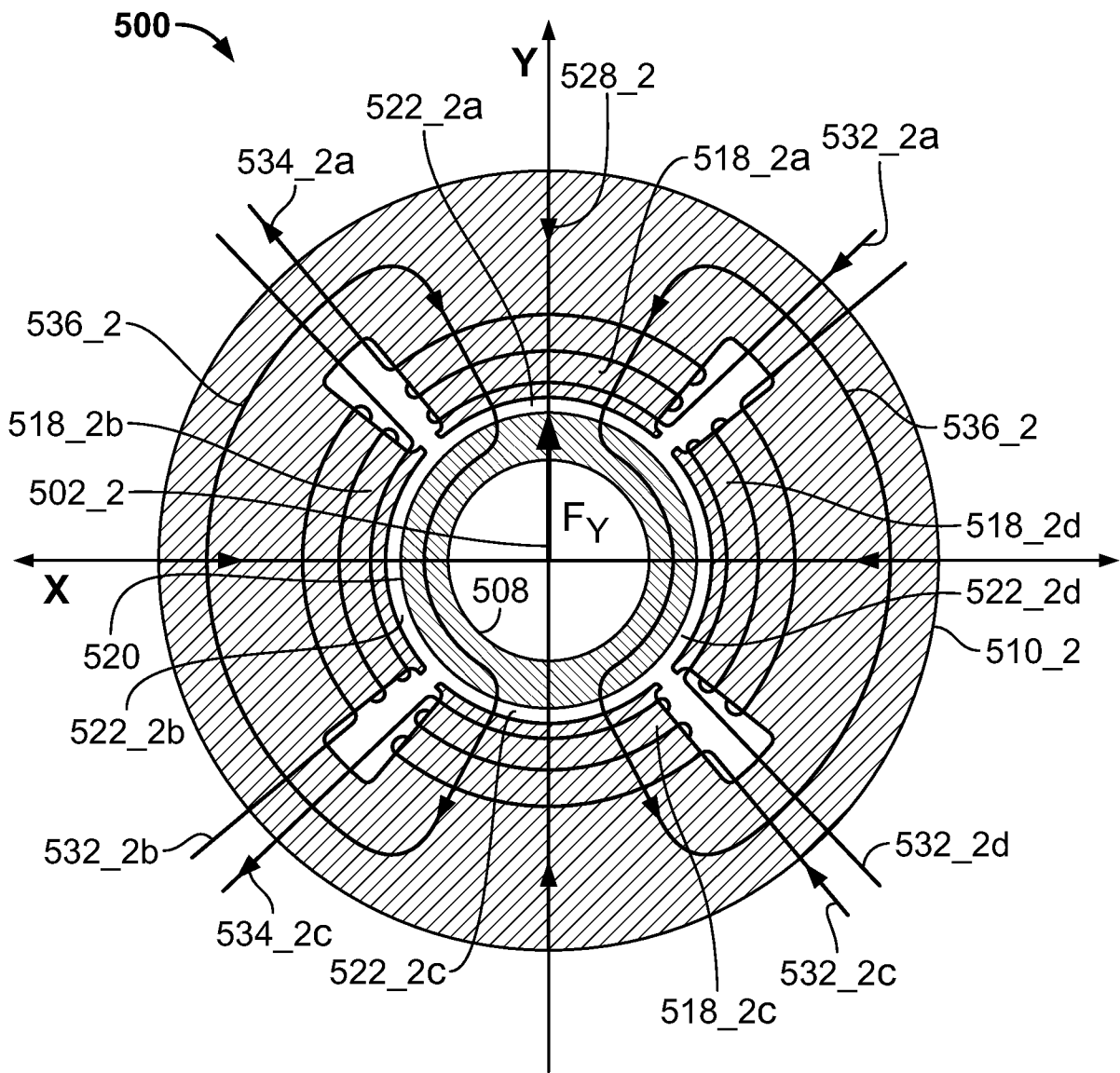


FIG. 5A



VIEW 5B-5B



**FIG. 5B**

VIEW 5C-5C

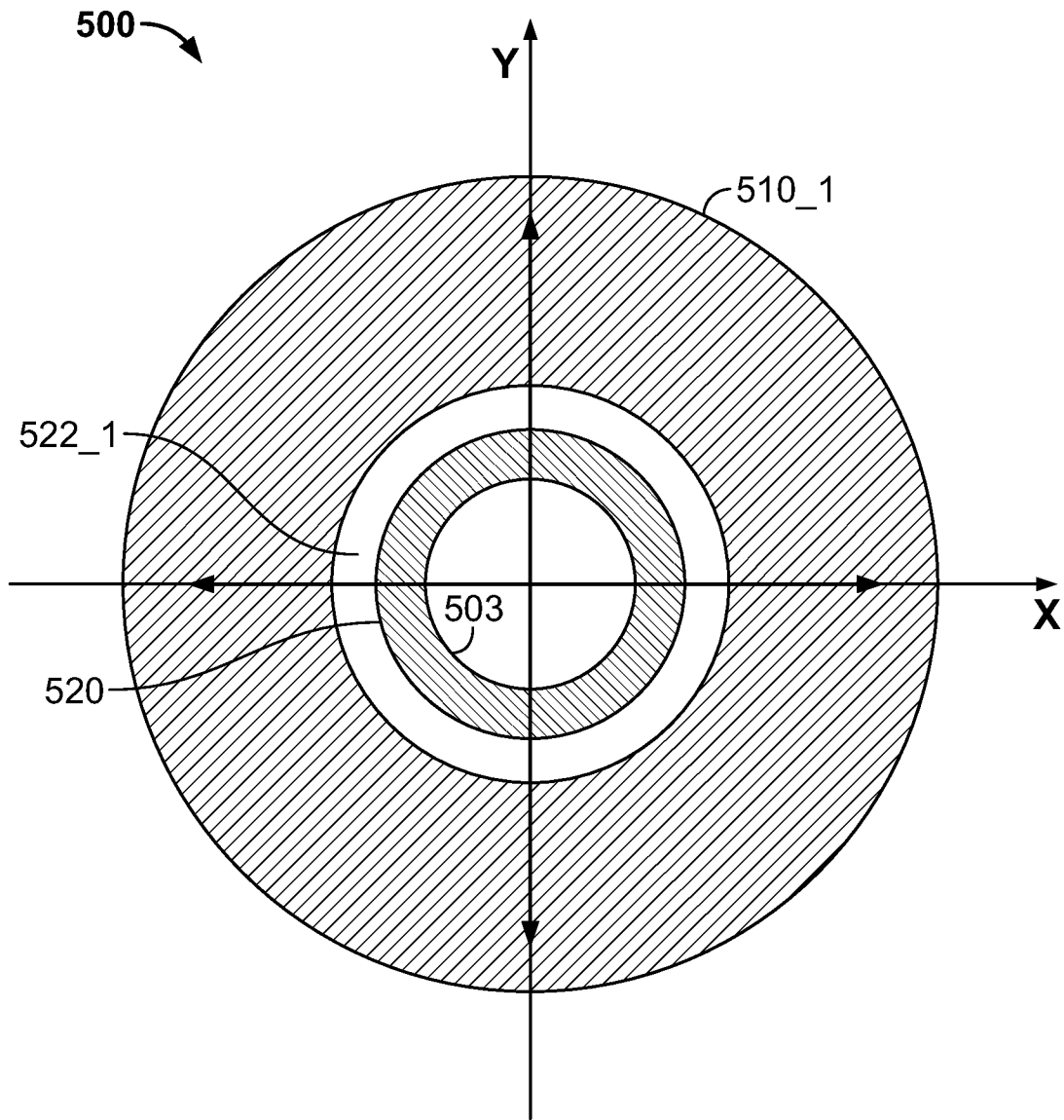


FIG. 5C

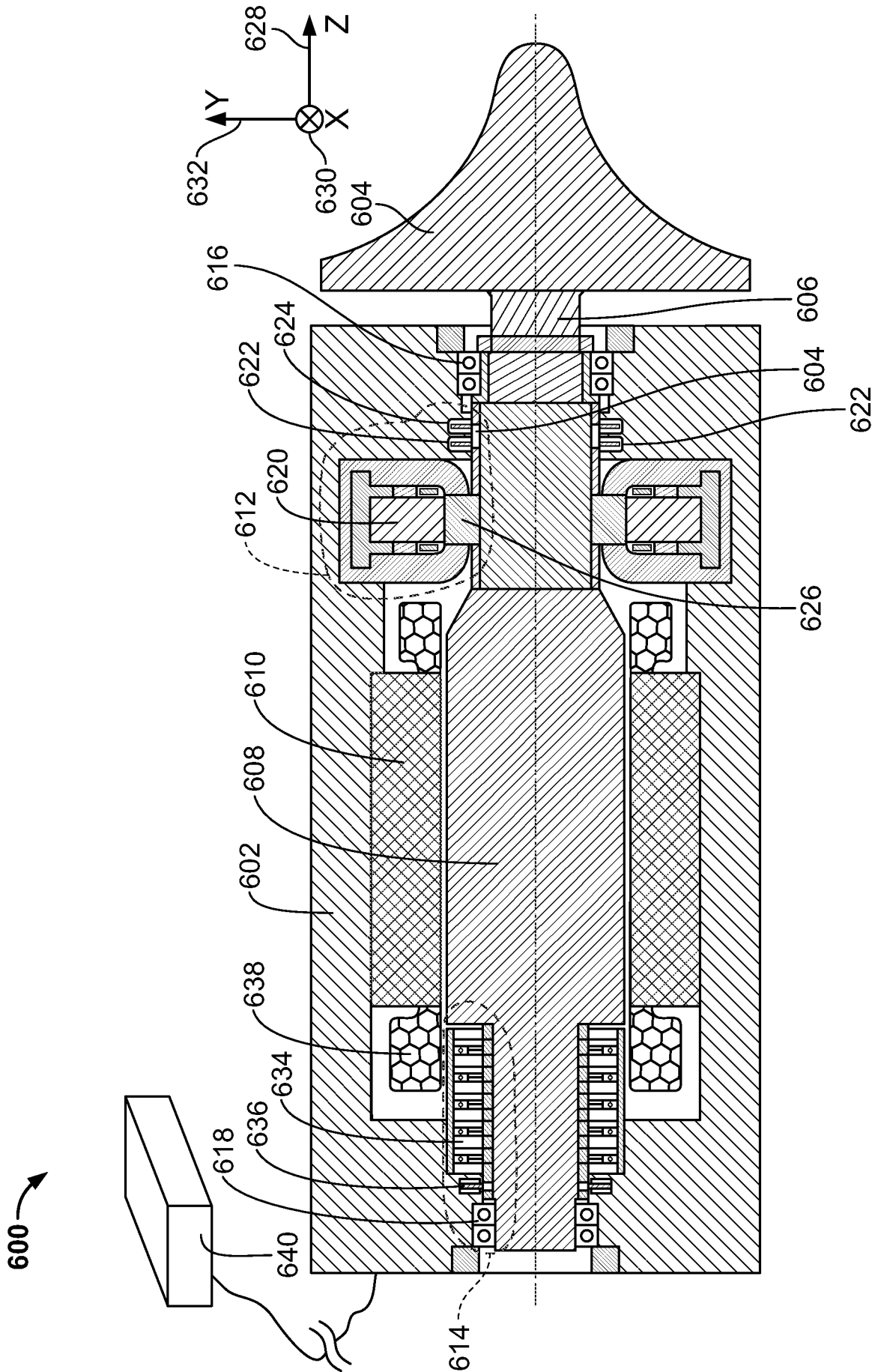


FIG. 6

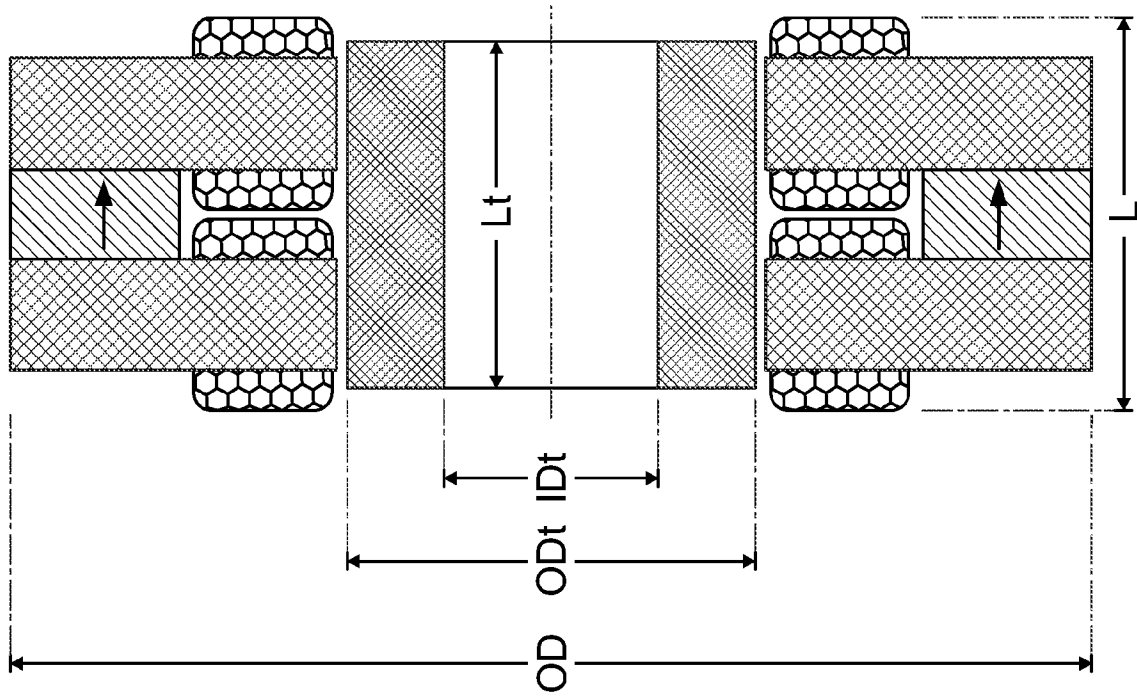


FIG. 8

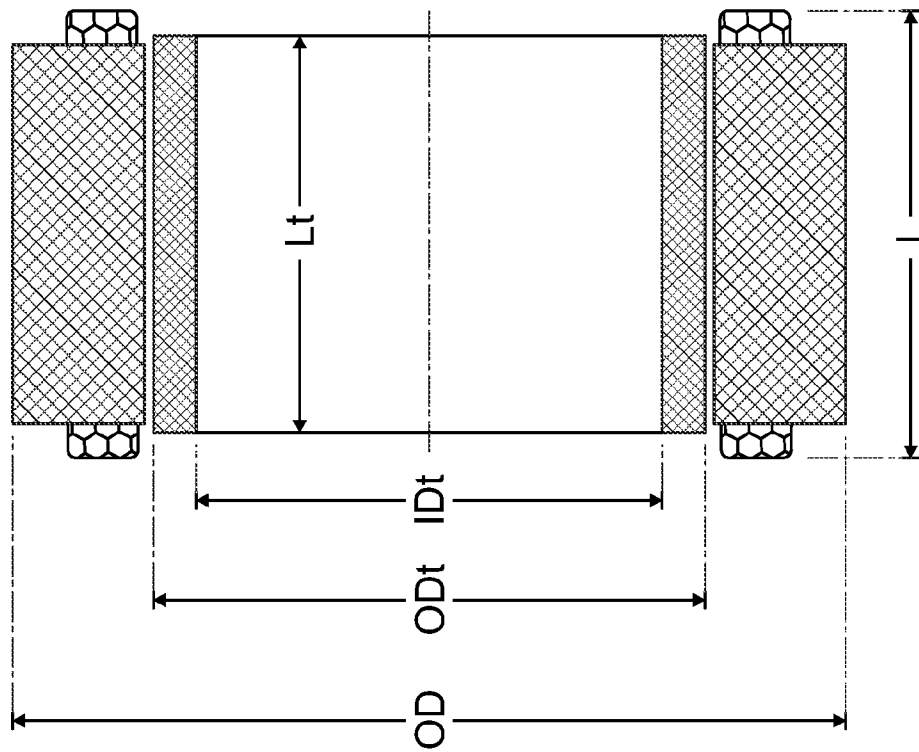


FIG. 7