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(71) Applicant: **ROTOLIPTIC TECHNOLOGIES INCORPORATED** [CA/CA]; 201-39012 Discovery Way, Squamish, British Columbia V8B 0E5 (CA).

(72) Inventors: **MONTIE, Greg John**; 201-39012 Discovery Way, Squamish, British Columbia V8B 0E5 (CA). **CALLAWAY, Bryan Allen**; 3010 NE 117th Street, Seattle, Washington 98125 (US).

(74) Agent: **DE KLEINE, Geoffrey** et al.; Borden Ladner Gervais LLP, 100 Queen Street, Suite 1300, Ottawa, Ontario K1P 1J9 (CA).

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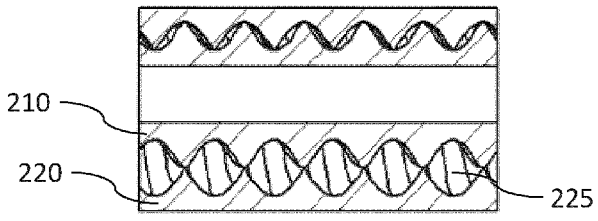


FIG. 2B

SECTION D-D

(57) Abstract: Rotary positive displacement machines based on trochoidal geometry, that comprise a helical rotor that undergoes planetary motion within a helical stator are described. The rotor can have a hypotrochoidal cross-section, with the corresponding stator cavity profile being the outer envelope of the rotor as it undergoes planetary motion, or the stator cavity can have an epitrochoidal cross-section with the corresponding rotor profile being the inner envelope of the trochoid as it undergoes planetary motion. In some embodiments, the geometry is offset in a manner that provides structural and/or operational advantages in the rotary machine.

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HELICAL TROCHOIDAL ROTARY MACHINES WITH OFFSET

Cross-Reference to Related Applications

[0001] This application is related to and claims priority benefits from U.S. Provisional Patent Application Serial No. 62/729,763 filed September 11, 2018, Serial No. 62/730,025 filed September 12, 2018, and Serial No. 62/783,088 filed December 20, 2018, each of which is hereby incorporated by reference herein in its entirety.

Field of the Invention

[0002] The present invention relates to rotary positive displacement machines, particularly rotary machines based on trochoidal geometry, the machines comprising a helical rotor that undergoes planetary motion within a helical stator.

Background of the Invention

[0003] Rotary machines, in which at least one rotor has planetary motion within a stator or housing, can be employed, for example, as positive displacement pumps, rotary compressors, vacuum pumps, expansion engines, and the like.

[0004] Pumps are devices that can move a working fluid from one place to another. There is a wide range of end uses for various types of pumps, including irrigation, fire-fighting, flood control, water supply, gasoline supply, refrigeration, chemical movement and sewage transfer. Rotary pumps are typically positive displacement pumps comprising a fixed housing, gears,

cams, rotors, vanes and similar elements. Rotary pumps usually have close running clearances (only a small distance or gap between their moving and stationary parts), do not require suction or discharge valves, and are often lubricated only by the fluid being pumped.

[0005] A positive displacement pump moves fluid by trapping a volume of fluid in a chamber and forcing the trapped volume into a discharge pipe. Some positive displacement pumps employ an expanding chamber on the suction side and a decreasing chamber on the discharge side. Fluid flows into the pump intake as the chamber on the suction side expands, and the fluid flows out of the discharge pipe as the chamber collapses. The output volume is the same for each cycle of operation. An ideal positive displacement pump can produce the same flow rate at a given pump speed regardless of the discharge pressure.

[0006] Various classes of rotary machines based on trochoidal geometries are known. Such rotary machines comprise a rotor or stator whose cross-section is bounded by a certain family of curves, known as trochoids or trochoidal shapes. These include machines with the following configurations:

[0007] (1) rotary machines in which the rotor is hypotrochoidal in cross-section, and undergoes planetary motion (spins about its axis and orbits eccentrically) within a stator that is shaped as an outer envelope of that rotor (with the rotor having one more apex or lobe than the stator cavity);

[0008] (2) rotary machines in which the stator cavity is hypotrochoidal in cross-section, and the rotor undergoes planetary motion within the stator and is shaped as the inner envelope of that stator (with the rotor having one less apex or lobe than the stator cavity);

[0009] (3) rotary machines in which the rotor is epitrochoidal in cross-section, and undergoes planetary motion within a stator that is shaped as an outer envelope of that rotor (with the rotor having one less apex or lobe than the stator cavity); and

[0010] (4) rotary machines in which the stator cavity is epitrochoidal in cross-section, and the rotor undergoes planetary motion within the stator and is shaped as the inner envelope of that stator (with the rotor having one more apex or lobe than the stator cavity).

[0011] Thus, in all of these configurations, the rotor or stator is a trochoidal component, meaning it has a cross-sectional shape that is a trochoid.

[0012] Generally, as used herein, an object is said to undergo "planetary motion" when it spins about one axis and orbits about another axis.

[0013] Rotary machines, such as those described above, can be designed for various applications including, for example, pumps, compressors, and expansion engines. The design, configuration and operation of different rotary machines can offer particular advantages for certain applications.

[0014] Progressive cavity pumps (PCPs) are another type of rotary positive displacement machine that can offer advantages for certain applications. In PCPs, a rotor is disposed and rotates eccentrically within a helical stator cavity. The material to be pumped (typically a fluid) follows a helical path along the pump axis. The rotor is typically formed of rigid material and the stator (or stator lining) of resilient or elastomeric material. The rotor is typically helical with a circular transverse cross-section displaced from the axis of the helix, and defines a single-start thread. The corresponding stator cavity is a double helix (two-start thread) with the same thread direction as

the rotor, and in transverse cross-section has an outline defined by a pair of spaced apart semi-circular ends joined by a pair of parallel sides. The pitch (the axial distance between adjacent threads) of the stator is the same as the pitch of the rotor, and the lead of the stator (the axial distance or advance for one complete turn) is twice that of the rotor.

[0015] In PCPs, the rotor generally seals tightly against the elastomeric stator as it rotates within it, forming a series of discrete fixed-shape, constant-volume chambers between the rotor and stator. The fluid is moved along the length of the pump within the chambers as the rotor turns relative to the stator. The volumetric flow rate is proportional to the rotation rate. The discrete chambers taper down toward their ends and overlap with their neighbors, so that the flow area is substantially constant and in general, there is little or no flow pulsation caused by the arrival of chambers at the outlet. The shear rates are also typically low in PCPs in comparison to those in other types of pumps. In PCPs, where the rotor touches the stator, the contacting surfaces are generally traveling transversely relative to one another, so small areas of sliding contact occur.

Summary of the Invention

[0016] In a one aspect, a rotary machine comprises a stator and a rotor disposed within the stator; the rotor has a rotor axis and a helical profile, and has a rotor shape; the rotor shape, at any cross-section transverse to the rotor axis along at least a portion of a length of the rotor, is inwardly offset from a hypotrochoidal shape; and the stator has a stator axis and a helical profile, and has a stator shape at any cross-section transverse to the stator axis along at least a portion of a length of the stator that is an outer envelope formed

when the rotor shape undergoes planetary motion. The rotor is configured to undergo planetary motion within the stator.

[0017] In some embodiments, the rotor shape has n lobes, where n is an integer, the stator shape has (n-1) lobes, the pitch of the rotor is the same as the pitch of the stator; and the ratio of the lead of the rotor to the lead of the stator is n:(n-1). In some such embodiments, the hypotrochoidal shape is an ellipse, n = 2, the pitch of the rotor is the same as the pitch of the stator, and the ratio of the lead of the rotor to the lead of the stator is 2:1.

[0018] In some embodiments of the rotary machines described in one aspect above, the helical profile of the stator defines at least one inwardly protruding helical thread, and the helical axis of the rotor defines at least one outwardly protruding helical thread.

[0019] In some such embodiments, the rotor shape is inwardly offset from a hypotrochoidal shape to a degree such that the minimum radius of curvature of the at least one outwardly protruding helical thread of the rotor, in a plane normal to the at least one outwardly protruding helical thread, is substantially the same as the radius of curvature of the at least one inwardly protruding helical thread of the stator, in a plane normal to the inwardly protruding helical thread.

[0020] In some such embodiments, the rotor and stator each have a longitudinal axis, and the rotor shape is inwardly offset from a hypotrochoidal shape to a degree such that the minimum radius of curvature of the at least one outwardly protruding helical thread of the rotor, in a plane normal to the longitudinal axis of the rotor, is substantially the same as the

radius of curvature of the at least one inwardly protruding helical thread of the stator, in a plane normal to the longitudinal axis of the stator.

[0021] In some such embodiments, the rotor has a rotor sweep width across the at least one outwardly protruding helical thread in a plane normal to the helical thread, and the stator has a stator sweep width across the at least one inwardly protruding helical thread in a plane normal to the helical thread; and the rotor shape is inwardly offset from a hypotrochoidal shape to a degree such that the rotor sweep width is substantially the same as the stator sweep width.

[0022] In some such embodiments, the rotor and stator each have a longitudinal axis; and the rotor has a rotor sweep width across the at least one outwardly protruding helical thread, in a plane normal to the longitudinal axis of the rotor; the stator has a stator sweep width across the at least one inwardly protruding helical thread, in a plane normal to the longitudinal axis of the stator; and the rotor shape is inwardly offset from a hypotrochoidal shape to a degree such that the rotor sweep width is substantially the same as the stator sweep width.

[0023] In some such embodiments, the rotor has a rotor arc length around the at least one outwardly protruding helical thread in a plane normal to the helical thread; the stator has a stator arc length around the at least one inwardly protruding helical thread in a plane normal to the helical thread; and the rotor shape is inwardly offset from a hypotrochoidal shape to a degree such that the rotor arc length is substantially the same as the stator arc length.

[0024] In some such embodiments, the rotor and stator each have a longitudinal axis; the rotor has a rotor arc length around the at least one

outwardly protruding helical thread in a plane normal to the longitudinal axis of the rotor; the stator has a stator arc length around the at least one inwardly protruding helical thread in a plane normal to the longitudinal axis of the stator; and the rotor shape is inwardly offset from a hypotrochoidal shape to a degree such that the rotor arc length is substantially the same as the stator arc length.

[0025] In another aspect, a rotary machine comprises a stator and a rotor disposed within the stator; the stator has a stator axis and a helical profile, and has a stator shape; the stator shape, at any cross-section transverse to the stator axis along at least a portion of a length of the stator, is outwardly offset from an epitrochoidal shape; the rotor has a rotor axis and a helical profile, and has a rotor shape at any cross-section transverse to the rotor axis, along at least a portion of a length of the rotor, that is an inner envelope formed when the stator shape undergoes planetary motion. The rotor is configured to undergo planetary motion within the stator.

[0026] In some embodiments, the stator shape has n-1 lobes, where n is an integer, the rotor shape has n lobes, the pitch of the rotor is the same as the pitch of the stator; and the ratio of the lead of the rotor to the lead of the stator is n:(n-1). In some such embodiments, n = 2, the pitch of the rotor is the same as the pitch of the stator, and the ratio of the lead of the rotor to the lead of the stator is 2:1.

[0027] In some embodiments of the rotary machines described in another aspect above, the helical profile of the stator defines at least one inwardly protruding helical thread, and the helical axis of the rotor defines at least one outwardly protruding helical thread.

[0028] In some such embodiments, the stator shape is outwardly offset from an epitrochoidal shape to a degree such that the minimum radius of curvature of the at least one outwardly protruding helical thread of the rotor, in a plane normal to the at least one outwardly protruding helical thread, is substantially the same as the radius of curvature of the at least one inwardly protruding helical thread of the stator, in a plane normal to the inwardly protruding helical thread.

[0029] In some such embodiments, the rotor and stator each have a longitudinal axis, and the stator shape is outwardly offset from an epitrochoidal shape to a degree such that the minimum radius of curvature of the at least one outwardly protruding helical thread of the rotor, in a plane normal to the longitudinal axis of the rotor, is substantially the same as the radius of curvature of the at least one inwardly protruding helical thread of the stator, in a plane normal to the longitudinal axis of the stator.

[0030] In some such embodiments, the rotor has a rotor sweep width across the at least one outwardly protruding helical thread, in a plane normal to the helical thread; the stator has a stator sweep width across the at least one inwardly protruding helical thread, in a plane normal to the helical thread; and the stator shape is outwardly offset from an epitrochoidal shape to a degree such that the rotor sweep width is substantially the same as the stator sweep width.

[0031] In some such embodiments, the rotor and stator each have a longitudinal axis; the rotor has a rotor sweep width across the at least one outwardly protruding helical thread, in a plane normal to the longitudinal axis of the rotor; the stator has a stator sweep width across the at least one inwardly protruding helical thread, in a plane normal to the longitudinal axis

of the stator; and the stator shape is outwardly offset from an epitrochoidal shape to a degree such that the rotor sweep width is substantially the same as the stator sweep width.

[0032] In some such embodiments, the rotor has a rotor arc length around the at least one outwardly protruding helical thread in a plane normal to the helical thread; the stator has a stator arc length around the at least one inwardly protruding helical thread in a plane normal to the helical thread; and the stator shape is outwardly offset from an epitrochoidal shape to a degree such that the rotor arc length is substantially the same as the stator arc length.

[0033] In some such embodiments, the rotor and stator each have a longitudinal axis; the rotor has a rotor arc length around the at least one outwardly protruding helical thread, in a plane normal to the longitudinal axis of the rotor; the stator has a stator arc length around the at least one inwardly protruding helical thread, in a plane normal to the longitudinal axis of the stator; and the stator shape is outwardly offset from an epitrochoidal shape to a degree such that the rotor arc length is substantially the same as the stator arc length.

[0034] In some embodiments of the rotary machines described in both aspects above, the rotary machine is a multi-stage machine and a plurality of chambers are formed between cooperating surfaces of the rotor and the stator. In some embodiments, each of the plurality of fluid chambers has approximately the same volume.

Brief Description of the Drawings

[0035] FIGS. 1A-1G (Prior Art) are schematic diagrams illustrating, in transverse cross-section, the geometry of an elliptical rotor and stator assembly at different stages of a single revolution of the elliptical rotor.

[0036] FIG. 2A shows a side view of a rotor-stator assembly showing an outer cylindrical surface of the stator. FIG. 2B is a cross-sectional view of the rotor-stator assembly of FIG. 2A, taken in the direction of arrows D-D, showing a helical rotor disposed within a helical stator cavity. FIG. 2C shows an end view and three cross-sectional views taken in the direction of arrows E-E in FIG. 2A, showing the helical rotor with a two-lobe, elliptical transverse cross-section.

[0037] FIG. 3A is a side view of a helical rotor with an elliptical transverse cross-section. FIG. 3B is another side view of the helical rotor of FIG. 3A, orthogonal to the view of FIG. 3A. FIG. 3C is a cross-sectional view of the helical rotor of FIG. 3A taken in the direction of arrows A-A in FIG. 3B.

[0038] FIG. 4A is an end view of a stator with a helical cavity. FIG. 4B is a transverse cross-sectional view of the stator of FIG. 4A. FIG. 4C is an isometric view of the stator of FIG. 4A (with the dashed line indicating the stator cavity).

[0039] FIG. 5 illustrates a portion of a rotor-stator assembly, showing a helical rotor disposed inside a translucent helical stator.

[0040] FIG. 6A shows a side view of a rotor-stator assembly showing an outer cylindrical surface of the stator. FIG. 6B is a cross-sectional view of the rotor-stator assembly of FIG. 6A, showing a helical rotor disposed within a helical stator cavity. FIG. 6C shows an end view and various cross-sectional

views taken in the direction of arrows A-A, B-B and C-C in FIG. 6A, showing the helical rotor with a three-lobe transverse cross-section.

[0041] FIG. 7A is a side view of a helical rotor with a three-lobe transverse cross-section. FIG. 7B is an isometric view of the helical rotor of FIG. 7A.

[0042] FIG. 8A is side view of a stator with a helical cavity, showing an outer cylindrical surface of the stator. FIG. 8B is a longitudinal cross-sectional view of the stator of FIG. 8A. FIG. 8C is another longitudinal cross-sectional view of the stator of FIG. 8A orthogonal to the cross-sectional view of FIG. 8B. FIG. 8D is an isometric view of the stator of FIG. 8A.

[0043] FIG. 9A is a side view of a rotary machine with a helical rotor-stator assembly having trochoidal geometry. FIG. 9B is a cross-sectional view of the rotary machine of FIG. 9A, taken in the direction of arrows A-A in FIG. 9A.

[0044] FIG. 10 is a schematic diagram illustrating the geometry of an ellipse rotating about the head of a rotating radial arm.

[0045] FIG. 11 is a cross-sectional diagram illustrating a portion of a rotor-stator assembly of a rotary machine.

[0046] FIG. 12 is a transverse cross-sectional diagram illustrating rotor-stator geometry for a rotor that has a cross-sectional profile that is inwardly offset from each point on an ellipse, and a correspondingly offset stator cavity profile.

[0047] FIG. 13A shows the cross-sectional shape of a helical stator cavity with no offset, in a plane normal to a longitudinal access of the stator. FIG. 13B shows a close up view of the inverse apex of the helical stator cavity of

FIG. 13A, from the same angle as FIG. 13A. FIG. 13C shows the cross-sectional shape of the stator cavity of FIG. 13A in a plane normal to the helical path of the stator inverse apex. FIG. 13D shows a close up view of the helical stator cavity of FIG. 13B from the same angle as FIG. 13C.

[0048] FIG. 14A shows the cross-sectional shape of a helical stator cavity, in a plane normal to a longitudinal access of the stator, for a stator with an inward offset. FIG. 14B shows a close up view of the helical stator cavity of FIG. 14A from the same angle as FIG. 14A. FIG. 14C shows the cross-sectional shape of the stator cavity of FIG. 14A in a plane normal to the helical path of the stator inverse apex region. FIG. 14D shows a close up view of the inverse apex region from the same angle as FIG. 14C.

[0049] FIG. 15A shows the cross-sectional shape of a helical elliptical rotor with no offset, in a plane normal to a longitudinal access of the rotor. FIG. 15B shows the cross-sectional shape of the rotor of FIG. 15A in a plane normal to the helical path of the rotor tips.

[0050] FIG. 16A shows the cross-sectional shape of a helical rotor with an offset, in a plane normal to a longitudinal access of the rotor. FIG. 16B shows the cross-sectional shape of the offset rotor of FIG. 16A, in a plane normal to the helical path of the rotor tips.

[0051] FIG. 17A shows the sweep width W_1 across the inverse apex region for a stator cavity with an offset, in a plane normal to a longitudinal access of the stator. FIG. 17B shows the sweep width W_2 across the inverse apex region for the offset stator cavity of FIG. 17A, in a plane normal to the helical path of the stator inverse apex region.

[0052] FIG. 18A shows the sweep width W_3 across the rotor tips for a rotor

with no offset, in a plane normal to a longitudinal access of the rotor. FIG. 18B shows the sweep width W_4 across the rotor tips for the elliptical rotor of FIG. 18A, in a plane normal to the helical path of the stator inverse apex region.

[0053] FIG. 19A shows the sweep width W_5 across the rotor tips for a rotor with an offset, in a plane normal to a longitudinal access of the rotor. FIG. 19B shows the sweep width W_6 across the rotor tips for the rotor of FIG. 19A, in a plane normal to the helical path of the stator inverse apex region.

[0054] FIG. 20 is a graph showing results of testing of a 2-stage helical trochoidal rotary pump in which the overall efficiency and volumetric efficiency of the pump are plotted against the number of cycles.

Detailed Description of Illustrative Embodiment(s)

[0055] The present application relates to rotary machines in which a helical rotor undergoes planetary motion within a stator. They can provide advantages for various applications, some of which are discussed below.

[0056] The rotary machines are based on trochoidal geometries, with the rotor or stator having a trochoidal geometry (in transverse cross-section, i.e. perpendicular to its axis). The rotor can be hypotrochoidal, with the corresponding stator cavity profile being the outer envelope of the rotor as it undergoes planetary motion. Alternatively, the stator cavity can have an epitrochoidal cross-sectional geometry with the corresponding rotor profile being the inner envelope formed by the trochoid as it undergoes planetary motion. In such machines, one or more specific points on the envelope (whether it be the rotor or the stator) is in continuous contact with the

corresponding component, and the contact point traces a trochoidal profile as the components execute their relative motion.

[0057] FIGS. 1A-1G are schematic diagrams illustrating the geometry of an example of a known rotary machine where the rotor has a cross-sectional shape that is hypotrochoidal, and the stator cavity is shaped as an outer envelope of the rotor as it undergoes planetary motion. In this example the hypotrochoidal rotor is an elliptical rotor. The rotor 110 and stator 120 are shown at different points in time during a single revolution of the elliptical rotor within the stator. FIG. 1A shows elliptical rotor 110 in a first position within stator 120. Stator inner surface 125 comprises an inverse apex 140. A portion of each of rotor tips 130 and 135 is in contact with inner surface 125 of stator 120, and outer surface of rotor 110 is in contact with inverse apex 140. Rotor 110 spins about its center and rotates eccentrically in the direction indicated by arrow X-X (counter-clockwise) about axis 115. FIG. 1B shows elliptical rotor 110 in a second position after rotor 110 has rotated. A portion of each of rotor tips 130 and 135 remains in contact with stator inner surface 125, and outer surface of rotor 110 remains in contact with inverse apex 140. FIG. 1C shows elliptical rotor 110 in a third position after further rotation. FIG. 1D shows elliptical rotor 110 in a fourth position with its major axis oriented vertically, as indicated by dashed line V-V. A portion of rotor tip 130 is in contact with inverse apex 140 and a portion of rotor tip 135 is in contact with stator inner surface 125 directly above inverse apex 140. For the remainder of the description below for FIGS. 1E-1G, reference numerals have been omitted for clarity. FIGS. 1E-1G show elliptical rotor 110 after further rotations in a counter-clockwise direction. FIG. 1F shows elliptical rotor 110 in a position with its major axis oriented horizontally, as indicated by dashed line H-H. Thus, inner surface 125 of stator 120 in cross-section is

designed such that at least a portion of each of rotor tips 130 and 135 is in contact with stator inner surface 125 at all times during a complete revolution of elliptical rotor 110. Inverse apex 140 is in contact with the outer surface of elliptical rotor 110 at all times during a complete revolution of elliptical rotor 110. The contact of elliptical rotor 110 with stator 120 at three positions, as described above, divides the interior volume of stator 120 into three chambers (for example, as shown in FIG. 1F). When elliptical rotor 110 is in contact with stator 120 at only two distinct positions (for example when the major axis of elliptical rotor 110 is oriented vertically, as in FIG. 1D), elliptical rotor 110 divides the interior volume of stator 120 into just two chambers. Ports (not shown in FIGS. 1A-1G) can be provided for inflow and outflow of fluid as desired. The material being conveyed (typically a fluid) moves in an arc or circumferential direction through the rotary machine. Examples of such a machine are described in U.S. Patent Application Publication No. US2015/0030492, which is incorporated by reference herein.

[0058] Herein, the terms horizontal, vertical, front, rear and like terms related to orientation are used in reference to the drawings with the particular orientations as illustrated. Nonetheless, the rotary machines and related sub-assemblies described herein can be placed in any orientation suitable for their end-use application.

[0059] In embodiments of the present rotary machines, the hypotrochoid and outer envelope (rotor and stator transverse cross-sectional profiles, respectively) are each swept along helical paths, the axes of those helices being the axes of rotation of those components in that reference frame in which both parts undergo simple rotary motion (the “centers” of those components). The axes of the rotor and stator helices are offset from one

another by a distance equal to the eccentricity of the rotor. The helical rotor and corresponding stator have the same pitch, and the ratio of the lead of the rotor to the lead of the stator is the same as the ratio of their number of lobes (which is the also the same as the ratio of their number of starts). As used herein, "pitch" is defined as the axial distance between adjacent threads (or crests or troughs, for example, on a helix), and "lead" is defined as the axial distance or advance for one complete turn (360°). Pitch and lead are equal with single start helices; for multiple start helices the lead is the pitch multiplied by the number of starts.

[0060] Thus, in embodiments of the present rotary machines, when a transverse cross-section is taken in any plane perpendicular to the axis of rotation, the hypotrochoid and envelope (that is, the cross-sectional shape of the rotor and stator, respectively) are seen just as they would be in the usual two-dimensional profile, such as shown in FIGS. 1A-1G, for example. For example, in one embodiment, the outer surface of a helical rotor is defined by an ellipse swept along a helical path, and a corresponding stator cavity is defined by sweeping the corresponding outer envelope along a helical path with half the lead of the helical rotor. The rotor profile is a double-start helix, and the stator profile is a single-start helical cavity. For such a machine, when a transverse cross-section is taken in any plane perpendicular to the axis of rotation, the outer profile of the rotor and inner profile of the stator will be similar to those illustrated for those components in FIGS. 1A-1G.

[0061] FIGS. 2A-C illustrate an example of such a machine. FIG. 2A shows a side view of a stator 220. The exterior surface of stator 220 is cylindrical. FIG. 2B is a cross-sectional view taken in the direction of arrows D-D in FIG. 2A, and shows a helical rotor 210 disposed within a helical

stator cavity 225 defined by stator 220. FIG. 2C shows an end view and various cross-sectional views taken in the direction of arrows E-E in FIG. 2A. Rotor 210 has an elliptical transverse cross-section, as shown in FIG. 2C. As the cross-section E-E progresses along the axis of rotation of rotor 210, the cross-sectional profile of the rotor and stator progresses in a manner analogous to the motion over time of rotor 110 within stator 120, as illustrated in FIGS. 1A-1G. In the embodiment illustrated in FIGS. 2A-2C, rotor 210 has two lobes and stator cavity 225 has one lobe.

[0062] FIG. 3A is a side view of a helical rotor 300 (with an elliptical transverse cross-section) similar to rotor 210 of FIGS. 2A-C. FIG. 3B is another side view of helical rotor 300, orthogonal to the view of FIG. 3A. FIG. 3C shows a cross-sectional view of rotor 300 taken in the direction of arrows A-A in FIG. 3B.

[0063] FIG. 4A is an end view, FIG. 4B is a cross-sectional view and FIG. 4C is an isometric view of a stator 400 (with the dashed line indicating the stator cavity). Stator 400 corresponds to rotor 300 of FIGS. 3A-C (in other words stator 400 can be used with rotor 300), and is similar to stator 220 of FIGS. 2A-C.

[0064] FIG. 5 illustrates an example of a portion of a machine such as illustrated in FIGS. 2A-2C, showing a helical rotor 510 disposed inside a translucent helical stator 520. The pitch of the rotor (distance between adjacent threads) is indicated by distance 530, and the lead of the rotor is indicated by distance 540. Because the rotor is a double-start helix, the lead is twice the pitch. The pitch of the stator is indicated by distance 550 and, because the stator is a single-start helix, distance 550 is also the lead of the stator. The rotor pitch 530 and stator pitch 550 are the same. In some

embodiments the rotor and stator are plastic. In other embodiments of the rotary machines described herein both the rotor and stator can be metal. In other embodiments, depending on the application, the rotor and/or stator can be made from ceramic, elastomeric or other suitable materials or combinations of materials. The material(s) of the rotor can be the same as, or different from, the material(s) of the stator.

[0065] In the embodiment illustrated in FIGS. 2A-2C, the rotor and stator surfaces bound one complete chamber or volume per envelope revolution (each volume constituting a single stage of the machine or pump). The boundaries of these chambers are simple helices at the "top" and "bottom" (the path of the hypotrochoid generating elements, or "points" on the envelope), and a contact curve between the rotor and stator in the "clockwise" and "counter-clockwise" direction. These chambers do not change size or shape as the device operates. The material to be pumped (typically a fluid) is moved in an axial direction through the pump, and the flow velocity is substantially constant.

[0066] There is a quasi-helical contact path between the rotor and the inner "ridge" of the stator at all times during rotation of the rotor (just as there is contact between the rotor and the inverse apex in the stator in the machine illustrated in FIGS. 1A-1G). The contact path with the stator moves or oscillates back and forth across the helical "ridge" of the rotor as the rotor rotates relative to the stator (in a manner similar to how the contact point moves back and forth across the tips of elliptical rotor in the machine of FIGS. 1A-1G). The rotor-stator contact path revolves around the machine as pumping action proceeds, "threading" the fluid (or material to be pumped) in

a spiral path along the helix, to that it is moved axially from one end of the stator cavity to the other.

[0067] Thus, the periodicity of contact between the helical rotor and stator occurs in space (moving along a continuous contact path over time) rather than in time (with intermittent contact between surfaces such as occurs, for example, in the machine illustrated in FIGS. 1A-1G, where the rotor tips only intermittently contact the inverse apex on the stator). Thus, in the present rotary machines, rather than periodically engaging and disengaging (or touching and separating), the contact surfaces and any associated seals slide across one another, or in close proximity to one another, continuously. This continuous contact line between rotor and stator can facilitate the provision of sealing in embodiments of the present machines.

[0068] Some embodiments of the present rotary machines operate with a small clearance between the helical rotor and stator, but without seals between them. In some embodiments it can be desirable to dispose a seal between these components to reduce leakage of fluid between stages.

[0069] FIGS. 6A-C illustrate another embodiment of a machine according to the present approach, where in cross-section, the helical trochoidal rotor has three lobes and the stator cavity has two lobes. The rotor and stator cavity are defined by sweeping these profiles along a helical path. This embodiment has a rotor/stator lead ratio of 3:2. FIG. 6A shows a side view of a cylindrical stator 620. FIG. 6B is a cross-sectional view taken in the direction of arrows D-D in FIG. 6A, and shows a helical rotor 610 disposed within stator cavity 625 defined by stator 620. FIG. 6C shows an end view and various cross-sectional views taken in the direction of arrows A-A, B-B, and C-C in FIG. 6A. Rotor 610 has rounded triangular transverse cross-section, as shown in

FIG. 6C. Stator cavity has a transverse cross-sectional profile that is roughly circular with two inverse apex regions, 620A and 620B swept along a helical path. As one moves along the axis of rotation of rotor 610, the cross-sectional profile of the rotor and stator progresses in a manner as shown in FIG. 6C.

[0070] FIG. 7A is a side view of a helical rotor 700 (with a 3-lobe, rounded triangular transverse cross-section) similar to rotor 610 of FIGS. 6A-C. FIG. 7B is an isometric view of rotor 700.

[0071] FIG. 8A is side view of a 2-lobe stator 800. FIG. 8B is a longitudinal cross-sectional view of stator 800, and FIG. 8C is another longitudinal cross-sectional view of stator 800 (orthogonal to the cross-sectional view of FIG. 8B). Both FIGS. 8B and 8C show the inner surface of the stator cavity. FIG. 8D is an isometric view of stator 800. Stator 800 is similar to stator 620 of FIGS. 6A-C.

[0072] FIGS. 9A and 9B illustrate an example of a rotary machine 900 with a helical rotor-stator assembly having trochoidal geometry. FIG. 9A is a side view of rotary machine 900, and FIG. 9B is a cross-sectional view taken in the direction of arrows A-A in FIG. 9A. Referring primarily to FIG. 9B, rotary machine 900 comprises helical rotor 910 and helical stator 920 defining stator cavity 925. Rotary machine 900 further comprises inlet housing 930 and outlet housing 935. Drive shaft 940 is fixed to carrier 945, and is mechanically coupled via sun gear 950 and ring gear 955 to cause eccentric rotation of rotor 910 within stator cavity 925. Rotary machine 900 further comprises thrust bearings 960 and 965, radial bearings 970 and shaft seals 980. As rotor 910 rotates with stator cavity 925, fluid can be drawn into rotary machine 900 via inlet port 990, and expelled via outlet port 995.

[0073] Most of the above description has focused on embodiments of helical trochoidal rotary machines with a trochoidal rotor (particularly an elliptical rotor) and corresponding outer envelope stator cavity. In other embodiments, helical trochoidal rotary machines can have an epitrochoidal stator cavity profile and corresponding rotor (inner envelope) profile that are each swept along helical paths. These embodiments have the same relative motion of the rotor and stator (with the same orbit and spin) as machines with a trochoidal rotor and corresponding outer envelope stator cavity.

[0074] The present approach can be applied to generate embodiments of helical rotary machines based on a hypotrochoidal or epitrochoidal rotor (with the corresponding stator cavity profile being the outer envelope or inner envelope, respectively of the rotor as it undergoes planetary motion), where the components have more than two or three lobes. Such machines will have more chamber "edge" for each trapped volume of fluid, so may tend to have more leakage per stage, poorer solids handling capability, and/or higher friction if dynamic seals are used. However, for some applications, for example mud motors, such embodiments with lower speed and higher torque can offer advantages.

[0075] In the rotary machines described herein, the rotor (and/or optionally the stator) can be rotated using any suitable drive mechanism. Some non-limiting examples of drive mechanisms are briefly discussed below.

[0076] The fundamental working principal is independent of which component of the machine (if any) is "fixed" and which is rotating. For example, in some embodiments the machine can be operated such that the rotor and stator each revolve around their respective centers (an inherently balanced design). In such embodiments, even though both components are

rotating about their axes, the relative motion of the components is basically the same as in fixed stator embodiments. In some embodiments, for example, the machine can be operated such that the stator is fixed and the rotor undergoes planetary motion within it. This is mechanically simple and compact, but sometimes requires counterweights to provide balance. In other embodiments, the outer stator (or housing) undergoes planetary motion about the inner rotor. Other variations are possible.

[0077] For 2:1 (rotor:stator lobe) rotary machines with hypotrochoidal rotor with outer envelope stator cavity, or epitrochoidal stator with inner envelope rotor, an example of a suitable drive mechanism has an external gear fixed to the stator meshing with an internal gear with twice as many teeth fixed to the rotor, the distance between the gear centers being equal to the eccentricity of the hypotrochoid, that center distance being maintained by bearings fixed to each part and interacting with an element that revolves with the rotor center; the revolving element being driven by a shaft passing through the sun gear. This type of mechanism is known, and used for instance in Wankel rotary engines. Alternatively, instead of using an internal gear a pair of external gear meshes can be used to achieve a 2:1 gear ratio with the output rotating in the same direction as the input.

[0078] For machines with other ratios, the gear ratio can be modified accordingly. In a machine having a three lobe rotor and a two lobe stator, the gear ratio is 3:2. In general, for a machine having an (n+1) lobe rotor and an n lobe stator, the gear ratio can be (n+1):n. For epitrochoid with outer envelope or hypotrochoid with inner envelope machines, the gears can be fixed to the corresponding component, for example, the external gear can be fixed to the rotor and the internal gear can be fixed to the stator.

[0079] Other drive mechanisms that do not involve gears can be used. For example, some embodiments are rotary machines in which the rotor is mounted to a flexible or angled shaft (for example, fitted with universal joints) so that it rotates eccentrically, and power is transmitted from the concentric rotation of one end of the drive shaft to the eccentrically rotating rotor. Thus, the shaft can be coupled to and driven by a motor, with the stator acting as a guide for the rotor. Other examples use, for example, Schmidt couplings and/or cycloidal drive mechanisms, in lieu of gears, to provide the relative motion of the rotor and stator.

[0080] It is possible to make a machine based on the present approach with a helical rotor and stator having a single stage, multiple stages or, in some embodiments, with less than a complete stage (where there is no complete trapped chamber or volume of fluid between the ends of the pump). For the latter, end plates can be provided at each end of the rotor-stator, with an inlet port provided in one end plate and an outlet port in the other. If somewhat more than one complete rotor revolution is provided (i.e. sufficient length and number of rotor pitches that at least one bounded volume of fluid is isolated from both ends of the pump simultaneously), end plates may not be needed.

[0081] In multi-stage embodiments of the present machines as described above, if the rotor-stator geometry remains substantially constant along the axis of the machine, the volume and dimensions of the bounded volumes or fluid chambers formed between the helical rotor and the stator will be the same, and the volume of each fluid chamber will remain constant during operation of the machine, as the rotor rotates within the stator. This is explained further in reference to FIG. 10.

[0082] FIG. 10 is a schematic diagram illustrating the geometry of an ellipse rotating about the head of a rotating radial arm. In geometric configuration 1000, ellipse 1010 has a center C, a major axis indicated by dotted line A-A and a minor axis indicated by dashed line B-B. Major axis A-A is the longest diameter of ellipse 1010, and minor axis B-B is the shortest diameter of ellipse 1010. Ellipse 1010 rotates about center C at an angular velocity ω_1 in a counter-clockwise direction relative to a frame of reference in which center C is stationary. Center C is located at the head of a rotating radial arm 1020. Radial arm 1020 has length k and rotates about a fixed end O at an angular velocity ω_2 in a counter-clockwise direction relative to a frame of reference in which fixed end O is stationary. If angular velocity ω_1 is negative, it indicates that rotation of ellipse 1010 about center C is in a clockwise direction relative to a frame of reference in which center C is stationary. If angular velocity ω_2 is negative, it indicates that rotation of radial arm 1020 about fixed end O is in a clockwise direction relative to a frame of reference in which fixed end O is stationary.

[0083] Circle 1030 is the locus of the head of radial arm 1020 as it rotates about fixed end O. Line O-C is also referred to as the crank arm, and length k is referred to as the crank radius.

[0084] Geometric configuration 1000 can represent a helical rotor assembly in transverse cross-section. In embodiments of the rotary machines as described herein, it is desirable that inverse apex (or ridge) of the corresponding helical stator is in contact with the outer surface of helical elliptical rotor at all times during a complete revolution of elliptical rotor. This can be achieved by configuring the geometry 1000 such that the difference between the semi-major axis of the rotor with elliptical cross-

section (shown in FIG. 10 as length "*a*") and the semi-minor axis of the rotor (shown in FIG. 10 as length "*b*") is twice the crank radius, *k*. In other words, in preferred embodiments:

[0085] $a - b = 2k$

[0086] If the rotor and stator pitch and all dimensions (including *a*, *b* and *k* as shown in FIG. 10) remain constant along the length of the rotor-stator assembly, then the volume and dimensions of the fluid chambers formed between the helical rotor and the stator will be the same along the length of the assembly. Such rotary machines can be used, for example, as pumps and, if driven at constant speed can provide a fairly steady volumetric flow rate or output.

[0087] In other multi-stage embodiments, the rotor-stator geometry can be varied, in a continuous or stepwise manner, along the axis of the rotary machine. In some embodiments, such variations can cause the volume of the fluid chambers to vary along the axis of the machine, such as may be desirable for compressor or expander applications, for example. In other embodiments, it can be advantageous to vary the geometry of the rotor-stator along the axis of the rotary machine, while keeping the volume of the fluid chambers formed between the helical rotor and the stator approximately the same along a length of the rotor-stator assembly. Such embodiments are described in further detail below, again with reference to FIG. 10.

[0088] Instead of the rotor and stator pitch and other parameters (including *a*, *b* and *k*) being constant along the axis of the machine, the rotor-stator geometry can be varied along the axis of a rotary machine, for example, as follows:

[0089] (1) By varying the pitch of the rotor and stator. For example, the pitch can increase in the flow direction so that the volume of the fluid chambers increases along the axis of the machine. This may be desirable for compressor applications, for example.

[0090] (2) By varying the aspect ratio of the rotor (a/b) and keeping crank radius, k, constant, where a minus b remains equal to $2k$. The corresponding stator profile is varied along its axis accordingly.

[0091] (3) By varying the crank radius k, where a minus b remains equal to $2k$. This involves also changing the aspect ratio of the rotor by varying at least one of dimensions a or b. The corresponding stator profile is varied along its axis accordingly. When the crank radius is varied the rotor and stator axes will be inclined relative to one another (i.e. be non-parallel).

[0092] (4) By varying the degree of offset of the rotor from a true ellipse (or hypotrochoid) along the axis of the rotor, and correspondingly varying the stator profile along its axis.

[0093] In some embodiments, varying one or more of these parameters can cause the volume of the fluid chambers to vary along the axis of the machine, for example, getting smaller or larger. In some embodiments, the parameters are varied so that the size of the elliptical rotor cross-section and corresponding stator is scaled or reduced linearly in the axial direction.

[0094] In some embodiments, different rotor-stator geometries or profiles can be used in different portions or segments of the machine to meet various requirements. For example, a “precompressor” section with different dimensions but equal or slightly greater displacement can be used to reduce Net Positive Suction Head (NPSH) requirements in a pump. A different

geometry that is more favorable for sealing can be used downstream along the main body of the pump. In another example, a tapered embodiment can be used as a nozzle or diffuser.

[0095] In some embodiments, multiple parameters can be varied in combination so that the volume of fluid chambers formed between the helical rotor and the stator remains approximately the same along a length of the rotor-stator assembly, with the variation of one parameter at least partially compensating for the variation in another parameter with respect to the effect on the volume of the fluid chambers. For example, variations described in (2) and (3) may change the flux area, but the change in flux area could be compensated for by, for example, increasing the rotor-stator pitch. It can be advantageous to manipulate other characteristics by having a different geometry in one section of the rotor-stator assembly than in another section, even if the fluid throughput along the length is roughly or substantially constant. For example, it could be desirable to have a high flux area near the intake (to draw a fluid in and encapsulate it), and then gradually change the geometry towards the discharge end.

[0096] FIG. 11 is a sketch illustrating a portion of a rotor-stator assembly 1100 in cross-section, to illustrate an embodiment in which, multiple parameters are varied in combination so that the volume of the fluid chambers formed between a helical rotor 1110 and a corresponding stator 1120 remains approximately the same along a length of the rotor-stator assembly. In this embodiment, the rotor and stator axes are non-parallel. When the rotor and stator axes are non-parallel, instead of being mapped on to plane that is perpendicular to both axes, the “cross-sectional” profile of the rotor and stator is mapped on to the surface of a sphere which is

perpendicular to both axes (the center of sphere being the point at which the rotor axis 1115 and stator axis 1125, if extrapolated, would intercept).

[0097] The crank radius, k, is the arc length (on the surface of the sphere at that point along the axes) between the longitudinal axis 1115 of rotor 1110, and the longitudinal axis 1125 of stator 1120. Crank radius, k, is varying along the length of the assembly (decreasing toward the lower end of the illustrated assembly), and the rotor and stator longitudinal axes 1115 and 1125 are non-parallel. The length of minor transverse axis of the elliptical rotor 1110 mapped onto the sphere is shown in FIG. 11 as $2b$. As in FIG. 10 where a-b=$2k$, at any point along the length of rotor-stator assembly 1100 in FIG. 11 the major transverse axis ($2a$) of the elliptical rotor 1110 (mapped onto the sphere) is $2b+4k$. In the embodiment illustrated in FIG. 11, the crank radius k and the dimensions of the rotor and corresponding stator are continuously scaling or decreasing along a length of the assembly so that the rotor and stator transverse profiles at any axial position differ only in their size. The pitch of the rotor and stator can be correspondingly increased, so that the volume of the fluid chambers formed between rotor 1110 and stator 1120 remains approximately the same along the length of the rotor-stator assembly. In the embodiment of FIG. 1, the pitch is varied continuously, and the pitch between various pairs of points along the length of the assembly is shown gradually increasing, from P_0 to P_1 to P_2. To maintain constant chamber volume in the case described, instantaneous pitch at any point is inversely proportional to the square of the distance to that point from the center of the sphere (zero eccentricity point). Without such a change in pitch, the volume of fluid chamber would decrease, and such a machine could be used as a compressor, for example.

[0098] The changes in geometry can be continuous or gradual or there can be a step change. If the latter, preferably the eccentricity of the pump remains constant so that single rotor and stator parts can be used throughout the machine, and two or more rotor sections can be driven as a single component. In embodiments with a step change, it can be desirable to provide a space or chamber between the sections where the fluid can switch between flow paths. The pressure in this intermediate space is preferably slightly positive, to reduce the likelihood of cavitation. In some embodiments this can be achieved by providing a slightly smaller displacement in the upstream section. Alternatively, slip caused by pressure differential across the pump can provide this positive pressure. It can further be desirable in some instances to provide a pressure relief device in the intermediate space to control load on the upstream pump section and/or "motoring" of the downstream pump section.

[0099] In variations on the helical trochoidal rotary machines described herein, the rotor and stator profiles can be offset along the normals of their planar transverse cross-sections. For example, in some such embodiments where the rotor is hypotrochoidal and undergoes planetary motion within a stator that is shaped as an outer envelope of that rotor, the rotor and stator can have cross-sectional profiles that are inwardly offset. In other embodiments where the stator is epitrochoidal, and the rotor undergoes planetary motion within the stator and is shaped as the inner envelope of that stator, the rotor and stator can have cross-sectional profiles that are outwardly offset. Such variations in geometry can offer additional advantages, while still retaining at least some of the benefits provided by helical trochoidal rotary machines.

[0100] FIG. 12 is a transverse cross-sectional diagram of a rotor-stator assembly 1200, in which a rotor has a cross-sectional profile 1210 that is inwardly offset from each point on an ellipse 1215 by a fixed distance "d" measured perpendicular to a tangent to ellipse 1215 at that point. The resulting rotor profile 1210 is not a true ellipse. The corresponding stator cavity profile 1220 can be defined as the outer envelope generated when rotor profile 1210 undergoes planetary motion, or defined as the correspondingly inward offset of the envelope 1225 generated by the non-offset hypotrochoid (ellipse 1215).

[0101] Referring again to FIG. 12, with this "offset" geometry, the inverse apex region 1240 of stator is rounded with a circular arc, centered on the inverse apex 1245 of the "non-offset" geometry. In the plane of the diagram, the contact between inverse apex region 1240 of the stator and the rotor tips is continuous, but moves back and forth along the circular arc of the inverse apex region between points 1250 and 1255. The distance between these points along the circular arc is the stator arc length (A_S), and the shortest distance between these two points is the sweep width (W_S) of the inverse apex region. On the rotor, contact with the inverse apex region 1240 of the stator occurs between points 1260a and 1265a on one rotor tip and between points 1260b and 1265b on the other rotor tip. The distance between points 1260a and 1265a (or 1260b and 1265b) around the rotor is the rotor arc length (A_R), and the shortest distance between these two points is the sweep width (W_R) of the rotor.

[0102] For a helical rotor-stator assembly, contact between the rotor and stator occurs along curves that are the locus of contact points between the rotor and stator in each transverse "cross section". For non-offset trochoid

generating points in the envelope (i.e. the stator "inverse apex" of a hypotrochoid with outer envelope, or the "rotor tips" of an epitrochoid with inner envelope), this locus is a true helix. For offset trochoid generating points, the contact point moves across the arc length of the stator or rotor. This contact curve deviates from the true helix, but is visually substantially similar.

[0103] The locus of contact points between trochoid and envelope is more complex; in most embodiments, it sweeps across a substantially longer arc, so the contact path is a distorted helix. It is then "interrupted" as the contact point crosses the trochoid generating point. The resulting contact curves are discrete segments, roughly helical in appearance, but not true helices. These have a different slope than the continuous curve of the trochoid generating contact, and "bridge" points on that contact to form closed chambers.

[0104] FIG. 13A shows the cross-sectional shape 1310 of a helical stator cavity with no offset (such as the stator cavity 410 of FIGS. 4B and 4C) in a plane normal to a longitudinal access of the stator. FIG. 13B shows a close up view of the inverse apex region from the same angle as FIG. 13A. FIG. 13C shows the cross-sectional shape 1320 of the same stator cavity in a plane normal to the helical path of the stator inverse apex. FIG. 13D shows a close up view of the inverse apex region from the same angle as FIG. 13C. In this cross-section the tip or peak of the inverse apex is much sharper (the angle is more acute). More broadly, when a given planar profile is used to generate a helical pump, the apex becomes narrower and sharper in at least one direction. Practically, having an interior surface of the stator defining such a sharp helical thread (which is also a continuous contact line with the rotor)

can be problematic. Such a sharp feature can be subject to rapid wear, and can be fragile and prone to breakage.

[0105] FIG. 14A shows the cross-sectional shape 1410 of a helical stator cavity in a plane normal to a longitudinal access of the stator, for a stator with a similar size to that of FIGS. 13A-B but with an inward offset (as described in reference to FIG. 12). FIG. 14B shows a close up view of the inverse apex region from the same angle as FIG. 14A. From this viewpoint, the inverse apex region defines a circular arc with the radius of circle R_1. FIG. 14C shows the cross-sectional shape 1420 of the same stator cavity (with inward offset) in a plane normal to the helical path of the stator inverse apex region. FIG. 14D shows a close up view of the inverse apex region from the same angle as FIG. 14C. The inverse apex region defines a non-circular arc that has a minimum radius of curvature that is the radius of a circle R_2. Circle R_2 has a much smaller radius than circle R_1 (again, in this cross-section, the feature is sharper). Nonetheless, a stator with an offset geometry defines an inwardly protruding helical thread that is less sharp than in a helical stator of similar dimensions but with no offset.

[0106] FIG. 15A shows the cross-sectional shape 1510 of a helical hypotrochoidal rotor, in a plane normal to a longitudinal access of the rotor. The rotor has no offset (it is a true ellipse in cross-section), and corresponds to stator cavity shown in FIG. 13A. The tips of the rotor have a minimum radius of curvature that is the radius of circle R_3. FIG. 15B shows the cross-sectional shape 1520 of the rotor in a plane normal to the helical path of the rotor tips. In this projection, the threads of the helical rotor have a minimum radius of curvature that is the radius of circle R_4, The radius of circle R_4 is much smaller than the radius of circle R_3.

[0107] FIG. 16A shows the cross-sectional shape 1610 of a helical rotor in a plane normal to a longitudinal access of the rotor. The helical rotor in transverse cross-section has the same major diameter (*A-A*) and minor diameter (*B-B*) as the helical rotor of FIG. 15A, but is not a true ellipse. Its transverse cross-sectional shape 1610 is inwardly offset from each point on an ellipse (indicated by dashed outline 1615) by a fixed distance "*d*" measured normal to a tangent to the ellipse at each point on the ellipse. The offset rotor corresponds to the stator cavity illustrated in FIG. 14A. The tips of the offset rotor have a minimum radius of curvature that is the radius of circle R_5. Circle R_5 has a smaller radius than circle R_3. In other words the offset rotor is more "pointy" in transverse cross-section than a similarly sized elliptical (truly hypotrochoidal) rotor. FIG. 16B shows the cross-sectional shape 1620 of the offset rotor in a plane normal to the helical path of the rotor tips. At this angle, the threads or ridges of the helical rotor have a minimum radius of curvature which is the radius of circle R_6. Circle R_6 has a radius that is smaller than the radius of circle R_5, and much smaller than the radius of circle R_4.

[0108] For the stator with no offset illustrated in FIGS. 13A-D, the sweep width across the inverse apex is infinitesimally small. FIG. 17A shows the sweep width W_1 across the inverse apex region for a stator cavity with an offset (same as in FIG. 14A), having cross-sectional shape 1410 in a plane normal to a longitudinal access of the stator. FIG. 17B shows the sweep width W_2 across the inverse apex region for the same stator cavity with cross-sectional shape 1420 (same as in FIG. 14C) in a plane normal to the helical path of the stator inverse apex region. FIG. 18A shows the sweep width W_3 across the rotor tips for an elliptical rotor with cross-sectional shape 1510 (same as in FIG. 15A) in a plane normal to a longitudinal access of the rotor.

FIG. 18B shows the sweep width W_4 across the rotor tips for the same elliptical rotor with cross-sectional shape 1520 (same as in FIG. 15B) in a plane normal to the helical path of the stator inverse apex region. FIG. 19A shows the sweep width W_5 across the rotor tips for an offset rotor with cross-sectional shape 1610 (same as in FIG. 16A) in a plane normal to a longitudinal access of the rotor. FIG. 19B shows the sweep width W_6 across the rotor tips for the same rotor with cross-sectional shape 1620 (same as in FIG. 16B) in a plane normal to the helical path of the stator inverse apex region.

[0109] For the stator with no offset illustrated in FIGS. 13A-D, the arc length across the inverse apex is infinitesimally small. FIG. 17A shows the arc length A_1 across the inverse apex region for a stator cavity with an offset (same as in FIG. 14A), having cross-sectional shape 1410 in a plane normal to a longitudinal access of the stator. FIG. 17B shows the arc length A_2 across the inverse apex region for the same stator cavity with cross-sectional shape 1420 (same as in FIG. 14C) in a plane normal to the helical path of the stator inverse apex region. FIG. 18A shows the arc length A_3 across the rotor tips for an elliptical rotor with cross-sectional shape 1510 (same as in FIG. 15A) in a plane normal to a longitudinal access of the rotor. FIG. 18B shows the arc length A_4 across the rotor tips for the same elliptical rotor with cross-sectional shape 1520 (same as in FIG. 15B) in a plane normal to the helical path of the stator inverse apex region. FIG. 19A shows the arc length A_5 across the rotor tips for an offset rotor with cross-sectional shape 1610 (same as in FIG. 16A) in a plane normal to a longitudinal access of the rotor. FIG. 19B shows the arc length A_6 across the rotor tips for the same elliptical rotor with cross-sectional shape 1620 (same as in FIG. 16B) in a plane normal to the helical path of the stator inverse apex region.

[0110] In summary, the offset rotor has sharper features than the non-offset rotor, whereas the offset stator has a more rounded inverse apex region than the non-offset stator. For both the offset and non-offset components, the helicization makes the features sharper than they would be in a straight (non-helicized version) of the rotor-stator assembly. Because the lead of the stator is shorter than that of the rotor (by half in the case of a 2:1 rotor lobe:stator lobe rotary machine) the "sharpening" of the stator features upon helicization is more dramatic than for the corresponding rotor.

[0111] The degree of offset can be selected to give desirable relative rotor and stator profiles. In particular, the degree of offset can be selected to achieve a particular design objective that may offer practical advantages.

[0112] In one approach, the offset geometry can be selected based on the radius of curvature of the outwardly protruding thread of the rotor relative to the radius of curvature of the inwardly protruding inverse apex region (or thread) of the stator. In some embodiments, for example, the degree of offset may be selected so that circle R_6 in FIG. 16B (for the rotor) has about the same radius as circle R_2 in FIG. 14D (for the stator). Selecting the offset geometry of the stator-rotor assembly so that these radii are approximately or precisely matched, can assist with balancing stresses in the rotary machine, and improving durability. If there is a big discrepancy between these radii, one component may be more subject to failure than the other. For example, with a very small or no offset the inwardly protruding thread of the stator will be very sharp. If, during operation of the rotary machine there is a large contact load between the rotor and stator along their contact lines, the fragile stator thread may be prone to breakage or excessive wear. It may be possible to improve the durability of the rotor-stator assembly by using an offset

geometry to increase the minimum radius of curvature of the stator thread so that it is the same as or even greater than the minimum radius of curvature of the rotor thread (when viewed in a plane normal to the helical threads).

[0113] In other embodiments, the degree of offset may be selected so that circle R_5 in FIG. 16A (for the rotor) has about the same radius as circle R_1 in FIG. 14B (for the stator).

[0114] In another approach, the offset geometry can be selected based on the relative sweep widths of the rotor and stator. In some embodiments, the degree of offset may be selected so that the sweep width on the helical rotor is about the same as the sweep width on the corresponding helical stator (in a plane normal to the helical paths of the rotor and stator, respectively), or so that the sweep width on the rotor is even less than on the stator. For example, the degree of offset may be selected so that sweep width W_2 in FIG. 17B for the stator is about the same as sweep width W_6 in FIG. 19B for the rotor. Consideration of relative rotor/stator sweep widths can be important, for example, if dynamic seals are used on the rotor and stator. If the sweep widths are similar, for example, the rotor and stator seals can be made to be more similar in their properties.

[0115] In other embodiments, the degree of offset may be selected so that sweep width W_1 in FIG. 17A for the stator is about the same as sweep width W_5 in FIG. 19A for the rotor.

[0116] In another approach, the offset geometry can be selected based on the relative arc lengths on the rotor and stator. For example, the degree of offset may be selected so that the arc length on the helical rotor is about the same as the arc length on the corresponding helical stator (in a plane normal

to the helical paths of the rotor and stator, respectively, or so that the arc length on the rotor is shorter than on the stator. For example, the degree of offset may be selected so that arc length A_2 in FIG. 17B for the stator is about the same as arc length A_6 in FIG. 19B for the rotor. The relative rotor and stator arc lengths can be important, for example, in relation to the tendency of each component to be subject to wear. The component with the shorter arc length may be more subject to wear. It could be desirable to have the two components wear more evenly, or to have the component that is easier to repair or replace (typically the rotor) be the one which tends to wear more quickly.

[0117] In other embodiments, the degree of offset may be selected so that arc length A_1 in FIG. 17A for the stator is about the same as arc length A_5 in FIG. 19A for the rotor.

[0118] The offset geometry of the stator-rotor assembly can also be selected so that the tendency for a fluid leak path to exist or form between the stator and rotor (at their various contact points) is reduced. For example, if fluid leakage is assumed to be a function of a separation distance between the rotor and stator as well as the length of a constricted path between rotor and stator, it is possible to adjust these variables to reduce the tendency for leakage. For non-offset embodiments, the leak path looks more like an orifice, whereas for offset embodiments, the leak path looks more like a pipe or channel.

[0119] For rotary machines based on a stator that is epitrochoidal and the rotor is shaped as the inner envelope of that stator, the rotor and stator can have cross-sectional profiles that are outwardly offset along the normals of their planar transverse cross-sections. Even though the offset is the other way

around in such machines, the degree of offset can be selected based on similar considerations to those discussed above.

[0120] In other variations on the helical trochoidal rotary machines described herein, instead of being offset along the normals of their planar transverse cross-sections, the rotor and stator profiles can be offset along the normals of their outer or inner body surface, respectively. Geometrically, for example, this would be equivalent to adding a coating of substantially uniform thickness to the rotor or the inner surface of the stator, and removing a layer of substantially uniform thickness from the corresponding stator or rotor. For example, in embodiments where the rotor is hypotrochoidal and undergoes planetary motion within a stator that is shaped as an outer envelope of that rotor, the rotor profile can be inwardly offset in a manner equivalent to having a layer of substantially uniform thickness removed from the outer surface of the rotor, with the corresponding stator profile being inwardly offset in a manner equivalent to having a layer of substantially uniform thickness added to the inner surface or cavity of the stator. In other embodiments where the stator is epitrochoidal, and the rotor undergoes planetary motion within the stator and is shaped as the inner envelope of that stator, the rotor and stator can have cross-sectional profiles that are outwardly offset along the normals of their outer and inner surfaces, respectively, in a manner equivalent to adding a layer of substantially uniform thickness to the rotor and removing a layer of substantially uniform thickness from the inner surface or cavity of the stator.

[0121] As with other positive displacement machines, embodiments of the machines described herein can be used as hydraulic motors, pumps (including vacuum pumps), compressors, expanders, engines and the like. The helical

rotary machines described herein can provide relatively high displacement/pump volume for their size, relative to PCPs for example.

[0122] In one application, embodiments of the machines described herein can be used in electric submersible pump (ESP) systems, for example, as downhole pumps in the oil and gas industry for pumping production fluids to the surface.

[0123] In the same application, embodiments of the machines described herein can be used for top driven submersible pumps driven by rotating shafts connecting a surface mounted drive system to the pump for example, as downhole pumps in the oil and gas industry for pumping production fluids to the surface.

[0124] Various different embodiments of the machines described herein can be particularly suitable for:

[0125] handling highly viscous fluids, as shear is low and the pump chambers have constant shape and volume (unless designed otherwise);

[0126] handling large pressure differentials with modest specific flow, as numerous stages can readily be provided;

[0127] use as vacuum pumps and compressors, because they are fully scavenging;

[0128] handling fluids with significant gas or solids content (because of their low shear operation, and particularly if additional features are used to enhance solids handling or tolerance);

[0129] pumping applications that require a long, narrow form (e.g. ESP).

[0130] applications where positive displacement pumping with steady flow is a high priority (e.g. very dense materials, such as concrete; flow metering or dosing, e.g. filling injection molds).

[0131] There are some important differences between conventional progressive cavity pumps (PCPs), and rotary machines having architectures as described herein. In rotary machines having architectures as described herein, there is a continuous line of contact between the rotor and stator. In some embodiments a metal spring seal (similar to a slinky toy or piston ring) can be used between the stator and rotor to provide a positive seal with no elastomer. In PCPs the stator is often made from or lined with an elastomer, to provide sealing. This material often degrades and needs to be replaced. In PCPs, the rotor interacts with a particular portion of the stator in at least two orientations. In rotary machines as described herein, the moving line of contact along the ridge of the helical rotor only interacts with the stator in one orientation, which can provide operational advantages. A transverse cross-section of a typical PCP rotor- stator assembly shows a circular rotor positioned or contained between two parallel sides of the stator profile. This arrangement limits the ability of the rotor to move when a foreign particle such as sand or another hard substance becomes trapped in this contact region. The result is a potentially high abrasion condition. The rotor in rotary machines having architectures as described herein is not constrained in this manner. Furthermore, the rotary machines described herein have different flow characteristics than PCPs, which may be more favorable for certain applications.

[0132] All-metal PCPs typically have lower volumetric efficiencies and lower overall pump efficiencies than PCPs with an elastomer. The use of an

elastomer in a PCP also typically enhances the solids handling capability of the pump versus an all-metal PCP, resulting in longer operational lifetimes in many applications. For example, in one study in a high temperature oil well application, the overall efficiency of an all-metal pump ranged from about 20-50% with a lifetime of less than 500 days, whereas a comparable elastomer PCP operated with efficiency in the range of 25-65% with about a 30 day longer lifetime. The efficiency of both types of PCP tends to decline quite rapidly during operation of the pump.

[0133] Embodiments of the helical trochoidal rotary machines described herein have been shown to provide high volumetric and overall efficiencies, and to operate with low degradation in efficiency over time.

Example

[0134] Longevity testing was performed on a 2-stage helical trochoidal rotary pump (12 inches (30.48 cm) long, 2.8 inches (7.11 cm) diameter) having a rotor with an inward offset (relative to an elliptical transverse rotor cross-section) such that the rotor and stator peaks have a similar minimum radius. The rotor and stator were made of 4140 hardened steel. The operating fluid was mineral seal oil, a wellbore simulated fluid with a viscosity of 3 cP, intended to simulate a downhole lift application of oil with water cut. The pump was operated at 400 RPM with the pressure set at 25psi per stage (50 psi total), and the flow rate was 25 GPM. The pump was operated and tested under these conditions over a period of 136 days, which at 400 RPM represents 78 million cycles. FIG. 20 is a graph showing the overall efficiency (plot A) and the volumetric efficiency (plot B) of the pump versus the number of cycles. Total efficiency is a measure of how much shaft power is converted into useful work. Volumetric efficiency is a measure of slip. Slip

is the ratio of actual flow delivered by a pump at a given pressure to its theoretical flow, where the theoretical flow can be calculated by multiplying the pump's displacement per revolution by its driven speed. The observed volumetric and overall efficiency values are high, especially considering that both the rotor and stator are made of metal, and the pump did not have dynamic seals on the rotor or stator. As can be seen from FIG. 20, the pump demonstrated very little loss in overall and volumetric efficiency over the test period, and almost no loss over the first 70 million cycles.

[0135] While particular elements, embodiments and applications of the present invention have been shown and described, it will be understood, that the invention is not limited thereto since modifications can be made by those skilled in the art without departing from the scope of the present disclosure, particularly in light of the foregoing teachings.

What is claimed is:

1. A rotary machine comprising a stator and a rotor disposed within the stator,

said rotor having a rotor axis and a helical profile wherein, at any cross-section transverse to said rotor axis along at least a portion of a length of said rotor, said rotor has a rotor shape that is inwardly offset from a hypotrochoidal shape,

said stator having a stator axis and a helical profile, wherein said stator has a stator shape at any cross-section transverse to said stator axis along at least a portion of a length of said stator that is an outer envelope formed when said rotor shape undergoes planetary motion,

wherein said rotor is configured to undergo planetary motion within said stator.

2. The rotary machine of claim 1 wherein, at any cross-section transverse to said rotor axis along at least a portion of a length of said rotor, said rotor has a rotor shape that is inwardly offset from said hypotrochoidal shape along the normals of said transverse cross-section.

3. The rotary machine of claim 1 wherein, at any cross-section transverse to said rotor axis along at least a portion of a length of said rotor, said rotor has a rotor shape that is inwardly offset along the normals of the outer surface of said rotor.

4. The rotary machine of any of claims 1 to 3 wherein:

the rotor shape has n lobes, where n is an integer;

the stator shape has (n-1) lobes;

the pitch of the rotor is the same as the pitch of the stator; and

the ratio of the lead of the rotor to the lead of the stator is n:(n-1).

5. The rotary machine of claims 1 to 3 wherein said hypotrochoidal shape is an ellipse, and n = 2, wherein the pitch of the rotor is the same as the pitch of the stator, and the ratio of the lead of the rotor to the lead of the stator is 2:1.

6. The rotary machine of any of claims 1 to 5 wherein the rotary machine is a multi-stage machine and a plurality of chambers are formed between cooperating surfaces of said rotor and said stator.

7. The rotary machine of claim 6 wherein each of said plurality of fluid chambers has approximately the same volume.

8. The rotary machine of any of claims 1 to 5 wherein said helical profile of said stator defines at least one inwardly protruding helical thread, and said helical axis of said rotor defines at least one outwardly protruding helical thread, and wherein said rotor shape is inwardly offset from a hypotrochoidal shape to a degree such that the minimum radius of curvature of said at least one outwardly protruding helical thread of said rotor in a plane normal to said at least one outwardly protruding helical thread, is substantially the same as the radius of curvature of said at least one inwardly protruding helical thread of said stator in a plane normal to said inwardly protruding helical thread.

9. The rotary machine of any of claims 1 to 5 wherein said helical profile of said stator defines at least one inwardly protruding helical thread, and said helical axis of said rotor defines at least one outwardly protruding helical thread, and wherein said rotor and stator each have a longitudinal axis, and wherein said rotor shape is inwardly offset from a hypotrochoidal shape to a degree such that the minimum radius of curvature of said at least one outwardly protruding helical thread of said rotor in a plane normal to said longitudinal axis of said rotor is substantially the same as the radius of curvature of said at least one inwardly protruding helical thread of said stator in a plane normal to said longitudinal axis of said stator.

10. The rotary machine of any of claims 1 to 5 wherein said helical profile of said stator defines at least one inwardly protruding helical thread, and said helical axis of said rotor defines at least one outwardly protruding helical thread, and wherein:

said rotor has a rotor sweep width across said at least one outwardly protruding helical thread in a plane normal to said helical thread;

said stator has a stator sweep width across said at least one inwardly protruding helical thread in a plane normal to said helical thread; and

said rotor shape is inwardly offset from a hypotrochoidal shape to a degree such that said rotor sweep width is substantially the same as said stator sweep width.

11. The rotary machine of any of claims 1 to 5 wherein said helical profile of said stator defines at least one inwardly protruding helical thread, and said helical axis of said rotor defines at least one outwardly protruding helical thread, and wherein:

said rotor and stator each have a longitudinal axis;

said rotor has a rotor sweep width across said at least one outwardly protruding helical thread in a plane normal to said longitudinal axis of said rotor;

said stator has a stator sweep width across said at least one inwardly protruding helical thread in a plane normal to said longitudinal axis of said stator; and

said rotor shape is inwardly offset from a hypotrochoidal shape to a degree such that said rotor sweep width is substantially the same as said stator sweep width.

12. The rotary machine of any of claims 1 to 5 wherein said helical profile of said stator defines at least one inwardly protruding helical thread, and said helical axis of said rotor defines at least one outwardly protruding helical thread, and wherein:

said rotor has a rotor arc length around said at least one outwardly protruding helical thread in a plane normal to said helical thread;

said stator has a stator arc length around said at least one inwardly protruding helical thread in a plane normal to said helical thread; and

said rotor shape is inwardly offset from a hypotrochoidal shape to a degree such that said rotor arc length is substantially the same as said stator arc length.

13. The rotary machine of any of claims 1 to 5 wherein said helical profile of said stator defines at least one inwardly protruding helical thread, and said helical axis of said rotor defines at least one outwardly protruding helical thread, and wherein:

said rotor and stator each have a longitudinal axis;

said rotor has a rotor arc length around said at least one outwardly protruding helical thread in a plane normal to said longitudinal axis of said rotor;

said stator has a stator arc length around said at least one inwardly protruding helical thread in a plane normal to said longitudinal axis of said stator; and

said rotor shape is inwardly offset from a hypotrochoidal shape to a degree such that said rotor arc length is substantially the same as said stator arc length.

14. A rotary machine comprising a stator and a rotor disposed within the stator,

said stator having a stator axis and a helical profile wherein, at any cross-section transverse to said stator axis along at least a portion of a length of said stator, said stator has a stator shape that is outwardly offset from an epitrochoidal shape,

said rotor having a rotor axis and a helical profile, wherein said rotor has a rotor shape at any cross-section transverse to said rotor axis, along at least a portion of a length of said rotor, that is an inner envelope formed when said stator shape undergoes planetary motion,

wherein said rotor is configured to undergo planetary motion within said stator.

15. The rotary machine of claim 14 wherein, at any cross-section transverse to said stator axis along at least a portion of a length of said stator,

said stator has a stator shape that is outwardly offset from said epitrochoidal shape along the normals of said transverse cross-section.

16. The rotary machine of claim 14 wherein, at any cross-section transverse to said stator axis along at least a portion of a length of said stator, said stator has a stator shape that is outwardly offset along the normals of the inner surface of said stator.

17. The rotary machine of any of claims 14 to 16 wherein:
the stator shape has n-1 lobes, where n is an integer;
the rotor shape has n lobes;
the pitch of the rotor is the same as the pitch of the stator; and
the ratio of the lead of the rotor to the lead of the stator is n:(n-1).

18. The rotary machine of any of claims 14 to 16 wherein n = 2, the pitch of the rotor is the same as the pitch of the stator, and the ratio of the lead of the rotor to the lead of the stator is 2:1.

19. The rotary machine of any of claims 14 to 18 wherein the rotary machine is a multi-stage machine and a plurality of chambers are formed between cooperating surfaces of said rotor and said stator.

20. The rotary machine of claim 19 wherein each of said plurality of fluid chambers has approximately the same volume.

21. The rotary machine of any of claims 14 to 18 wherein said helical profile of said stator defines at least one inwardly protruding helical thread, and said helical axis of said rotor defines at least one outwardly protruding helical thread, and wherein said stator shape is outwardly offset from an epitrochoidal shape to a degree such that the minimum radius of curvature of said at least one outwardly protruding helical thread of said rotor in a plane normal to said at least one outwardly protruding helical thread, is substantially the same as the radius of curvature of said at least one inwardly protruding helical thread of said stator in a plane normal to said inwardly protruding helical thread.

22. The rotary machine of any of claims 14 to 18 wherein said helical profile of said stator defines at least one inwardly protruding helical thread, said helical axis of said rotor defines at least one outwardly protruding helical thread, and said rotor and stator each have a longitudinal axis, and wherein said stator shape is outwardly offset from an epitrochoidal shape to a degree such that the minimum radius of curvature of said at least one outwardly protruding helical thread of said rotor in a plane normal to said longitudinal axis of said rotor is substantially the same as the radius of curvature of said at least one inwardly protruding helical thread of said stator in a plane normal to said longitudinal axis of said stator.

23. The rotary machine of any of claims 14 to 18 wherein said helical profile of said stator defines at least one inwardly protruding helical thread, and said helical axis of said rotor defines at least one outwardly protruding helical thread, and wherein:

said rotor has a rotor sweep width across said at least one outwardly protruding helical thread in a plane normal to said helical thread;

said stator has a stator sweep width across said at least one inwardly protruding helical thread in a plane normal to said helical thread; and

said stator shape is outwardly offset from an epitrochoidal shape to a degree such that said rotor sweep width is substantially the same as said stator sweep width.

24. The rotary machine of any of claims 14 to 18 wherein said helical profile of said stator defines at least one inwardly protruding helical thread, and said helical axis of said rotor defines at least one outwardly protruding helical thread, and wherein:

said rotor and stator each have a longitudinal axis;

said rotor has a rotor sweep width across said at least one outwardly protruding helical thread in a plane normal to said longitudinal axis of said rotor;

said stator has a stator sweep width across said at least one inwardly protruding helical thread in a plane normal to said longitudinal axis of said stator; and

said stator shape is outwardly offset from an epitrochoidal shape to a degree such that said rotor sweep width is substantially the same as said stator sweep width.

25. The rotary machine of any of claims 14 to 18 wherein said helical profile of said stator defines at least one inwardly protruding helical thread, and said helical axis of said rotor defines at least one outwardly protruding helical thread, and wherein:

said rotor has a rotor arc length around said at least one outwardly protruding helical thread in a plane normal to said helical thread;

said stator has a stator arc length around said at least one inwardly protruding helical thread in a plane normal to said helical thread; and

said stator shape is outwardly offset from an epitrochoidal shape to a degree such that said rotor arc length is substantially the same as said stator arc length.

26. The rotary machine of any of claims 14 to 18 wherein said helical profile of said stator defines at least one inwardly protruding helical thread, and said helical axis of said rotor defines at least one outwardly protruding helical thread, and wherein:

said rotor and stator each have a longitudinal axis;

said rotor has a rotor arc length around said at least one outwardly protruding helical thread in a plane normal to said longitudinal axis of said rotor;

said stator has a stator arc length around said at least one inwardly protruding helical thread in a plane normal to said longitudinal axis of said stator; and

said stator shape is outwardly offset from an epitrochoidal shape to a degree such that said rotor arc length is substantially the same as said stator arc length.

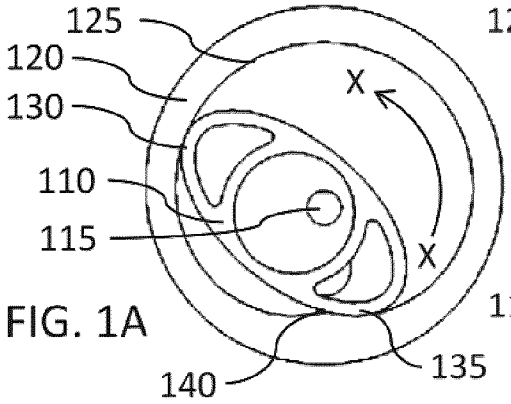


FIG. 1A

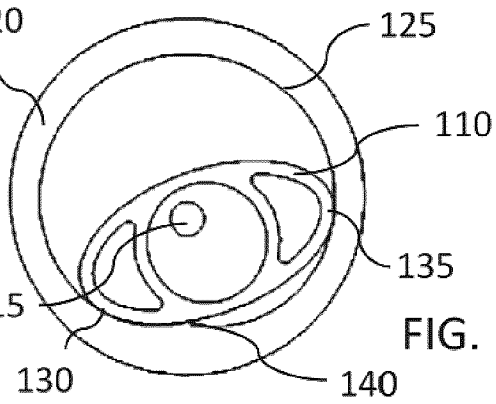


FIG. 1B

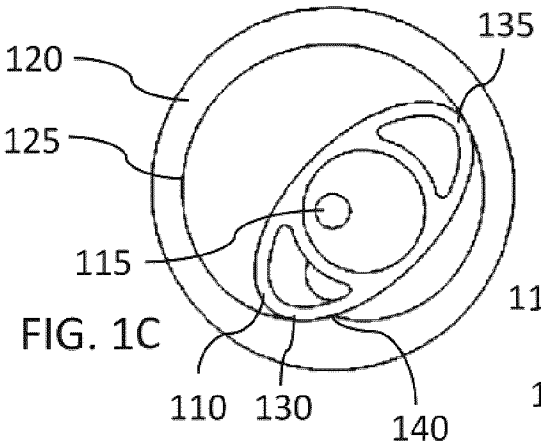


FIG. 1C

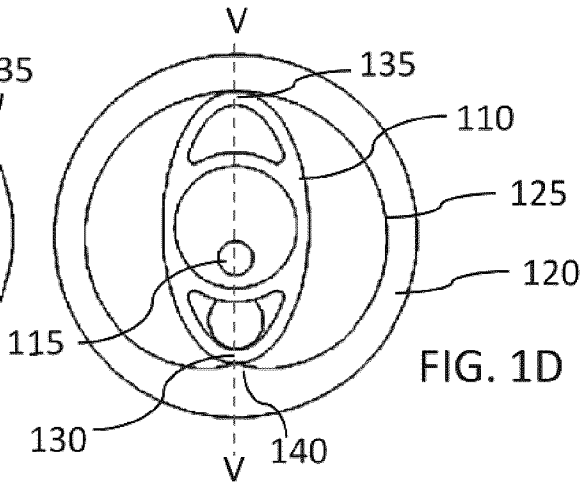


FIG. 1D

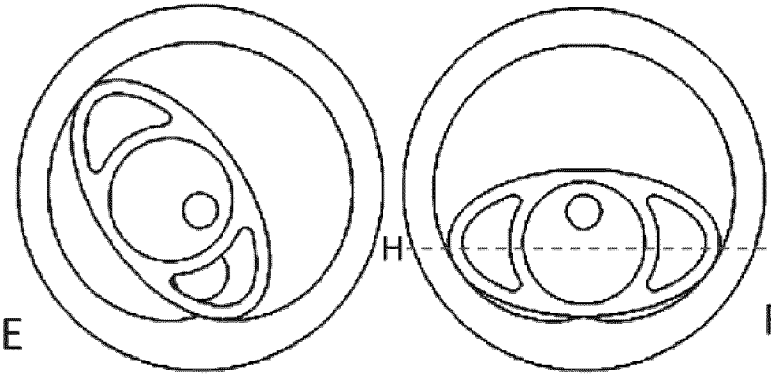


FIG. 1E

FIG. 1F

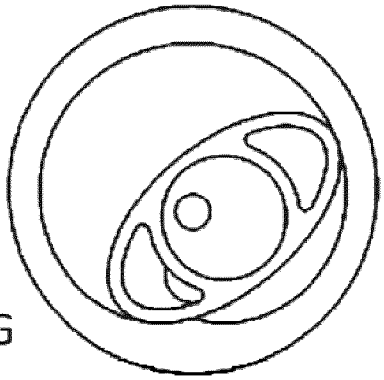


FIG. 1G

PRIOR ART

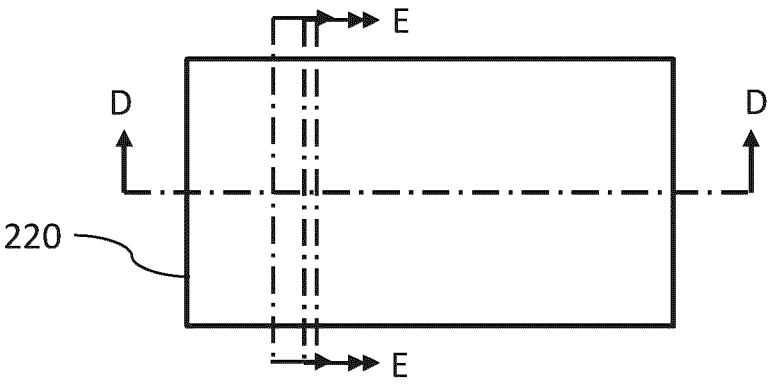
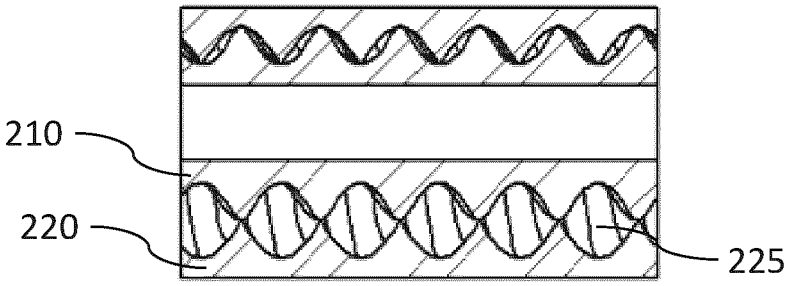
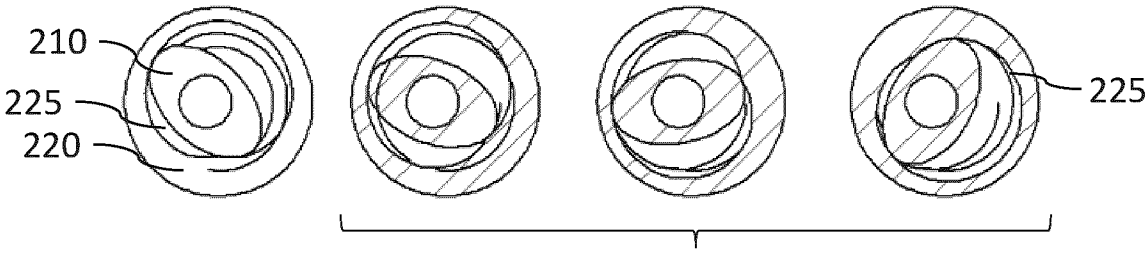


FIG. 2A



SECTION D-D

FIG. 2B



END VIEW

SECTIONS E-E

FIG. 2C

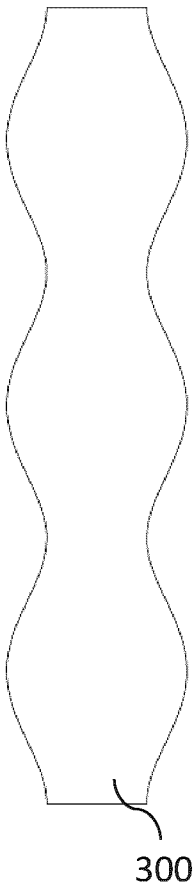


FIG. 3A

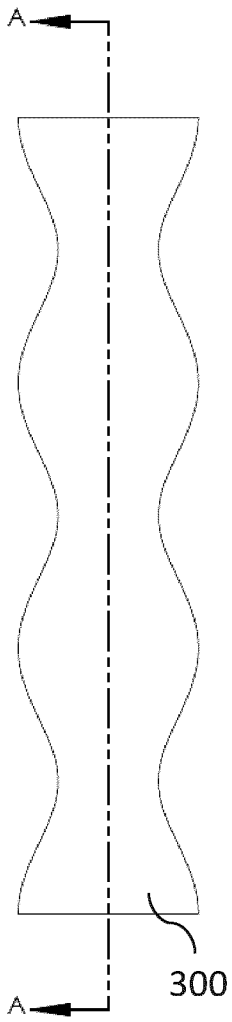


FIG. 3B

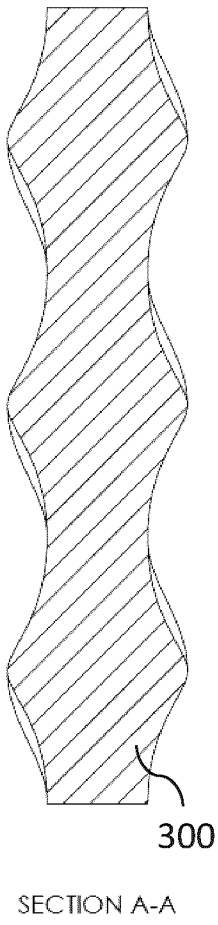


FIG. 3C

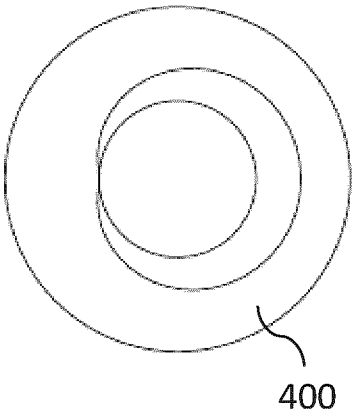


FIG. 4A

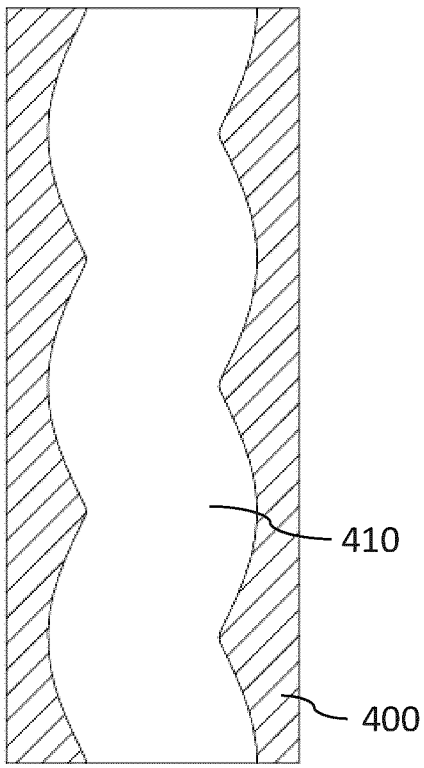


FIG. 4B

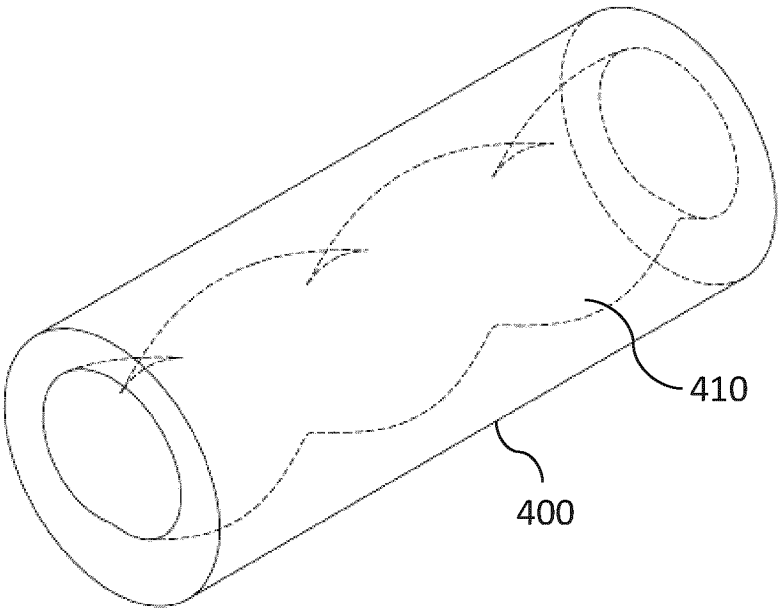


FIG. 4C

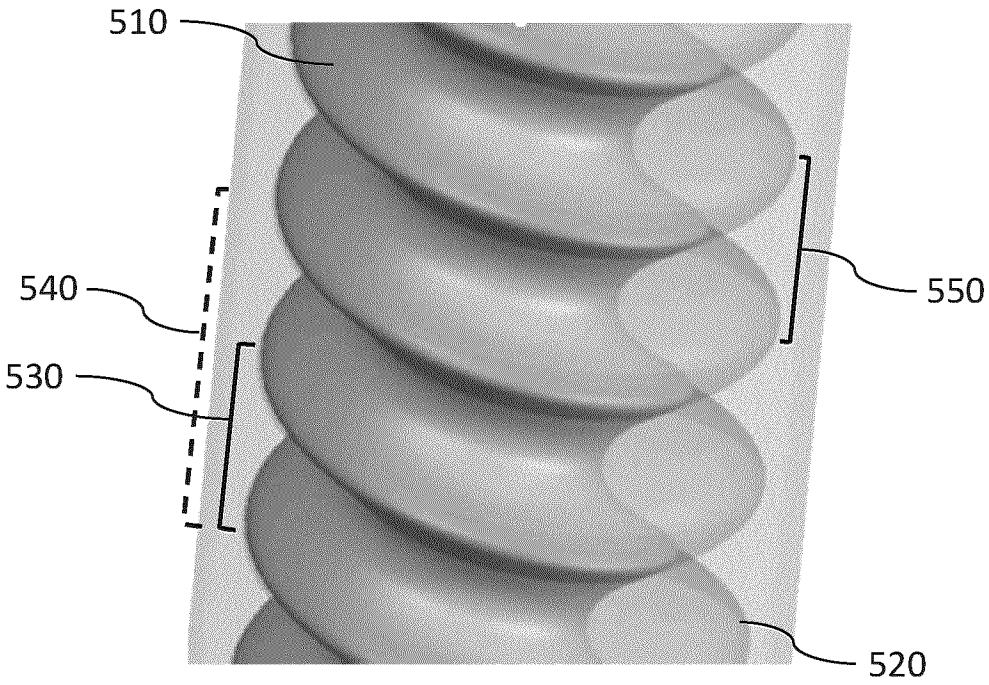


FIG. 5

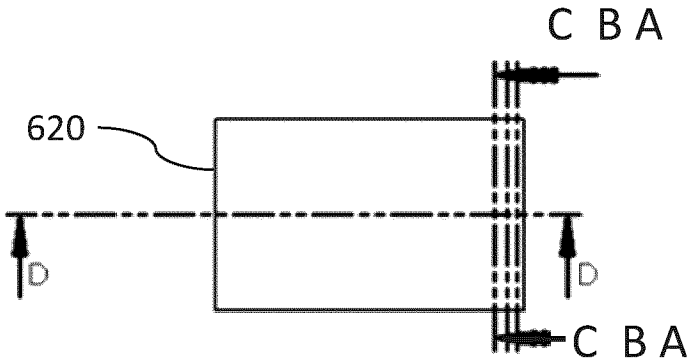
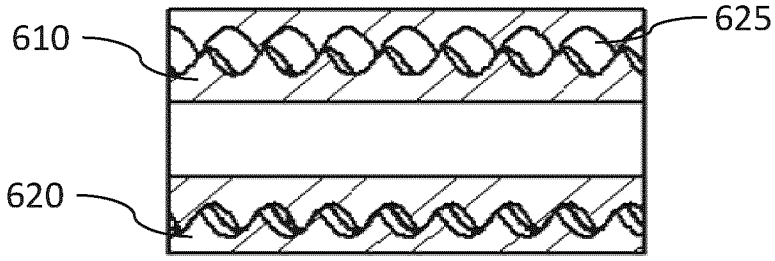
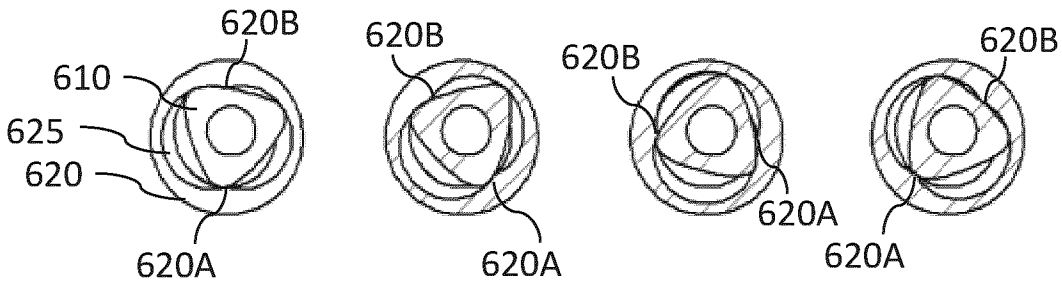


FIG. 6A



SECTION D-D

FIG. 6B



END VIEW SECTION A-A SECTION B-B SECTION C-C

FIG. 6C

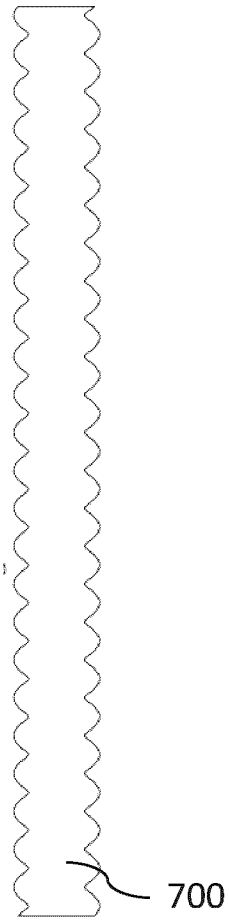


FIG. 7A

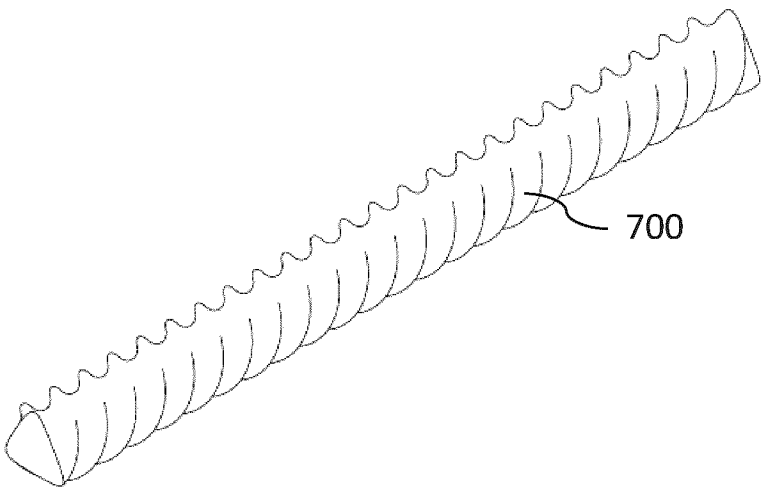


FIG. 7B

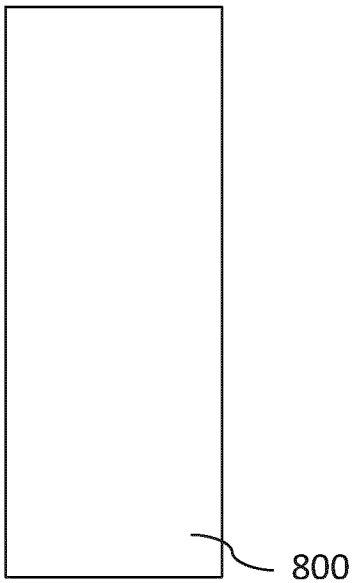


FIG. 8A

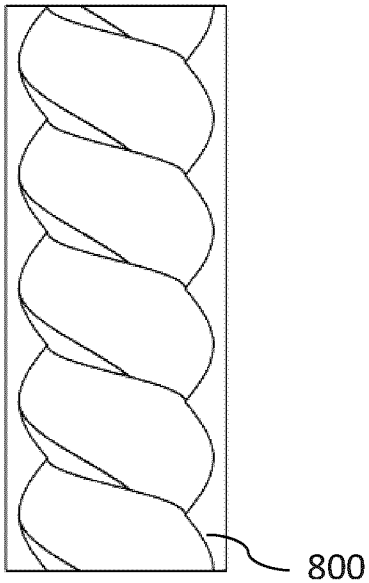


FIG. 8B

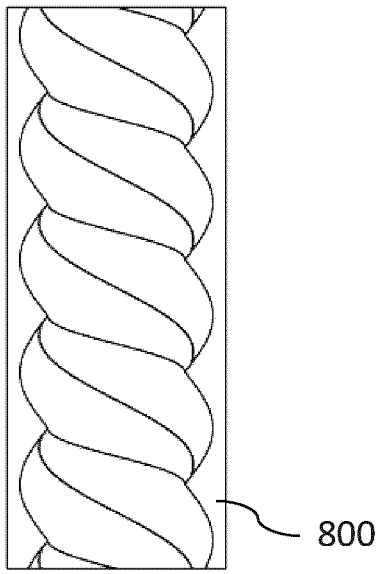


FIG. 8C

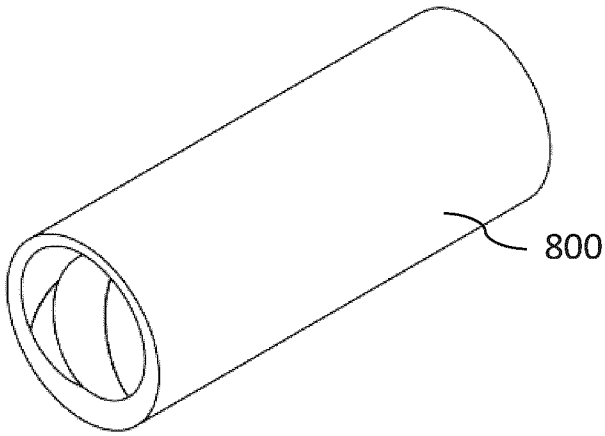


FIG. 8D

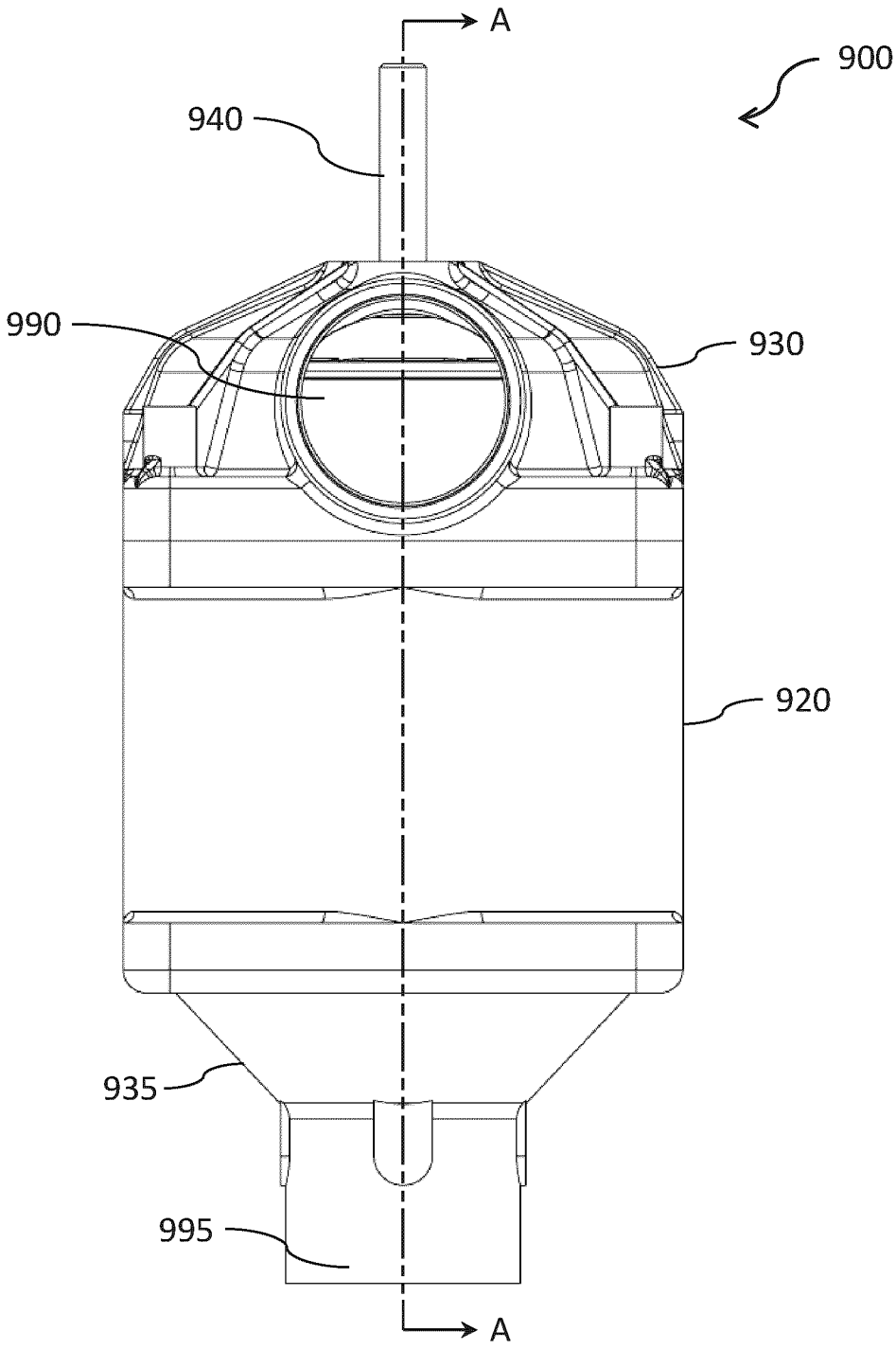


FIG. 9A

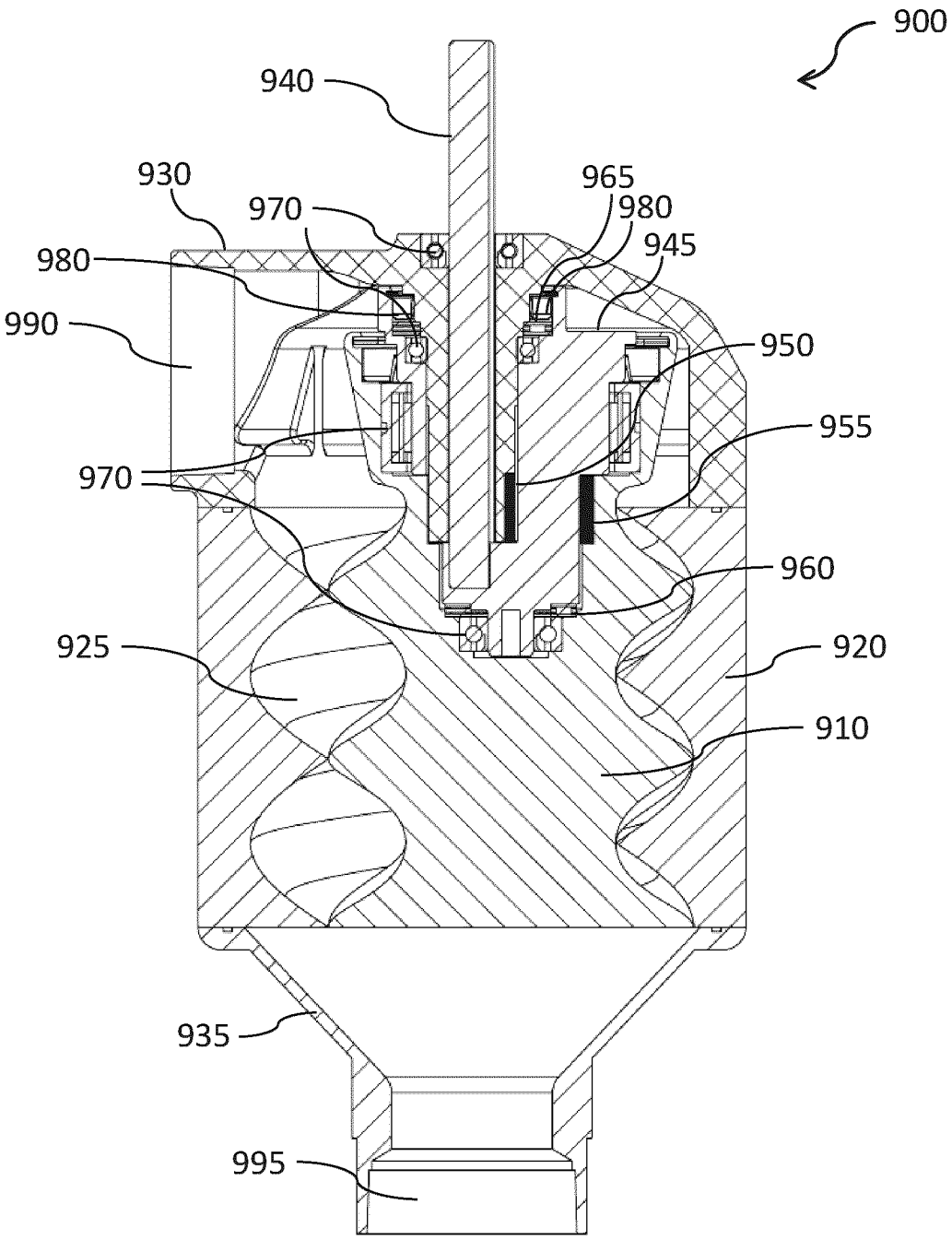

900
940
930
970
965
980
945
980
990
950
955
970
960
925
920
910
935
995

FIG. 9B

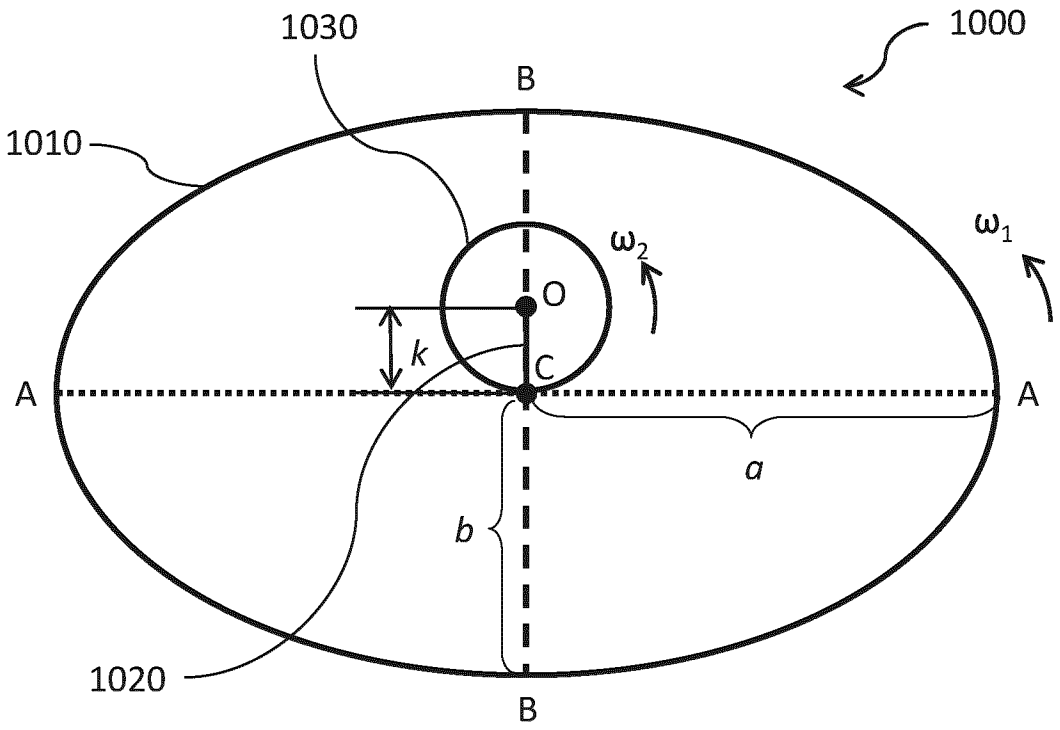


FIG. 10

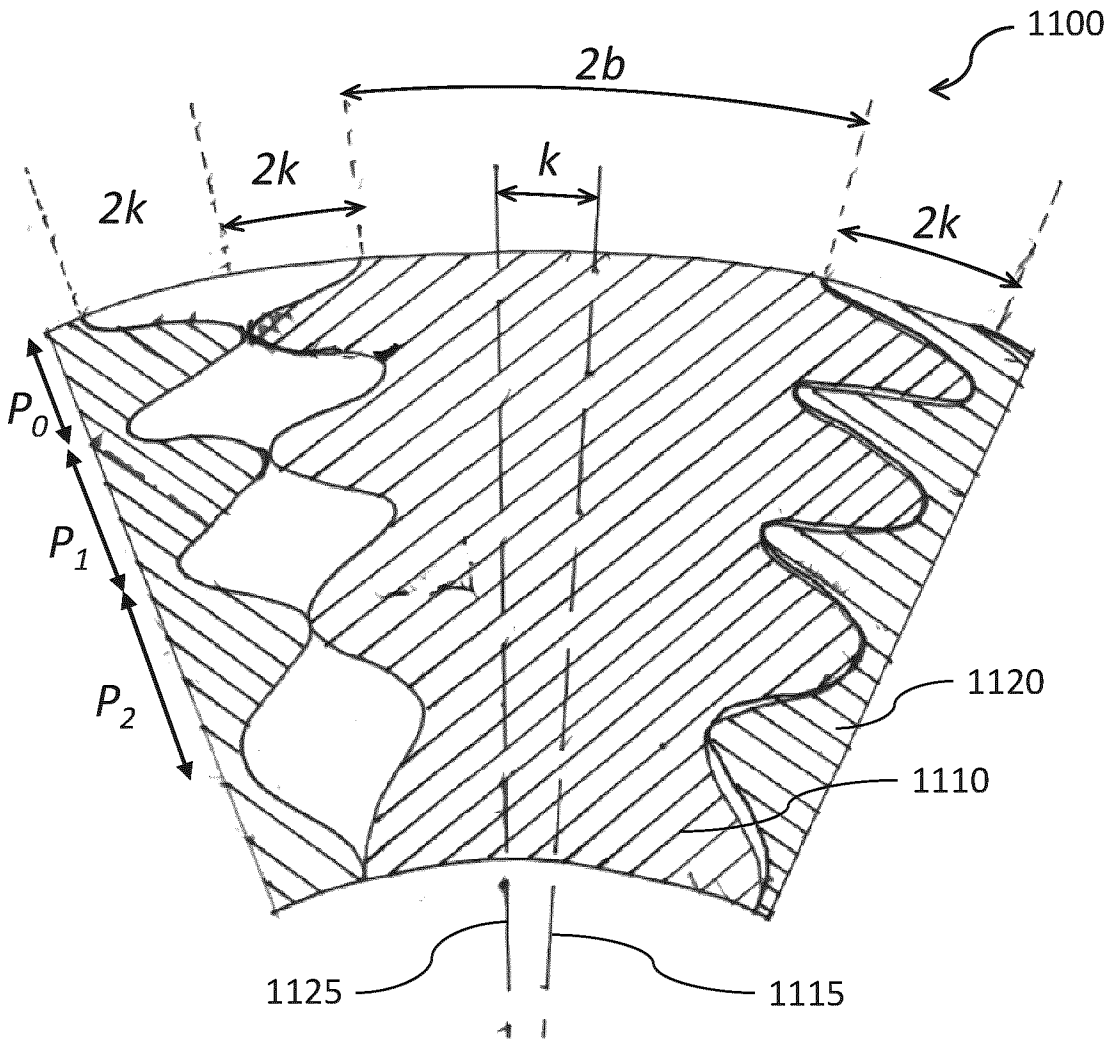


FIG. 11

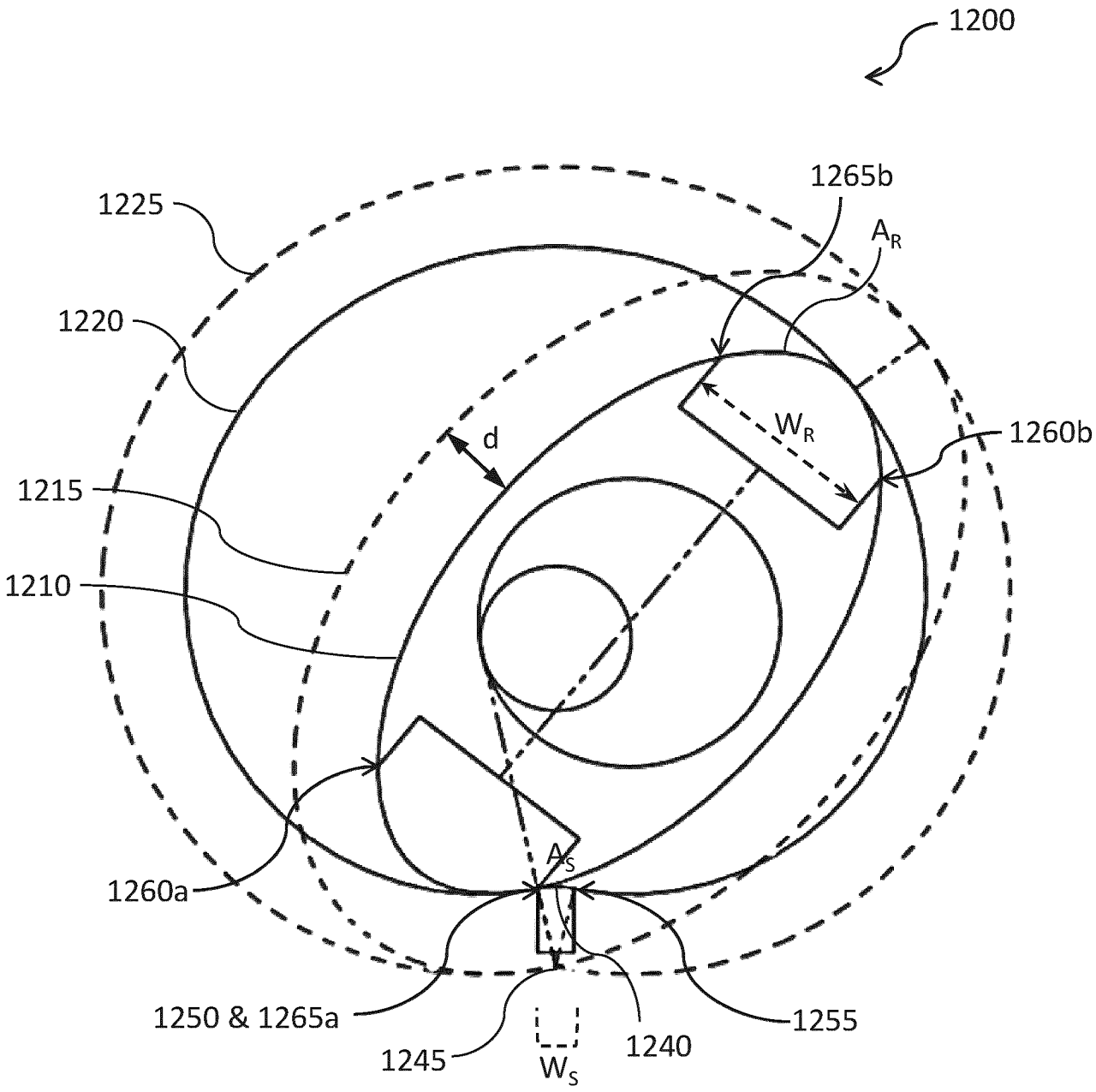

1200
1225
1265b
A_R
1220
W_R
1260b
d
1215
1210
A_S
1260a
1250 & 1265a
1245
W_S
1240
1255

FIG. 12

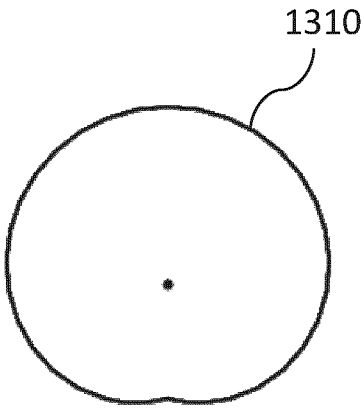


FIG. 13A



FIG. 13B

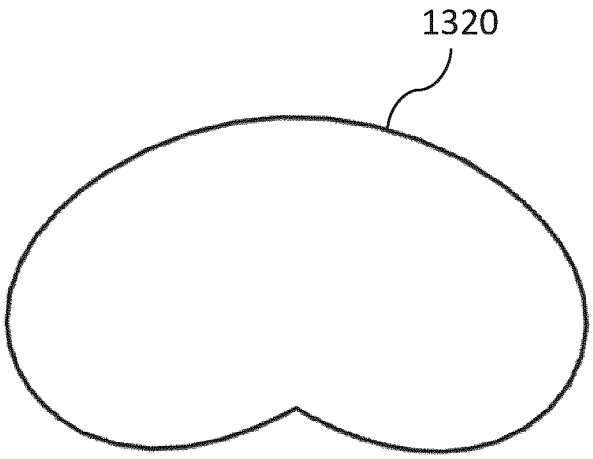


FIG. 13C



FIG. 13D

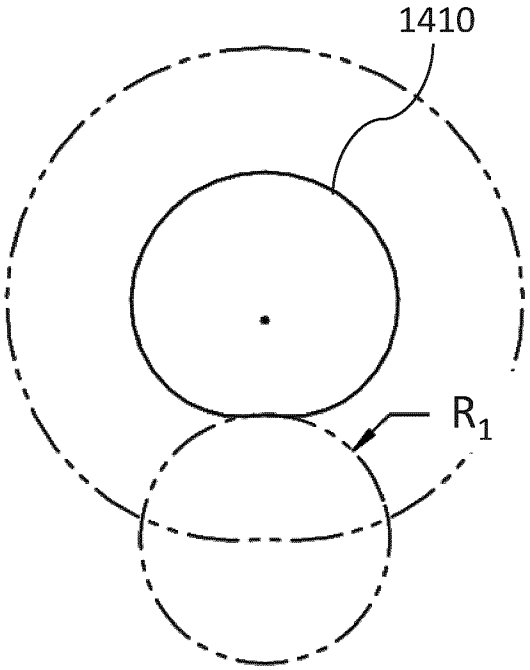


FIG. 14A



FIG. 14B

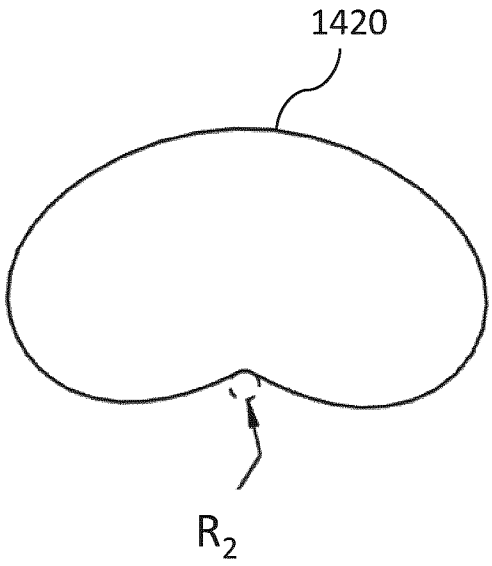


FIG. 14C

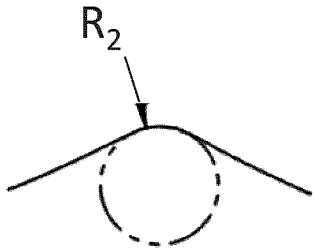


FIG. 14D

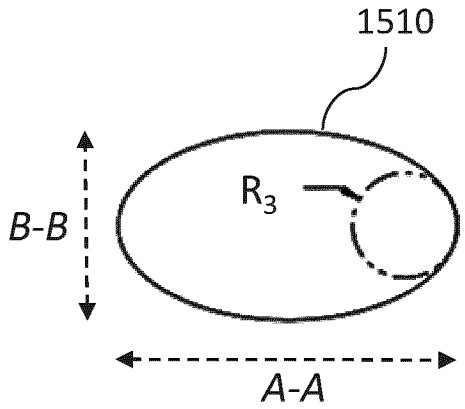


FIG. 15A

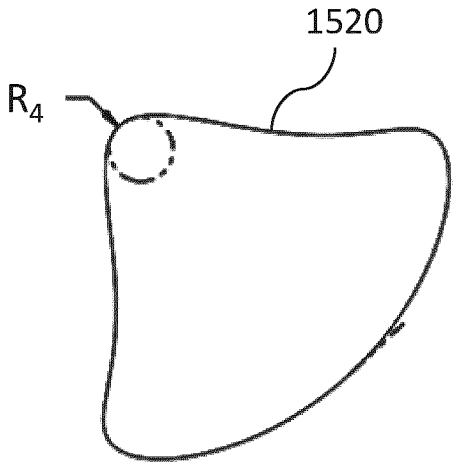


FIG. 15B

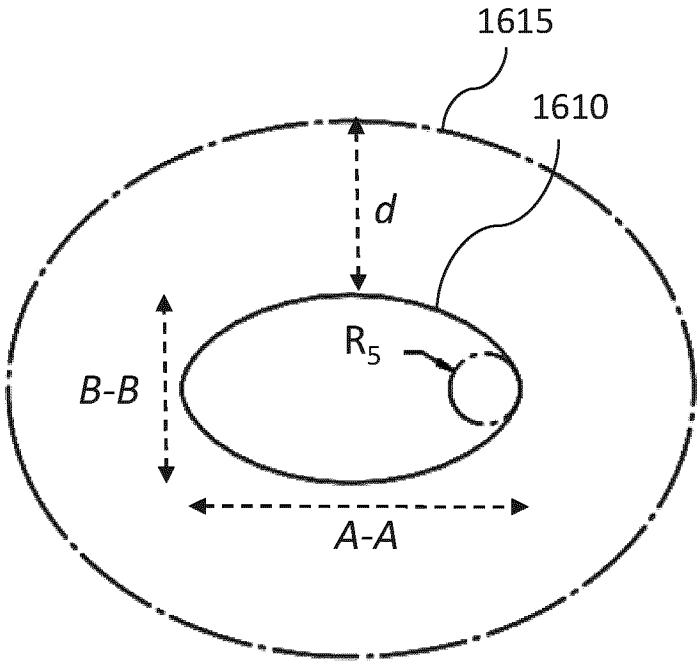


FIG. 16A

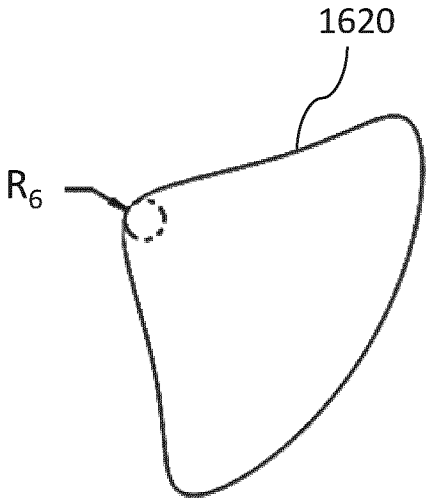


FIG. 16B

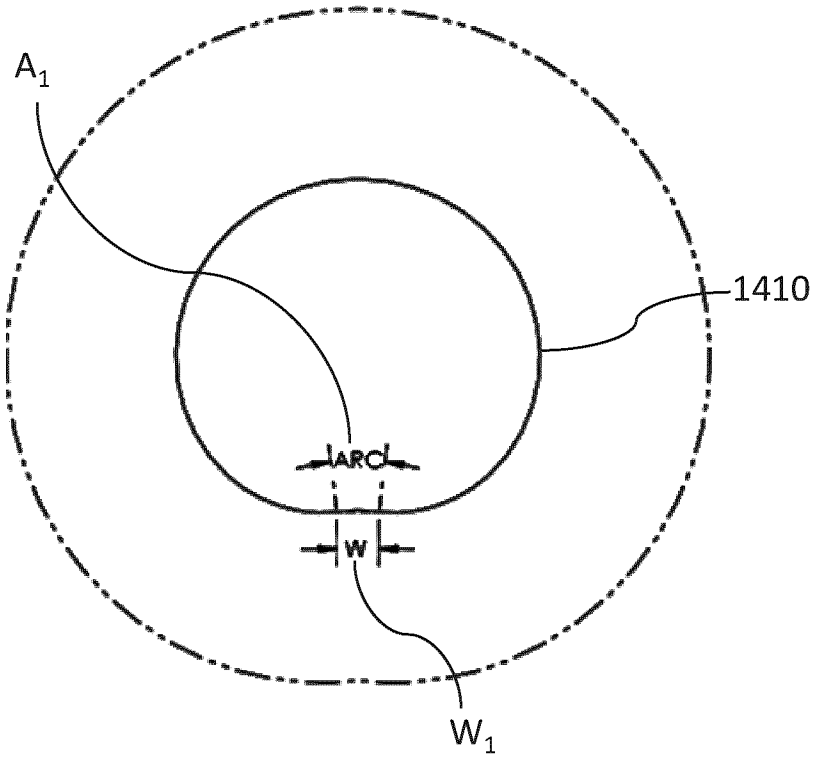


FIG. 17A

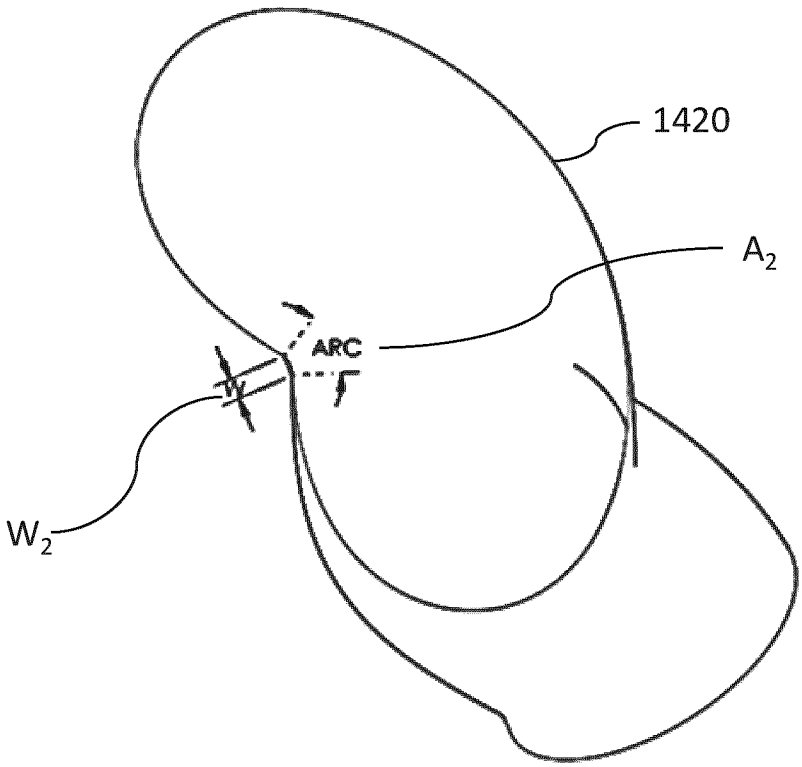


FIG. 17B

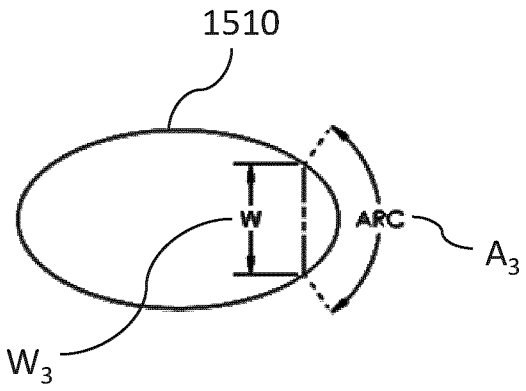


FIG. 18A

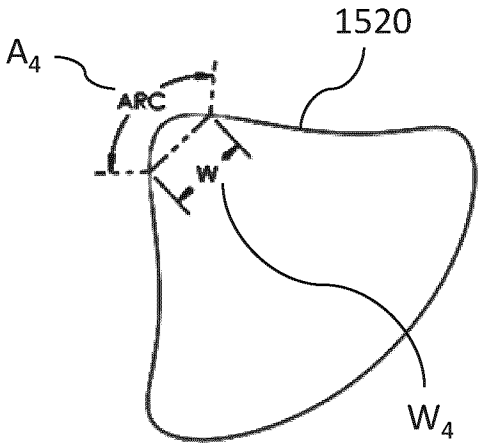


FIG. 18B

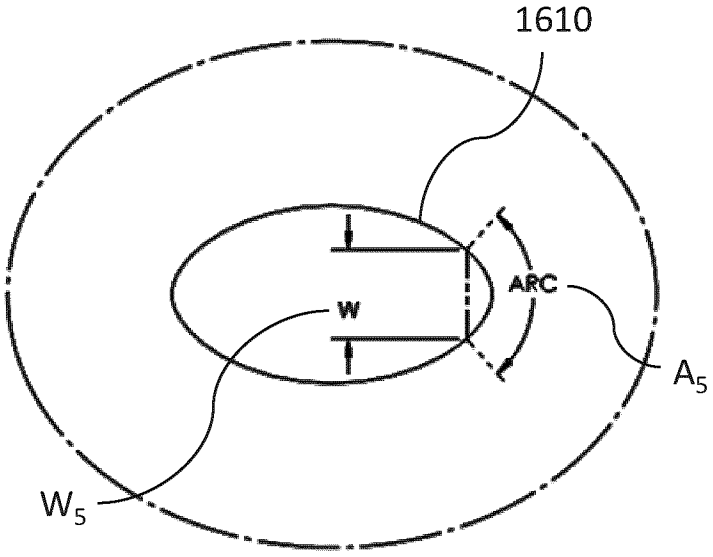


FIG. 19A

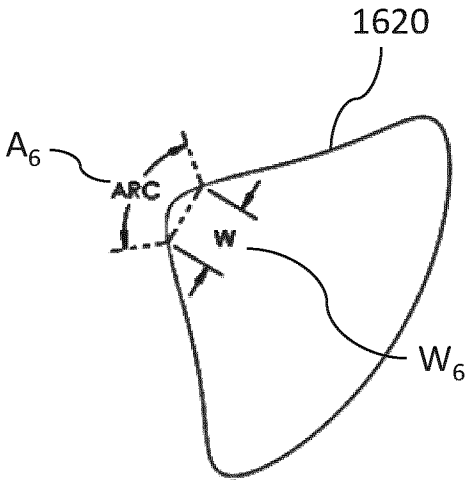


FIG. 19B

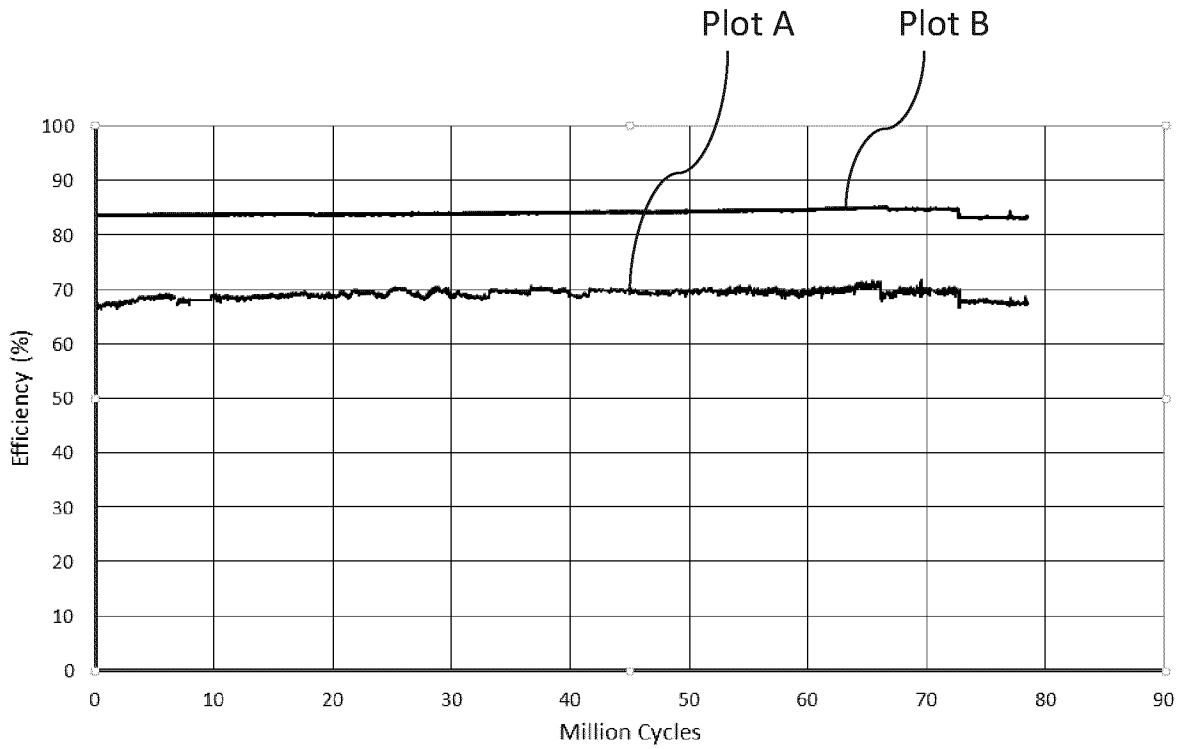

Plot A
Plot B
Efficiency (%)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
Million Cycles

FIG. 20

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CA2019/051273

A. CLASSIFICATION OF SUBJECT MATTER
IPC: ***F01C 21/08*** (2006.01) , ***F01C 1/107*** (2006.01) , ***F01C 21/10*** (2006.01) , ***F04C 15/00*** (2006.01) , ***F04C 2/107*** (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
F01C 21/08 (2006.01) , ***F01C 1/107*** (2006.01) , ***F01C 21/10*** (2006.01) , ***F04C 15/00*** (2006.01) , ***F04C 2/107*** (2006.01)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic database(s) consulted during the international search (name of database(s) and, where practicable, search terms used)
Questel-Orbit (Fampat)
(Keywords: trochoid, hypotrochoid, ellipse, epitrochoid, rotor, stator, profile, helical, offset)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5439359 A (LEROY, A., et al.) 8 August 1995 (08-09-1995) *Whole document*	1 to 26
A	EP 1988288 B1 (GRANN, H.) 16 March 2011 (16-03-2011) *Whole document*	1 to 26
A	US 7837451 B2 (WIEDENHOEFER, J. F., et al.) 23 November 2010 (23-11-2010) *Whole document*	1 to 26
A	US 6093004 A (VARADAN, R., et al.) 25 July 2000 (25-07-2000) *Whole document*	1 to 26

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

☑ See patent family annex.

*	Special categories of cited documents:
"A"	document defining the general state of the art which is not considered to be of particular relevance
"D"	document cited by the applicant in the international application
"E"	earlier application or patent but published on or after the international filing date
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O"	document referring to an oral disclosure, use, exhibition or other means
"P"	document published prior to the international filing date but later than the priority date claimed
"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&"	document member of the same patent family

Date of the actual completion of the international search 28 October 2019 (28-10-2019)	Date of mailing of the international search report 13 November 2019 (13-11-2019)
Name and mailing address of the ISA/CA Canadian Intellectual Property Office Place du Portage I, C114 - 1st Floor, Box PCT 50 Victoria Street Gatineau, Quebec K1A 0C9 Facsimile No.: 819-953-2476	Authorized officer Colin Watts (819) 639-7669

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/CA2019/051273

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		CA2121131A1	29 April 1993 (29-04-1993)
		CA2121131C	25 May 1999 (25-05-1999)
		DE69203728D1	31 August 1995 (31-08-1995)
		DE69203728T2	07 March 1996 (07-03-1996)
		EP0610435A1	17 August 1994 (17-08-1994)
		EP0610435B1	26 July 1995 (26-07-1995)
		FR2683001A1	30 April 1993 (30-04-1993)
		FR2683001B1	04 February 1994 (04-02-1994)
		JPH07501374A	09 February 1995 (09-02-1995)
		NO941482D0	22 April 1994 (22-04-1994)
		NO941482L	22 April 1994 (22-04-1994)
		NO306643B1	29 November 1999 (29-11-1999)
		WO9308402A1	29 April 1993 (29-04-1993)
EP 1988288 A1	05 November 2008 (05-11-2008)	EP1988288A1	05 November 2008 (05-11-2008)
		EP1988288B1	16 March 2011 (16-03-2011)
		AT502214T	15 April 2011 (15-04-2011)
		DE602007013183D1	28 April 2011 (28-04-2011)
		WO2008135116A1	13 November 2008 (13-11-2008)
US 7837451 B2	23 November 2010 (23-11-2010)	US2009220369A1	03 September 2009 (03-09-2009)
		US7837451B2	23 November 2010 (23-11-2010)
US 6093004 A	25 July 2000 (25-07-2000)	US6093004A	25 July 2000 (25-07-2000)
		CA2311972A1	19 December 2001 (19-12-2001)
		CA2311972C	12 October 2004 (12-10-2004)