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(54) Title: RADIAL PISTON PUMPS AND MOTORS

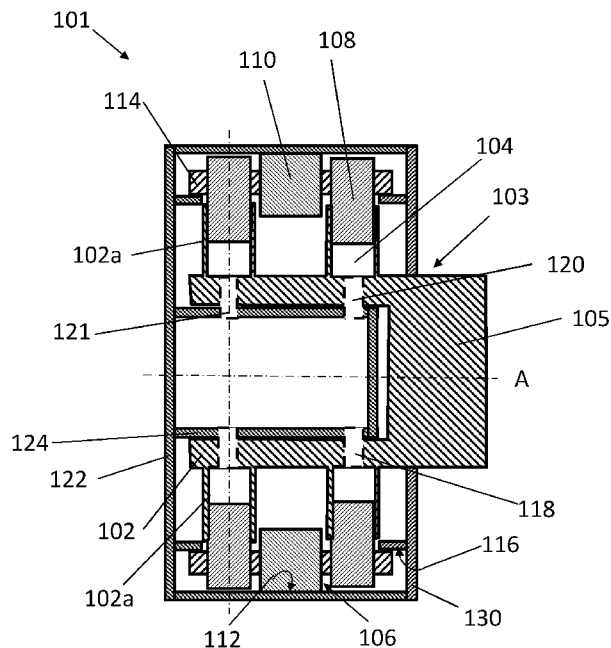


FIG. 2

(57) Abstract: A radial piston pump (101) comprising a rotor (103) is disclosed. The rotor (103) includes a drive shaft (105) arranged to transmit rotary motion to or from the pump (101) and a piston housing (102) including at least one piston chamber (104), the at least one piston chamber (104) being arranged to receive a piston (108). The drive shaft (105) and the piston housing (102) are integrally formed.



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Radial Piston Pumps and Motors

Field of the Invention

5 The present invention concerns radial piston pumps. More particularly, but not exclusively, this invention concerns internally impinged radial piston pumps. This invention also concerns piston pumps having a rotor including an integrally formed piston housing and drive shaft. This invention also concerns a variable displacement pump having a cam including a cam surface that varies across the width of the cam
10 such that axial movement of the cam relative to the piston housing changes the motion of the piston. This invention also concerns piston pumps having a primary roller arranged to follow a primary cam surface and a secondary roller arranged to follow a secondary cam surface. This invention also concerns piston pumps produced using additive manufacturing processes, for example 3D printing. It will be appreciated that
15 pumps in accordance with the present invention may also function as motors.

Background of the Invention

Radial piston pumps (and/or motors) are used in a wide variety of applications including automotive and aerospace applications.

20 Typically radial piston pumps comprise a plurality of pistons mounted in radially extending piston chambers formed in a solid piston housing. The piston housing may include a hollow centre with a shaft mounted eccentrically therein. Alternatively, the piston housing may be eccentrically mounted within a ring. Movement of the pistons may be produced by rotating the piston housing relative to
25 the shaft and/or ring. An inside (or internally) impinged pump may be defined as a pump in which the fluid flows into the pistons via the interior of the pump housing. An outside (or externally) impinged pump may be defined as a pump in which the fluid flows to and from the pistons via structure located around the exterior of the piston housing.

30 Fig. 1 shows a schematic view of a prior art inside impinged radial piston pump 1. The pump 1 comprises a cylindrical piston housing 2 including a plurality of radially extending piston chambers 4 formed in the body of the housing 2. A piston 8 that forms part of a piston assembly 6 is located in each piston chamber 4. Each piston assembly 6 includes a piston 8 and a cam follower 10 connected to the piston 6.
35 The cam follower 10 is in contact with an inward facing cam surface 12 that extends around the outside of the piston housing 2. The radius of the cam surface 12 varies periodically with distance around the perimeter of the housing 2.

 In use, the piston housing 2 rotates relative to the cam surface 12. A spring (not shown) urges the piston 8 radially outward from the piston chamber 4 and
40 accordingly maintains the cam follower 10 in contact with the cam surface 12. In some prior art pumps a spring is not required and centrifugal force, or the pressure of liquid flowing into the piston chamber 4, may be sufficient to maintain the follower in

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contact with the cam surface 12. Along portions of the cam surface 12 where the radius of the cam surface reduces with the relative rotation of the housing 2 and cam surface 12 the piston 8 is pushed into the piston chamber 4 as a result of the contact between the cam follower 10 and the cam surface 12. Consequently, any liquid
5 located in the piston chamber 4 is expelled from the piston chamber 4 under pressure. Conversely, when the profile of the cam surface 12 is such that the radius of the cam surface 12 increases with rotation the piston 8 moves radially outward and fluid can enter the piston chamber 4. Thus, rotation of the piston housing 2 relative to the
10 varying profile of the cam surface 12 causes the pistons 8 to reciprocate in the piston chambers 4 thereby moving fluid through the pump 1. Fluid flows into and out of the piston chambers 4 via the hollow centre of the piston housing 2 under the control of a series of check valves (not shown).

In prior art pumps in accordance with Fig. 1 the forces generated by the interaction of the cam follower 10 and the cam surface 12 (hereafter referred to as the
15 interaction forces) may be significant. The interaction forces may act against the rotary motion of the pump thereby reducing the efficiency of the pump. The interaction forces may reduce the life time of the piston and/or necessitate the introduction of bearings at the centre of the pump to manage the forces between the piston housing and the drive shaft and/or main housing of the pump. Accordingly, it
20 would be advantageous to reduce or better manage the interaction forces experienced by the pump.

Pumps in accordance with Fig. 1 often require hydrostatic lubrication (i.e. applying external pressure to a fluid film layer between two components) to maintain friction between the cam follower 10 and the cam surface 12 at acceptable levels. The
25 use of hydrostatic lubrication may lead to significant inefficiencies in the pump due to the need to provide a supply of pressurised fluid.

Pumps in accordance with Fig. 1 also comprise a high number of individual components which may lead to wasted space (and therefore larger pumps) or additional cost due to, for example, more complex assembly.

30 In many systems the choice of pump is constrained by available space and/or power. Accordingly, it is generally desirable to increase the efficiency of a pump, in particular over a range of speeds and/or reduce the size of pump required for a given flow rate.

The present invention seeks to mitigate the above-mentioned problems.
35 Alternatively or additionally, the present invention seeks to provide an improved pump.

Summary of the Invention

40 According to a first aspect of the invention, there is provided a radial piston pump comprising a rotor, the rotor including a drive shaft arranged to transmit rotary

motion to or from the pump and a piston housing including at least one piston chamber, the at least one piston chamber being arranged to receive a piston and wherein the drive shaft and the piston housing are integrally formed. Integrating several functions, for example the drive-shaft function and the piston-housing function into an integrally formed component may facilitate the design of more compact pumps. Additionally or alternatively, integrally forming the drive shaft and piston housing may reduce manufacture and/or assembly costs.

Alternatively or additionally, the pump may further comprise a main housing, the rotor being mounted for rotation relative to the main housing. The main housing may comprise a first cam surface arranged to control the radial movement of a piston located in the at least one piston chamber when the pump is in use. The main housing and the first cam surface may be integrally formed. Integrating the cam surface with the main housing of the pump may facilitate the design of more compact pumps and/or reduce manufacturing costs.

A cam surface may be defined as a surface arranged to control the radial movement of a piston as a result of the interaction between the cam surface and a cam follower connected to the piston. The cam follower may comprise a member mounted for rotation relative to the piston. The cam follower may be arranged to roll along the cam surface.

The at least one piston chamber may be a radially extending piston chamber. The piston housing, and therefore the rotor, may include a plurality of radially extending piston chambers. Each piston chamber may be arranged to receive a piston. Each piston chamber may be defined, at least in part, by a piston chamber wall that projects radially outward from the surface of the rotor. Accordingly, the piston housing may comprise a plurality of radially extending piston chamber walls, each piston chamber wall defining at least part of a separate piston chamber. Each piston chamber may comprise a first portion defined at least in part by a cavity formed in a solid body (for example the rotor). Each piston chamber may comprise a second portion defined at least in part by a chamber wall that projects radially from the outer surface of the solid body. Using a radially extending wall to form at least part of the piston chamber may result in a much lighter construction than a traditional piston housing in which the piston chamber is formed as a cavity in a solid body. Using a radially extending wall to form at least part of the piston chamber may also improve heat distribution. A chamber wall may be substantially tubular. A chamber wall may be spaced apart from every other chamber wall across the surface of the rotor. The piston housing may comprise a plurality of supporting members, each supporting member extending between two chamber walls.

The rotor may include a first series of piston chambers. The piston chambers of the first series may be spaced apart around the circumference of the piston housing at a first axial location. The rotor may include a second series of piston chambers. The piston chambers of the second series may be spaced apart around the circumference of the piston housing at a second axial location, spaced apart from the

first axial location along the axis of the rotor. Thus, the piston chambers of the first and second series may form two rings extending around the circumference of the rotor. The piston chambers of the second series may be offset angularly with respect to the piston chambers of the first series. Providing two (or more) series of piston chambers may allow the piston chambers to be accommodated in a more space-efficient manner than prior art pumps. Accordingly, providing two series of piston chambers may result in an increased flow rate for a pump of a given size. The rotor may include further series of piston chambers. Piston chambers of each further series may be spaced apart around the circumference of the piston housing at a further axial location, spaced apart from the any other series along the axis of the rotor.

The piston housing may comprise a plurality of piston chambers (and accordingly the pump may comprise a plurality of pistons). The piston housing may comprise more than 10, for example more than 20, for example more than 30 piston chambers. The piston housing may comprise an even number of piston chambers. Typically, radial piston pumps comprise an odd number of pistons as this may assist in reducing noise. However, pumps in accordance with the present invention may have a large number of pistons, for example more than 10 pistons such that the decrease in performance due to noise may be offset by the improved pressure balance offered by even numbers of pistons.

The pump may be an inside impinged pump. The pump may be an outside impinged pump.

The pump may further comprise a sequencing assembly. The sequencing assembly may be arranged to control the flow of fluid into and out of the at least one piston chamber as the rotor rotates relative to the main housing. At least part of the sequencing assembly may be integrally formed with the rotor and/or the main housing. Integrally forming at least part of the sequencing assembly with the rotor and/or the main housing may facilitate the design of smaller pumps by allowing one component to carry out multiple functions. A first element of the sequencing assembly may be integrally formed with the rotor. A second element of the sequencing assembly may be integrally formed with the main housing.

The sequencing assembly may comprise a first set of ports. Each of the first set of ports may be connected to at least one piston chamber such that, in use, fluid flows into and out of the piston chamber via a port of the first set. The sequencing assembly may comprise a second set of ports. Each port of the second set may be connected to either a pump inlet or a pump outlet. A port of the second set which is connected to a pump inlet may be referred to as an inlet port. A port of the second set which is connected to a pump outlet may be referred to as an outlet port. The sequencing assembly may be arranged such that when the rotor rotates the first set of ports moves relative to, for example rotates relative to, the second set of ports. The sequencing assembly may be arranged such that each port of the first set is aligned with at least one inlet port of the second set and at least one outlet port of the second set during one rotation. Each outlet port of the second set may be aligned with (for

example be located opposite) a portion of the cam surface that acts to push the piston into the piston chamber. Each inlet port of the second set may be aligned with a portion of the cam surface that allows the piston to move out of the piston chamber. Thus, the pump may be arranged such that rotation of the rotor causes the ports of the first set to move into and out of alignment with the ports of the second set in coordination with the movement of the piston into and out of the piston chamber.

Using two sets of ports to form the sequencing assembly may provide a mechanically simple and space efficient way of controlling the flow of fluid to or from the piston chambers.

The first set of ports may be integrally formed with the rotor. Thus, the drive shaft, piston housing and first set of ports of the sequencing assembly may be integrally formed. The ports of the second set may be integrally formed in the main housing. The main housing, cam surface and second set of ports of the sequencing assembly may be integrally formed. The two principal elements of the sequencing assembly (for example the ports of the first set and the ports of the second set) may be formed integrally with the rotor and the main housing. Integrating the two principle elements of the sequencing assembly into other components may remove the need for a separate sequencing assembly altogether, or significantly reduce the size of the sequencing-specific part of the sequencing assembly. Removing the need for a separate sequencing assembly may reduce the size of the pump and/or reduce the dead volume of the pump thereby increasing efficiency. Integrating the ports into the rotor and main housing may also provide a mechanically simple and reliable way of ensuring the flow of fluid remains synchronised with the movement of the pistons.

The various elements discussed above (for example the drive shaft and piston housing and/or the main housing and the first cam surface, both with or without elements of the sequencing assembly) and below (for example the second cam surface, flow galleries and external ports) may be integrally formed using an additive manufacturing process, for example 3D printing. Thus, the rotor may be an additively manufactured rotor. The main housing may be an additively manufactured main housing. It will be appreciated that when a component is produced using additive manufacturing, other processes, for example subtractive finishing processes, may be used to finish the component. The various elements discussed above may be made from steel using an additive manufacturing process.

The main housing may further comprise at least one integrally formed external port. The at least one external port may be arranged to allow connection of the pump to a fluid system. In use, the at least one external port may act as a pump inlet or a pump outlet. In use, fluid may flow into the pump via a pump inlet and/or out of the pump via a pump outlet. The main housing may comprise at least two integral external ports for connecting the pump to a fluid system; a pump inlet and a pump outlet.

The pump may further comprise at least one flow gallery along which fluid can flow when the pump is in use. The at least one flow gallery may be curvilinear.

The rotor may comprise at least one flow gallery, for example an integrally formed flow gallery, arranged to connect the at least one piston chamber to one of the ports of the first set. The main housing may comprise at least one flow gallery, for example an integrally formed flow gallery, arranged to connect the at least one external port to one of the ports of the second set. The rotor and/or the main housing may comprise a plurality of integrally formed flow galleries.

The main housing may further comprise a projection upon which the rotor is mounted for rotation. The projection may be integrally formed with the main housing. Thus the projection may be integrally formed with the cam surface and/or other integrally formed elements of the main housing. The projection may be substantially cylindrical. The projection may have a proximal end connected to the main housing. The projection may have a distal end located concentric with, and/or surrounded by, the cam surface. The ports of the second series may be formed in the surface of the projection. For example, the ports of the second series may extend circumferentially around the outer surface of the projection. The inlet ports of the second series may be spaced apart from the outlet ports of the second series along the longitudinal axis of the projection. The interior of the projection may include a plurality of integrally formed flow galleries.

The pump may comprise at least one piston assembly. Each piston assembly may comprise at least one piston. Each piston assembly may comprise at least one cam follower arranged to follow the first cam surface.

The pump may further comprise one or more second cam surfaces spaced apart from the first cam surface. The piston assembly may comprise a second cam follower arranged to follow the second cam surface. The pump may comprise at least one second cam surface for each piston assembly.

The second cam surface may be spaced apart radially from the primary cam surface. The second cam surface may be concentric with the first cam surface. The pump may be arranged such that the first cam follower and the second cam follower are both in contact with their respective cam surfaces at the same time. The second cam surface may be arranged to limit movement of the piston assembly, and thereby the first cam follower away from the first cam surface. At any given location around the cam surface the second cam surface may face in the opposite direction to the first cam surface. For example, in the case that the first cam surface is an inward facing surface, the second cam surface may be an outward facing surface (and vice versa). The second cam surface may be integrally formed with the main housing or the rotor.

The drive shaft, and therefore the rotor, may include an output spline, for example an integrally formed output spline. The output spline may be located at the opposite end of the rotor to the piston housing. The drive shaft may be arranged for connection to a motor, for example an electric motor. The drive shaft may extend outside the housing of the pump. The drive shaft may extend through an aperture formed in the housing of the pump, for example in the lid of the housing or in the main housing.

The radius of the outermost portion of the rotor in the region of the piston housing may be greater than, for example 50% greater than, the radius of the outermost portion of the rotor in the region of the drive shaft.

5 According to a second aspect of the invention there is provided a rotor for use as the rotor of the first aspect.

One or more of the following may be integrally formed as part of the rotor: a drive shaft; a piston housing including at least one piston chamber arranged to receive a piston; an element of the sequencing assembly, for example the first set of ports; at least one second cam surface and at least one flow gallery. It will be appreciated that
10 it is not essential for the drive shaft and the piston housing to be integrally formed. Any of the other elements listed above may be integrally formed with one or more of the other elements listed above.

According to a third aspect of the invention, there is provided a main housing for use as the main housing the first aspect.

15 One or more of the following may be integrally formed as part of the main housing: a first cam surface; at least one external port, for example a pump inlet or a pump outlet; an element of the sequencing assembly, for example the second set of ports; a projection for mounting the rotor thereon; a second cam surface and at least one flow gallery. It will be appreciated that it is not essential for the drive shaft and
20 the piston housing to be integrally formed. Any of the other elements listed above may be integrally formed with one or more of the other elements listed above.

According to a fourth aspect of the invention there is provided a radial piston pump comprising a primary cam surface, at least one secondary cam surface and at least one piston assembly comprising a first piston, the first piston being mounted for
25 reciprocal movement in a piston housing, said piston housing being arranged to rotate relative to the primary cam surface, the piston assembly further comprising

- a primary roller connected to the first piston and arranged to follow the primary cam surface when the piston housing rotates relative to the primary cam surface, and
- 30 - a secondary roller connected to the first piston and arranged to follow a secondary cam surface as the primary roller follows the primary cam surface.

Providing a second cam surface may remove the need for a spring arranged to urge each piston outwards (as discussed with reference to Fig. 1) and accordingly further reduce the number of components and potentially the size of the pump.
35 Additionally or alternatively, providing a secondary roller arranged to follow a secondary cam surface as set out above may facilitate designs in which the majority of both the radial thrust loads and torque loads generated by the interaction of the primary roller and the primary cam surface at a given instant in time can be rolled. That is to say, the torque load experienced by the piston due to the interaction of the
40 primary cam surface and primary cam follower may be reduced when a secondary cam following a secondary cam surface is used.

The loads generated by the interaction of the primary cam follower and the primary cam surface may be referred to as radial thrust loads, torque loads and axial thrust loads.

5 Radial thrust loads may be defined as loads acting parallel to the longitudinal axis of the piston. Thus, radial thrust loads may act to move the piston along the piston chamber in which it is located. Torque loads may be defined to as loads acting tangentially to the piston as it rotates relative to the cam surface. Thus, torque loads may act to bend the piston in the piston chamber and/or act against the rotational motion of the piston housing relative to the cam surface. Axial thrust loads may be
10 defined as loads acting along the axis of rotation of the piston housing relative to the cam surface. Axial thrust loads may act to bend the piston in the piston chamber.

The pump may be arranged such that both the primary and secondary rollers act to react loads generated during movement of the piston housing relative to the cam surfaces. Both the primary and secondary rollers may act to react loads generated
15 during movement of the piston housing for the majority of each rotation. The pump may be arranged such that both the primary and secondary rollers rotate as a result of interaction, for example contact, with their respective cam surface at the same time. The primary roller may be arranged to roll along the primary cam surface. The secondary roller may be arranged to roll along the secondary cam surface. It will be
20 appreciated that it may not be necessary for a roller to directly contact a cam surface in order to roll along that surface. For example, there may be a lubricant layer, for example a fluid layer, between the roller and the cam surface. It will be appreciated that there may be short periods of time in each cycle where one or other of the primary and secondary cam followers is not in contact with its respective cam surface.

25 It will be appreciated that the primary cam surface and/or the primary cam follower of the second aspect may be the first cam surface and/or the first cam follower of the first (or any other aspect) aspect respectively (and vice versa). Similarly, the secondary cam surface and/or the secondary cam follower of the second aspect may be the second cam surface and/or the second cam follower of the first (or
30 any other aspect) aspect respectively (and vice versa).

The primary cam surface may be spaced apart from the secondary cam surface. The primary cam surface may be spaced apart radially from the secondary cam surface. The primary cam surface may be spaced apart along the axis of the rotor from the secondary cam surface. The primary cam surface may be located radially
35 outside the secondary cam surface. The primary cam surface may be an inward facing cam surface. The secondary cam surface may be an outward facing cam surface. The width (i.e. the axial extent) of the primary cam surface may be greater than the width of the secondary cam surface. The second cam surface may be arranged to limit movement of the piston assembly, and thereby the first cam follower away from the
40 first cam surface.

The piston housing may be arranged rotate relative to the secondary cam surface. The primary cam surface and the secondary cam surface may be arranged such that the radial distance between the two surfaces remains substantially constant.

In the case that the pump comprises a plurality of piston assemblies each containing a secondary roller, each secondary roller may follow the same cam surface. The primary cam surface may form a closed loop, for example a closed loop around the outside of the piston housing. The secondary cam surface may form a closed loop, for example a closed loop around the outside of the piston housing. The secondary cam surface may be integrally formed with the main housing. The secondary cam surface may be integrally formed with the main housing using an additive manufacturing process. Thus, the primary cam surface and the secondary cam surface may be integrally formed.

In the case that the pump comprises a plurality of piston assemblies each containing a secondary roller, each secondary roller may follow a different cam surface. In that case, the position of the secondary cam surface may be fixed relative to the piston housing. That is to say, each secondary cam surface may be arranged to rotate with the rotor and relative to the main housing. Each secondary cam surface may be integrally formed with the rotor and/or the piston housing. Each secondary cam surface may be integrally formed with the rotor using an additive manufacturing process. Thus, the rotor, drive shaft and a plurality of secondary cam surfaces may be integrally formed.

The pump may comprise a plurality of secondary cam surfaces, each secondary cam surface being arranged to react torque loads generated through movement of the piston housing relative to the primary cam surface through interaction with a secondary roller. Each secondary cam surface may form a recess, for example a slot arranged to receive a secondary roller while the primary roller follows the primary cam surface. The pump may be arranged such that as the primary roller follows the primary cam surface the secondary roller remains in the same recess defined by the same secondary cam surface and follows that cam surface. Thus, the secondary roller may roll on a secondary cam surface. In this way, the secondary roller/secondary cam surface may react torque loads generated by the interaction of the primary roller and the primary cam surface. The depth of the recess may be greater than the radius of the secondary roller. Each secondary cam surface may be mounted for rotation with the rotor. It will be appreciated that the secondary cam surfaces may be provided in a number of ways. For example, the rotor may comprise a plurality of radially extending cam surface support rods. Each cam surface support rod may include a pair of prongs at the distal end of the rod, the prongs forming a u-shaped recess in which the secondary roller is located when the pump is in use.

The primary roller may be mounted for rotation relative to the first piston.

The secondary roller may be mounted for rotation relative to the first piston.

The pump may be an internally impinged radial piston pump.

The piston assembly may comprise a second piston, the first and second pistons being arranged on either side of the primary roller. Providing a second piston and arranging the pistons of a piston assembly on either side of the primary roller may assist in balancing and thereby reducing the loads experienced by the pump. The first and second pistons may be arranged on either side of the primary roller such that the pistons are spaced apart along the longitudinal axis of the piston housing. The first piston of a piston assembly may be located in a piston chamber of the first series of piston chambers. The second piston of a piston assembly may be located in a piston chamber of the second series of piston chambers.

The position of the second piston may be fixed relative to the first piston. Fixing the position of the first piston relative to the second piston (or vice versa) may reduce the torque loads experienced by the pump.

The piston assembly may comprise a single piston. Having only one piston for each primary roller may allow for a reduced contact stress between the primary roller and the primary cam surface in comparison with piston assemblies having two or more pistons per primary roller.

A portion of the piston may be hollow. A piston may comprise an internal cavity running along a portion, for example the majority, of its length. A hollow piston may have a reduced inertia compared to a similarly sized prior art piston.

Accordingly, using a hollow piston may allow for a faster frequency of reciprocation of the piston and/or increase the efficiency of the pump. In use, the hollow centre of the piston may be filled with a liquid having a similar density to the liquid flowing through the pump. Alternatively, the internal cavity may be sealed and the piston filled with air and/or another liquid. The hollow piston may be produced using an additive manufacturing process.

The primary and/or secondary roller may comprise a roller bearing (also known as a rolling element bearing), for example a ball bearing, a cylindrical roller bearing or a needle roller bearing. In use, the surface of the roller that is adjacent to the cam surface may be the outer race of a roller bearing. The first or second roller may comprise a member, for example a shaft, pin or caster, mounted on a roller bearing for rotation relative to the piston assembly. In use, the surface of the roller that is adjacent to the cam surface may be the outer surface of the member.

The piston assembly may comprise a second secondary roller. The second secondary roller may be arranged to contact a second secondary cam surface. The two secondary rollers may be located on either side of the primary roller. The two secondary cam surfaces may be located on either side of the primary cam surface. The piston assembly may comprise a secondary roller arranged to contact more than one secondary cam surface simultaneously.

The piston assembly may comprise a thrust bearing, i.e. a bearing used to support axial loads between rotating elements. The thrust bearing may be arranged to support axial thrust loads in a direction parallel to the longitudinal axis of the rotor/piston housing. Providing a thrust bearing as set out above may be particularly

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beneficial when the pump is a variable displacement pump in which the primary cam surface moves axially relative to the rotor/piston housing (see the fifth aspect below).

A piston may comprise a lubrication outlet. The lubrication outlet may be arranged to provide fluid to the primary and/or secondary cam surface when the pump is in use. The lubrication outlet may be arranged to provide a hydraulic bearing, in the form of a fluid film on the primary and/or secondary cam surface when the pump is in use. Forming a hydraulic bearing between a roller and the corresponding cam surface (i.e. the cam surface the roller follows) may extend the life of the pump by reducing wear and/or increase the efficiency of the pump. In the case that the piston is a hollow piston the lubrication outlet may be connected to the cavity of the piston such that fluid flows from the cavity to the cam surface via the lubrication outlet.

The axis of rotation of the first roller may be inline or offset from the axis of rotation of the second roller.

According to a fifth aspect, the invention may provide a radial piston pump comprising at least one piston mounted for reciprocal movement in a piston housing and a cam including a cam surface arranged to control the motion of the at least one piston when the piston housing rotates relative to the cam about a first axis, wherein the cam is mounted for axial movement relative to the piston housing along the first axis and the profile of the cam surface varies across the width of the cam such that moving the cam relative to the piston housing along the first axis changes the motion of the piston. Being able to change the motion of the piston may allow the number of piston cycles per revolution and/or the amplitude of a piston stroke to be varied while the pump is in use. Being able to vary the motion of the piston while the pump is in use may increase the efficiency of the pump by allowing the motion of the piston to be adjusted depending on the speed or desired flowrate. Accordingly, providing a moveable cam surface having a profile that varies along the length of the cam may increase the efficiency of the pump. Providing a variable displacement pump where the cam moves axially relative to the piston housing may facilitate more compact pump designs in comparison to prior art pumps.

The cam surface may have a width (i.e. the axial extent of the cam surface). The radius of the cam surface may vary around the circumference of the cam. The radius of the cam surface may be defined as the distance between the cam surface and the point about which the piston housing rotates relative to the cam surface. The profile of the cam surface may be defined as the variation of the radius of the cam surface around the circumference of the cam. The profile of the cam surface may vary across the width of the cam.

The radius of the cam surface may vary periodically around the circumference of the cam. The profile of the cam surface may be defined in terms of a frequency and an amplitude. The amplitude of the profile of the cam surface will, at least in part, determine the stroke length of a piston located in a piston chamber. The frequency of the cam surface will, at least in part, determine the number of strokes

each piston completes for one revolution of the piston housing relative to the cam surface.

The amplitude of the profile of the cam surface may increase with distance from a first end (i.e. across the width) of the cam. At a first location the cam profile may have a first amplitude A_1 and a first frequency F_1 . At a second location, spaced apart along the longitudinal axis of the cam from the first location, the cam profile may have a second amplitude A_2 and the first frequency F_1 . The second amplitude A_2 may be greater than the first amplitude A_1 . Thus, moving the cam relative to the piston housing along the first axis may change the amplitude of the piston movement. Moving the cam relative to the piston housing along the first axis may increase the stroke length.

The frequency of the profile of the cam surface may increase from a first end of the cam. Thus, moving the cam relative to the piston housing along the first axis may change the frequency of the piston movement. Moving the cam relative to the piston housing along the first axis may increase the number of strokes each piston completes for one revolution of the piston housing.

The profile of the cam surface may vary such that the inside surface of the cam is substantially frustroconical (i.e. have the shape of a truncated cone). The cam itself may be substantially frustroconical in shape. The cam surface may be substantially circular at the first end of the cam. The cam surface may have a lobed profile at a second, opposite, end of the cam. The profile of the cam surface may vary in a smooth manner between the first end and the second end of the cam. The lobed profile of the cam surface may be arranged to provide 2 or more piston cycles per revolution. For example, the profile of the cam surface may have a frequency of 2, 4 or 8. The cam surface may be the primary cam surface.

The radius of the cam surface may vary sinusoidally around all or some of the circumference of the cam. The cam surface may have a sinusoidal profile across some or all of the width of the cam.

The radius of the cam surface may vary non-sinusoidally around all or some of the circumference of the cam. The cam surface may have a non-sinusoidal profile across some or all of the width of the cam. Non-sinusoidal profiles may assist in reducing noise and/or increasing the efficiency of the pump. The radius of the cam surface may increase with circumferential distance at a slower rate than the radius decreases with distance around the circumference. Such a profile may result in the piston moving radially outward more slowly than it moves inward. Such a profile may thereby reduce cavitation. The radius of the cam surface may remain substantially constant around a portion of the circumference before increasing and/or decreasing. Such a profile may result in the piston 'dwelling' in the same position thereby facilitating an increase in the distance between inlet and outlet ports which may reduce leakage.

The profile of the cam surface may change from a sinusoidal profile to a non-sinusoidal profile across the width of the cam surface. It may be that non-sinusoidal

profiles offer particular benefits at certain, for example higher, pump speeds where non-linear effects may become more significant. It will be appreciated that a non-sinusoidal cam surface may also be used with a fixed displacement pump.

5 The pump may comprise a hydraulic actuator, for example a cylinder and piston, arranged to move the cam relative to the piston housing along the first axis. Using hydraulic pressure to move the cam may simplify the design of the pump compared with prior art pumps. Alternatively, an electro-mechanical actuator may be arranged to move the cam relative to the piston housing along the first axis.

10 The pump may comprise a plurality of piston assemblies, each piston assembly including

- at least one piston,
- a roller arranged to follow the cam surface when the piston housing rotates relative to the cam surface, and
- a thrust bearing, the axis of the thrust bearing being parallel to the first axis.

15 Providing a thrust bearing having an axis parallel to the first axis may reduce the load on the pistons as a result of the piston assembly sliding along the cam surface when the cam surface moves along the first axis relative to the piston housing. Providing a pump in which the cam moves axially relative to the piston housing in order to alter the motion of the piston assembly may facilitate designs in which the out of plane

20 loads can be managed in the piston assembly rather than at a central bearing.

The roller may be the primary roller. The cam surface may be the primary cam surface. The piston assembly may further comprise a secondary roller and a secondary cam surface.

25 As will be appreciated by the person skilled in the art, a thrust bearing is a roller bearing arranged to allow rotation between two parts but being designed to support a primarily axial load. Such bearings are well known in the art and will not be discussed further here.

The piston housing may be mounted for rotation relative to a sequencing element, for example the second element of the sequencing assembly of the first aspect. The cam may be mounted for rotational movement relative to the sequencing element about the first axis such that the phase of the surface profile of the cam and the sequencing element may be varied. It will be appreciated that other elements of the sixth aspect, as discussed below, may be combined with the pump of the fifth aspect.

35 According to a sixth aspect, the invention may provide a radial piston pump comprising at least one piston mounted for reciprocal movement in a piston chamber of a piston housing, a cam including a cam surface arranged to control the motion of the at least one piston when the piston housing rotates relative to the cam about a first axis, and a sequencing element arranged to permit the flow of fluid into and out of the

40 at least one piston chamber as the piston housing rotates relative to the sequencing assembly about the first axis and wherein the cam is mounted for rotation about the first axis such that the phase between the sequencing assembly and the profile of the

cam surface can be varied. Varying the phase of the surface profile of the cam and the sequencing element may allow the relationship between the flow of fluid into and out of the piston chamber and the movement of the piston into and out of the piston chamber to be varied. Providing a cam mounted for rotation about the first axis
5 relative to the sequencing assembly may provide a mechanically simple and compact method of switching the direction of flow through the pump and/or increase the efficiency of the pump. For example, at high frequencies/speeds it may be advantageous to pre-phase the pump (i.e. commence the supply of pressurised fluid to the piston chamber before the downward motion of the piston is fully complete).

10 The sequencing element may comprise a plurality of ports. Each port may be connected to an external port that can act as either an inlet to the pump, an outlet to the pump or both. The cam may be mounted for rotation about the first axis between a first angular position and a second angular position relative to the sequencing element. In the first angular position, the pump may be arranged such that a first port of the
15 sequencing element is in fluid communication with the piston chamber when the piston is adjacent to a first circumferential portion of the cam surface. In the second angular position, the pump may be arranged such that the first port is in fluid communication with the piston chamber when the piston is adjacent to a second, different, portion of the cam surface. The first portion may be a portion of the cam
20 surface which permits the piston to move radially outward (an outward portion). The second portion may be a portion of the cam surface which acts to push the piston into the chamber (an inward portion).

The first port may be an inlet port. Thus, moving the cam from the first angular position to the second angular position may permit pre-phasing of the pump.

25 In the first angular position a second port of the sequencing element may be in fluid communication with the piston chamber when the piston is adjacent to the second portion of the cam. In the second angular position the second port may be in fluid communication with the piston chamber when the piston is adjacent to the first portion of the cam. In the first angular position the first port may act as an inlet port and the second port may act as an outlet port. In the second angular position the first
30 port may act as an outlet port and the second port may act as an inlet port. Thus, moving the cam from the first angular position to the second angular position may reverse the direction of flow through the pump.

35 The cam may be mounted for rotation about the first axis relative to the sequencing assembly such that the angular position of a given port relative to the cam surface may be varied. Varying the angular position of a given port relative to the surface of the cam may allow the phase between the flow of fluid into and out of the piston chamber and the movement of the piston to be varied.

40 The pump may comprise a main housing. The position of the sequencing element may be fixed relative to the main housing. The sequencing element may be integrally formed with the main housing. The cam may be mounted for rotational

movement about the first axis relative to the main housing and therefore the sequencing element.

5 The pump may be arranged such that, in normal operation, while the piston housing rotates relative to the sequence assembly the cam is stationary relative to the sequencing assembly such that a sequencing port remains in the same position relative to a given point on the surface of the cam.

10 According to a seventh aspect of the invention, there is provided a method of manufacturing a radial piston pump, the pump comprising a drive shaft arranged to transmit rotary motion to or from the pump and a piston housing including at least one piston chamber, the piston chamber being arranged to receive a piston, the method comprising the step of forming a rotor including the drive shaft and the piston housing as a single piece using an additive manufacturing process.

Providing a rotor incorporating a drive shaft and piston housing as a single piece may facilitate the design of smaller pumps.

15 The method may comprise the step of forming a piston housing including a least one piston chamber by using an additive manufacturing process to form a piston chamber wall extending radially from the outer surface of the rotor. The piston chamber wall may define, at least in part, the at least one piston chamber. In the case that the piston housing includes a plurality of piston chambers, the method may include the step of producing a plurality of piston chamber walls, each piston chamber wall being spaced apart from any other piston chamber wall.

20 It will be appreciated that the step of producing the piston housing using an additive manufacturing process may include building up layers of material such that the rotor is formed with the piston chambers already substantially present therein. That is to say, the piston chambers may be formed without the need to remove a substantial amount of material from the piston housing (a small amount of finishing may be used).

25 The method may include producing a single-piece rotor including one or more of the following features using an additive manufacturing process: a drive shaft, a piston housing, an element of a sequencing assembly, for example a first set of ports and a flow gallery arranged to control the flow of fluid between a piston chamber and port of the first set, and a plurality of second cam surfaces.

30 The pump may further comprise a main housing, the main housing comprising a first cam surface arranged to control the radial movement of a piston located in the at least one piston chamber, and wherein the method further comprises the step of forming the main housing and the first cam surface as a single piece using an additive manufacturing process.

35 The method may include producing a single-piece main housing including one or more of the following features using an additive manufacturing process: a first cam surface, a second cam surface, an external port, a second set of ports, a projection and a flow gallery connecting a port of the second set to the external port.

40

As discussed with reference to the rotor above, additive manufacturing may be used to build up the rotor and/or the main housing such that the rotor and/or main housing is formed with voids (for example flow galleries or ports) or other features (for example cam surfaces, fluid inlets and outlets) already present therein.

5 The method may include the step of closing the main housing with a lid.

 According to an eighth aspect, the invention provides a method of producing a flow of fluid through a radial piston pump, the pump comprising a primary cam surface, a secondary cam surface, spaced apart radially from the primary cam surface and a plurality of piston assemblies, each piston assembly comprising a first piston, a
10 primary roller and a secondary roller, the method comprising rotating the piston housing relative to the first and secondary cam surfaces while rolling the primary roller along the primary cam surface and the secondary roller along the secondary cam surface such that the piston moves radially.

 The primary roller may roll along the primary cam surface while the
15 secondary roller simultaneously rolls along the secondary cam surface. The primary and secondary rollers may contact the respective cam surfaces such that both rollers react a portion of the loads, for example the radial thrust and/or torque loads, produced when the pump is in use. It will be appreciated that a roller that follows and/or rolls along a cam surface may travel along a cam surface for a significant
20 distance in the same direction and/or move back and forward relative to the cam surface such that its position relative to the cam surface does not change significantly over time.

 The method may comprise the step of manufacturing at least part of the pump, for example the rotor and/or the main housing and/or the cam (if present) of the pump
25 using an additive manufacturing process. The method may comprise the step of using additive manufacturing to produce the form of the rotor and/or main housing. The method may further comprise a step of finishing the basic form using a subtractive manufacturing process. The method may comprise the step of manufacturing at least part of the piston assembly using an additive manufacturing process.

30 According to a ninth aspect of the invention, there is provided a method of varying the flow of fluid through a radial piston pump, the piston pump comprising a piston housing including a plurality of pistons mounted therein and a cam surface, each piston being connected to a cam follower arranged to follow the cam surface when the piston housing rotates relative to the cam surface about a first axis, and
35 wherein the profile of the cam surface varies with distance along the first axis, the method comprising the steps of:

- rotating the piston housing relative to the cam surface at a first location such that a first piston motion is produced,
- rotating the piston housing relative to the cam surface at a second location,
40 spaced apart from the first location along the first axis, such that a second, different, piston motion is produced.

The method may comprise the step of moving the cam relative to the piston housing in a first direction from the first location to the second location. The method may comprise the set of moving the cam relative to the piston housing in a second, opposite, direction from the second location to the first location. The method may
5 comprise the step of moving the cam relative to the piston housing in the first and/or second direction while the piston housing is rotating relative to cam. The method may comprise the step of moving the cam relative to the main housing of the pump while the axial position of the rotor relative to the main housing is fixed.

The method may further comprise the step of rotating the cam relative to a
10 sequencing element. The method may comprise the step of rotating the cam about the first axis from a first angular position relative to the sequencing element to a second angular position relative to the sequencing element such that the flow of fluid through the pump is reversed.

The pump may be arranged to pump a liquid. The pump may produce flow
15 rates of 0.1 to 50 litres per second. The pump may have a displacement of 5 to 1000 cc per revolution. The pump may have a weight in the range of 0.1 to 50kg. The pump may have a power output of 0.1 to 500 kw.

It will of course be appreciated that features described in relation to one aspect of the present invention may be incorporated into other aspects of the present
20 invention. For example, the method of the invention may incorporate any of the features described with reference to the apparatus of the invention and *vice versa*. Apparatus having features described in relation to one aspect of the present invention may incorporate any of the features described with reference to another aspect of the apparatus of the invention. Methods having features described in relation to one
25 aspect of the present invention may incorporate any of the features described with reference to another aspect of the method of the invention

The present application discusses aspects of the invention with reference to pumps, but it will be appreciated that a pump may also function as a motor. Accordingly, any features discussed in relation to a pump may be incorporated into a
30 motor.

Description of the Drawings

Embodiments of the present invention will now be described by way of
35 example only with reference to the accompanying schematic drawings of which:

Fig. 2 shows a schematic cross-sectional view of a pump according to a first embodiment of the invention;

Fig. 3 shows a schematic plan view of the pump of the first embodiment.

40 Fig. 4 shows a cross-sectional view of a pump according to a second embodiment of the invention;

Fig. 5 shows a perspective view of the rotor of the pump of the second embodiment;

Fig. 6 shows a perspective view of (a) the front and (b) the rear of the main housing of the pump of the second embodiment;

5 Fig. 7 shows a perspective view of the piston assembly of the pump of the second embodiment;

Fig. 8 shows a cross-sectional schematic view of a pump according to a third embodiment of the invention;

10 Fig. 9 shows a cross-sectional view of a pump according to a fourth embodiment of the invention.

Fig. 10 shows a perspective cross-sectional view of the piston housing of the pump of the fourth embodiment; Fig. 11 shows a perspective view of the cam of the pump of the fourth embodiment;

15 Fig. 12 shows a perspective view of the piston assembly of the pump of the fourth embodiment.

Fig. 13 shows a perspective view of a piston assembly of a pump in accordance with a fifth embodiment.

20 Detailed Description

Fig. 2 shows a cross-sectional schematic view of a pump 101 in accordance with a first example embodiment of the invention. The pump 101 comprises a rotor 103 including an integrally formed drive shaft 105 and piston housing 102. The piston housing 102 comprises a plurality of radially extending tube-like walls 102a that appear rectangular when viewed in cross-section in Fig. 2 and which project from the outer surface of the rotor 103. Each cylindrical wall 102a is spaced apart from the other cylindrical walls 102a and defines a piston chamber 104 in which a piston 108 is received. The piston chamber walls 102a (and the corresponding pistons 108) are arranged in two rows, each row extending around the circumference of the rotor 103. The two rows are spaced apart along the longitudinal axis of the rotor 103, labelled A in Fig. 2. In the cross-sectional view of Fig. 2, four pistons 108 can be seen; one pair of pistons 108 on either side (upper and lower) of the rotor 103. The two pistons 108 of each pair are joined by a pin 114 that extends through the distal end of each piston 108. The pin 114 is mounted for rotation relative to the two pistons 108. Located between each pair of pistons 108, along the axis of the pin 114 is a roller 110 mounted for rotation relative to the pistons 108 and the pin 114. The two pistons 108, pin 114, and roller 110 may together be referred to as a piston assembly 106. A flow gallery 118 in the single piece rotor 103 links each piston chamber 104 to a port 120 formed in an inside surface of the rotor 103. When assembled, as shown in Fig. 2, the roller 110 contacts an inward facing primary cam surface 112. The outer surface of the pin 114 simultaneously contacts an outward facing secondary cam surface 116 at either

end. The two secondary cam surfaces 116 are spaced apart along the longitudinal axis A of the rotor 103 and are located radially inside and concentric with the primary cam surface 112. The primary cam surface 112 and left-hand side secondary cam surface 116 are integrally formed as part of a main housing 122. Also integrally formed with the main housing 122 is a central cylindrical projection 124, which appears rectangular when viewed in cross-section in Fig. 2. The projection 124 is concentrically located with respect to the cam surfaces 112, 116 and extends from the rear wall of the housing 122, shown on the left hand side of Fig. 2 into a cavity the radial extent of which is defined by the primary cam surface 112. The rotor 103 is mounted for rotation on the cylindrical projection 124 such that the ports 120 formed in the inside surface of the rotor 103 (the rotor-side ports 120) are aligned axially with a series of ports 121 (the main-housing side ports 121) extending around the circumference of the projection 124. A lid 130 closes off the cavity defined by the cam surface 112. The right-hand side secondary cam surface 116 is integrally formed with the lid 130. The drive shaft 105 projects through an aperture in the lid 130. A plurality of flow galleries (not shown) extend along the interior of the projection 124 and link each port 121 with either a pump inlet (not shown), in which case the port 121 is an inlet port 121_{in} or a pump outlet (not shown), in which case the port 121 is an outlet port 121_{out}.

Fig. 3 shows a cross-sectional plan view of the pump of Fig. 2. When viewed in cross-section in Fig. 3 it can be seen that the profile of the primary cam surface 112 includes two regions of reduced radius 112a located at approximately 90 degrees and 270 degrees around its circumference. The cam surface 112 also includes two regions of increased radius 112b located at approximately 0 degrees and 180 degrees. Accordingly, the profile of the primary cam surface 112 varies periodically with a frequency of two. The profile of the secondary cam surface 116 varies in a similar manner such that the radial distance between the primary cam surface 112 and secondary cam surface 116 remains substantially constant around the closed-loop cam surfaces.

In use, rotation of the drive shaft 105 causes the piston housing 102 which is formed as a single piece with the drive shaft 105 to rotate. Roller bearing 110 and pin 114 each follow the corresponding cam surface 110, 116 as the piston housing 102 moves relative to the main housing 122. As a piston moves towards a region of reduced radius 112a the radius of the inward-facing cam surface 112 decreases and the piston is pushed into the piston chamber 104 expelling the liquid located therein through flow gallery 118 to port 120. Similarly, as a piston moves towards a region of increased radius 112b the radius of the primary cam surface 112 increases and so does the radius of the secondary cam surface 116. As a result of the increase in radius of the secondary, outward facing, cam surface 116, the contact between the pin 114 and the cam surface 116 pulls the piston 108 out of its piston chamber 104 drawing liquid into the piston chamber 104 through flow gallery 118 and port 120.

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As the rotor rotates relative to the main housing each rotor-side port 120 moves into and out of alignment with the ports 121 formed in the main housing. Outlet ports 121_{out} formed in the main housing 122 are located opposite regions where the radius of the cam surface 112 reduces with rotation. Accordingly, as fluid is expelled from the piston chamber 104 the rotor-side port 120 comes into alignment with a main housing-side outlet port 121_{out} connected to the pump outlet and the fluid in the piston chamber 104 is expelled to the pump outlet via the ports 120, 121_{out}. Similarly, inlet ports 121_{in} formed in the main housing 122 are located opposite regions of increasing radius of the cam surface 112. As a piston 108 moves out of its piston chamber 104 the rotor-side port 120 comes into alignment with a main housing-side inlet port 121_{in} connected to the pump inlet and fluid is drawn into the piston chamber 104 from the pump inlet via the ports 120, 121_{in}. As the profile of the cam surfaces 112, 116 has a frequency of two, this cycle is repeated twice for each complete rotation of the piston housing 102 relative to the main housing 122 and the pump may be referred to as a two-stroke pump.

The passage above describes the apparatus 101 being used as a pump. It will be appreciated that the apparatus 101 can also be used as a motor by driving a flow of fluid through the apparatus 101 and thereby turning the drive shaft 105.

The rotor 103 including piston housing 102 and drive shaft 105 is made as a single part in steel using an additive manufacturing process. The main housing 122 including piston housing 102, cylindrical projection 124, primary cam surface 112 and a secondary cam surface 116 is also made as a single part using an additive manufacturing process. The piston 108 is made using an additive manufacturing process. Once the rotor 103 and main housing 122 have been formed using additive manufacturing, subtractive manufacturing techniques are used to finish the components.

Providing primary and secondary rollers 110, 114 and multiple cam surfaces 112, 116 in accordance with the present embodiment may remove the need for a spring arranged to urge each piston outwards (as discussed with reference to Fig. 1) and accordingly further reduce the number of components and potentially the size of the pump.

Pumps in accordance with the present embodiment may be smaller and/or more efficient than prior art pumps for a given flow rate for a number of reasons. Integrating multiple functions (for example the drive shaft, piston housing and elements of the sequencing functions in one component allows for the number of components to be reduced, in particular because additional bearings and seals that would have been needed between separate components are no longer required. Using additive manufacturing to produce the rotor, main housing, lid and elements of the piston assembly increases design freedom allowing each component to be more efficiently packaged. Using additive manufacturing to produce various components allows the commercial production of features such as the radially projecting piston

chamber walls which can reduce the weight of a component compared to prior art pumps.

Fig. 4 shows a cross sectional view of a pump 201 in accordance with a second example embodiment of the invention. Figures 5 to 7 show the rotor, main housing, and piston assembly respectively of the pump of the second embodiment in more detail.

Only those aspects of the second embodiment which differ significantly from the first embodiment will be discussed here.

The rotor 203 of the pump of the second embodiment (see Fig. 5 for more detail) comprises a drive shaft 205 having an output spline 205a at a first end which is integrally formed with the piston housing 202 at the other end. The piston chamber walls 202a of the piston housing 202 are arranged in two parallel rings extending around the circumference of the housing 202 with cross-bracing 102b extending between each wall 202a.

The main housing 222 (see Fig. 6 for more detail) comprises a cam surface 212 having a profile with four lobes. That is to say the cam surface 212 has a frequency of four and the pump 201 is a four stroke pump. The housing 222 includes two external ports 232; a pump inlet and a pump outlet. A series of flow channels 218 extends between the external ports 132 and the internal ports 220. The exterior of the flow channels can be seen in Fig. 6(b). The flow galleries 118 are also seen in cross section in Fig. 4, with several branching, curvilinear flow galleries 218 extending along the interior of the projection 224 and connecting the main housing-side ports 120 with the pump inlet/outlet.

Each piston 208 of a piston assembly 206 (see Fig. 7) has a cavity 208a extending along the length of the piston. An outlet aperture 208b is formed in the wall of the cavity 208a adjacent the distal end of the piston 208. As in the previous embodiment, the pistons 208 are arranged symmetrically either side of a primary roller 110. An interlocking shaft 244 extends thorough the upper end of both pistons 208 and the roller 210, and protrudes beyond the pistons 208. A needle bearing 214 sits on each protruding end of the interlocking shaft 244. In use, the outer surface of the outer race of each needle bearing 214 rolls along a secondary cam surface 216 formed in a slot 224. The roller bearing 210 of each piston assembly 206 sits radially outside the piston housing 202 and contacts the inward facing cam surface 212.

In use, the cavity 208a of each piston 208 is filled with a liquid having a similar density to the liquid being moved by the pump. Liquid may flow from the cavity 208a to the cam surface 212 via the outlet 208b thereby providing a hydraulic bearing between the roller 210 and the cam surface 212.

Pumps in accordance with the present embodiment may experience reduced radial thrust loads as the hollow piston has a reduced inertia compared with prior art pistons which may allow them to run at higher frequencies. Interlocking the two pistons 108 such that their position relative to one another is fixed has been found to better balance the loads experienced by the piston assembly.

Fig. 8 shows a cross-sectional view of a variable displacement radial piston pump 301 in accordance with a third embodiment of the invention. Only those aspects of the third embodiment which differ significantly from the first and second embodiments will be discussed in detail. In contrast to the first and second
5 embodiments, the primary cam surface 312 of the third embodiment forms part of a component, cam 311, which is separate from the main housing 322. The cam surface 312 of the cam 311 is flared such that the inner diameter of the cam surface 312 increases with distance along the longitudinal axis of the pump. Each piston assembly 306 of the third embodiment is associated with a different pair of secondary cam
10 surfaces 316. The secondary cam surfaces 316 of the third embodiment are integrally formed in the piston housing 302. Each secondary cam surface 316 of the third embodiment defines a slot 317 (shown in cross-section in Fig. 8). When assembled, as shown in Fig. 8, the roller 310 contacts the cam surface 312 of the cam 311. Each end of the pin 314 is located in a corresponding slot 317 and in contact with the secondary
15 cam surface 316 that defines the slot.

In use, the cam 311 is mounted for movement along the longitudinal axis of the pump (labelled A in Fig. 8). As a result of the flaring of the cam surface 312 when the cam 311 is moved parallel to the drive shaft 305 the profile of the portion of the cam surface 312 with which the roller bearing 310 is in contact will change and
20 accordingly the movement of the piston will be altered. In the third embodiment, the degree of excursion of the piston increases as the cam is moved to the right of Fig. 8 and decreases as the cam is moved to the left. Thus, by varying the axial position of the cam 311 relative to the piston assemblies 306 of the piston housing 304 the displacement of the pistons, and accordingly the volumetric flow rate of the pump can
25 be varied. Pumps in accordance with the second embodiment may therefore allow for increased efficiency over a wider range of speeds than prior art pumps. Mounting the cam 311 for movement along an axis parallel to that of the drive shaft may also allow pumps in accordance with the second embodiment to have a more compact design than prior art variable displacement pumps.

30 In use, slot 317 in piston housing 306 rotates with the piston assembly relative to the cam and each end of the pin 314 moves up and down in the slot 317 as the roller 310 follows the cam surface 312. Each end of the pin 314 rolls on the secondary cam surface 316 of the slot 317.

Using a secondary roller 314 in combination with a primary roller 310 may
35 allow both the torque loads generated by the interaction of the cam surface 312 and roller 310 to be rolled. In pumps in accordance with the present embodiment this may reduce the amount of work required to rotate the piston housing 302 relative to the cam surface 310, thereby increasing the efficiency of the pump. It may also remove the need for a separate bearing between the rotor 303 and the protrusion of the main
40 housing 324 (or in pumps having a separate drive shaft and piston housing reducing the load may remove the need for a bearing between those two components). Removing the need for separate bearings may reduce the complexity and/or cost of

the pump, reduce maintenance costs and/or extend the life of the pump, increase the efficiency of the pump and/or allow the size of the pump to be reduced.

Fig. 9 shows a cross-sectional view of a variable displacement radial piston pump 401 in accordance with a fourth embodiment of the invention. Fig. 10 shows the piston housing 402 of the fourth embodiment in more detail.

Fig. 11 shows the cam 411 of the fourth embodiment in more detail. At a first end, the cam surface 412 is substantially circular, while at the other end, the cam surface 412 curves in a periodic manner creating a profile with six lobes 412a and a larger minimum diameter than the circle of the first end. The profile of the cam varies gradually across the width of the cam surface between the circular profile of the first end and the lobed profile of the second end.

Fig. 12 shows a close-up view of a piston assembly 406 for use in the pump 401 of the fourth embodiment. As in the previous embodiments, two pistons 408 are located on either side of a roller bearing 410 that, in use, follows cam surface 412. A shaft 414 extends through the centre of the roller 410 and out the far side of both pistons 408. The shaft 414 is connected to each piston 408 via a needle bearing 446 which allows the shaft 414 to roll relative to the rest of the piston assembly 406. In addition to the primary roller 410 and the secondary roller 414 the piston assembly 406 of the third embodiment includes a pair of thrust bearings 450, one on either side of the roller 410.

In use, axial thrust bearings 450 react the load generated by the sliding movement of the cam 411 relative to the piston assembly 406. Accordingly, pumps in accordance with the fourth embodiment may experience lower frictional losses than comparable pumps without axial bearings.

Fig. 13 shows a piston assembly 506 for use in a fifth example embodiment of the invention. In contrast to the embodiments described above the piston assembly 506 of the fifth embodiment comprises only a single piston 508. At the distal end of the piston 508 the piston assembly 506 comprises a roller bearing 510 that, in use, follows a corresponding primary cam surface (not shown). A shaft 514 extends perpendicular to the longitudinal axis of the piston 508 and is connected to the piston 508 via a pair of needle bearings 546 which allow the shaft 514 to roll relative to the rest of the piston assembly 506. The roller bearing 510, shaft 514, and needle bearings 546 are arranged such that the piston assembly is symmetrical about the centre line of the piston 508. In contrast to the previous embodiments, the axis of rotation of the secondary roller 514 is radially offset from the axis of rotation of the primary roller 510. The piston 508 of the fifth embodiment is hollow, with the internal cavity 508a being sealed such that the piston is filled with air.

Having a single piston per primary roller may reduce the contact stress on the primary roller in comparison to pumps having two pistons in each piston assembly. This may be particularly advantageous for variable displacement pumps due to the reduced contact area between the roller and the cam surface as a result of the cam surface being non-parallel with the longitudinal axis of the roller.

Whilst the present invention has been described and illustrated with reference to particular embodiments, it will be appreciated by those of ordinary skill in the art that the invention lends itself to many different variations not specifically illustrated herein. By way of example only, certain possible variations will now be described.

5 For example, while the embodiments are described above as pumps, it will be appreciated that they can also be used as hydraulic motors. While the examples given above have an integrally formed rotor and main housing, it will be appreciated that there may be situations where it is advantageous to have the elements of the rotor and/or main housing formed separately.

10 Where in the foregoing description, integers or elements are mentioned which have known, obvious or foreseeable equivalents, then such equivalents are herein incorporated as if individually set forth. Reference should be made to the claims for determining the true scope of the present invention, which should be construed so as to encompass any such equivalents. It will also be appreciated by the reader that
15 integers or features of the invention that are described as preferable, advantageous, convenient or the like are optional and do not limit the scope of the independent claims. Moreover, it is to be understood that such optional integers or features, whilst of possible benefit in some embodiments of the invention, may not be desirable, and may therefore be absent, in other embodiments.

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1. A radial piston pump comprising a rotor, the rotor including a drive shaft arranged to transmit rotary motion to or from the pump and a piston housing including at least one piston chamber, the at least one
5 piston chamber being arranged to receive a piston and wherein the drive shaft and the piston housing are integrally formed.
2. A radial piston pump according to claim 1, wherein the pump further comprises a main housing, the rotor
10 being mounted for rotation relative to the main housing, the main housing comprising a first cam surface arranged to control the radial movement of a piston located in the at least one piston chamber when the pump is in use and wherein the main housing and the
15 first cam surface are integrally formed.
3. A radial piston pump according to claim 2, wherein the rotor further comprises a sequencing assembly arranged to control the flow of fluid into and out of the at least one piston chamber as the rotor rotates relative
20 to the main housing and wherein at least part of the sequencing assembly is integrally formed with the rotor and/or the main housing.
4. A radial piston pump according to claim 3, wherein the sequencing assembly comprises a first set of ports
25 integrally formed with the rotor.
5. A radial piston pump according to claim 3 or claim 4, wherein the sequencing assembly comprises a second set of ports integrally formed with the main housing.
6. A radial piston pump according to claim 5, wherein the
30 main housing further comprises at least one integrally formed pump inlet or pump outlet and at least one integrally formed flow gallery connecting the at least

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one pump inlet or pump outlet with a port of the second set.

7. A radial piston pump according to any of claims 2 to claim 6, wherein the main housing further comprises a
5 second cam surface spaced apart from the first cam surface.

8. A radial piston pump according to any previous claim, wherein the rotor includes a first series of piston chambers spaced apart around the circumference of the
10 piston housing at a first location and a second series of piston chambers spaced apart around the circumference of the piston housing at a second location, spaced apart from the first location along the longitudinal axis of the rotor.

15 9. A radial piston pump according to any previous claim, wherein the at least one piston chamber is defined at least in part by a wall, the wall projecting radially from the surface of the rotor.

10. A radial piston pump according to any previous
20 claim, wherein the pump is an inside impinged pump.

11. A rotor for use as the rotor of any previous claim.

12. A main housing for use as the main housing of any of claims 2 to 11.

13. A method of manufacturing a radial piston pump, the
25 pump comprising a drive shaft arranged to transmit rotary motion to or from the pump and a piston housing including at least one piston chamber, the piston chamber being arranged to receive a piston, the method comprising the step of forming a rotor including the
30 drive shaft and the piston housing as a single piece using an additive manufacturing process.

14. A method according to claim 13, wherein the pump further comprises a main housing, the main housing

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comprising a first cam surface arranged to control the radial movement of a piston located in that at least one piston chamber, and wherein the method further comprises the step of forming the main housing and the first cam surface as a single piece using an additive manufacturing process.

15. A method of manufacturing a radial piston pump substantially as herein described with reference to the accompanying drawings.

10 16. A radial piston pump substantially as herein described with reference to the accompanying drawings.

17. A radial piston pump comprising at least one piston mounted for reciprocal movement in a piston housing and a cam including a cam surface arranged to control the motion of the at least one piston when the piston housing rotates relative to the cam about a first axis, wherein the cam is mounted for axial movement relative to the piston housing along the first axis and the profile of the cam surface varies across the width of the cam such that moving the cam relative to the piston housing along the first axis changes the motion of the piston.

18. A radial piston pump according to claim 17, wherein the profile of the cam surface varies across the width of the cam such that moving the cam relative to the piston assembly along the first axis changes the amplitude of the piston motion.

19. A radial piston pump according to claim 17 or claim 18, wherein the profile of the cam surface varies across the width of the cam such that moving the cam relative to the piston assembly along the first axis changes the frequency of the piston motion.

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20. A radial piston pump according to any of claims 17 to 19, wherein the cam surface has a sinusoidal profile along at least a portion of its width.
21. A radial piston pump according to any of claims 17 to 20, wherein the cam surface has a non-sinusoidal profile along at least a portion of its width.
22. A radial piston pump according to any of claims 17 to 21, wherein the piston is mounted for reciprocal movement in a piston chamber formed in the piston housing and the pump further comprises a sequencing element arranged to permit the flow of fluid into and out of the piston chamber as the piston housing rotates relative to the sequencing assembly about the first axis, and wherein the cam is mounted for rotation about the first axis relative to the sequencing element such that the phase difference between the movement of the piston and the flow of fluid to and from the piston chamber can be varied.
23. A radial piston pump according to any of claims 17 to 22, wherein a hydraulic actuator is arranged to move the cam relative to the piston assembly along the first axis.
24. A radial piston pump according to any of claims 17 to 23, wherein the cam surface is located radially outside the piston housing.
25. A radial piston pump according any of claims 17 to 24, wherein the pump is an internally impinged radial piston pump.
26. A radial piston pump according to any of claims 17 to 25, wherein the pump comprises a plurality of piston assemblies, each piston assembly including
- at least one of the plurality of pistons,

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- a roller arranged to follow the cam surface when the piston housing rotates relative to the cam surface, and

5 - a thrust bearing, the axis of the thrust bearing being parallel to the first axis.

27. A radial piston pump according to any of claims 17 to 26, wherein the profile of the cam surface is arranged to provide 2 or more piston cycles per revolution.

10 28. A method of varying the flow of fluid through a radial piston pump, the piston pump comprising a piston housing including a plurality of pistons mounted therein and a cam surface, each piston being connected to a cam follower arranged to follow the cam surface
15 when the piston housing rotates relative to the cam surface about a first axis, and wherein the profile of the cam surface varies with distance along the first axis, the method comprising the steps of:

20 - rotating the piston housing relative to the cam surface at a first location such that a first piston motion is produced,

25 - rotating the piston housing relative to the cam surface at a second location, spaced apart from the first location along the first axis, such that a second, different, piston motion is produced.

29. A method according to claim 28, wherein the method comprises the step of manufacturing the cam surface using an additive manufacturing process.

30 30. A method according to claim 28 or 29, wherein the piston pump further comprises a sequencing element and the method further comprises the step of rotating the cam about the first axis from a first angular position relative to the sequencing element to a second angular

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position relative to the sequencing element such that the flow of fluid through the pump is reversed.

31. A method of varying the flow of fluid through a radial piston pump substantially as herein described with reference to the accompanying drawings.

32. A radial piston pump substantially as herein described with reference to the accompanying drawings.

33. A radial piston pump comprising a primary cam surface, at least one secondary cam surface and at least one piston assembly comprising a first piston, the first piston being mounted for reciprocal movement in a piston housing, said piston housing being arranged to rotate relative to the primary cam surface, the piston assembly further comprising

- a primary roller connected to the first piston and arranged to follow the primary cam surface when the piston housing rotates relative to the primary cam surface, and

- a secondary roller connected to the first piston and arranged to follow a secondary cam surface as the primary roller follows the primary cam surface.

34. A radial piston pump according to claim 33, wherein the piston housing is arranged to rotate relative to the at least one secondary cam surface.

35. A radial piston pump according to claim 34, wherein the secondary cam surface is integrally formed with the primary cam surface.

36. A radial piston pump according to claim 33, wherein the at least one secondary cam surface is arranged to rotate with the piston housing relative to the primary cam surface.

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37. A radial piston pump according to claim 36, wherein the at least one secondary cam surface is integrally formed with the piston housing.
38. A radial piston pump according to claim 36 or claim 5 37, wherein the at least one secondary cam surface defines a recess arranged to receive the secondary roller while the primary roller follows the primary cam surface.
39. A radial piston pump according to any of claims 33 10 to 38, wherein the pump is an internally impinged radial piston pump.
40. A radial piston pump according to any of claims 33 to 39, wherein the first cam surface is spaced apart from the second cam surface.
- 15 41. A radial piston pump according to any of claims 33 to 40, wherein the piston assembly comprises a second piston, the first and second pistons being arranged on either side of the primary roller.
42. A radial piston pump according to claim 41, wherein 20 the position of the second piston is fixed relative to the first piston.
43. A radial piston pump according to any of claims 33 to 42, wherein a portion of the first piston is hollow.
44. A radial piston pump according to any of claims 33 25 to 43, wherein the primary or secondary roller comprises a roller bearing.
45. A radial piston pump according to claim 44, wherein the pump is arranged such that, in use, the surface of the roller adjacent to the corresponding cam surface is 30 the outer race of the roller bearing.
46. A radial piston pump according to claim 44, wherein the primary or secondary roller comprises a member connected to the piston assembly by a roller bearing

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and the pump is arranged such that, in use, the surface of the roller adjacent to the cam surface is the outer surface of the member.

47. A radial piston pump according to any of claims 33
5 to 46, wherein the piston assembly comprises a thrust bearing.

48. A radial piston pump according to any of claims 33
to 47, wherein the at least one piston comprises a
lubrication outlet arranged to provide fluid to the
10 primary or secondary cam surface such that a hydraulic bearing, in the form of a fluid film on the cam surface, is formed when the pump is in use.

49. A method of producing a flow of fluid through a
radial piston pump, the pump comprising a first cam
15 surface, a second cam surface, spaced apart radially from the first cam surface and a plurality of piston assemblies, each piston assembly comprising a first piston, a primary roller and a secondary roller, the method comprising rotating the piston housing relative
20 to the first cam surface while rolling the primary roller along the first cam surface and rolling the secondary roller along the second cam surface such that the piston moves radially.

50. A method according to claim 49, wherein the method
25 comprises the step of manufacturing at least part of the piston assembly using an additive manufacturing process.

51. A method of moving fluid through a radial piston
pump substantially as herein described with reference
30 to the accompanying drawings.

52. A radial piston pump substantially as herein
described with reference the accompanying drawings.

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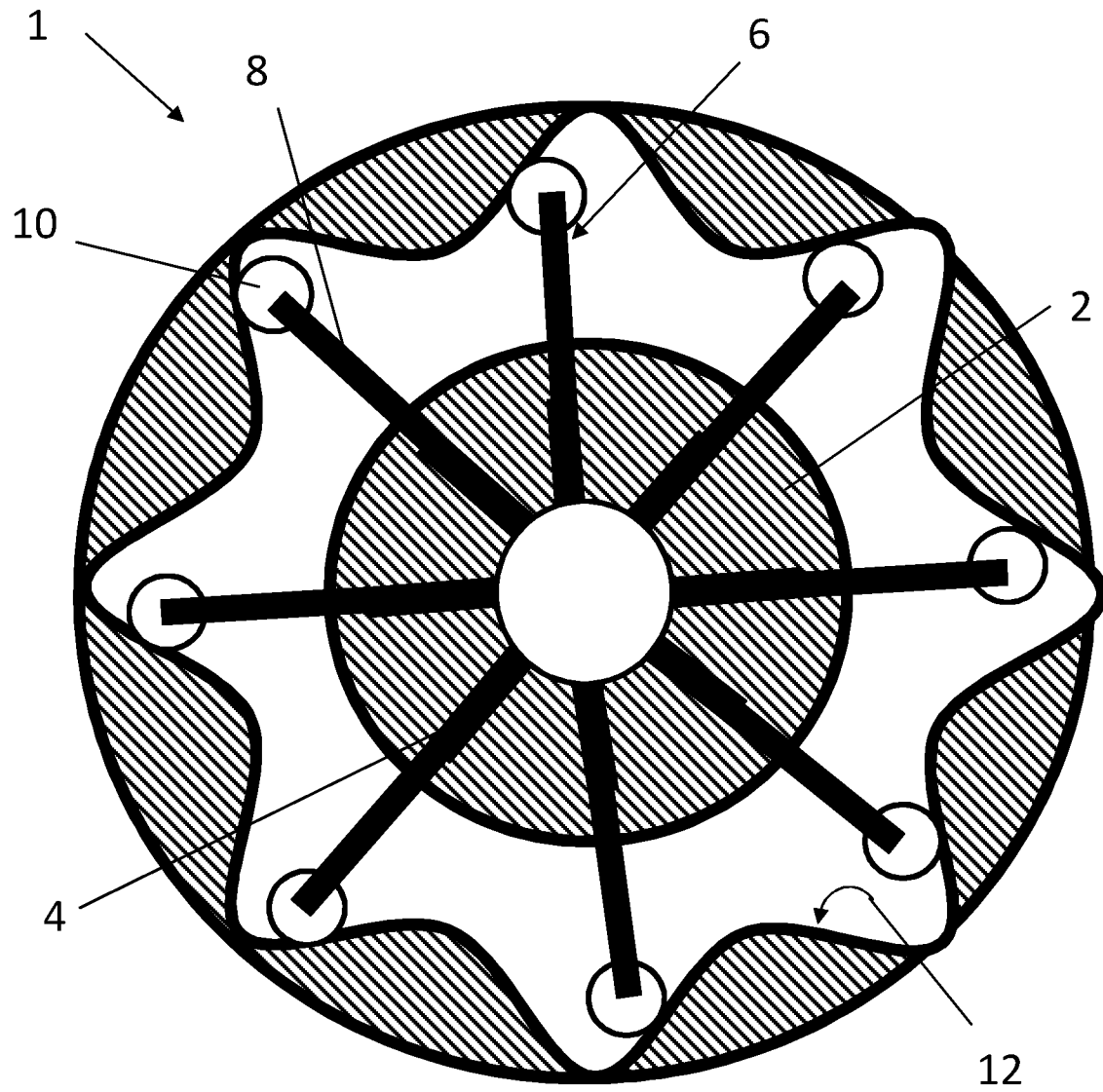


FIG. 1
PRIOR ART

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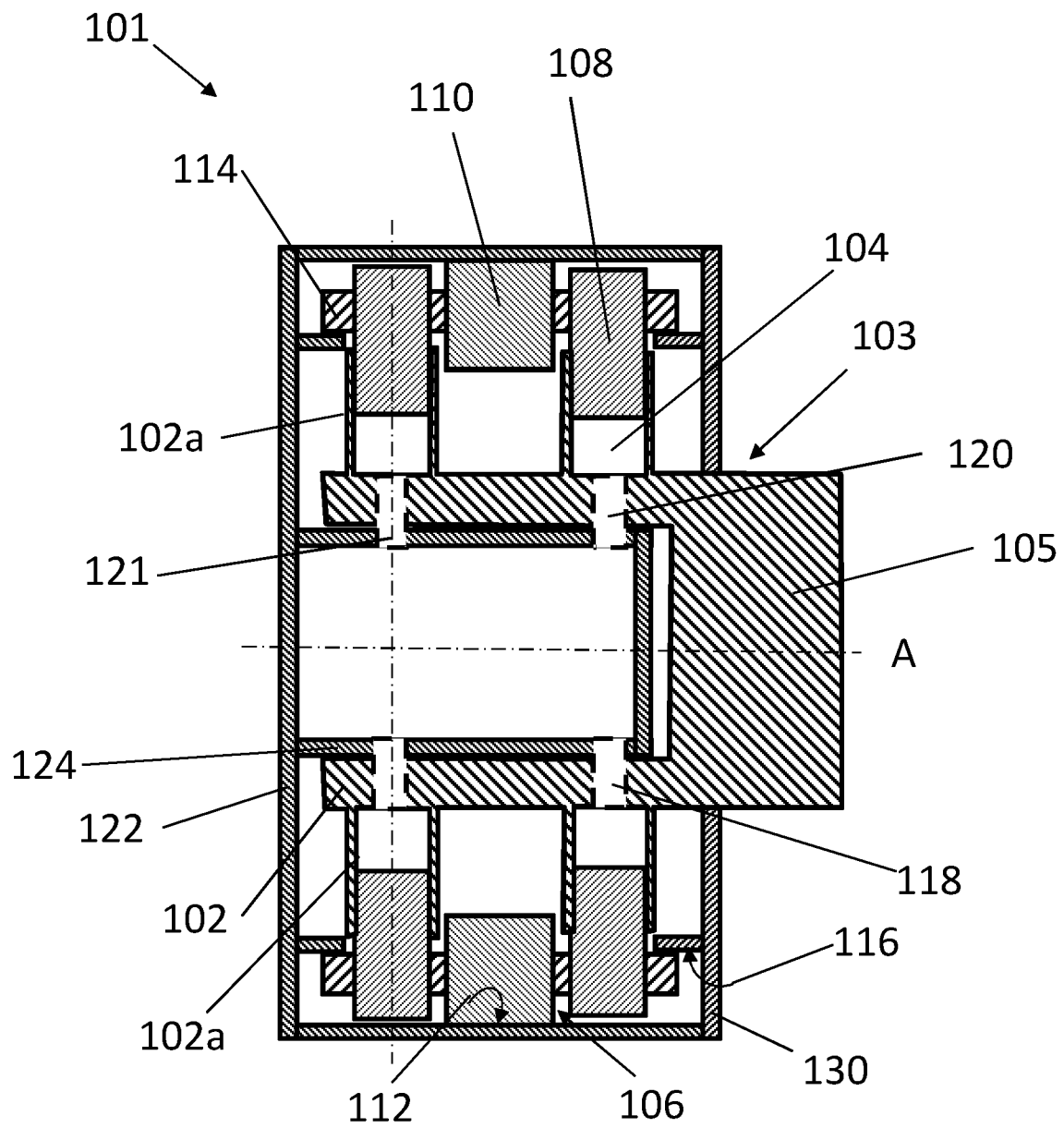


FIG. 2

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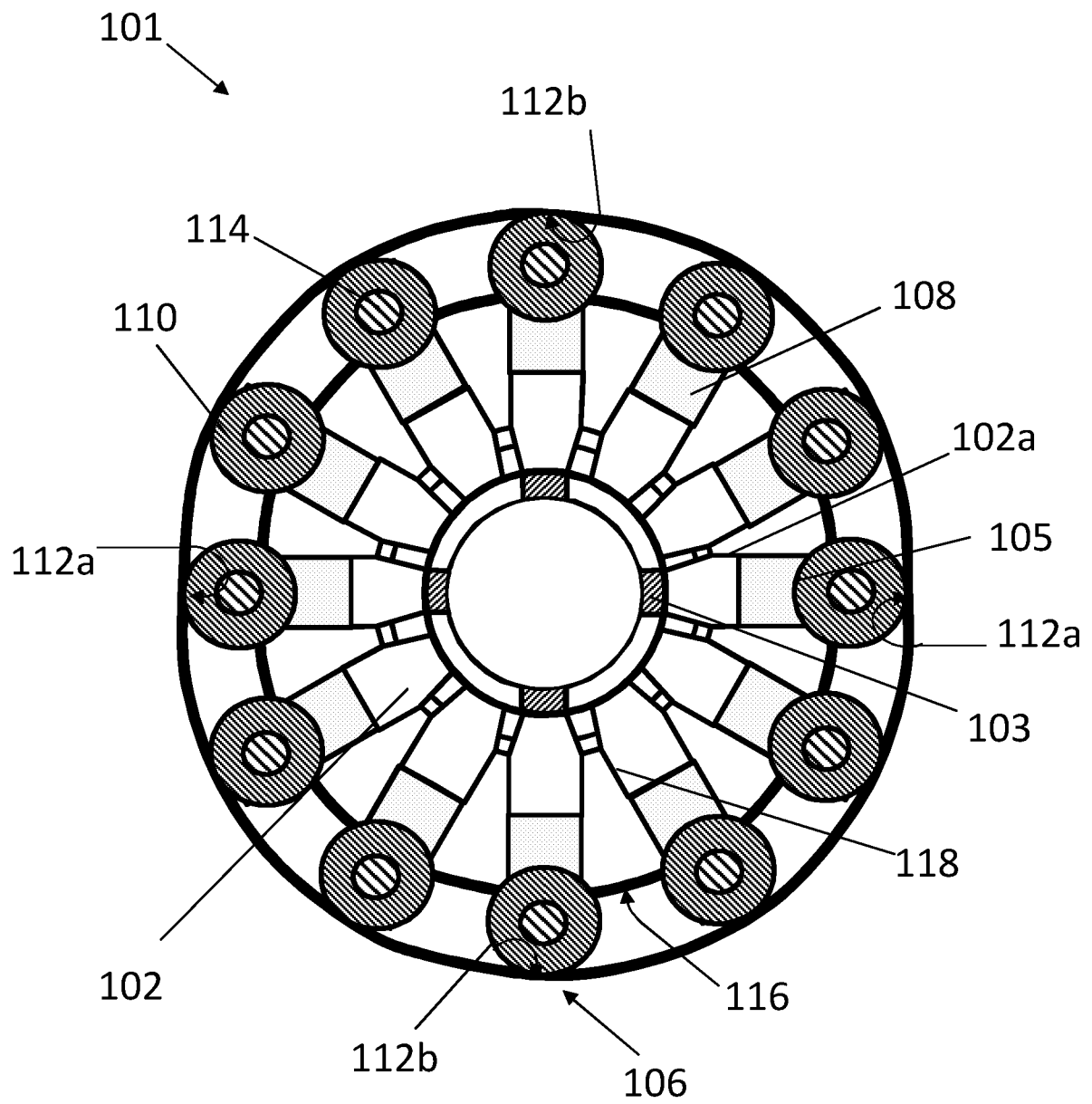


FIG. 3

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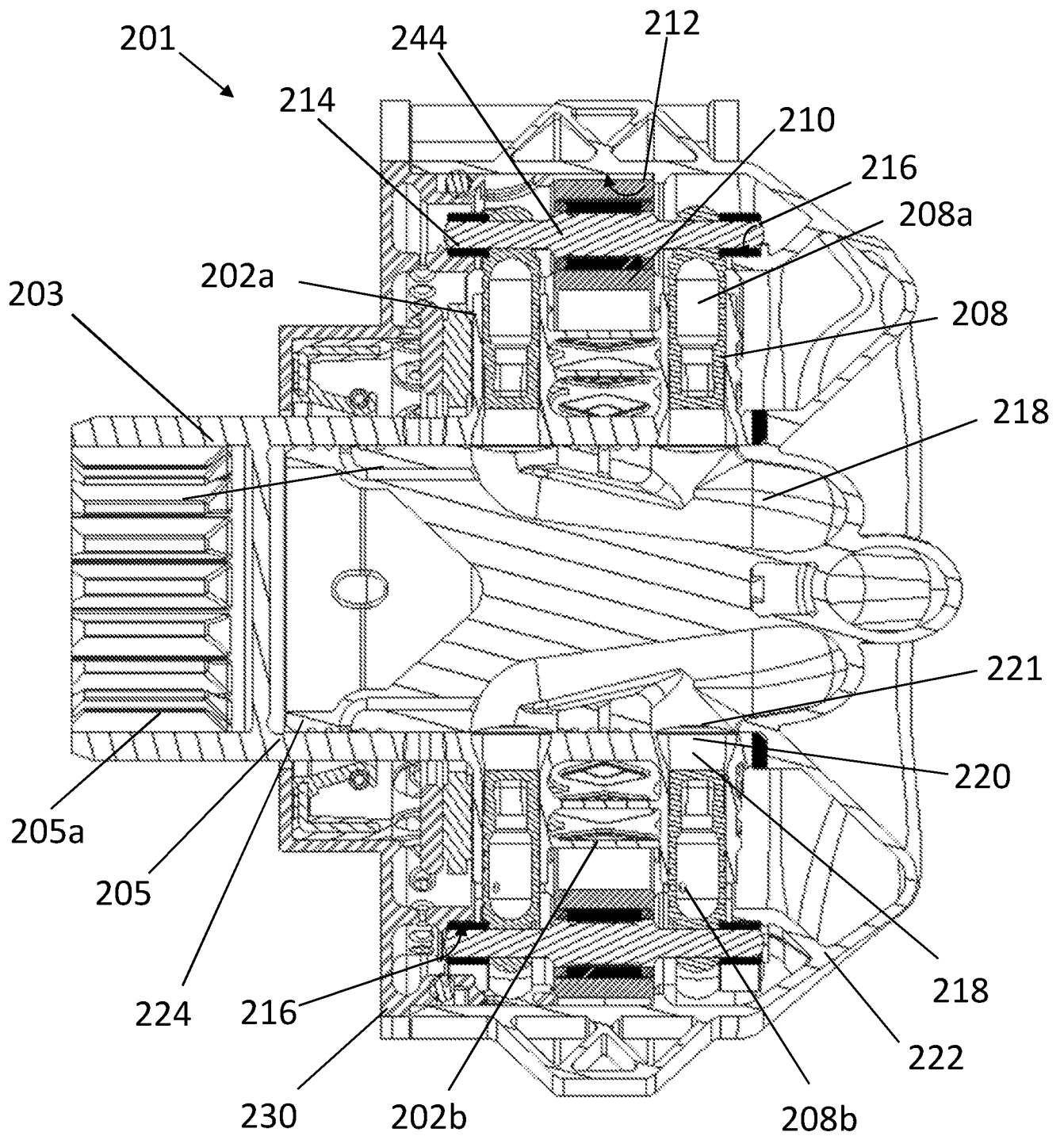


FIG. 4

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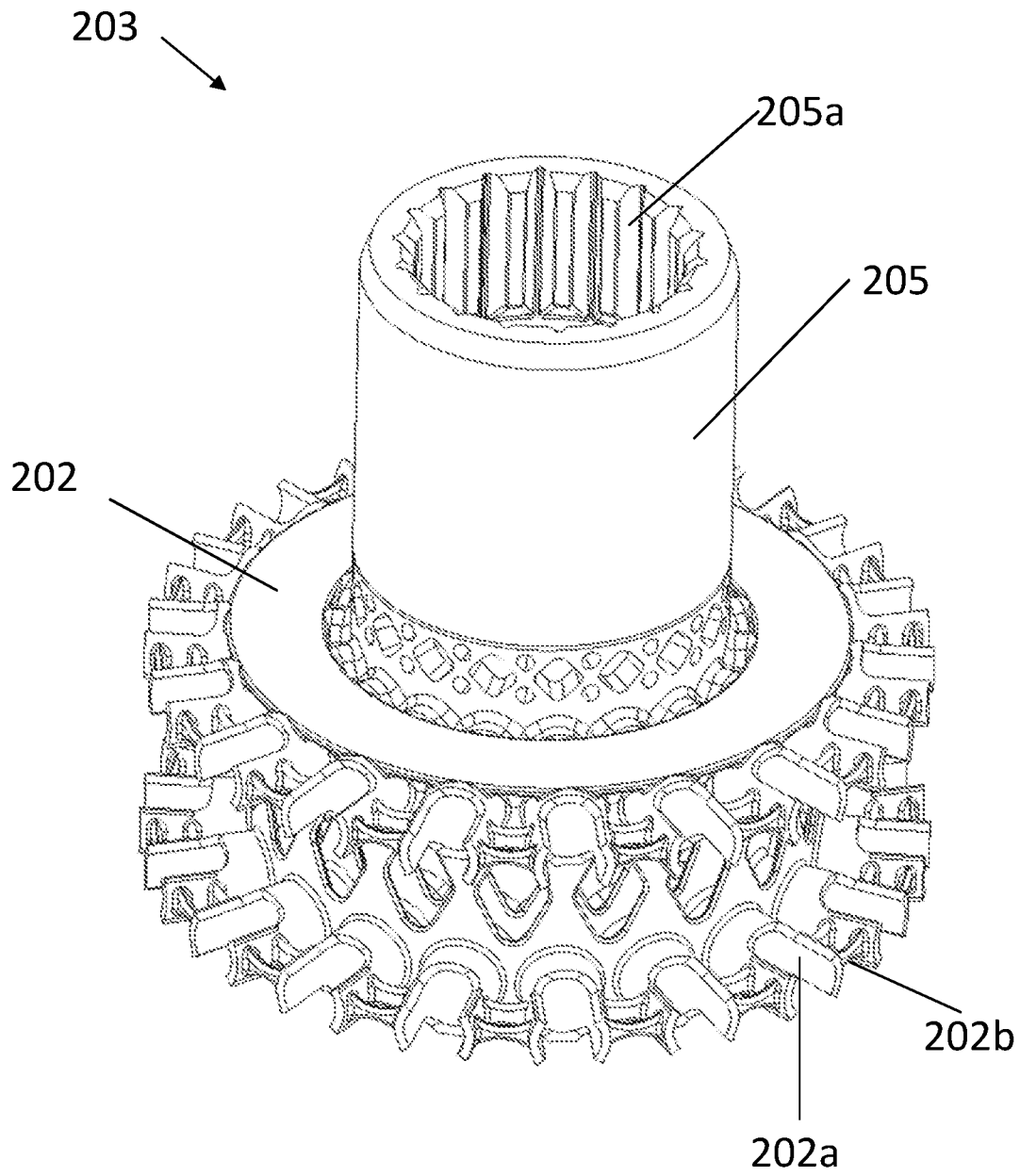


FIG. 5

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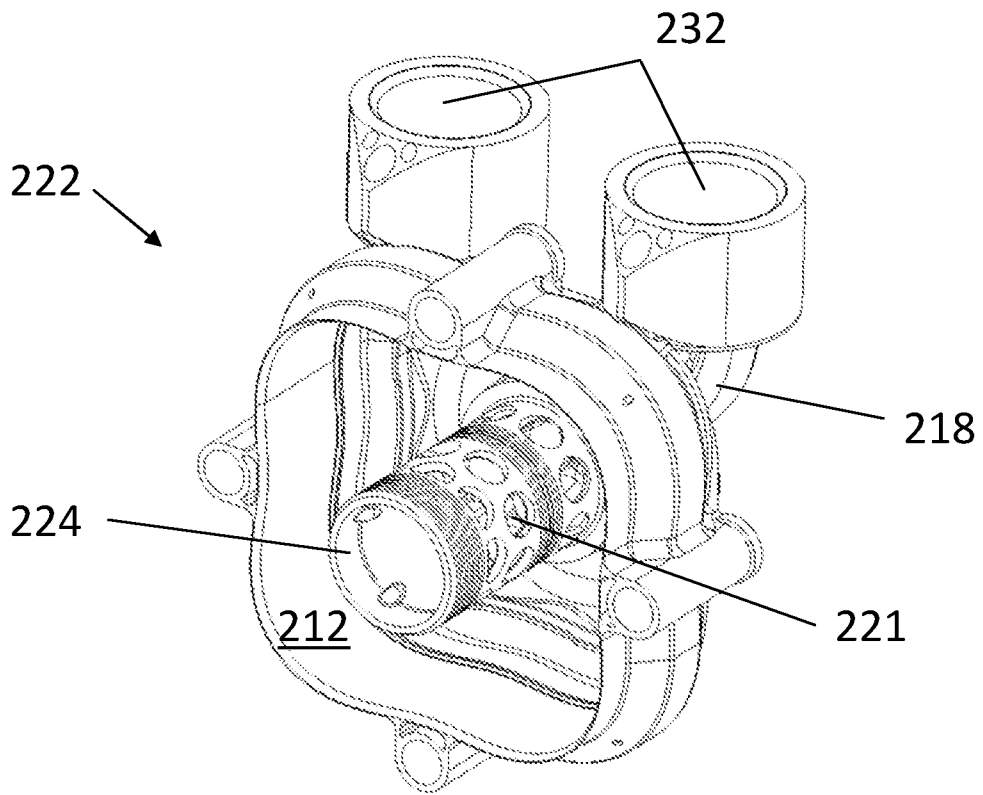


FIG. 6(a)

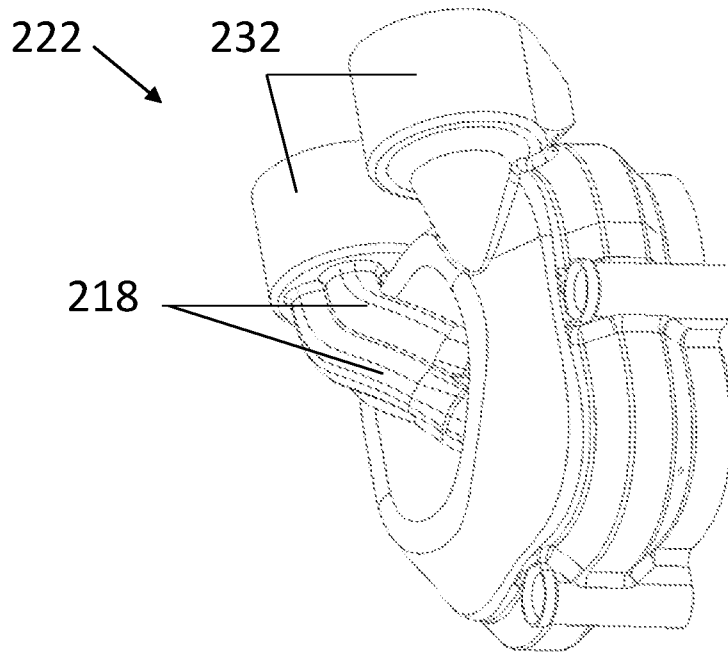


FIG. 6(b)

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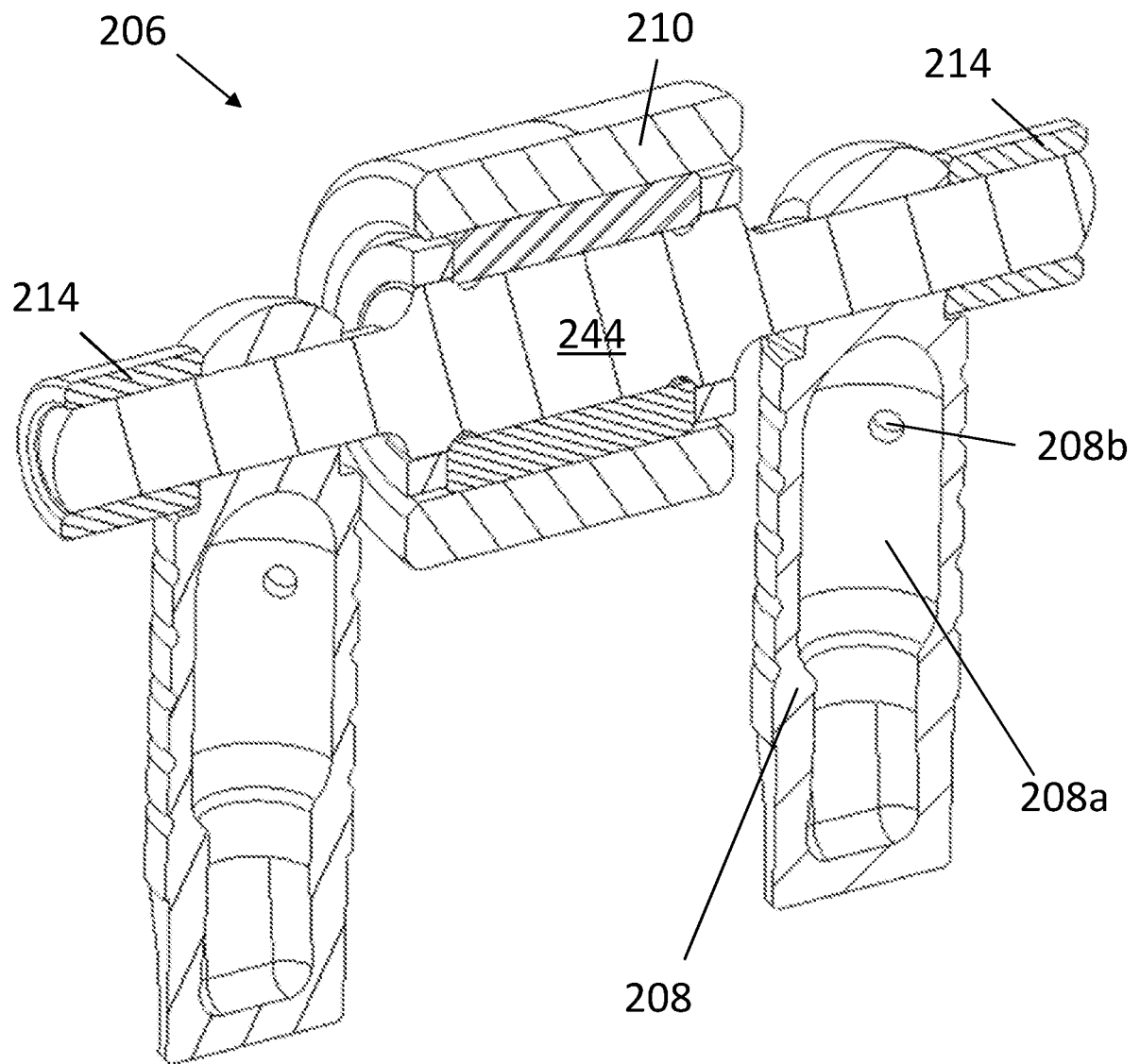


FIG. 7

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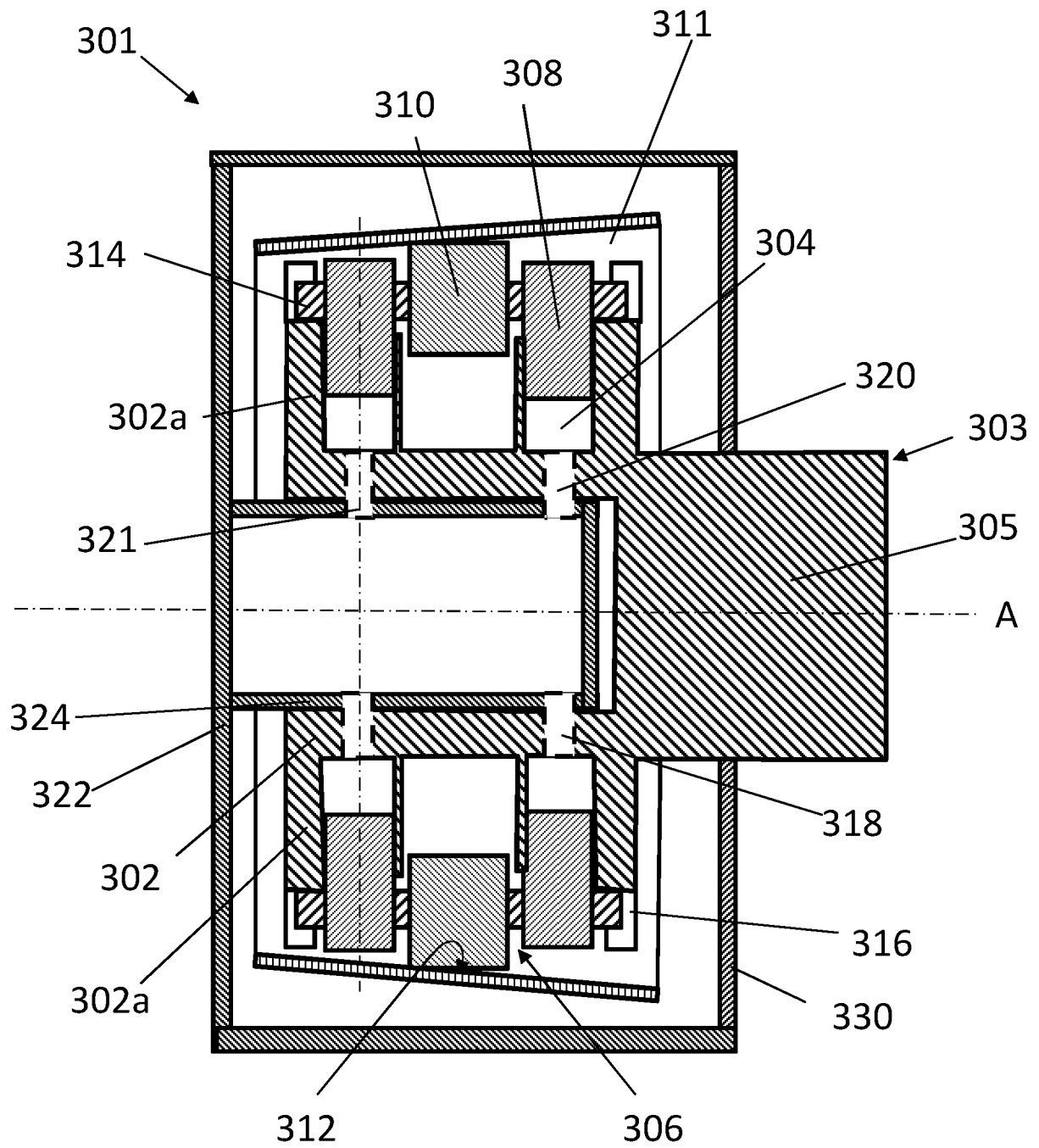


FIG. 8

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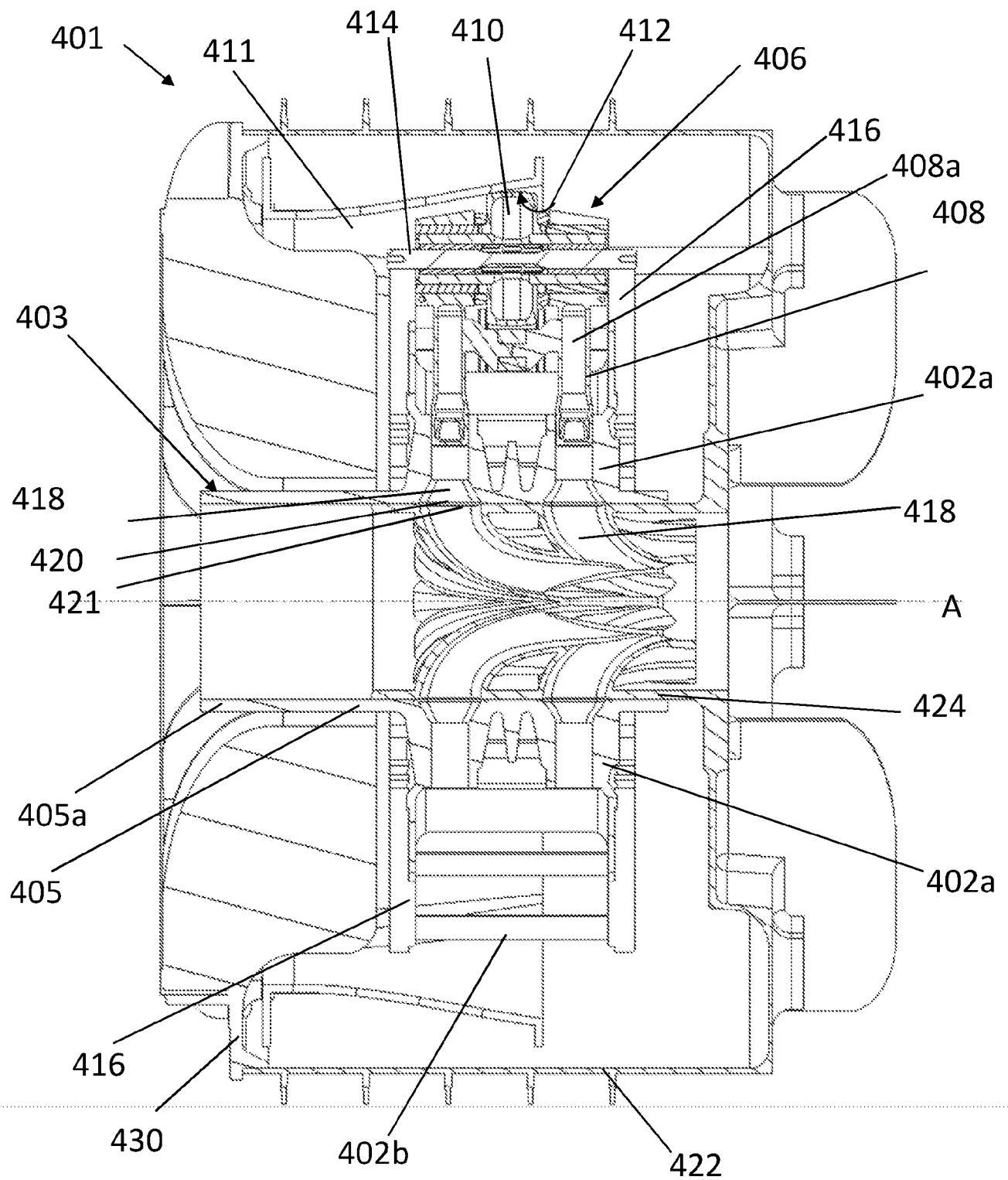


FIG. 9

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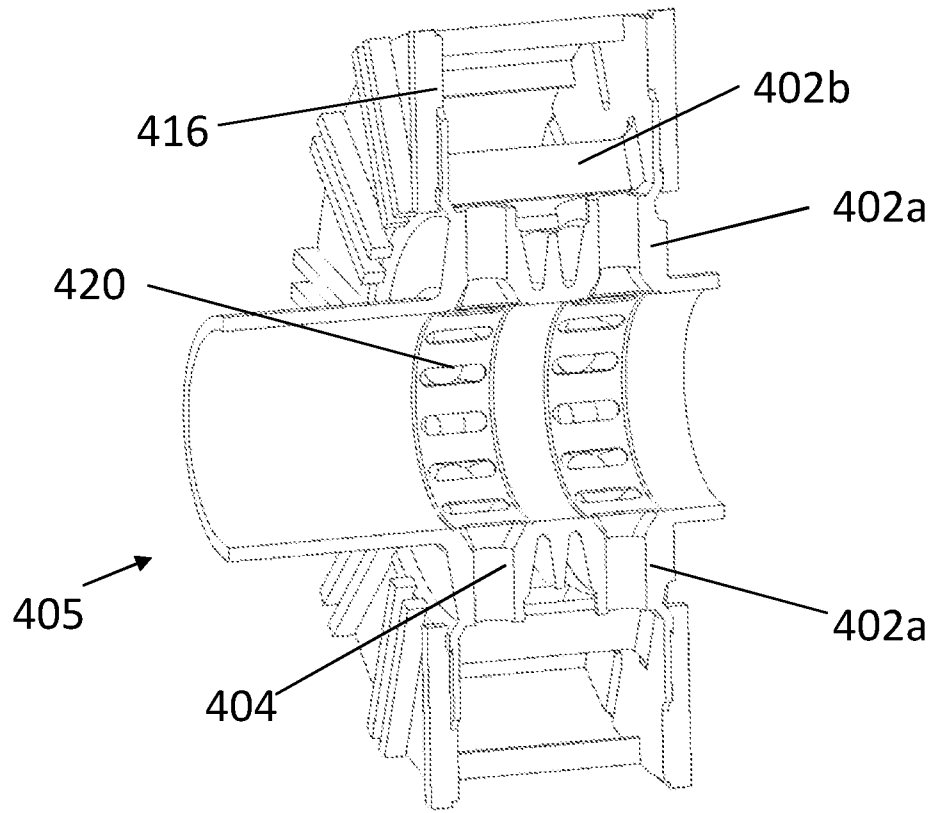


FIG. 10

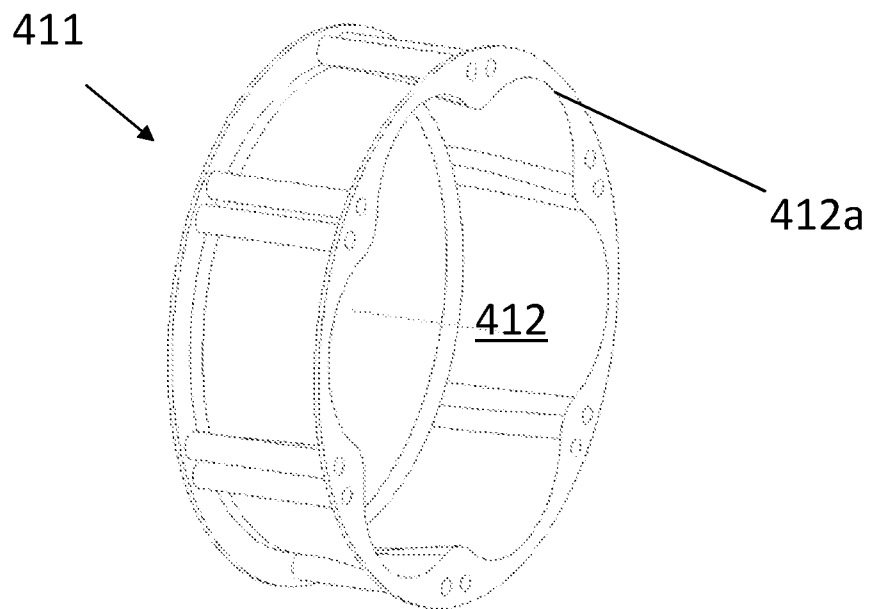


FIG. 11

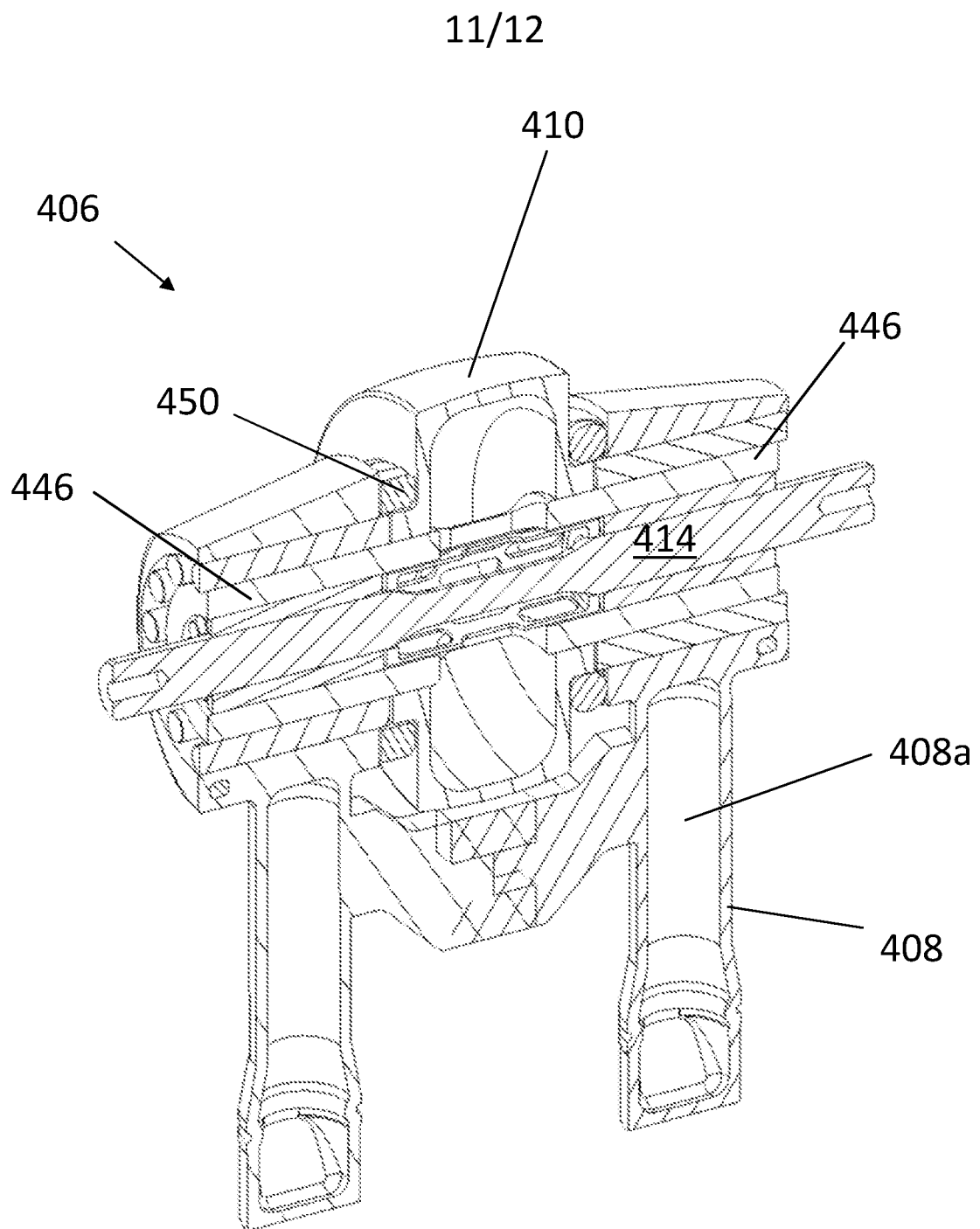


FIG. 12

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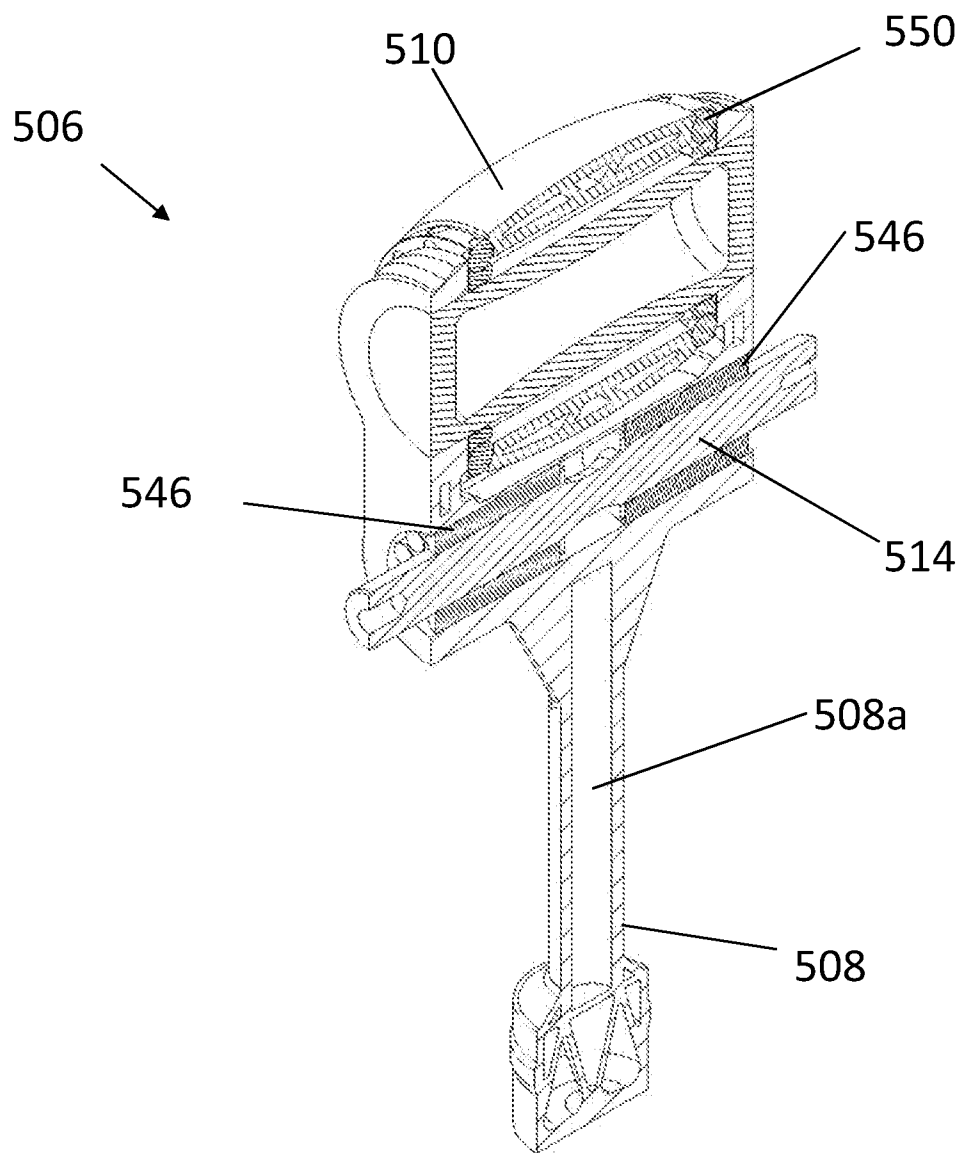


FIG. 13

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2016/052150

A. CLASSIFICATION OF SUBJECT MATTER INV. F04B1/04 F04B1/107 ADD. F03C1/30 F03C1/32 F03C1/36 F03C1/047		
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) F04B F03C		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-Internal, WPI Data		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 3 875 851 A (FOSTER KENNETH WILLIAM SAMUEL) 8 April 1975 (1975-04-08)	1-6,8-16
Y	figures 1, 2, 3, 5 column 2, line 23 - column 4, line 67 -----	7
X	US 4 522 110 A (SAMUELSSON EINAR [SE]) 11 June 1985 (1985-06-11)	1-6,8-16
A	figures 1, 2 column 3, line 18 - column 4, line 17 -----	7
Y	FR 796 163 A (D APP DE TRANSMISSION) 31 March 1936 (1936-03-31)	7
A	page 1, line 58 - page 2, line 27; figure 1 ----- -/--	1-6,8-16
☒ 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 "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	Date of mailing of the international search report	
12 October 2016	14/12/2016	
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Ricci, Saverio	

INTERNATIONAL SEARCH REPORT

International application No

PCT/GB2016/052150

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 099 372 B1 (UNIPAT AG [CH]) 20 December 1989 (1989-12-20) figures 1-5 column 2, line 44 - column 3, line 29 column 4, line 27 - column 5, line 14 -----	1-16

INTERNATIONAL SEARCH REPORT

International application No.
PCT/GB2016/052150

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of Item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

1-16

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. claims: 1-16

A radial piston pump comprising a drive shaft and a piston housing integrally formed.

2. claims: 17-32

A radial piston pump comprising a cam which can move axially in order to change the volumetric flow rate of the pump.

3. claims: 33-52

A radial piston pump comprising a primary roller and a secondary roller.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/GB2016/052150

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