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Mizzell, Jr.

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(54) **PERMANENT MAGNETIC ASSEMBLIES AND METHODS OF ASSEMBLING SAME**

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H01F 7/02 (2006.01)
H02K 1/02 (2006.01)

(52) **U.S. Cl.**

CPC ***H01F 7/021*** (2013.01); ***H02K 1/02*** (2013.01)

(58) **Field of Classification Search**

CPC H01F 7/021; H01F 7/0273; H02K 1/02
See application file for complete search history.

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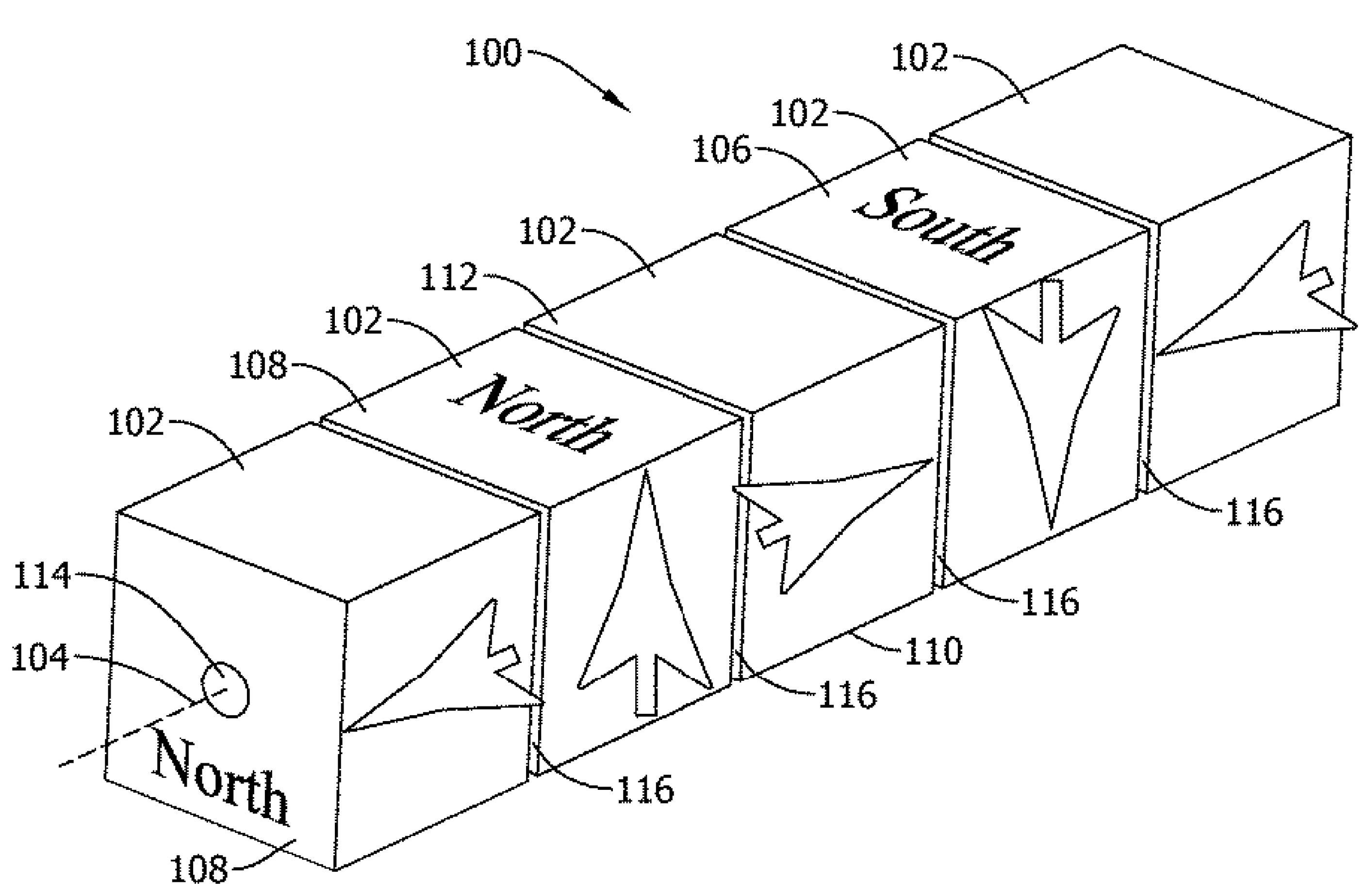
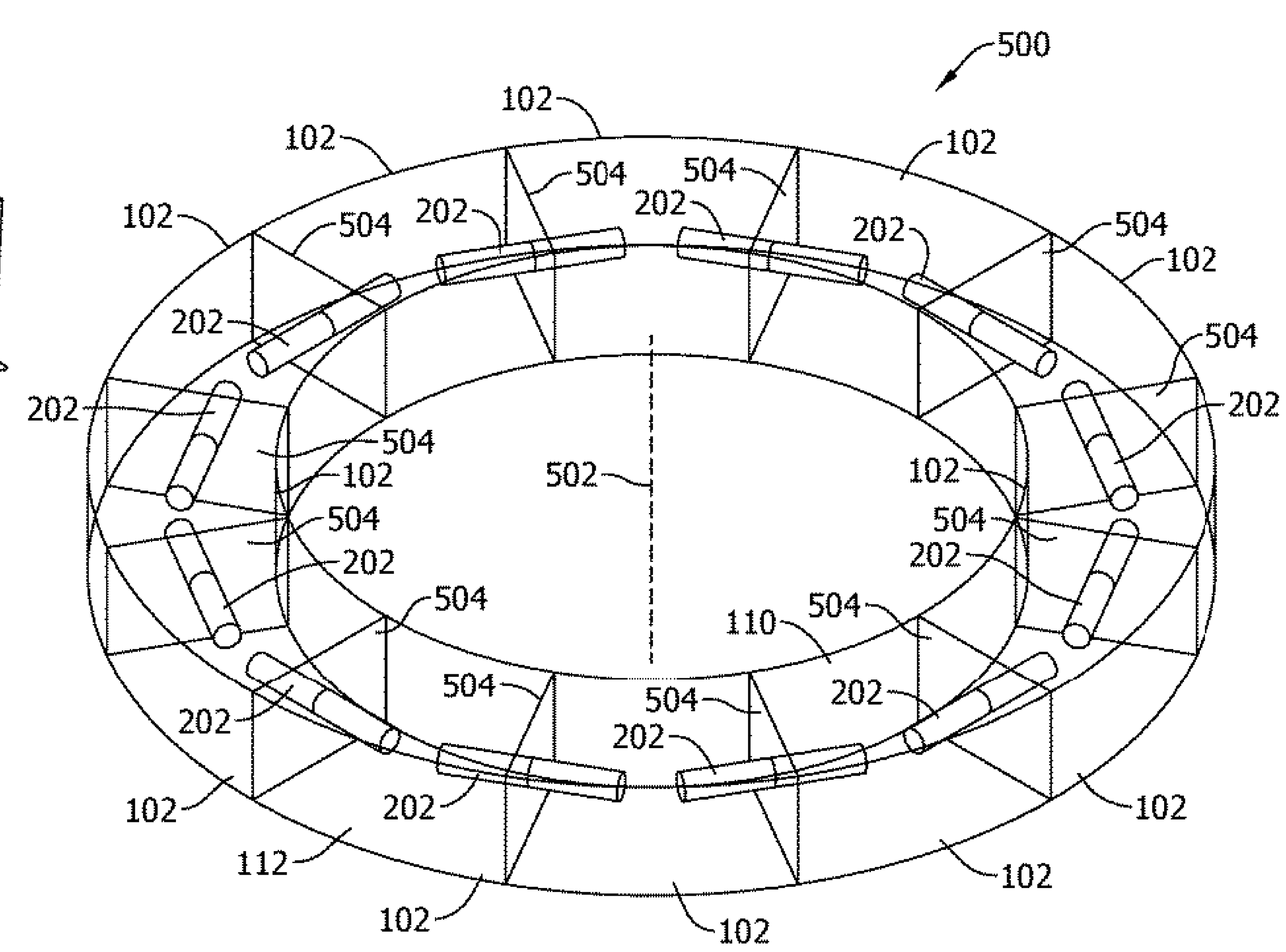
(57) **ABSTRACT**

A magnetic assembly includes magnets arranged in a Halbach array. The magnets include a first magnet and a second magnet positioned adjacent the first magnet. The first magnet and the second magnet have adjacent surfaces. A cavity is formed in the each of the adjacent surfaces and is aligned with the cavity formed in the adjacent surface of the adjacent magnet. The magnetic assembly also includes a ferromagnetic pin positioned within the aligning cavities to connect the first magnet and the second magnet. The ferromagnetic pin has a size, a shape, and a magnetic permeability that facilitate a magnetic force between the first surface and the second surface inducing a magnetic flux path through the ferromagnetic pin such that an apparent magnetic force between the first surface and the second surface is one of i) a repelling force less than 5 newtons (N) and ii) an attracting force.

20 Claims, 21 Drawing Sheets





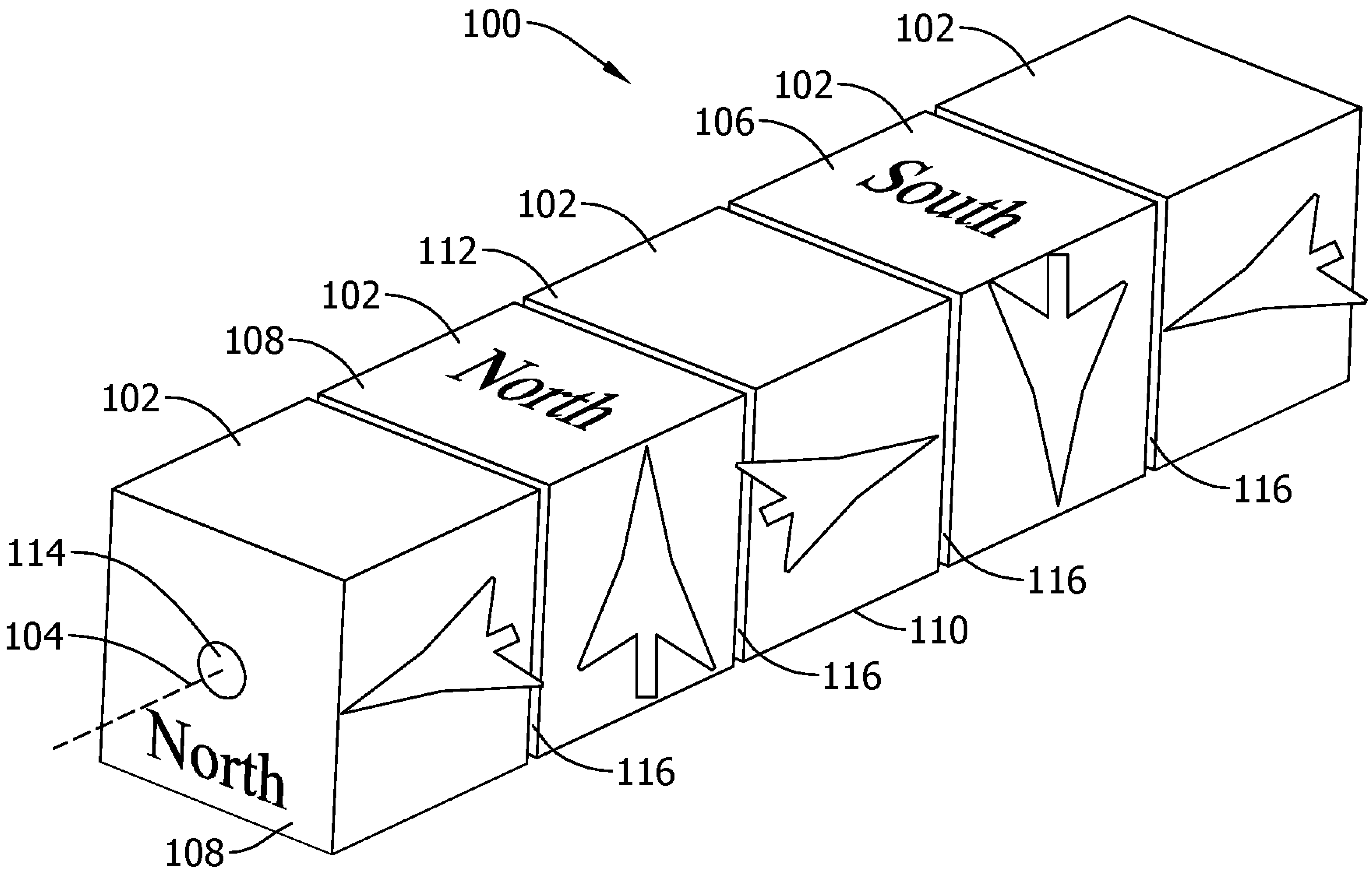
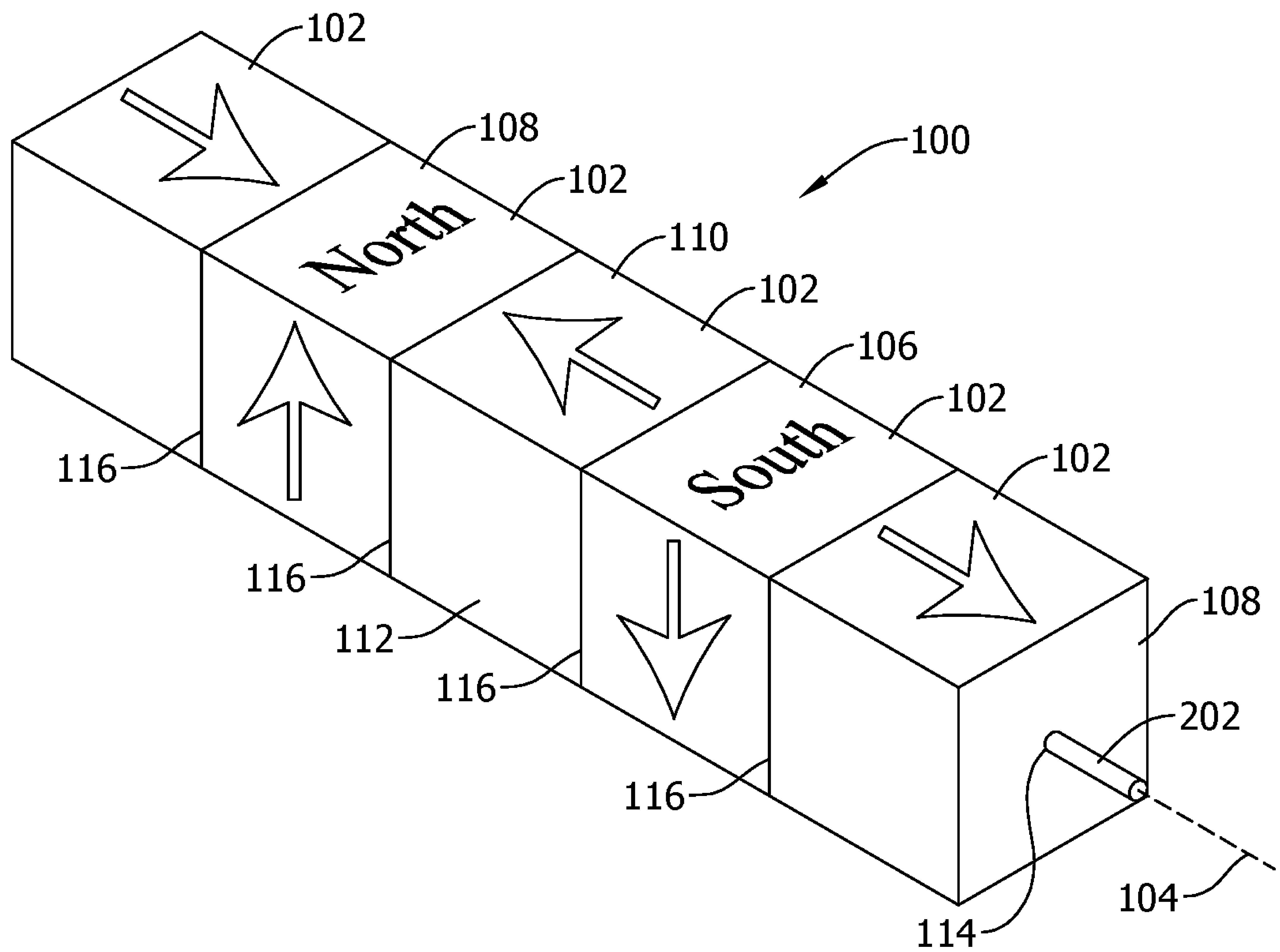

100
102
102
106
South
102
112
102
108
North
102
114
104
North
108
116
116
110
116
116

FIG. 1


102
108
102
110
102
106
102
102
100
North
South
116
116
112
116
116
108
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104
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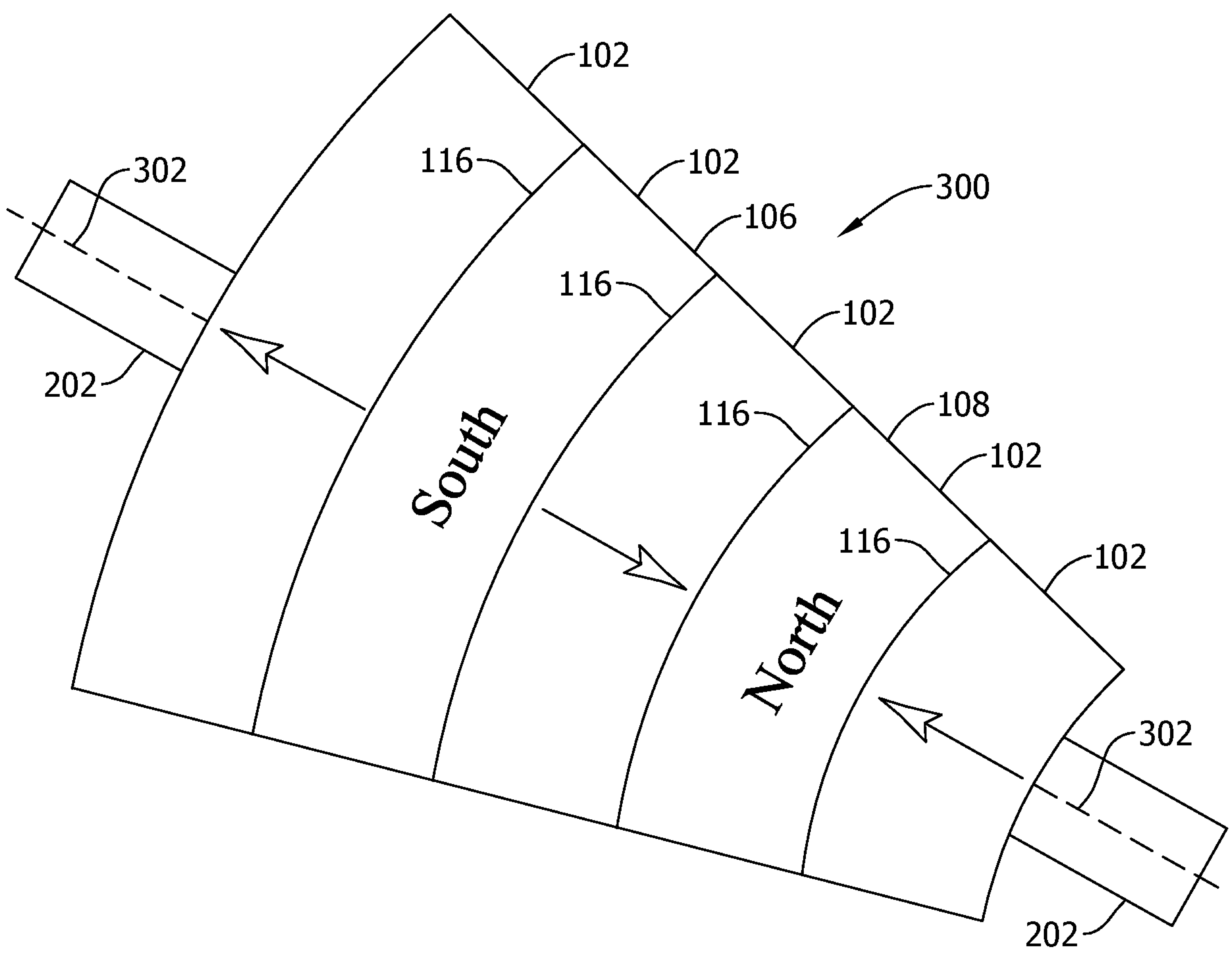
FIG. 2


102
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102
102
102
102
106
108
116
116
116
116
300
302
302
202
202
South
North

FIG. 3

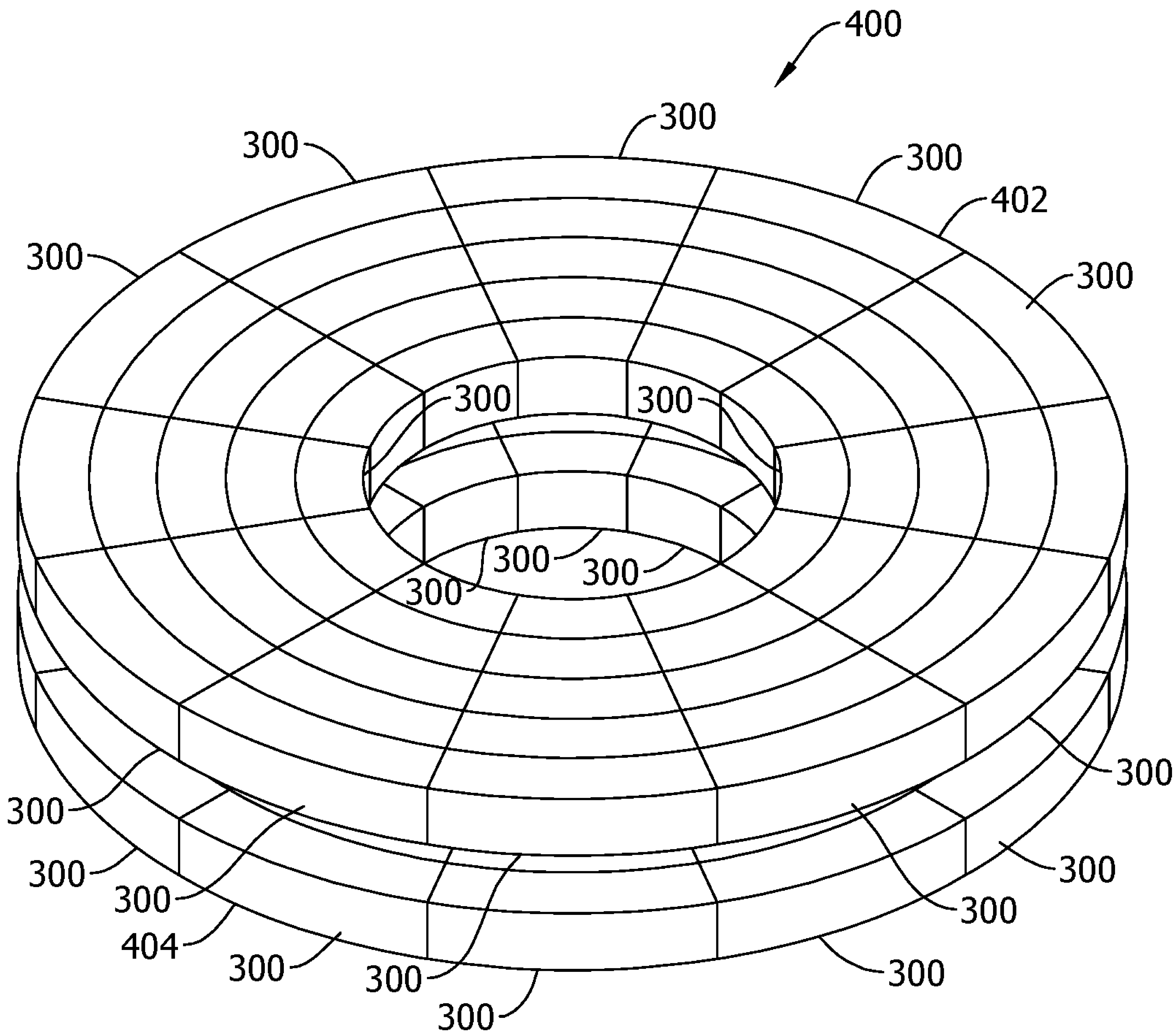

400
300
300
300
402
300
300
300
300
300
300
300
300
300
300
300
300
404
300
300
300
300
300

FIG. 4

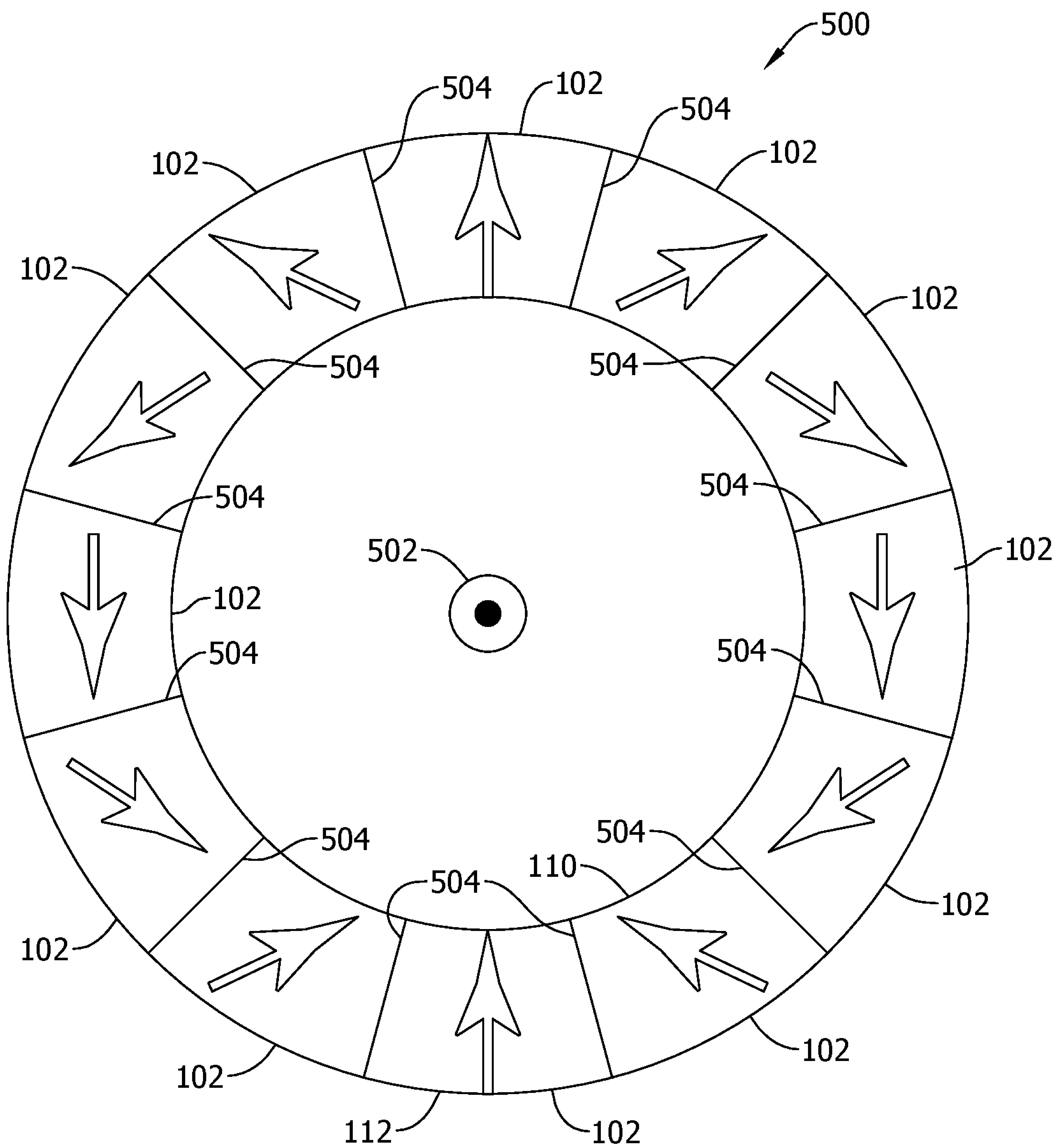

500
504
102
504
102
102
102
102
504
504
504
504
102
502
102
504
504
504
504
504
110
102
102
102
102
112
102

FIG. 5

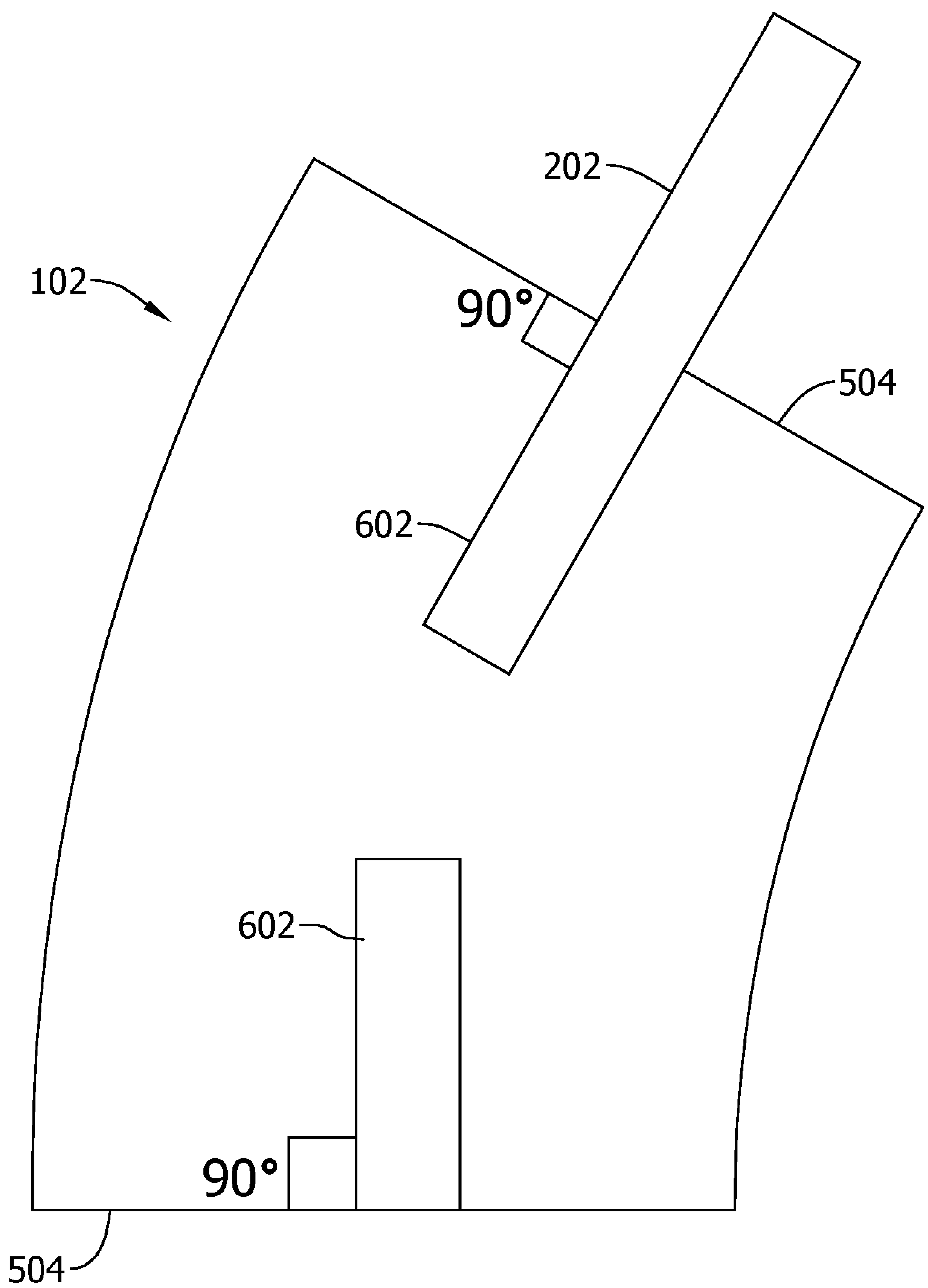


FIG. 6

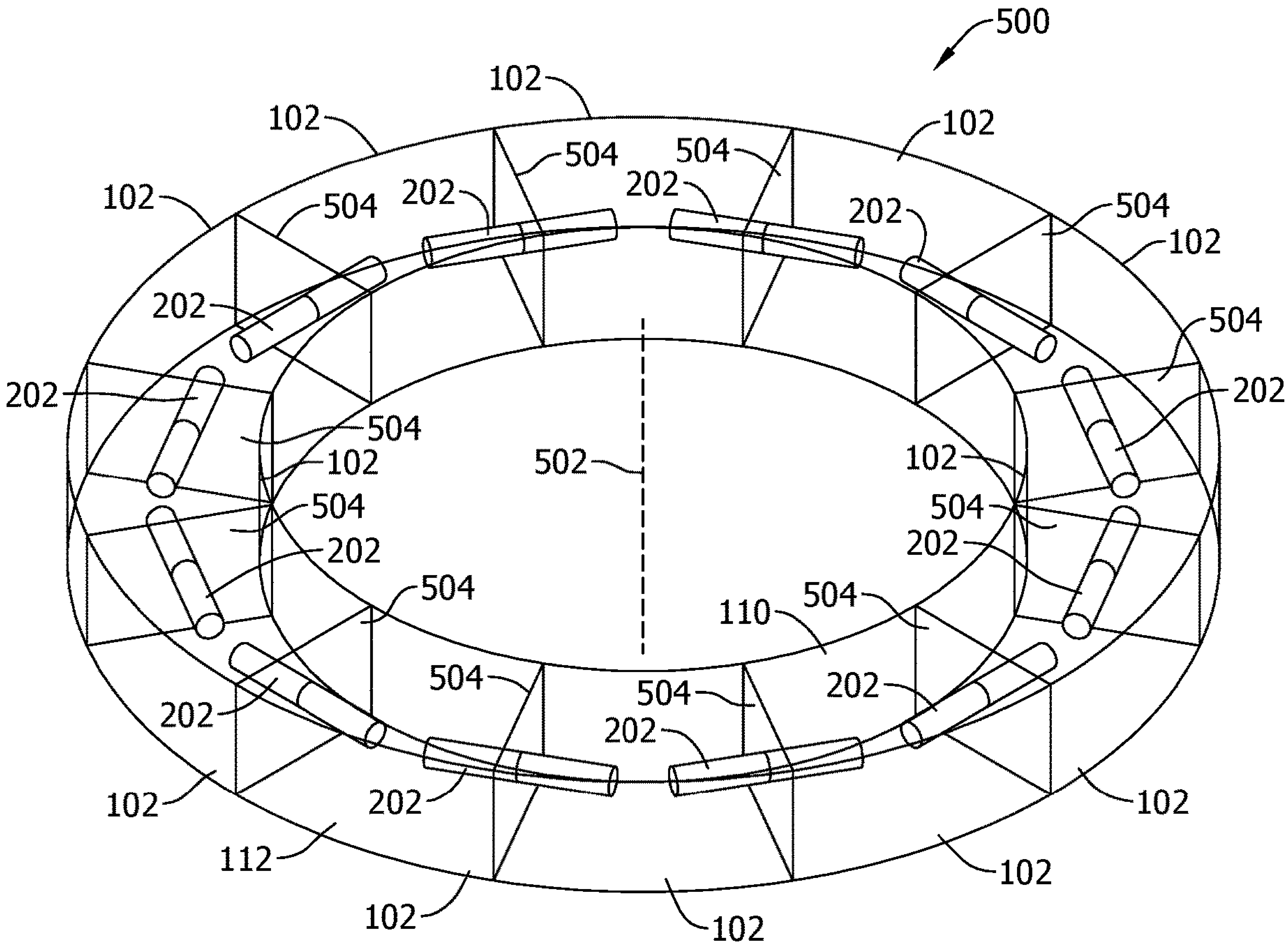

500
102
102
102
102
102
102
102
102
102
102
102
102
102
102
504
504
504
504
504
504
504
504
504
504
504
504
202
202
202
202
202
202
202
202
202
202
202
202
502
110
112

FIG. 7

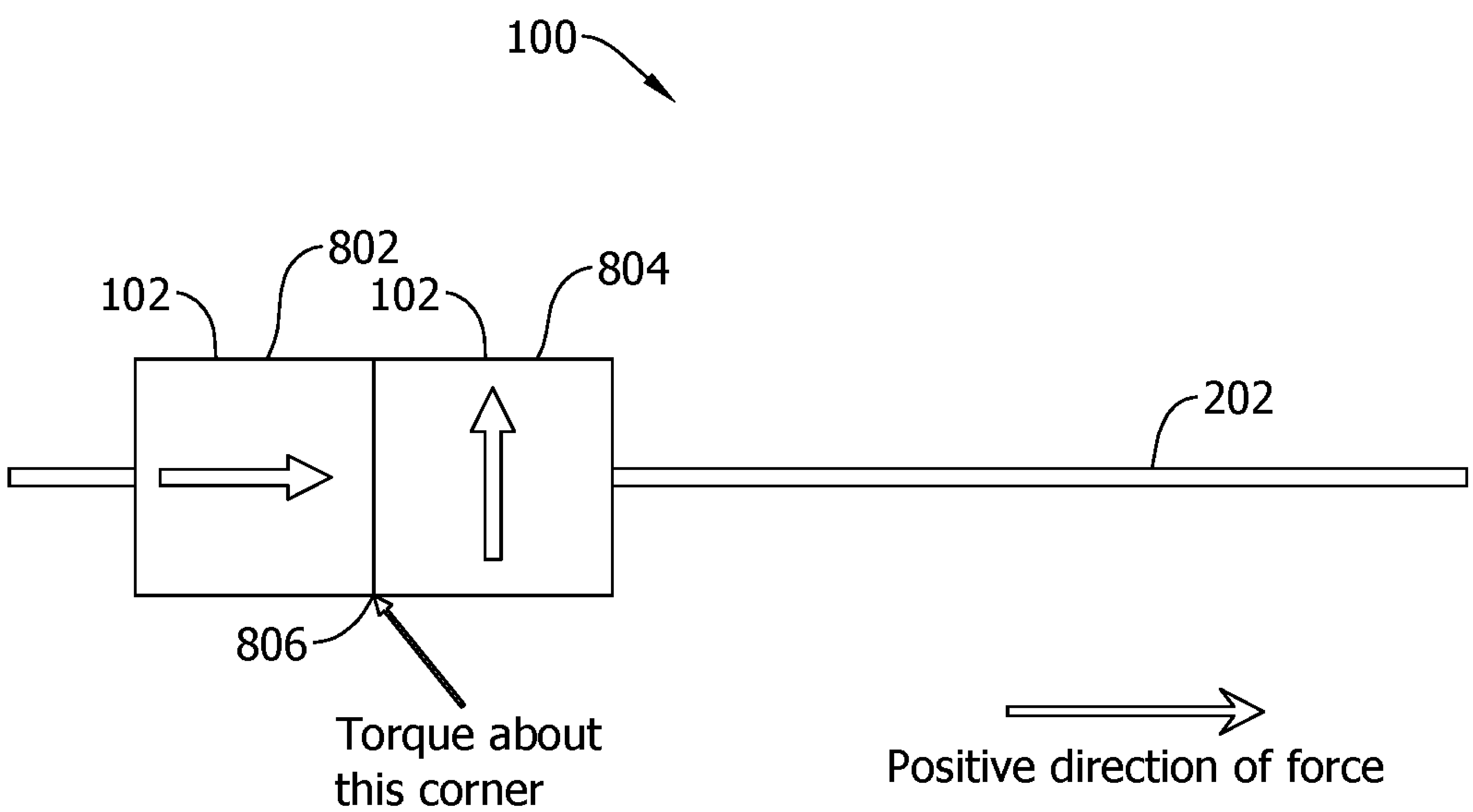

100
102
802
102
804
202
806
Torque about this corner
Positive direction of force

FIG. 8

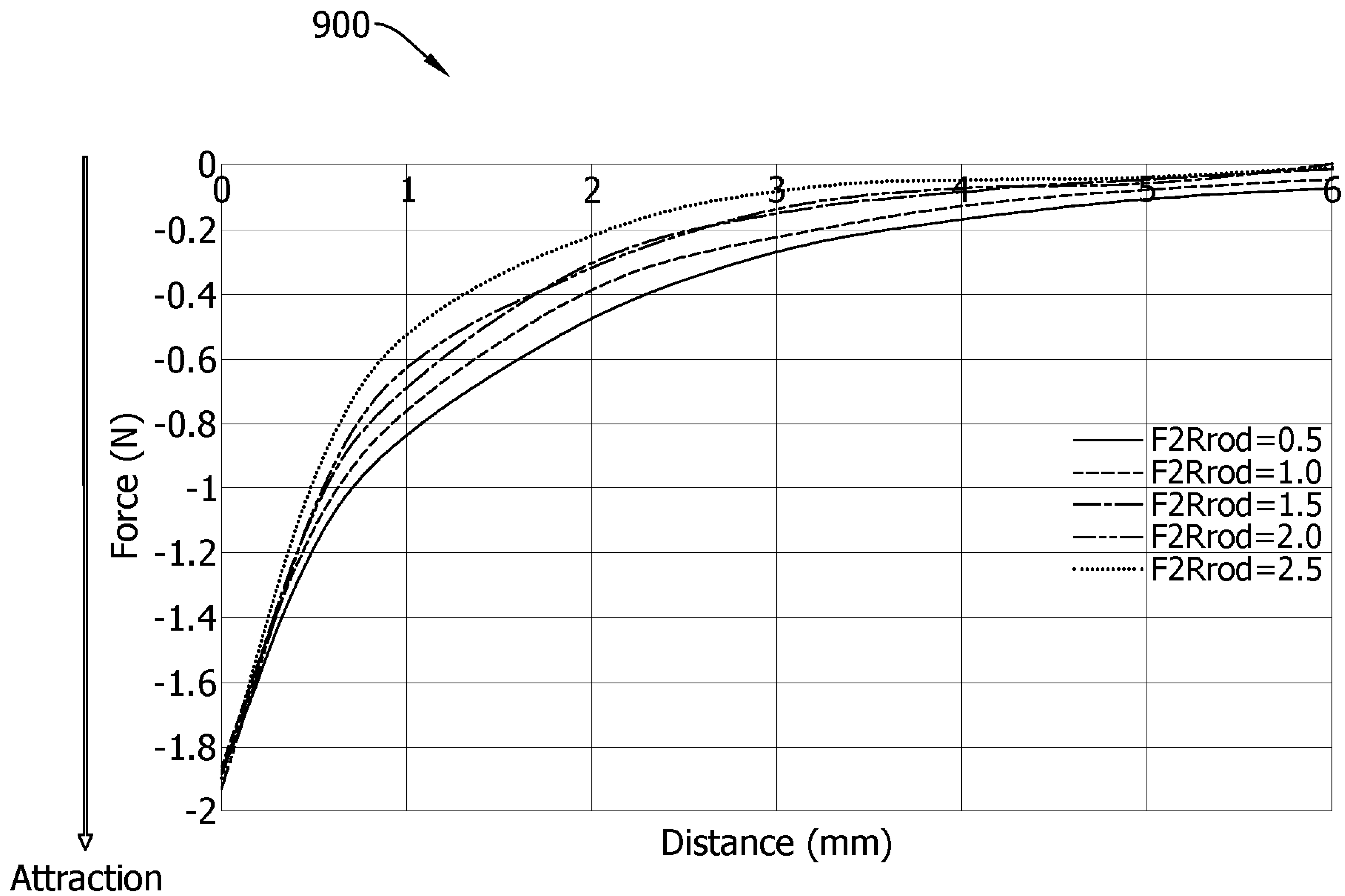

900
Force (N)
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
0
1
2
3
4
5
6
Distance (mm)
Attraction
F2Rrod=0.5
F2Rrod=1.0
F2Rrod=1.5
F2Rrod=2.0
F2Rrod=2.5

FIG. 9

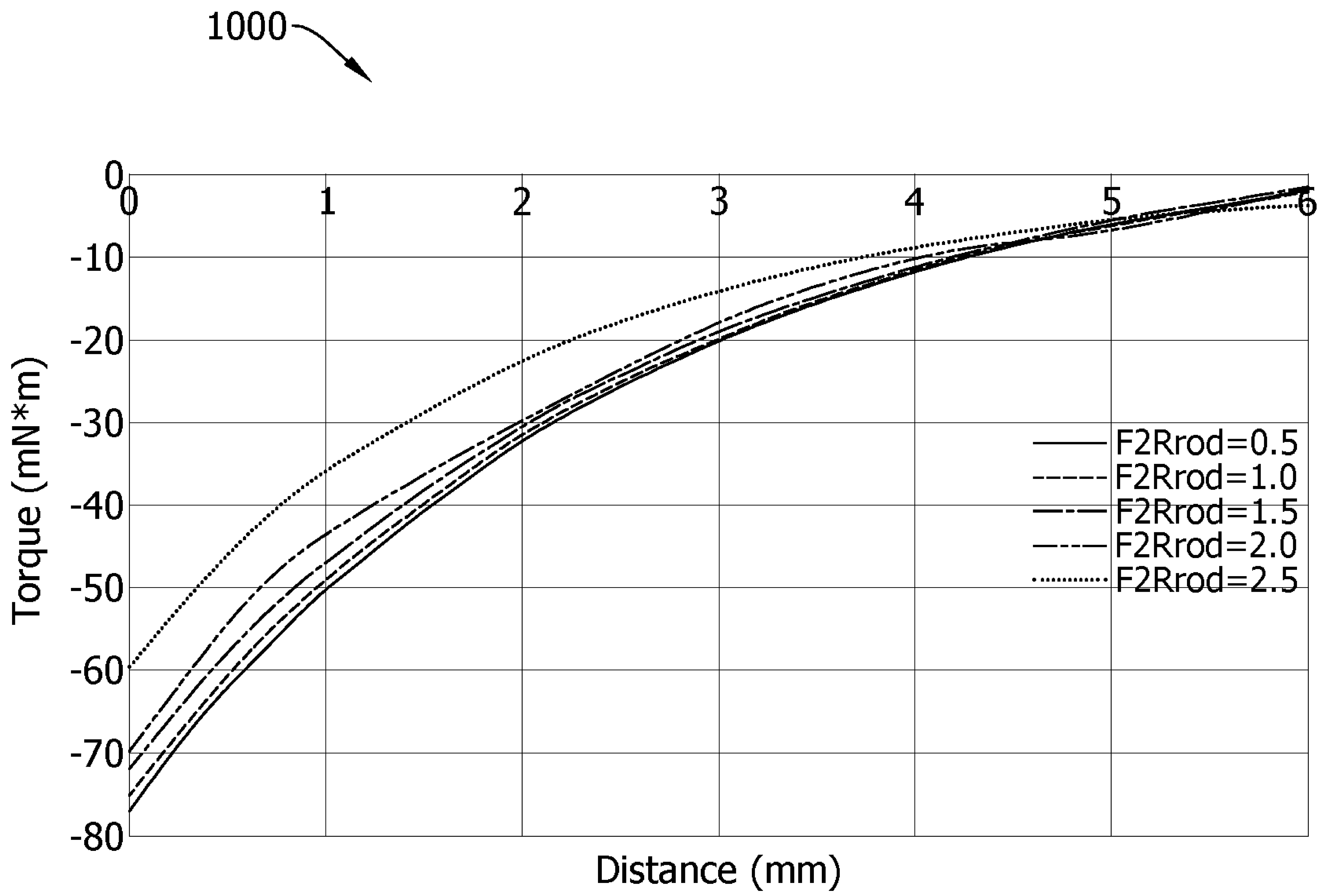

1000
0
-10
-20
-30
-40
-50
-60
-70
-80
Torque (mN*m)
0
1
2
3
4
5
6
Distance (mm)
F2Rrod=0.5
F2Rrod=1.0
F2Rrod=1.5
F2Rrod=2.0
F2Rrod=2.5

FIG. 10

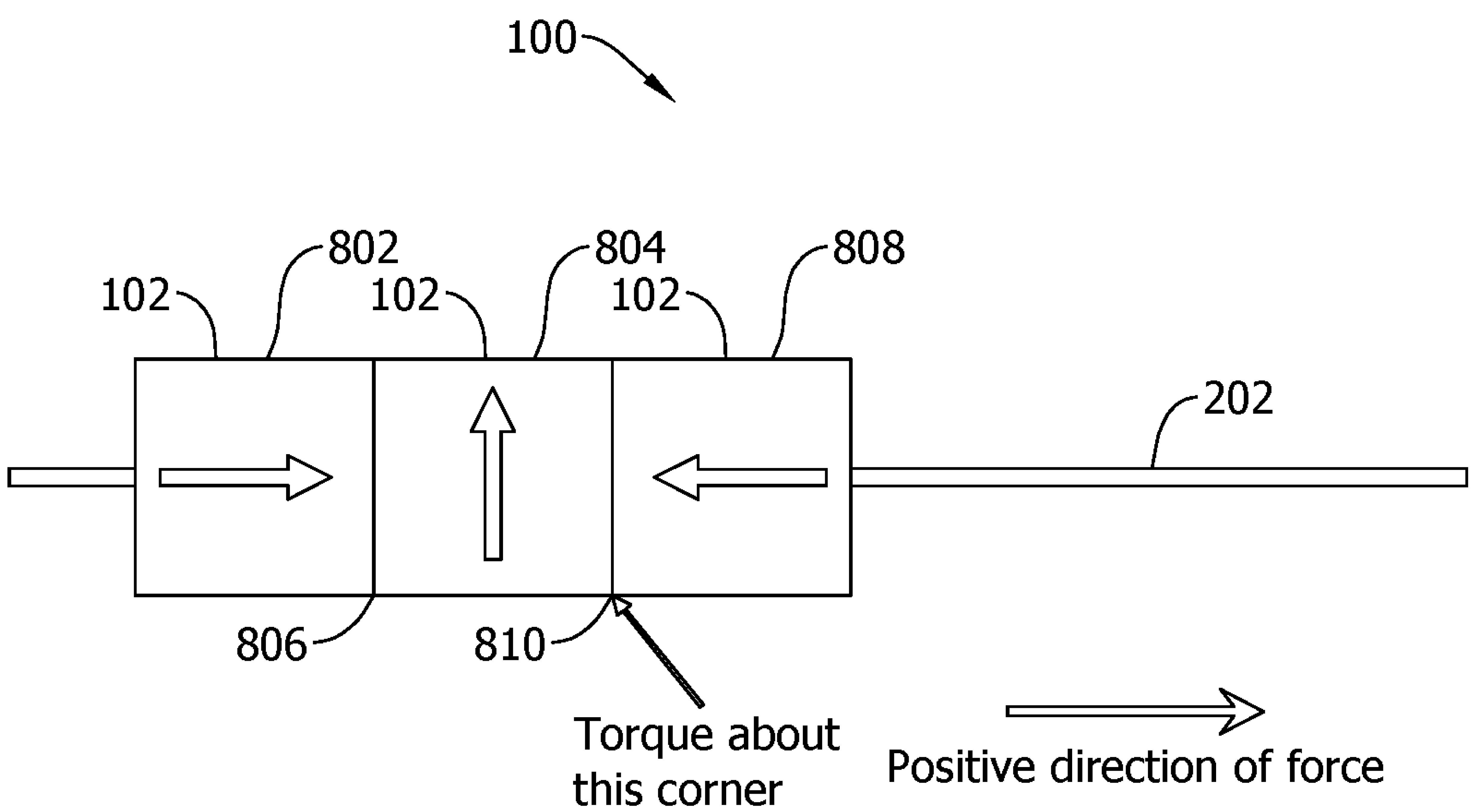

100
102
802
102
804
102
808
202
806
810
Torque about this corner
Positive direction of force

FIG. 11

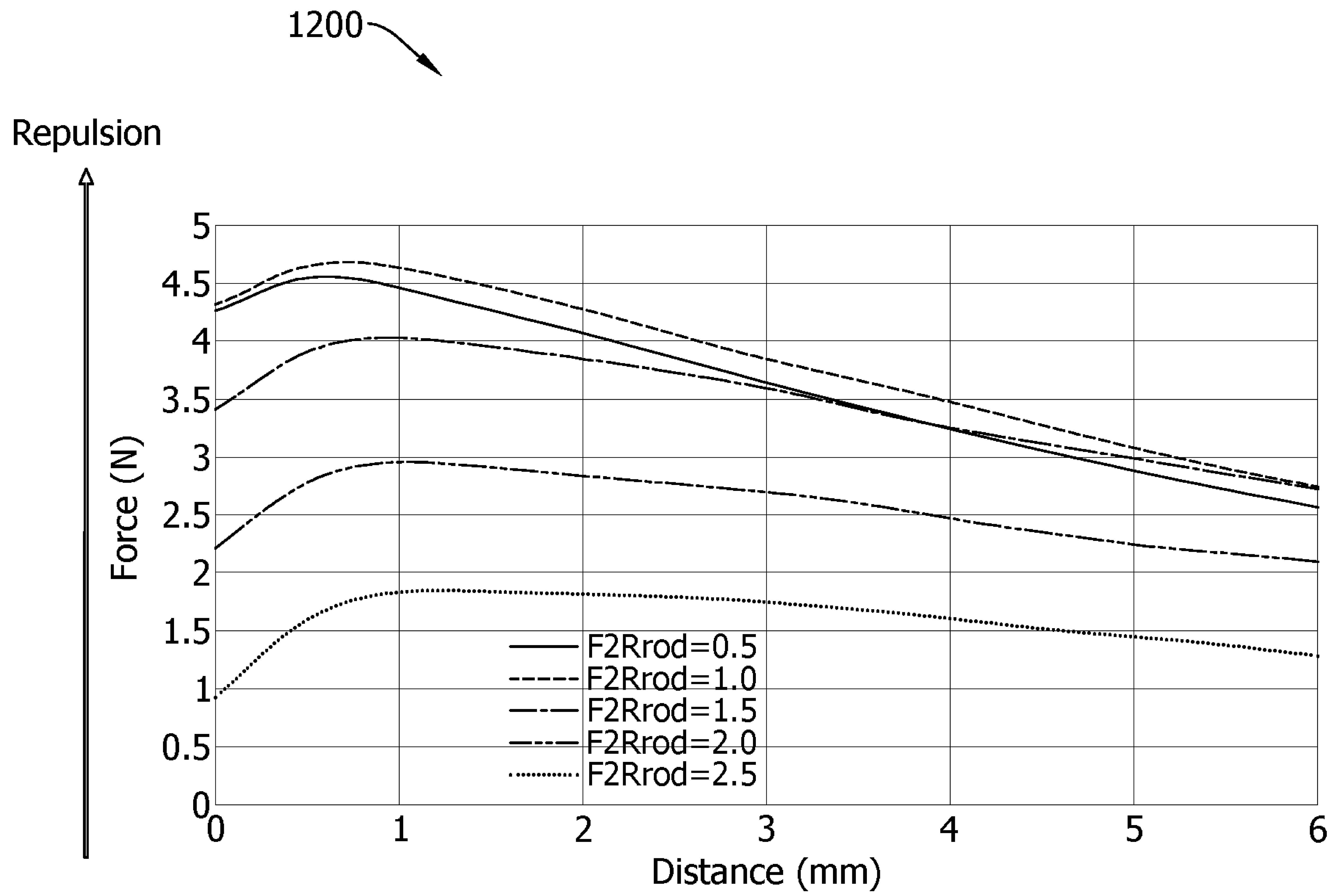

1200
Repulsion
Force (N)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
1
2
3
4
5
6
Distance (mm)
F2Rrod=0.5
F2Rrod=1.0
F2Rrod=1.5
F2Rrod=2.0
F2Rrod=2.5

FIG. 12

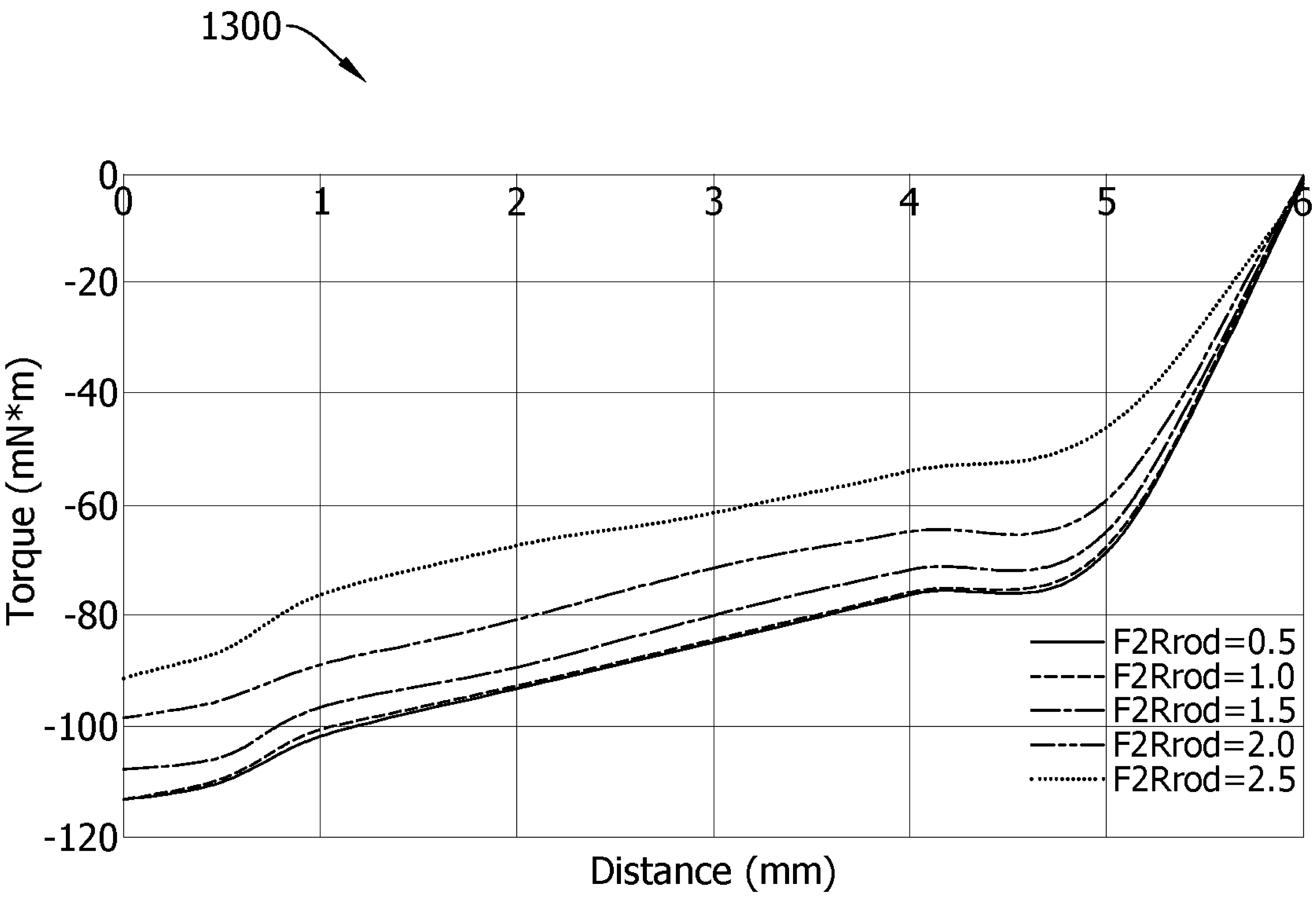

1300
0
-20
-40
-60
-80
-100
-120
0
1
2
3
4
5
6
Torque (mN*m)
Distance (mm)
F2Rrod=0.5
F2Rrod=1.0
F2Rrod=1.5
F2Rrod=2.0
F2Rrod=2.5

FIG. 13

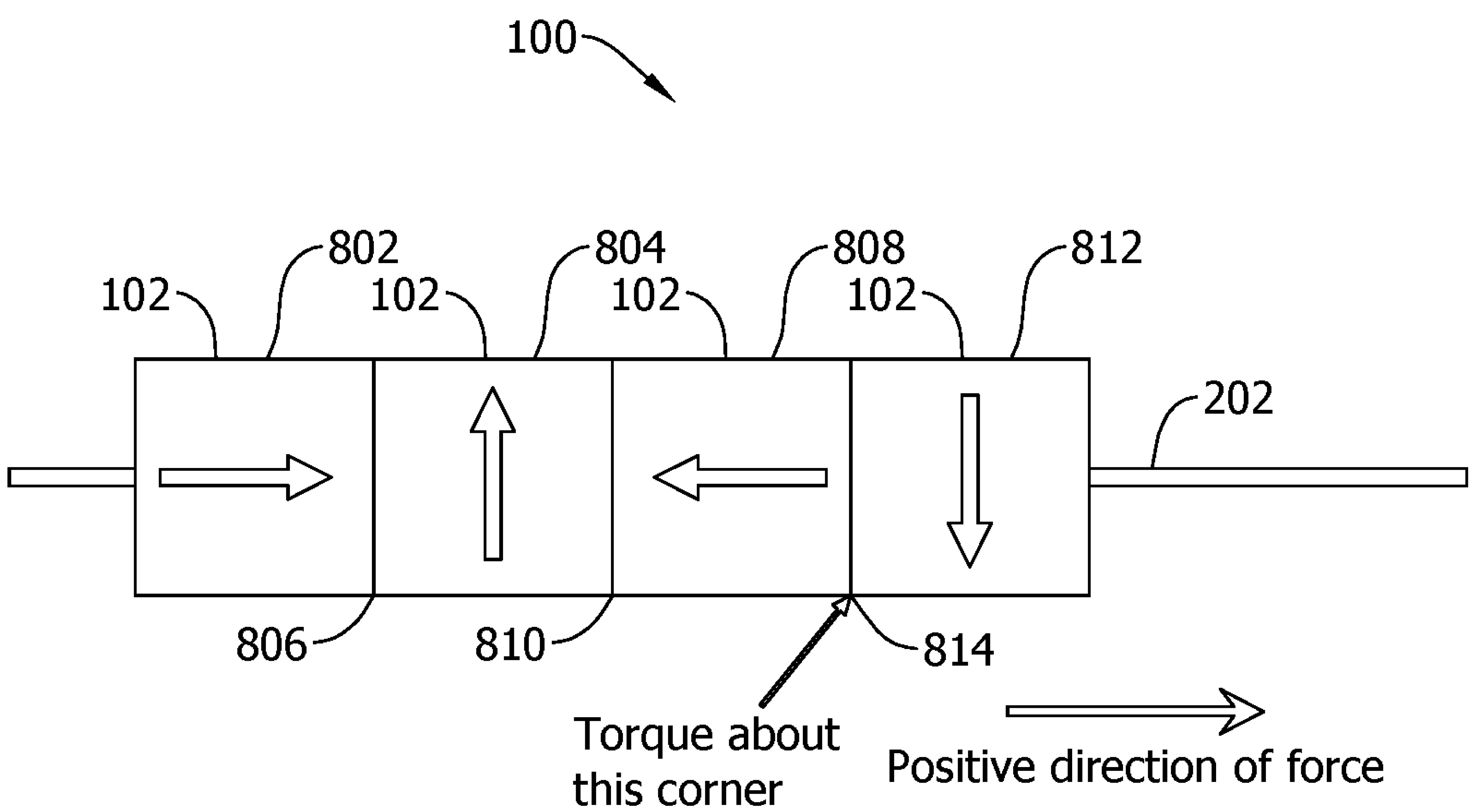

100
802
804
808
812
102
102
102
102
202
806
810
814
Torque about this corner
Positive direction of force

FIG. 14

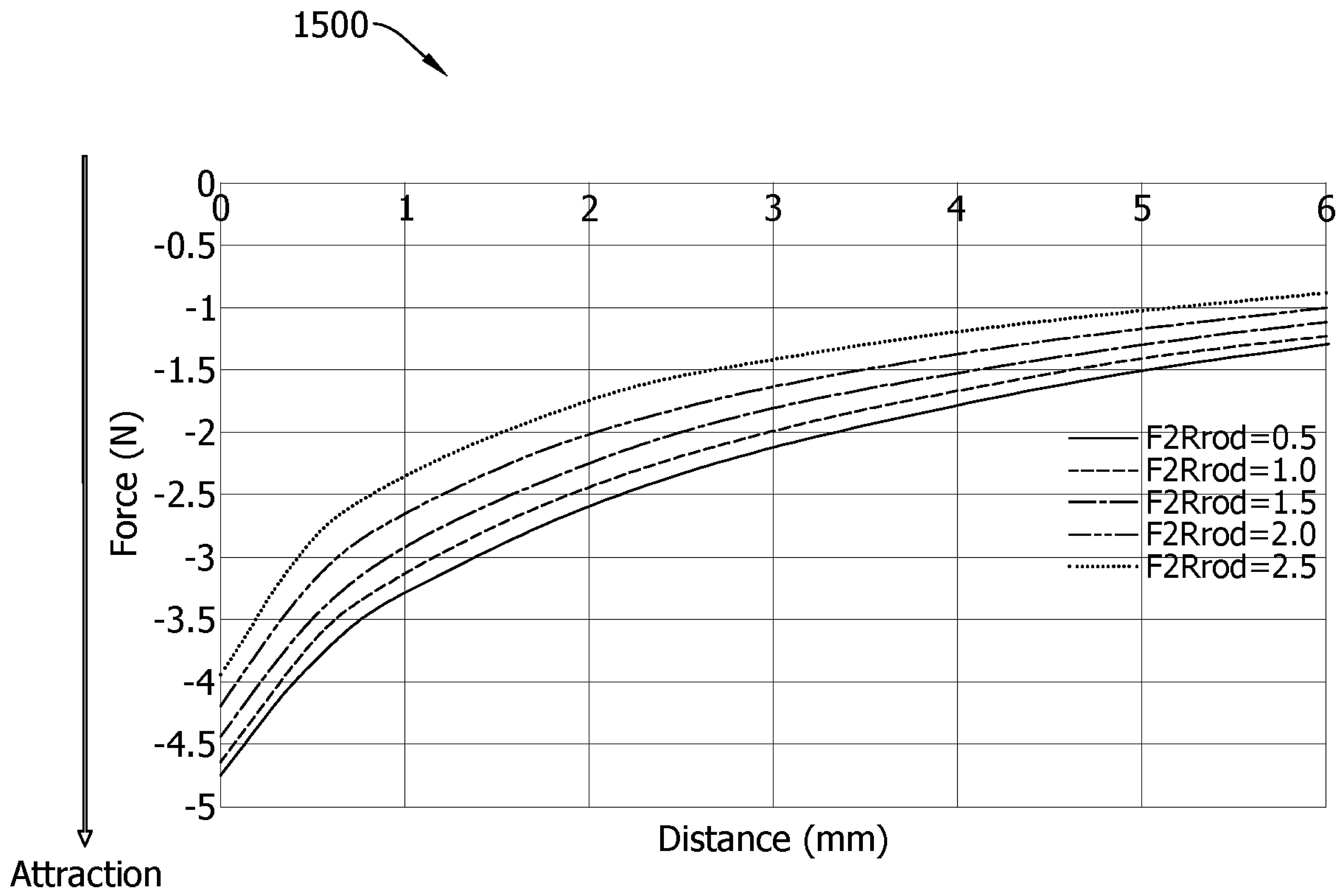

1500
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
Force (N)
0
1
2
3
4
5
6
F2Rrod=0.5
F2Rrod=1.0
F2Rrod=1.5
F2Rrod=2.0
F2Rrod=2.5
Distance (mm)
Attraction

FIG. 15

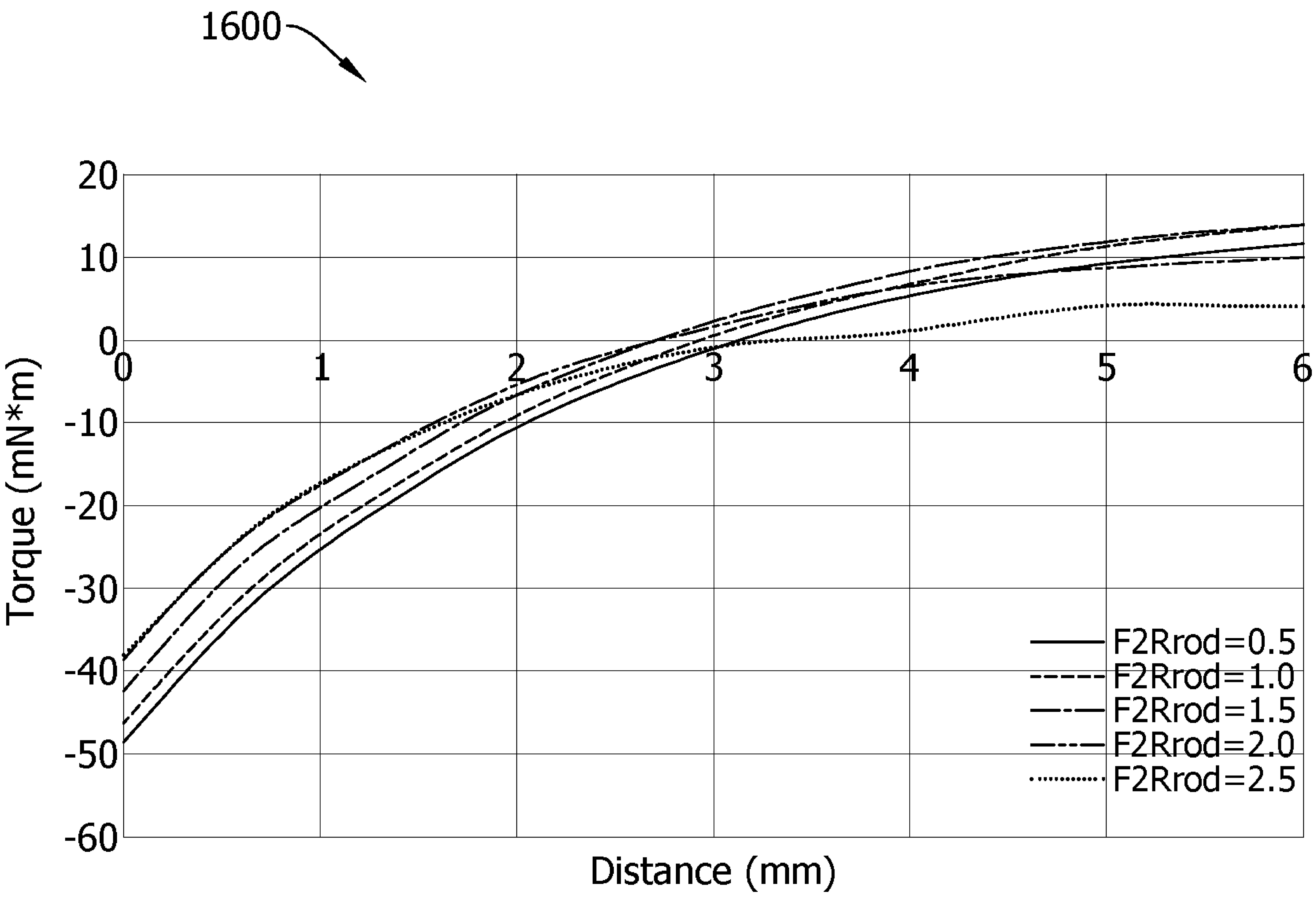

1600
20
10
0
-10
-20
-30
-40
-50
-60
0
1
2
3
4
5
6
Torque (mN*m)
Distance (mm)
F2Rrod=0.5
F2Rrod=1.0
F2Rrod=1.5
F2Rrod=2.0
F2Rrod=2.5

FIG. 16

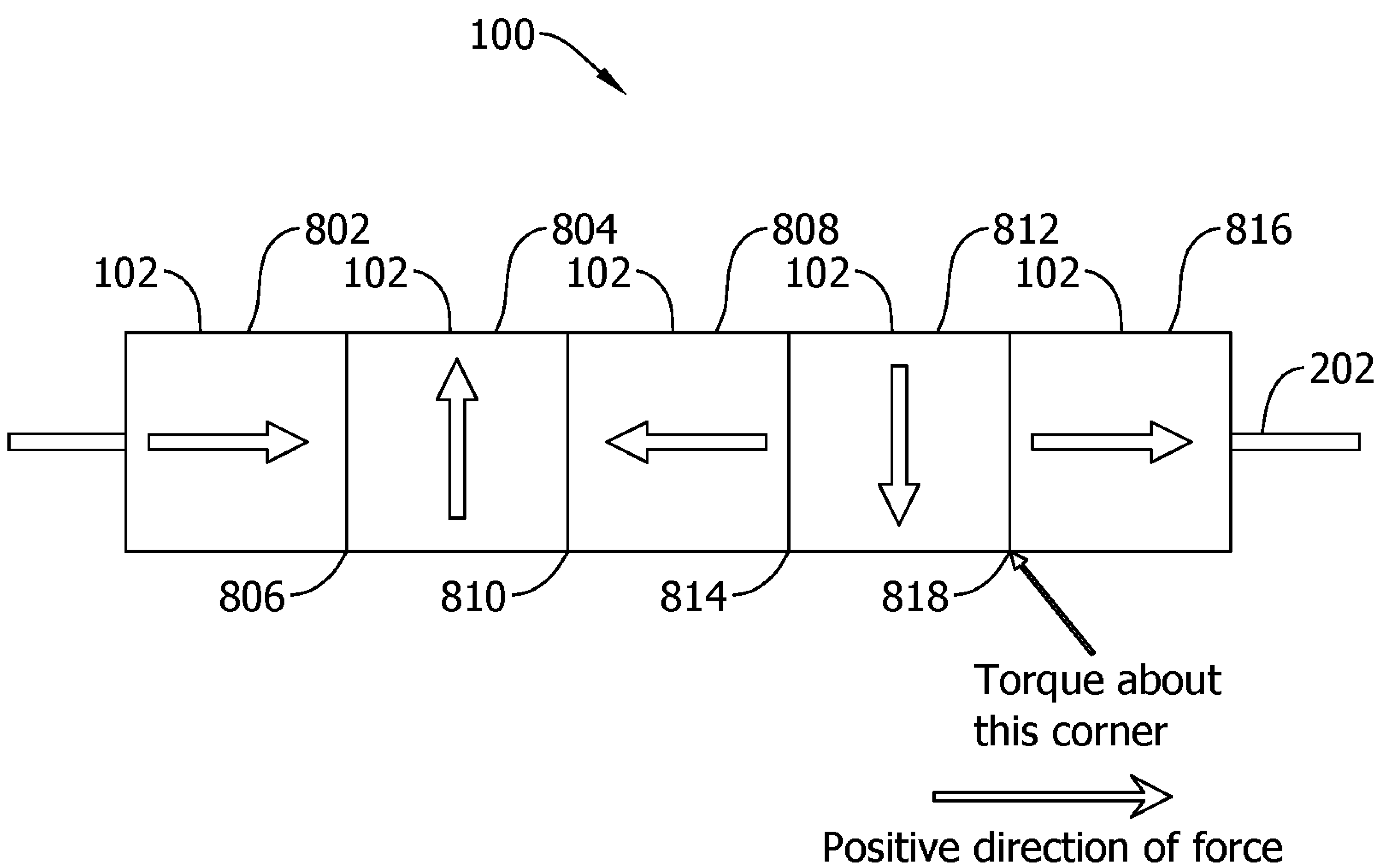

100
102
802
102
804
102
808
102
812
102
816
202
806
810
814
818
Torque about
this corner
Positive direction of force

FIG. 17

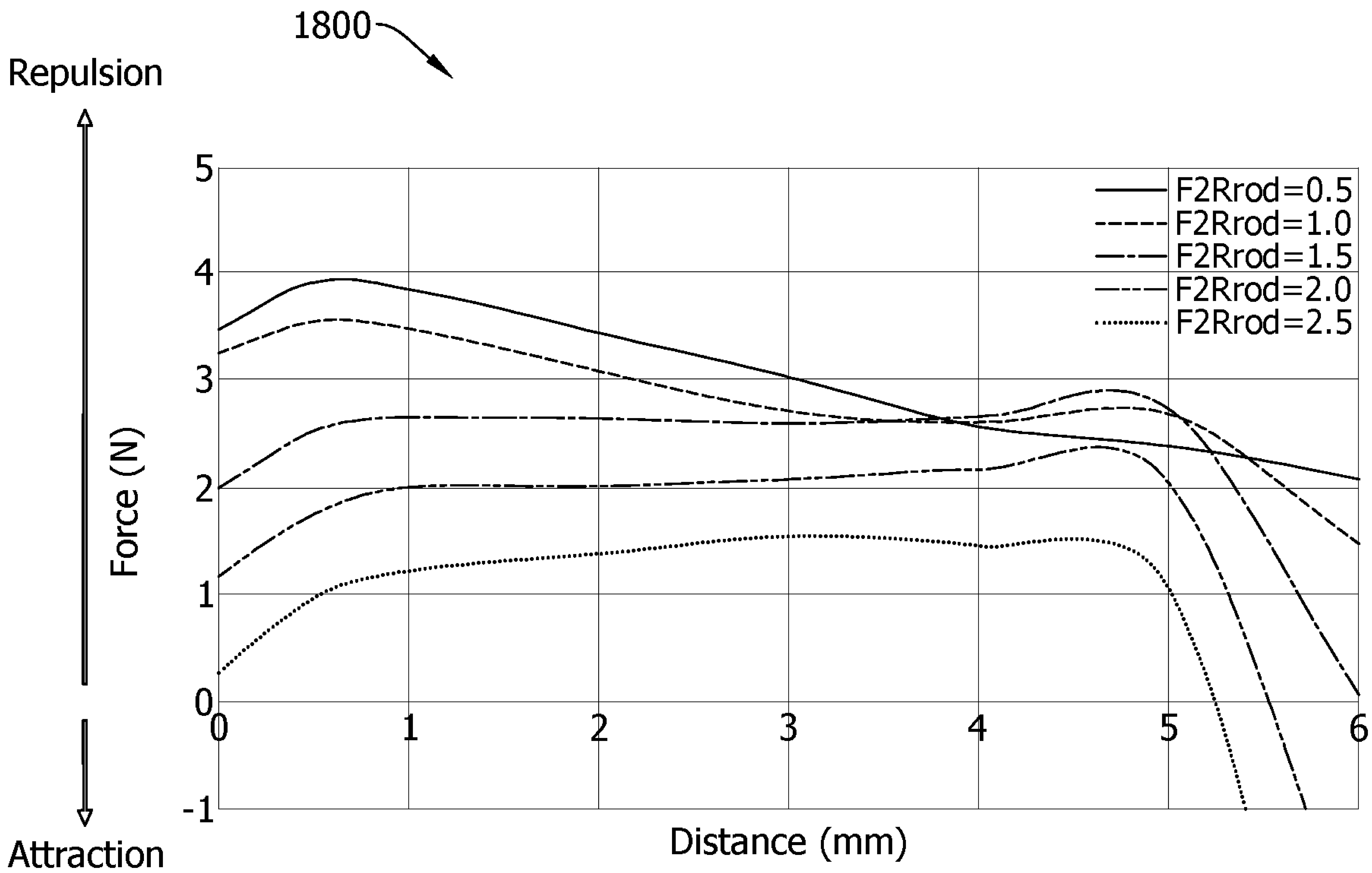

1800
Repulsion
Attraction
Force (N)
Distance (mm)
F2Rrod=0.5
F2Rrod=1.0
F2Rrod=1.5
F2Rrod=2.0
F2Rrod=2.5
5
4
3
2
1
0
-1
0
1
2
3
4
5
6

FIG. 18

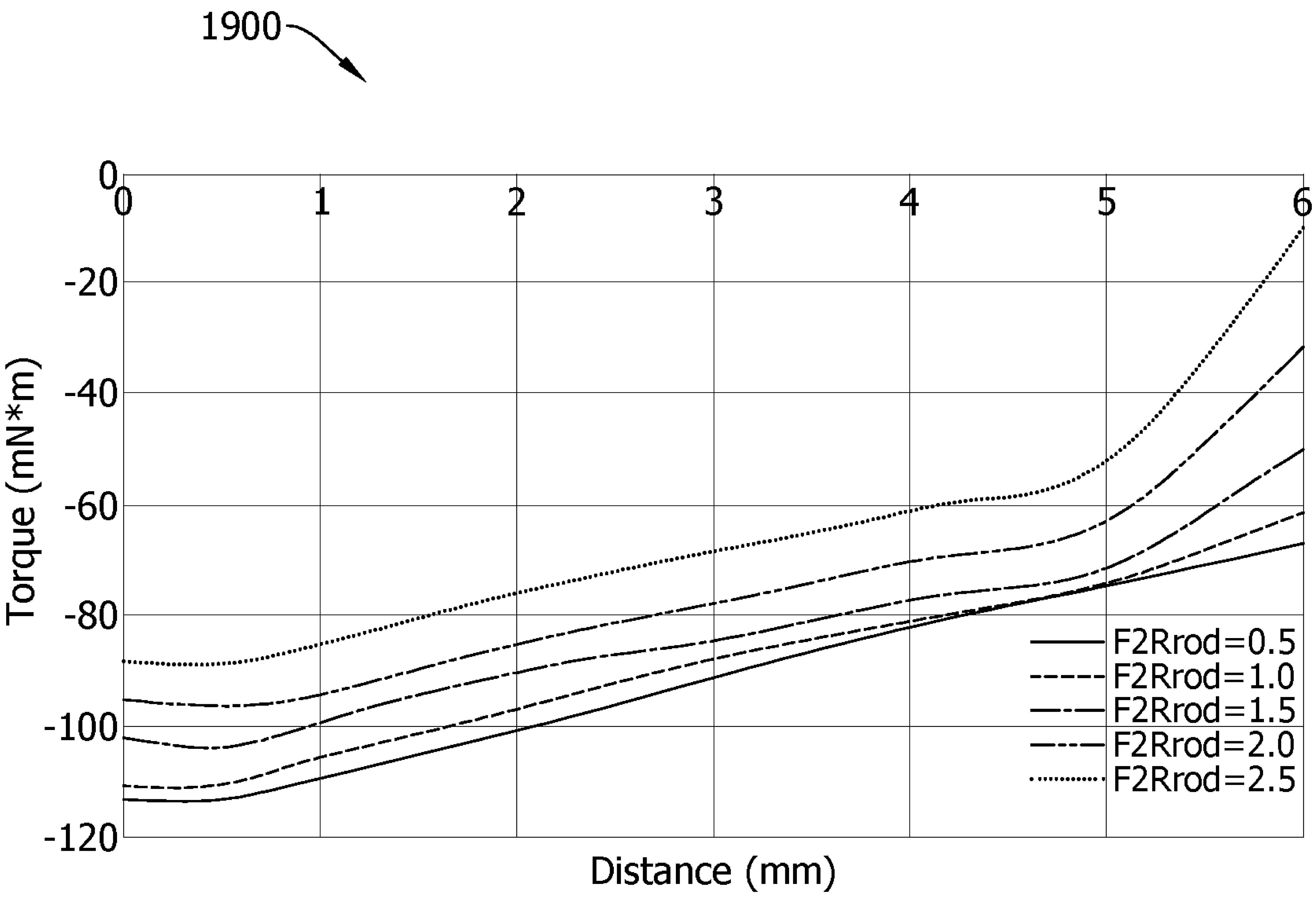

1900
0
-20
-40
-60
-80
-100
-120
0
1
2
3
4
5
6
Torque (mN*m)
Distance (mm)
F2Rrod=0.5
F2Rrod=1.0
F2Rrod=1.5
F2Rrod=2.0
F2Rrod=2.5

FIG. 19

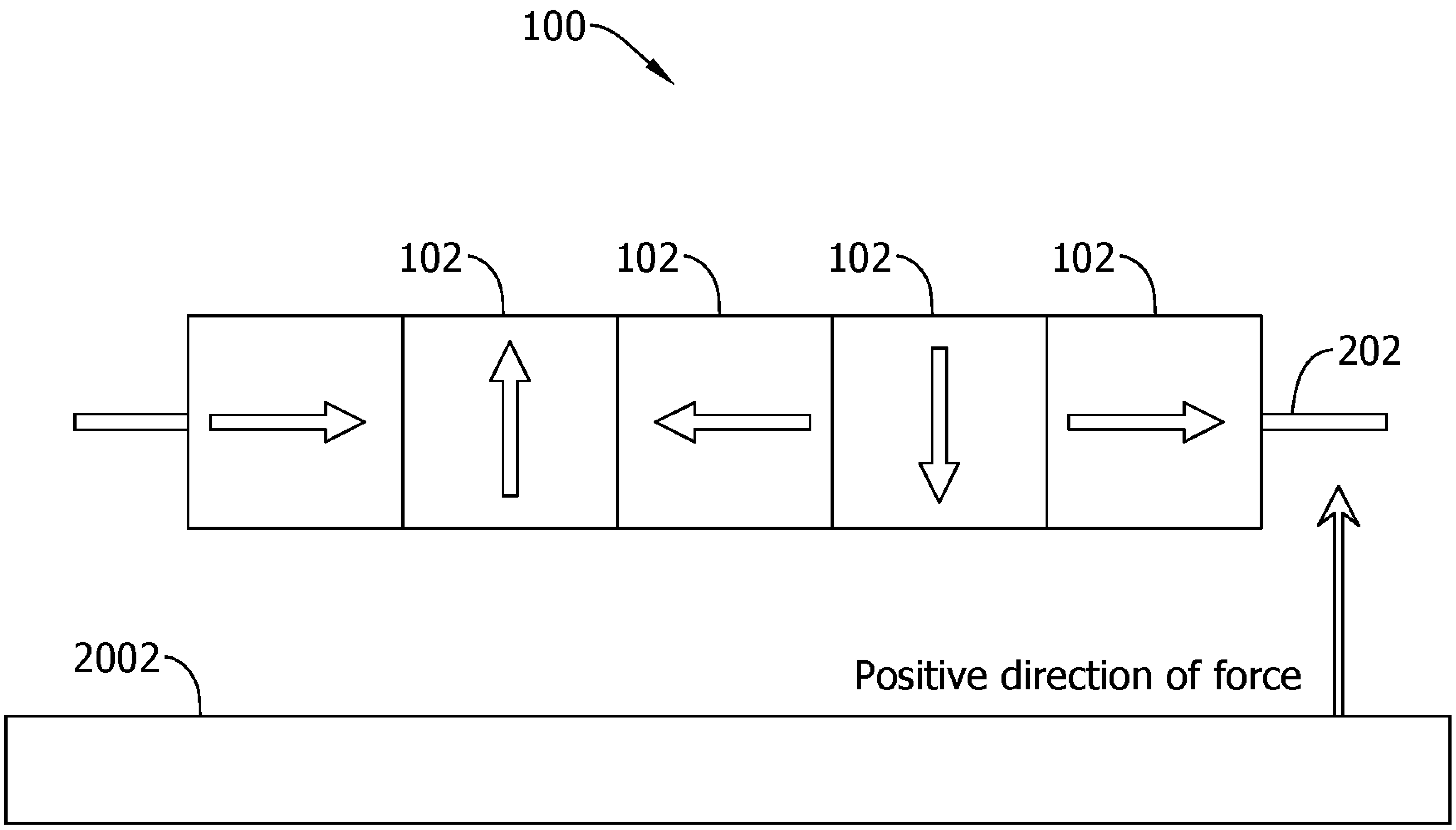
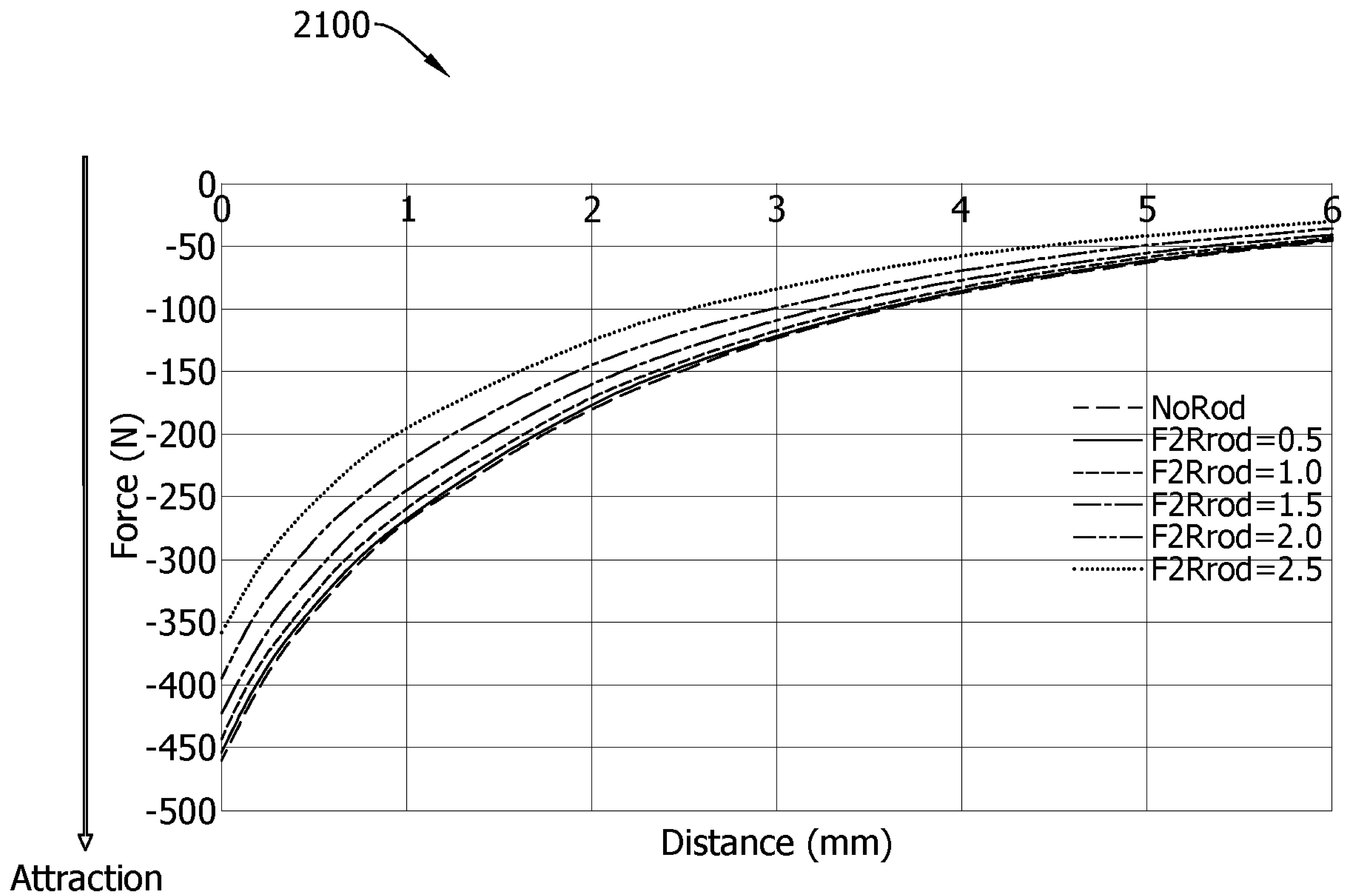


FIG. 20



2100
0
-50
-100
-150
-200
-250
-300
-350
-400
-450
-500
Force (N)
0
1
2
3
4
5
6
Distance (mm)
NoRod
F2Rrod=0.5
F2Rrod=1.0
F2Rrod=1.5
F2Rrod=2.0
F2Rrod=2.5
Attraction

FIG. 21

PERMANENT MAGNETIC ASSEMBLIES AND METHODS OF ASSEMBLING SAME

CROSS-REFERENCE TO RELATED APPLICATION

This application claims priority to U.S. Provisional Patent Application Ser. No. 63/262,428, filed on Oct. 12, 2021, the disclosure of which is hereby incorporated by reference in its entirety.

BACKGROUND

This disclosure is directed to permanent magnetic assemblies, and, more specifically, to permanent magnetic assemblies arranged in a Halbach array.

Permanent magnets include two poles, a north pole and a south pole, and generate magnetic flux lines corresponding to a magnetic field running from the north pole to the south pole. Arrangements of permanent magnets are used to produce different magnetic field patterns for different applications. For example, in a Halbach array, permanent magnets are arranged such that a magnetic field density on one side of the array is substantially greater than that on the other side of the array. This property is useful in various applications, such as in electric motors. Adjacent magnets in a Halbach array experience opposing magnetic forces. These forces produce a torque about a point of rotation in the magnets. As such, an adhesive and/or other means for securing the magnets together is typically used to join the magnets of the Halbach array together and prevent the magnets from repelling away from one another. The addition of the adhesive or other means to secure the magnets together increases the manufacturing cost and complexity of such Halbach arrays, and because adhesive may fail over time, reduces the operating lifetime of the Halbach array. Personnel safety is also a consideration in handling larger magnets when assembling them into an array.

BRIEF DESCRIPTION OF THE DISCLOSURE

In one aspect, a magnetic assembly includes a plurality of magnets arranged in a Halbach array. The Halbach array has a strong side facing a first direction and a weak side facing a second direction opposite the first direction. The plurality of magnets includes a first magnet and a second magnet positioned adjacent the first magnet. The first magnet has a first surface and the second magnet has a second surface adjacent the first surface. At least one first cavity is formed in the first magnet and extends inward from the first surface. At least one second cavity is formed in the second magnet and extends inward from the second surface. The first and second cavities are aligned along a third direction perpendicular to the first direction and the second direction. The magnetic assembly also includes at least one ferromagnetic pin positioned within the at least one first cavity and the at least one second cavity to connect the first magnet and the second magnet. The at least one ferromagnetic pin has a size, a shape, and a magnetic permeability that facilitate a magnetic force between the first surface and the second surface in the third direction inducing a magnetic flux path through the at least one ferromagnetic pin such that an apparent magnetic force in the third direction between the first surface and the adjacent second surface is one of i) a repelling force less than 5 newtons (N) and ii) an attracting force.

In another aspect, a magnetic assembly includes a plurality of magnets arranged in a linear Halbach array. The

Halbach array has a strong side facing a first direction and a weak side facing a second direction opposite the first direction. Each of the plurality of magnets is shaped as a radial arc segment of the Halbach array and has opposing radial end surfaces. An arc length of the Halbach array increases as the Halbach array extends along a longitudinal axis that is oriented perpendicular to the first direction and the second direction. Each of the plurality of magnets has a through-hole defined therein that extends from one radial end surface to the other radial end surface. Each through-hole is longitudinally aligned with a through-hole defined within an adjacent magnet. The magnetic assembly also includes a ferromagnetic pin positioned within each through-hole to connect adjacent magnets. The ferromagnetic pin has a size, a shape, and a magnetic permeability that facilitate a magnetic force between a respective pair of adjacent magnets in the longitudinal direction inducing a magnetic flux path through the ferromagnetic pin such that an apparent magnetic force between each pair of adjacent magnets is one of i) a repelling force less than 5 newtons (N) and ii) an attracting force.

In another aspect, a method of assembling a magnetic assembly including a first magnet and a second magnet arranged in a Halbach array includes selecting a size of a ferromagnetic pin to connect the first magnet and the second magnet. The size of the ferromagnetic pin is selected based on (i) a reduction in a magnetic repelling force between the first magnet and the second magnet resulting from the ferromagnetic pin and (ii) a reduction in a magnetic field strength of the Halbach array resulting from cavities formed in the first magnet and the second magnet to accommodate the ferromagnetic pin having the selected size. The method also includes inserting the ferromagnetic pin having the selected size into cavities in the first magnet and the second magnet to connect the first magnet and the second magnet.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a perspective view of an example magnetic assembly in a partially assembled state.

FIG. **2** is a perspective view of the example magnetic assembly shown in FIG. **1** in an assembled state with a holding pin in position.

FIG. **3** is a perspective view of another example magnetic assembly, illustrated in the form of a 30° section of a 12 section motor. This assembly is a Halbach set from inner radius to outer radius.

FIG. **4** is a perspective view of an example motor assembly that includes the magnetic assembly shown in FIG. **3**.

FIG. **5** is a plan view of another example Halbach magnetic assembly.

FIG. **6** is a sectional view of an example magnet and pins that may be used in the magnetic assembly shown in FIG. **5**.

FIG. **7** is another perspective view of the magnetic assembly shown in FIG. **5**, illustrating internal components of the magnetic assembly.

FIG. **8** is a side elevation view of the example magnetic assembly shown in FIGS. **1** and **2** in a partially assembled state.

FIG. **9** is a graph illustrating the relationship between distance and magnetic force between adjacent magnets in the example magnetic assembly shown in FIG. **8** for rods of varying diameters.

FIG. **10** is a graph illustrating the relationship between distance and torque resulting from magnetic forces between adjacent magnets in the example magnetic assembly shown in FIG. **8** for rods of varying sizes.

FIG. **11** is a side elevation view of the example magnetic assembly shown in FIGS. **1**, **2**, and **8** in a further partially assembled state.

FIG. **12** is a graph illustrating the relationship between distance and magnetic force between adjacent magnets in the example magnetic assembly shown in FIG. **11** for rods of varying diameters.

FIG. **13** is a graph illustrating the relationship between distance and torque resulting from magnetic forces between adjacent magnets in the example magnetic assembly shown in FIG. **11** for rods of varying diameters.

FIG. **14** is a side elevation view of the example magnetic assembly shown in FIGS. **1**, **2**, **8**, and **11** in a further partially assembled state. This depicts Magnet 4 in position adjacent to Magnet 3.

FIG. **15** is a graph illustrating the relationship between distance and magnetic force between adjacent magnets in the example magnetic assembly shown in FIG. **14** for rods of varying diameters.

FIG. **16** is a graph illustrating the relationship between distance and torque resulting from magnetic forces between adjacent magnets in the example magnetic assembly shown in FIG. **14** for rods of varying diameters.

FIG. **17** is a side elevation view of the example magnetic assembly shown in FIGS. **1**, **2**, **8**, **11**, and **14** in an assembled state.

FIG. **18** is a graph illustrating the relationship between distance and magnetic force between adjacent magnets in the example magnetic assembly shown in FIG. **17** for rods of varying sizes and materials.

FIG. **19** is a graph illustrating the relationship between distance and torque resulting from magnetic forces between adjacent magnets in the example magnetic assembly shown in FIG. **17** for rods of varying sizes and materials.

FIG. **20** is a side elevation view of the example magnetic assembly shown in FIG. **17** positioned proximate to a steel plate.

FIG. **21** is a graph illustrating the relationship between distance and magnetic force between the example magnetic assembly shown in FIG. **20** and the steel plate for rods of varying sizes and materials.

DETAILED DESCRIPTION OF THE DISCLOSURE

Magnetic assemblies of the present disclosure provide improved Halbach arrays. For example, magnetic assemblies of the present disclosure include pins or rods of a selected size, shape, and position to join permanent magnets of a Halbach array by reducing or substantially eliminating repelling magnetic forces characteristically present between adjacent magnets of a Halbach array. Accordingly, embodiments of the magnetic assemblies disclosed herein provide a Halbach array that does not require adhesives or other means to join adjacent magnets together, which reduces the cost and complexity of manufacture and extends the operational lifetime of the Halbach array.

As known in the art, the term "Halbach array" refers to an arrangement of permanent magnets that augments magnetic field on one side of the array (also referred to herein as a "strong side" of the array) while reducing the magnetic field on the other side of the array (also referred to herein as a "weak side" of the array) using a spatially rotating pattern of magnetization of the permanent magnets.

In one embodiment, the magnetic assembly includes a plurality of magnets arranged in a Halbach array. The Halbach array has a strong side facing a first direction and

a weak side facing a second direction opposite the first direction. The plurality of magnets includes a first magnet and a second magnet positioned adjacent the first magnet. The first magnet includes a first surface and the second magnet includes a second surface adjacent the first surface. The first magnet includes at least one (one or more than one) first cavity formed in the first surface and extending inward from the first surface. The second magnet includes at least one (one or more than one) second cavity formed in the second surface and extending inward from the second surface. The at least one first cavity and the at least one second cavity are aligned along a third direction that is perpendicular to the first direction and the second direction. The magnetic assembly further includes at least one ferromagnetic pin positioned within the at least one first cavity and the at least one second cavity. The at least one ferromagnetic pin has a size, a shape, and a magnetic permeability sufficient to create a magnetic flux path between the first magnet and the second magnet in the third direction. As described in detail herein, the creation of the magnetic flux path facilitates reducing a repelling magnetic force that otherwise exists between the first magnet and the second magnet in the third direction. The repelling magnetic force may be reduced to within a targeted threshold (e.g., less than 5 newtons (N) of repelling force between the first magnet and the second magnet) or may be reduced such that a net attracting force (e.g., of between 1 N and 10 N) exists between the first magnet and the second magnet in the third direction. By using ferromagnetic pin(s) to reduce, or eliminate, the repelling magnetic force between the first magnet and the second magnet, a need for adhesives to bond the first magnet to the second magnet may be reduced or eliminated. In some embodiments, the magnetic assembly may include any suitable number of additional magnets and ferromagnetic pins similarly arranged, such that a force that exists between each pair of adjacent magnets is reduced to a repelling force within the targeted threshold or transitions to a net attracting force. The Halbach array may be, for example, a linear Halbach array, a cylindrical Halbach array, or another type of Halbach array.

In some embodiments, the ferromagnetic pin(s) are sized, shaped, and have a magnetic permeability sufficient to create at least a minimal net attracting force between magnets within the Halbach array, while making minimal or limited impact on the net magnetic force of the Halbach array on the strong side. In some embodiments, such as relatively large Halbach arrays, multiple smaller ferromagnetic pin(s) may be used to limit or reduce the amount of magnetic material removed from the magnets in order to form the cavities for the ferromagnetic pin(s), while still providing a sufficient flux path to maintain a net attracting force between adjacent magnets. Suitably, the ferromagnetic pin(s) are sized and shaped such that the amount of magnetic material removed from the magnets of the Halbach array to create the cavities for the ferromagnetic pin(s) reduces a magnetic field strength of the Halbach array by 5% or less.

As used herein, the term "magnetic permeability" refers to the ability of a material (e.g., a ferromagnetic material) to support the formation of a magnetic field within the material in response to an applied magnetic field. The magnetic permeability may be measured in henries (H) per meter (m) ($H \cdot m^{-1}$), or equivalently, volt-seconds (V-s) per amperemeters (A-m), or newtons per ampere squared ($N \cdot A^{-2}$). Magnetic permeability is typically represented by the Greek letter μ. Magnetic permeability may also be described in terms of a relative permeability (μ/μ_0), where μ_0 is the permeability of free space ($4\pi \times 10^{-7}$ $H \cdot m^{-1}$).

The magnetic permeability μ of a material can be represented by the equation $\mu=B/H$, where B is the flux density, which may be measured in tesla or $V{\cdot}s{\cdot}m^{-2}$, and H is the magnetizing force of the applied magnetic field (also referred to as the magnetizing field), which may be measured in $A{\cdot}m^{-1}$. The flux density B (also referred to as magnetic flux density or magnetic inductance) is the number of lines of force passing through a unit area of the material. The magnetizing force induces the lines of force through the material. The magnetic permeability of a material therefore governs the magnetic flux able to pass through an object made from the material having a given volume. That is, for objects having the same volumetric shape, objects made from a material having a greater magnetic permeability are able to carry a greater magnetic flux, that is, a greater amount of magnetic flux may pass through the object, in response to the same magnetizing force. The amount of magnetic flux that passes through an object may also be referred to as magnetization of the object. As the material reaches a saturation flux density or a saturation level, an increase in the magnetizing force does not appreciably increase the flux density or the magnetization (although the flux density may continue to increase at a significantly smaller rate due to paramagnetism). The saturation flux density is a magnetic characteristic of a material and changes between materials (e.g., changes between different ferromagnetic materials).

As used herein, the terms "ferromagnetic" or "ferromagnetic material" refer to a material having a magnetic permeability that enables the material to be magnetized in response to an applied magnetic field. This may be due to the presence of unpaired electrons. Non-limiting examples of ferromagnetic materials include iron, nickel, cobalt, alloys of one or more of these elements, ferritic stainless steel, and low carbon steel.

As used herein, the term "permanent magnet" refers to a material that creates a persistent magnetic field in the absence of an externally applied magnetic field. Ferromagnetic materials may also be permanent magnets. Non-limiting examples of permanent magnets include samarium cobalt magnets, neodymium magnets, alnicos (iron alloys that include aluminum, nickel, and cobalt), and ceramic magnets (ferrites).

Unless otherwise indicated, approximating language, such as "generally," "substantially," and "about," as used herein indicates that the term so modified may apply to only an approximate degree, as would be recognized by one of ordinary skill in the art, rather than to an absolute or perfect degree. Accordingly, a value modified by a term or terms such as "about," "approximately," and "substantially" is not to be limited to the precise value specified. In at least some instances, the approximating language may correspond to the precision of an instrument for measuring the value. Additionally, unless otherwise indicated, the terms "first," "second," etc. are used herein merely as labels, and are not intended to impose ordinal, positional, or hierarchical requirements on the items to which these terms refer. Moreover, reference to, for example, a "second" item does not require or preclude the existence of, for example, a "first" or lower-numbered item or a "third" or higher-numbered item.

FIGS. **1** and **2** illustrate an example magnetic assembly **100** including a plurality of magnets **102** arranged in a linear Halbach array along an axis **104**. Each magnet **102** has a north-south polarity, indicated by an arrow shown on each magnet **102**, with the arrow pointing from a south pole **106** towards a north pole **108** of each magnet **102**. The magnetic field generally runs from south pole **106** to north pole **108** of each magnet **102**, and a combined magnetic field of magnets **102** is formed by superimposing the magnetic field of each magnet **102**. Magnets **102** are arranged with a rotating pattern of magnetization, such that an axis of polarization of each magnet **102** is shifted or alternated with respect to adjacent magnets **102**, for example, by 90 degrees, about an axis perpendicular to axis **104**. Due to this arrangement, a magnetic field density on one side **110** (the lower side as shown in FIG. **1** and upper side as shown in FIG. **2**, also referred to herein as the "strong side") is significantly greater than the magnetic field density on the other side **112** (the upper side as shown in FIG. **1** and the lower side as shown in FIG. **2**, also referred to herein as the "weak side"). The first side **110** and the second side **112** face opposite directions, irrespective of an orientation of the magnetic assembly **100**. In some embodiments, for example, there is no substantial magnetic field on weak side **112** of magnetic assembly **100**.

As shown in FIG. **2**, magnetic assembly **100** further includes at least one ferromagnetic rod or pin **202**. In certain embodiments, the ferromagnetic pin **202** is formed of a ferromagnetic material selected from the group consisting of ferritic stainless steel, low carbon steel, and iron-cobalt alloys. The ferromagnetic pin **202** extends through a geometric center of each of the magnets **102** and through the entirety of the magnetic assembly **100**. Cavities **114** are formed in the center of each magnet **102** and the cavities **114** of adjacent magnets **102** align along the axis **104** and receive the pin **202**. As shown in FIGS. **1** and **2**, the example magnetic assembly **100** is a linear Halbach array with the aligning cavities **114** of the magnets **102** forming a linearly-extending through-hole in the magnetic assembly **100** along the axis **104**, and the ferromagnetic pin **202** also extends linearly through the through-hole.

The magnets **102** are suitably permanent magnets that each create a persistent magnetic field to enable the magnetic assembly **100** to function as described herein. Non-limiting examples of permanent magnets used as the magnets **102** include samarium cobalt magnets, neodymium magnets, alnicos (iron alloys that include aluminum, nickel, and cobalt), and ceramic magnets (ferrites). In certain embodiments, the magnets **102** are permanent rare earth magnets selected from the group consisting of samarium cobalt magnets and neodymium magnets. Various grades of permanent magnets **102** may be used, and may be selected based on desired magnetic properties of the magnets **102**. For example, in some instances, permanent magnets **102** may be demagnetized over time by magnetic interaction with the magnetic fields of adjacent magnets **102**. Demagnetization may be exacerbated at increased temperatures that may be experienced by the magnets **102** in operation of the magnetic assembly **100**. Certain grades of rare earth permanent magnets now known or subsequently developed that improve resistance to demagnetization may suitably be utilized as the permanent magnets **102**.

Suitably, the ferromagnetic pin **202** has a magnetic permeability that enables magnetization of the ferromagnet pin **202** at locations between adjacent magnets **102**. The magnetic permeability is dependent on the ferromagnetic material utilized for the ferromagnetic pin **202**. Non-limiting examples of ferromagnetic materials suitable for used as the ferromagnetic pin **202** include iron, nickel, cobalt, alloys of one or more of these elements, ferritic stainless steel, and low carbon steel. In certain embodiments, the ferromagnetic pin **202** is made from a ferromagnetic material selected from the group consisting of ferritic stainless steel, low carbon steel, and iron-cobalt alloys.

In Halbach arrays, such as the magnetic assembly **100**, the adjacent magnets **102** create a repelling magnetic force therebetween. The direction of the repelling magnetic force between adjacent magnets **102** is substantially perpendicular to the direction of the strong side **110** and the weak side **112** of the magnetic assembly **100**, and may causes translational and/or rotational movement of the adjacent magnets **102** relative to the axis **104**. The ferromagnetic pin **202** extends between adjacent magnets **102** in the direction of the repelling magnetic force, and the magnetic permeability of the ferromagnetic pin **202** enables the repelling magnetic force to induce a magnetic flux that passes through the ferromagnetic pin **202**. Thereby, a magnetic flux path is created in the ferromagnetic pin **202**.

The amount of magnetic flux that is able to pass through the ferromagnetic pin **202** depends on the magnetic permeability of the ferromagnetic pin **202**, which correlates to the flux density, as well as the volumetric shape of the pin **202**, which controls the cross-sectional area through which the magnetic flux passes. In certain embodiments, the ferromagnetic pin **202** is a cylinder or is prism-shaped (e.g., a rectangular prism, a triangular prism, or other polygonal prism), with a suitable length to extend through the entirety of the magnetic assembly **100**. The ferromagnetic pin **202** is not limited to cylinders or prism shapes and may have any elongate shape, for example any elongate shape that has a substantially constant cross-section along a central region. The volume of the ferromagnetic pin **202** may be controlled by adjusting the cross-sectional area (e.g., the diameter for cylindrical ferromagnetic pins **202**). As the cross-sectional area of the ferromagnetic pin **202** increases, at a constant magnetic permeability, a greater magnetic flux may pass through the pin **202**. However, as the cross-sectional area of the ferromagnetic pin **202** increases, the amount of magnetic material that is removed from each magnet **102** to form the cavities **114** also increases. That is, the cavities **114** define a void space volume in the magnetic assembly, and the absence of magnetic material in these areas reduces a magnetic field strength of the magnetic assembly **100**. Suitably, the ferromagnetic pin **202** is sized (e.g., has a cross-sectional area) such that the magnetic material removed from the magnets **102** (i.e., the void space volume created in the magnetic assembly **100**) reduces a magnetic field strength of the magnetic assembly **100** by 5% or less. The percent reduction of the magnetic field strength of the magnetic assembly **100** is determined as the magnetic field strength at the strong side **110** relative to the magnetic field strength at the strong side for an assembly without the cavities **114** in the magnets **102**. To balance the size restrictions on the ferromagnetic pin **202**, ferromagnetic materials having a greater magnetic permeability may be utilized to increase the flux density of the pin **202**.

In some embodiments, such as that shown in FIGS. **1** and **2**, the ferromagnetic pin **202** is cylindrical. Each magnet **102** includes a cavity **114** sized and shaped to receive a portion of the ferromagnetic pin **202** therein. In the illustrated embodiment, each cavity **114** is a through-hole **114** that extends entirely through the magnet **102** between opposing surfaces **116** of the magnet **102** that each face an adjacent surface **116** of an adjacent magnet **102** when the magnetic assembly **100** is assembled. In other embodiments, instead of forming a through-hole, a cavity **114** may be formed in each opposing surface **116** of the magnet **102** that faces an adjacent surface **116** of an adjacent magnet **102**, and the cavities **114** extend inward from the respective surface **116** and terminate at a bulk, solid region interposed between and separating the cavities **114** in the respective magnet **102**. In the illustrated embodiment, a single cavity **114** is formed in each magnet **102** at the opposing surfaces **116**. In other embodiments, multiple cavities **114** may be formed in each surface **116** that faces an adjacent surface **116** of an adjacent magnet **102**. The multiple cavities **114** may form multiple through-holes **114** with the cavities formed at the opposing surface **116** of the magnet **102**, or may be separated by a solid region of the magnet **102**.

When the magnetic assembly **100** is assembled, the through-hole **114** of each magnet **102** aligns along the linear axis **104** with the through-hole **114** of an adjacent magnet **102**. The ferromagnetic pin **202** is at least partially disposed in each through-hole **114** of the magnets **102**. For example, as shown in FIG. **2**, the magnets **102** may be aligned to enable pin **202** to extend linearly though each respective through-hole **114** along the axis **104**. That is, in the embodiment of FIGS. **1** and **2**, a single ferromagnetic pin **202** extends through every magnet **102** in the magnetic assembly **100**. In other embodiments, magnetic assembly **100** may include a plurality of ferromagnetic pins **202**, where each ferromagnetic pin **202** extends into the cavity **114** of two adjacent magnets **102** (see, e.g., FIGS. **5**-**7**). In embodiments where multiple ferromagnetic pins **202** are used, the magnetic permeability and/or volumetric shape of each ferromagnetic pin **202** may be suitably selected to enable the magnetic assembly **100** to function as described herein and, in particular, to facilitate reducing or eliminating the magnetic repelling force between adjacent magnets **102** in a direction perpendicular to the strong side **110** and the weak side **112**.

In the absence of the ferromagnetic pin **202**, the magnets **102** arranged in a Halbach array that are adjacent one another (e.g., meeting or adjoining at an adjacent surface **116**) magnetically repel one another. Magnetic repelling forces between the adjacent magnets **102** cause translational and/or rotational displacement of the magnets **102** relative to the axis **104**. The ferromagnetic pin **202** is suitably sized and shaped (i.e., has a suitable volumetric shape) and has a suitable magnetic permeability such that a repelling magnetic force between adjacent magnets **102** is reduced or eliminated entirely (i.e., resulting in an attracting force between adjacent magnets **102**). Specifically, the magnetic permeability of the ferromagnetic pin **202** enables the repelling magnetic force between adjacent magnets **102** to induce a magnetic flux that passes through the ferromagnetic pin **202** between the adjacent magnets **102**. The induction of the magnetic flux path in the ferromagnetic pin **202** reduces the apparent magnetic force between the adjacent magnets. The magnetic permeability and the volumetric shape control the amount of magnetic flux able to pass through the ferromagnetic pin **202** between adjacent magnets **102**, and are suitably selected so that the amount of magnetic flux induced in the ferromagnetic pin **202** causes a sufficient reduction in the apparent magnetic force between the adjacent magnets such that the repelling force is reduced, in some embodiments, to less than 5 N or transitions to an attracting force. In embodiments, where the apparent force between adjacent magnet **102** is a reduced repelling force, the repelling force may be less than 5 N, less than 4 N, less than 3 N, less than 1 N, less than 9 N, about 5 N, about 4 N, about 3 N, about 2 N, about 1 N, such as between 1 N and 5 N. In embodiments, where the apparent force between adjacent magnet **102** transitions to an attracting force, the attracting force may be greater than 1 N, greater than 3 N, greater than 5 N, greater than 7 N, greater than 9 N, about 1 N, about 2 N, about 3 N, about 4 N, about 5 N, about 6 N, about 7 N, about 8 N, about 9 N, about 10 N, such as between 1 N and 10 N.

Reference made herein to attracting and repelling force is expressed as an absolute value, and it will be understood that a repelling force and an attracting force having equivalent absolute values reflects an equivalence between the magnitude of the forces, not an equivalence between the direction and/or orientation of the forces.

As such, when the magnets **102** are arranged on the ferromagnetic pin **202**, with the ferromagnetic pin **202** extending through the aligning through-holes **114** of the magnets **102**, the repelling magnetic force between magnets **102** is reduced or eliminated which enables the magnetic assembly **100** to be held in a desired shape and alignment (i.e., without substantial translation and/or rotation of the magnets **102** relative to the axis **104**). Thereby, the ferromagnetic pin **202** facilitates reducing or eliminating the need for adhesives and/or mechanical devices (e.g., clamps) that are otherwise used to hold the magnetic assembly **100** together. In the absence of adhesives, the adjacent surface **116** of adjacent magnets **102** are in face-to-face contact. While a presence of the ferromagnetic pin **202** may reduce or eliminate a need for adhesives and other mechanical devices to hold the assembly **100**, in some embodiments, adhesives are applied to adjacent surfaces **116** to further strengthen bonding between magnets **102**. The through-holes **114** and the ferromagnetic pin **202** may also be suitably sized and shaped to create an interference fit that holds each magnet **102** on the ferromagnetic pin **202**. Additionally or alternatively, the presence of the ferromagnetic pin **202** may enable the magnets **102** to be held in place on the ferromagnetic pin **202** due to the torque produced by a repelling force that may remain, albeit reduced, between the adjacent magnets **102**. Specifically, the repelling force between adjacent magnets **102** may urge or bias one of the adjacent magnets **102** in a rotational direction, creating increased interference between the pin **202** and the magnet **102**, holding the torqued magnet **102** in place.

The size and shape (i.e., the volumetric shape) of the ferromagnetic pin **202** that enables such a reduction in repelling magnetic force depends on factors such as the magnetic permeability of the pin **202**, the magnetic properties of magnets **102**, an overall arrangement of magnetic assembly **100**, a presence of other objects in proximity to magnetic assembly **100** that may affect its magnetic field, and the position of the pin **202** between adjacent magnets **102**. The saturation flux density of the ferromagnetic pin **202** is also suitably greater than the flux density required to be induced in the ferromagnetic pin **202** in order to facilitate reducing the repelling magnetic force between adjacent magnets. In view of these considerations, for a given magnetic assembly **100**, a shape, size, and position for the ferromagnetic pin **202** may be determined by analyzing (e.g., using finite element analysis) the forces present in the magnetic assembly **100** for a number of differently size, shape, and position combinations, for ferromagnetic pins **202** having the same and/or different magnetic permeabilities, and identifying one or more combinations that satisfy the operating requirements of magnetic assembly **100**, such as those that minimize or reduce below a threshold the repelling force between adjacent magnets **102**. Details of such a determinations are described elsewhere herein.

FIG. **3** illustrates another example magnetic assembly **300**. Like magnetic assembly **100** shown in FIGS. **1** and **2**, magnetic assembly **300** is a linear Halbach array. Magnetic assembly **300** includes magnets **102** and at least one ferromagnetic pin **202**, which generally function as described with respect to FIGS. **1** and **2**. In the embodiment shown in FIG. **3**, magnets **102** are shaped as radial arc segments with arc lengths that progressively increase along axis **302**, such that, together, magnets **102** define a wedge shape. Adjacent magnets **102** are connected by the ferromagnetic pin **202** extending through aligning through-holes defined in each magnet **102** and extending between the radial end surfaces **116** of each magnet **102**. The adjacent radial end surfaces **116** of adjacent magnets **102** may be in face-to-face contact. The through-hole defined in each of the magnets **102** may extend through a center of each radial end surface **116** of the respective magnet **102**. In some embodiments, one or more of the pairs of the adjacent magnets **102** in the magnetic assembly **300** has multiple pairs of aligning through-holes defined in each of the pair of adjacent magnets **102**, and each pair of aligning through-holes has a ferromagnetic pin **202** positioned therein to connect the pair of adjacent magnets **102**. As shown in FIG. **4**, a plurality of magnetic assemblies **300** may be arranged into a motor assembly **400** forming an upper disk **402** and a lower disk **404** from magnetic assemblies **300**. More specifically, each of upper disk **402** and lower disk **404** may be formed by positioning a plurality of magnetic assemblies **300** adjacent one another along circumferential ends of each magnetic assembly **300** to form a disk. By positioning each magnetic assembly **300** with its respective strong side **110** oriented toward a central space between upper disk **402** and lower disk **404**, a magnetic field may be substantially contained within the space between upper disk **402** and lower disk **404**. Motor assembly **400** may be used in, for example, an electric motor, an alternator, or another rotating electric device. In the illustrated embodiment, each of the upper disk **402** and the lower disk **404** of the motor assembly **400** includes 12 Halbach sets or assemblies **300**. Each assembly **300** of the upper disk **402** is aligned with an assembly **300** of the lower disk **404**, with the strong sides **110** of aligning assemblies **300** oriented toward each other. In other embodiments, each of the upper disk **402** and the lower disk **404** of the motor assembly **400** may include greater than or fewer than 12 Halbach sets or assemblies **300**. The upper disk **402** and the lower disk **404** include the same number of Halbach sets or assemblies **300**, or may include a different number of Halbach sets or assemblies **300**.

FIGS. **5-7** illustrate another example magnetic assembly **500** including a plurality of magnets **102** and a plurality of ferromagnetic pins **202**. In this embodiment, magnets **102** are arranged as a cylindrical or circular Halbach array centered around an axis **502**. As indicated by an arrow shown on each magnet **102**, the polarity of each magnet **102** is rotated with respect to adjacent magnets **102** about an axis parallel to axis **502**. The magnetic field of magnetic assembly **500** is largely contained within a region radially inward of strong side **110** of magnetic assembly **500**. As shown in FIG. **6**, each magnet **102** of magnetic assembly **500** is shaped as a radial arc segment, having two flat end surfaces **504** (i.e., at circumferential ends of the arc-shaped magnet **102**). Each magnet **102** of magnetic assembly **500** includes two cavities **602**. Each cavity **602** of a magnet **102** extends perpendicularly inward into the magnet **102** from one of the flat end surfaces **504**. Each cavity **602** is sized and shaped to receive at least a portion of a respective pin **202** therein. In the embodiment illustrated in FIGS. **5-7**, each ferromagnetic pin **202** has a length that is approximately equal to or less than twice the length of each cavity **602** such that, when assembled, one end of the ferromagnetic pin **202** is received in the cavity **602** of a first magnet **102**, and the other end of the ferromagnetic pin **202** is received within the cavity **602** of a second magnet **102** that adjoins or abuts the first magnet **102** along end surface **504**. Each cavity **602** of a magnet **102** aligns with a cavity **602** of an adjacent magnet **102** to facilitate a ferromagnetic pin **202** being received by each of a pair of adjacent cavities **602**. As shown in FIG. **7**, when assembled, magnets **102** are arranged in a circular array with flat end surfaces **504** of each magnet **102** adjoining or being positioned adjacent to flat end surfaces **504** of adjacent magnets **102**. Each ferromagnetic pin **202** is positioned within cavities **602** of adjacent magnets **102** such that the ferromagnetic pin **202** extends from the cavity **602** defined in a first magnet **102** to the cavity **602** defined in a second magnet **102** adjoining or adjacent to the first magnet **102**. As with the embodiments shown in FIGS. **1-3**, the ferromagnetic pins **202** of magnetic assembly **500** are suitably sized and shaped and have a suitable magnetic permeability to reduce a magnetic repelling force between adjacent magnets **102**, while minimizing the loss of magnetic material of the magnetic assembly **500**.

Specific parameters (size, shape, and magnetic strength) of the magnetic assemblies of the present disclosure can vary based on the intended use or application of the Halbach array. Halbach arrays can be very small (millimeters in diameter or length) to very large (many meters in diameter or length). The magnets used in such Halbach arrays can be, for example and without limitation, cubes, rectangles or arc segments in geometrical shape. Exemplary applications of Halbach arrays of the present disclosure include, for example and without limitation windmill turbines, electric marine applications, MRI machines, electric vehicles, and medical implant components (e.g., magnetic couplings, high efficiency, light weight electric motors).

FIGS. **8-21** illustrate steps in an example analysis (e.g., finite element analysis) used to determine parameters (e.g., size and material) for the pin used in magnet assembly to reduce or eliminate magnetic forces between adjacent magnets.

FIG. **8** is a side view of magnetic assembly **100** (shown in FIG. **1**) in a partially assembled state. As shown in FIG. **8**, magnetic assembly **100** includes a first magnet **802** and a second magnet **804** arranged in a two-magnet linear Halbach array along pin **202**. FIG. **9** is a graph **900** illustrating the relationship between distance and magnetic force between adjacent magnets in the example magnetic assembly shown in FIG. **8** for cylindrical ferromagnetic pins **202** of varying diameters. More specifically, FIG. **9** illustrates the relationship between the distance between first magnet **802** and second magnet **804** (in millimeters, mm) and the magnetic force between first magnet **802** and second magnet **804** (in newtons, N) along an axis of the ferromagnetic pin **202**. The relationship is shown for a plurality of different ferromagnetic pin diameters (0.5 millimeters, 1.0 millimeters, 1.5 millimeters, 2.0 millimeters, and 2.5 millimeters). FIG. **10** is a graph **1000** illustrating the relationship between distance and torque resulting from magnetic forces between adjacent magnets **102** in the example magnetic assembly **100** shown in FIG. **8**. More specifically, FIG. **10** illustrates the relationship between the distance between first magnet **802** and second magnet **804** in millimeters (mm) and a torque in millinewton meters (mN·m) along a point **806** (shown in FIG. **8**) located at a corner of first magnet **802** adjoining second magnet **804**. The relationship is shown for the same ferromagnetic pin diameters as shown in FIG. **9**.

As described in further detail herein, in some embodiments, the thickness or diameter of the ferromagnetic pin **202** is selected to reduce a repelling magnetic force or increase an attracting magnetic force between magnets **102**. This selection may be balanced with selection of the ferromagnetic material of the pin **202** which determines the magnetic permeability of the pin **202**.

FIG. **11** is a side view of magnetic assembly **100** (shown in FIG. **1**) in a further partially assembled state. More specifically, magnetic assembly **100** is shown in FIG. **11** with a third magnet **808** positioned adjacent to the second magnet **804**. FIG. **12** is a graph **1200** illustrating a relationship between a distance between second magnet **804** and third magnet **808** in millimeters and a magnetic force between second magnet **804** and third magnet **808** in newtons (N) along an axis of the ferromagnetic pin **202**. The relationship is shown for the same ferromagnetic pin diameters as shown in FIG. **9**. FIG. **13** is a graph **1300** illustrating a relationship between the distance between second magnet **804** and third magnet **808** in millimeters (mm) and a torque in millinewton meters (mN·m) along a point **810** (shown in FIG. **11**) located at a corner of second magnet **804** adjoining third magnet **808** resulting from magnetic forces between the adjacent magnets **804** and **808**. The relationship is shown for the same ferromagnetic pin diameters as shown in FIG. **9**.

FIG. **14** is a side view of magnetic assembly **100** (shown in FIG. **1**) in a further partially assembled state. More specifically, magnetic assembly **100** is shown in FIG. **14** with a fourth magnet **812** positioned adjacent to third magnet **808**. FIG. **15** is a graph **1500** illustrating a relationship between a distance between third magnet **808** and fourth magnet **812** in millimeters and a magnetic force between third magnet **808** and fourth magnet **812** in newtons (N) along an axis of the ferromagnetic pin **202**. The relationship is shown for the same ferromagnetic pin diameters as shown in FIG. **9**. FIG. **16** is a graph **1600** illustrating the relationship between a distance between third magnet **808** and fourth magnet **812** in millimeters (mm) and a torque in millinewton meters (mN·m) along a point **814** (shown in FIG. **14**) located at a corner of third magnet **808** adjoining fourth magnet **812** resulting from magnetic forces between the adjacent magnets **808** and **812**. The relationship is shown for the same ferromagnetic pin diameters as shown in FIG. **9**.

FIG. **17** is a side view of magnetic assembly **100** (shown in FIG. **1**) in a further partially assembled state. More specifically, magnetic assembly **100** is shown in FIG. **17** with a fifth magnet **816** positioned adjacent to fourth magnet **812**. FIG. **18** is a graph **1800** illustrating a relationship between a distance between fourth magnet **812** and fifth magnet **816** in millimeters and a magnetic force between fourth magnet **812** and fifth magnet **816** in newtons (N) along an axis of the ferromagnetic pin **202**. The relationship is shown for the same pin diameters as shown in FIG. **9**. FIG. **19** is a graph **1900** illustrating the relationship between a distance between fourth magnet **812** and fifth magnet **816** in millimeters (mm) and a torque in millinewton meters (mN·m) along a point **818** (shown in FIG. **17**) located at a corner of fourth magnet **812** adjoining fifth magnet **816** resulting from magnetic forces between the adjacent magnets **812** and **816**. The relationship is shown for the same ferromagnetic pin diameters as shown in FIG. **9**.

FIG. **20** is a side view of magnetic assembly **100** (shown in FIG. **1**) disposed parallel to a surface of and at a distance from a ferromagnetic plate **2002** (e.g., a steel plate). FIG. **21** is a graph **2100** illustrating a relationship between the distance between magnetic assembly **100** and ferromagnetic plate **2002** in millimeters (mm) and a magnetic force between magnetic assembly **100** and ferromagnetic **2002** in newtons (N) in a direction normal to ferromagnetic plate **2002**. The relationship is shown for the same pin diameters as shown in FIG. **9**.

Graphs **900**, **1200**, **1500**, **1800**, and **2100** (shown respectively in FIGS. **9**, **12**, **15**, **18**, and **21**) may be used to facilitate selecting a thickness for the ferromagnetic pin **202**. For example, data from graph **2100** may be used to initially identify a desired pin thickness or diameter that results in a suitable (e.g., the greatest) attracting force between magnetic assembly **100** and another object, such as ferromagnetic plate **2002**. Once the desired or preferred pin characteristics (e.g., thickness) are identified, data from graphs **900**, **1200**, **1500**, and **1800** may be used to verify that the desired or preferred pin thickness will result in a net attracting force or minimal repelling force between each pair of adjacent magnets **102** of magnetic assembly **100**. Additionally or alternatively, data from graphs **900**, **1200**, **1500**, and **1800** may be used in conjunction with data from graph **2100** to select a ferromagnetic pin thickness or diameter that provides a suitable (e.g., a maximum) attracting force for magnetic assembly **100**, while at the same time providing an attracting force or minimal repelling force between each pair of adjacent magnets **102** of magnetic assembly **100**.

In the illustrated embodiment, for example, data from graph **2100** generally indicates that a thinner pin will provide the greatest magnitude of attracting force between magnetic assembly **100** and ferromagnetic plate **2002**. Accordingly, in some embodiments, pin **202** is initially selected to have a relatively small thickness (e.g., 0.5 millimeters) to increase or maximize the magnetic strength of magnetic assembly **100**.

Data from graphs **900**, **1200**, **1500**, and **1800** may then be used verify that there is an attracting magnetic force between each pair of adjacent magnets **102** of magnetic assembly **100** for the desired or preferred thickness, or if a repelling magnetic force is present between a pair of adjacent magnets **102**, the repelling force is sufficiently weak (e.g., less than 5 N, such as less than 3 N, or less than 1 N of repelling force). As illustrated in FIG. **9**, for example, as the first two magnets **102** of magnetic assembly **100** (i.e., first magnet **802** and second magnet **804**) approach each other on pin **202**, the magnitude of the attracting magnetic force (as indicated by a negative force on graph **900**) continues to increase for all pin sizes from a distance of approximately six millimeters until magnets **102** make contact (at distance 0 mm). This indicates that the desired pin thickness (i.e., a ferromagnetic pin with a diameter of 0.5 millimeters) has a suitable attracting force for use in magnetic assembly **100**.

As indicated in graph **1200**, however, there is a repelling magnetic force between second magnet **804** and third magnet **808** for each pin thickness. As indicated in graph **1200**, the repelling force generally decreases as the thickness of the pin increases, thereby suggesting that a larger diameter pin should be used to minimize the repelling force between second magnet **804** and third magnet **808**. Based on the data from graph **1200**, for example, a ferromagnetic pin thickness of 1.5 or 2 millimeters may be selected to reduce the repelling force between second magnet **804** and third magnet **808**, while maintaining the maximum overall attracting magnetic force of magnetic assembly **100**. For example, turning back to FIG. **21**, graph **2100** indicates that using a ferromagnetic pin thickness of 1.5 or 2 millimeters will reduce the overall attracting magnetic force of magnetic assembly **100**, but will still provide a larger magnetic force as compared to using a ferromagnetic pin with the largest pin thickness on graph **2100** (i.e., 2.5 millimeters).

As illustrated in FIG. **15**, there is an attracting magnetic force between third magnet **808** and fourth magnet **812** (as indicated by a negative force on graph **1500**) for all pin sizes. This indicates that the pin thickness identified based on graphs **900**, **1200**, and **2100** (i.e., a ferromagnetic pin with a diameter of 1.5-2 millimeters) has a suitable attracting force for use in magnetic assembly **100**.

As indicated in graph **1800** (shown in FIG. **18**), there is a repelling magnetic force between fourth magnet **812** and fifth magnet **816** for each pin thickness and material when the fourth magnet **812** and fifth magnet **816** are positioned proximate one another (e.g., less than 5 mm apart from one another). As indicated in graph **1800**, the repelling force generally decreases as the thickness of the pin increases, thereby suggesting that a larger diameter pin should be used to minimize the repelling force between fourth magnet **812** and fifth magnet **816**. For example, the previously identified pin thicknesses of 1.5 millimeters and 2.0 millimeters provide a reduced repelling force between fourth magnet **812** and fifth magnet **816** as indicated in graph **1800**, while still providing a relatively large overall magnetic force of magnetic assembly **100**, as indicated in graph **2100**.

The foregoing process can generally be applied to any type of Halbach array to facilitate assembling the Halbach array without the use of adhesives or other means to join adjacent magnets together. The process can be applied iteratively, with one of the primary starting objectives being to minimize the amount of magnetic material removed from the magnets in the Halbach array (i.e., using the smallest diameter rod possible), while at the same time achieving at least a minimal attracting force or at most a minimal repelling force between each magnet in the array.

Graphs **1000**, **1300**, **1600**, and **1900** (shown respectively in FIGS. **10**, **13**, **16**, and **19**) illustrate an amount of torque being applied to the last-added magnet **102**, which would cause magnets **102** to flip if not otherwise restrained. In certain embodiments, a ferromagnetic pin **202** with a thickness and magnetic characteristics resulting in a stronger torque may be selected, because the torque creates a binding force against pin **202**, which keeps magnets **102** from sliding and helps hold magnets **102** in place. Additionally or alternatively, graphs **1000**, **1300**, **1600**, and **1900** may be used to confirm that the torque applied on the last-added magnet **102** due to the magnetic interaction with other magnets in the magnetic assembly **100** will produce a sufficient binding effect or frictional force on the last-added magnet **102** to overcome any repelling forces. In the embodiment illustrated in FIGS. **8-21**, for example, there is a repelling magnetic force between second magnet **804** and third magnet **808** for each pin thickness, as shown in FIG. **12**. As noted above, a ferromagnetic pin thickness of 1.5 or 2 millimeters may be selected based on data from graph **1200**. The torque data from FIG. **13** may then be used to verify that there is sufficient torque on third magnet **808** to create a sufficient binding or frictional force between the third magnet **808** and the pin **202**. For example, FIG. **13** indicates that the torque on third magnet **808** increases as the ferromagnetic pin thickness decreases, and is greater than 100 millinewton meters (mN·m) for pin thicknesses less than 2.0 millimeters.

Similar analyses may be performed to facilitate selection of other parameters of magnetic assembly **100**, such as a location of the ferromagnetic pin **202** relative to the magnets **102**, a magnetic permeability of the ferromagnetic pin **202**, and a number of ferromagnetic pins **202** included in magnetic assembly **100**.

In some embodiments, the length of the ferromagnetic pin **202** may be selected to permit assembly of all magnets in the magnetic assembly **100**. Once the magnetic assembly **100** is assembled, excess portions of the ferromagnetic pin **202** (e.g., portions of the ferromagnetic pin **202** extending beyond the first and last magnets **102**) may be cut or removed to limit the size of the magnetic assembly **100**. Additionally or alternatively, the ferromagnetic pin **202** may be subjected to one or more mechanical operations (e.g., machining, stamping, pressing, crimping, and combinations thereof) to form a stop or protrusion along the ferromagnetic pin **202** to facilitate keeping the magnets of magnetic assembly **100** in place. In yet other embodiments, multiple ferromagnetic pins may be used in magnetic assembly **100**. For example, a two-pin magnetic assembly **100** may include a first ferromagnetic pin **202** that extends through three magnets **102**, and a second ferromagnetic pin **202** that extends through another two magnets **102**, where each of the first and second ferromagnetic pins **202** includes protrusions or stops at each end to inhibit movement of the magnets **102**.

Although specific features of various embodiments of the disclosure may be shown in some drawings and not in others, this is for convenience only. In accordance with the principles of the disclosure, any feature of a drawing may be referenced and/or claimed in combination with any feature of any other drawing.

This written description uses examples to illustrate the present disclosure, including the best mode, and also to enable any person skilled in the art to practice the disclosure, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the disclosure is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they have structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal language of the claims.

What is claimed is:

1. A magnetic assembly comprising:

a plurality of magnets arranged in a Halbach array having a strong side facing a first direction and a weak side facing a second direction opposite the first direction, the plurality of magnets comprising a first magnet and a second magnet positioned adjacent the first magnet, the first magnet having a first surface and the second magnet having a second surface adjacent the first surface, at least one first cavity being formed in the first magnet and extending inward from the first surface and at least one second cavity being formed in the second magnet and extending inward from the second surface, the first and second cavities being aligned along a third direction perpendicular to the first direction and the second direction; and

at least one ferromagnetic pin positioned within the at least one first cavity and the at least one second cavity to connect the first magnet and the second magnet, the at least one ferromagnetic pin having a size, a shape, and a magnetic permeability that facilitate a magnetic force between the first surface and the second surface in the third direction inducing a magnetic flux path through the at least one ferromagnetic pin such that an apparent magnetic force in the third direction between the first surface and the adjacent second surface is one of i) a repelling force less than 5 newtons (N) and ii) an attracting force.

2. The magnetic assembly of claim **1** wherein the apparent magnetic force in the third direction between the first surface and the adjacent second surface is an attracting force between 1 N and 10 N.

3. The magnetic assembly of claim **1**, wherein the at least one ferromagnetic pin is connected to the first magnet and the second magnet by an interference fit within the at least one first cavity and the at least one second cavity, respectively.

4. The magnetic assembly of claim **1**, wherein the at least one ferromagnetic pin is one of cylindrical and prism-shaped, and a cross-sectional area and a magnetic permeability of the at least one ferromagnetic pin facilitate the magnetic force between the first surface and the second surface in the third direction inducing the magnetic flux path through the at least one ferromagnetic pin.

5. The magnetic assembly of claim **1**, wherein a void space volume created in the Halbach array by the at least one first cavity formed in the first magnet and the at least one second cavity formed in the second magnet reduces a magnetic field strength of the Halbach array by 5% or less.

6. The magnetic assembly of claim **1**, wherein a flux density in the at least one ferromagnetic pin is less than a saturation flux density of the at least one ferromagnetic pin.

7. The magnetic assembly of claim **1**, wherein the first surface and the adjacent second surface are in face-to-face contact.

8. The magnetic assembly of claim **1**, wherein the at least one ferromagnetic pin is made from a magnetic material selected from the group consisting of ferritic stainless steel, low carbon steel, and iron-cobalt alloys.

9. The magnetic assembly of claim **1**, wherein each of the plurality of magnets of the Halbach array is a rare earth magnet selected from the group consisting of samarium cobalt magnets and neodymium magnets.

10. The magnetic assembly of claim **1**, wherein:

the plurality of magnets comprises a third magnet positioned adjacent the second magnet, the second magnet having a third surface opposite the second surface and the third magnet having a fourth surface adjacent the third surface, at least one third cavity being formed in the second magnet and extending inward from the third surface and at least one fourth cavity being formed in the third magnet and extending inward from the fourth surface, the third and fourth cavities being aligned along a fourth direction perpendicular to the first direction and the second direction; and

the magnetic assembly comprises at least one second ferromagnetic pin positioned within the at least one third cavity and the at least one fourth cavity to connect the second magnet and the third magnet, the at least one second ferromagnetic pin having a size, a shape, and a magnetic permeability that facilitate a magnetic force between the third surface and the fourth surface in the fourth direction inducing a magnetic flux path through the at least one second ferromagnetic pin such that an apparent magnetic force in the fourth direction between the third surface and the adjacent fourth surface is one of i) a repelling force less than 5 N and ii) an attracting force.

11. A magnetic assembly comprising:

a plurality of magnets arranged in a linear Halbach array having a strong side facing a first direction and a weak side facing a second direction opposite the first direction, each of the plurality of magnets shaped as a radial arc segment having opposing radial end surfaces, wherein an arc length of the Halbach array increases as the Halbach array extends along a longitudinal axis oriented perpendicular to the first direction and the second direction, each of the plurality of magnets having a through-hole defined therein extending from one radial end surface to the other radial end surface, wherein each through-hole is longitudinally aligned with a through-hole defined within an adjacent magnet; and

a ferromagnetic pin positioned within each through-hole to connect adjacent magnets, wherein the ferromagnetic pin has a size, a shape, and a magnetic permeability that facilitate a magnetic force between a respective pair of adjacent magnets in the longitudinal direction inducing a magnetic flux path through the ferromagnetic pin such that an apparent magnetic force between each pair of adjacent magnets is one of i) a repelling force less than 5 newtons (N) and ii) an attracting force.

12. The magnetic assembly of claim **11**, wherein the ferromagnetic pin is connected to each of the respective pair of adjacent magnets by an interference fit within each of the respective aligned through-holes.

13. The magnetic assembly of claim **11**, wherein the ferromagnetic pin has one of a cylindrical shape and a prism shape, and a cross-sectional area and a magnetic permeability of the ferromagnetic pin facilitate the magnetic force between the respective pair of adjacent magnets in the longitudinal direction inducing the magnetic flux path through the ferromagnetic pin.

14. The magnetic assembly of claim **11**, wherein the ferromagnetic pin is made from a magnetic material selected from the group consisting of ferritic stainless steel, low carbon steel, and iron-cobalt alloys.

15. The magnetic assembly of claim **11**, wherein each of the plurality of magnets of the Halbach array is a rare earth magnet selected from the group consisting of samarium cobalt magnets and neodymium magnets.

16. The magnetic assembly of claim **11**, wherein adjacent radial end surfaces of each pair of adjacent magnets are in face-to-face contact.

17. The magnetic assembly of claim **11**, wherein the through-hole of each of the plurality of magnets extends through a center of each radial end surface of the respective magnet.

18. The magnetic assembly of claim **11**, wherein at least one pair of adjacent magnets has multiple aligned through-holes formed in adjacent radial end surfaces of the at least one pair of adjacent magnets, each of the aligning through-holes having a ferromagnetic pin positioned therein to connect the at least one pair of adjacent magnets.

19. A method of assembling a magnetic assembly including a first magnet and a second magnet arranged in a Halbach array, the method comprising:

selecting a size of a ferromagnetic pin to connect the first magnet and the second magnet, wherein the size of the ferromagnetic pin is selected based on (i) a reduction in a magnetic repelling force between the first magnet and the second magnet resulting from the ferromagnetic pin and (ii) a reduction in a magnetic field strength of the Halbach array resulting from cavities formed in the first magnet and the second magnet to accommodate the ferromagnetic pin having the selected size; and

inserting the ferromagnetic pin having the selected size into cavities in the first magnet and the second magnet to connect the first magnet and the second magnet.

20. The method of claim **19**, wherein the magnetic assembly further includes a third magnet positioned adjacent the second magnet when assembled, the method further comprising:

after selecting the size of the ferromagnetic pin to connect the first magnet and the second magnet, performing an iterative analysis of the selected size by determining a reduction in the magnetic repelling force between the third magnet and the second magnet resulting from the ferromagnetic pin and a reduction in the magnetic field strength of the Halbach array resulting from cavities formed in the first magnet, the second magnet, and the third magnet to accommodate the ferromagnetic pin;

based on the iterative analysis, selecting the size of the ferromagnetic pin to connect the first magnet, the second magnet, and the third magnet; and

inserting the ferromagnetic pin having the selected size into cavities formed in the first magnet, the second magnet, and the third magnet to connect the first magnet, the second magnet, and the third magnet.

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