

Gearbox for a pumpField of the Disclosure

The present disclosure relates to a gearbox, in particular a gearbox suitable for use in a pump (e.g. a radial hydraulic pump). The present disclosure further relates to a pump comprising the gearbox, to systems comprising the gearbox and/or the pump, and to methods of operating the gearbox and/or pump.

Background to the Disclosure

Radial hydraulic pumps, such as radial piston pumps, comprise one or more pistons that extend radially with reference to a drive shaft. Each piston is connected at one end to the drive shaft, and at an opposing end to an external tappet, also known as a stroke ring, which surrounds the drive shaft. The attachment of the pistons is such that as the distance between the external tappet and the drive shaft increases, a volume within the piston increases (and therefore a pressure within the piston decreases). Within such a pump, either the drive shaft or the external tappet is eccentric; therefore, as the drive shaft rotates, the drive shaft and the tappet cooperate to continuously vary the volumes of each piston. The variation in these volumes of the pistons causes a change in the pressure within the pistons, which change in pressure may be used to drive the flow of a fluid.

Such a pump is shown in Figure 1, which depicts a conventional radial hydraulic pump 100 that comprises a drive shaft 102, an external tappet 104, and a first and second piston 106, 108. The drive shaft is fixed to rotate around an axis of rotation 110. An inner end 112 of the first piston 106 is fixed to the drive shaft, while an outer end 114 of this first piston is fixed to the external tappet. Since the axis of rotation of the drive shaft does not coincide with the centre of the drive shaft, rotation of the drive shaft causes the distance between the inner end and the outer end of the first piston to change through the cycle, with one full rotation of the drive shaft corresponding to one cycle between the maximum and minimum distances between these two ends and of the first piston. Similarly, the extension of the second piston 108 varies through the cycle (with the second piston being located opposite the first piston, and the extension of the second piston mirroring that of the first piston). The extension and compression of the pistons alters the pressure in those pistons so that the pistons draw in and expel fluids at points in the cycle corresponding to extension and compression respectively.

The pistons may be arranged to draw in fluid from an internal region of the pump, e.g. the pistons 106, 108 may draw in fluid from their inner ends, where the internal region of the pump may be connected to the fluid supply. This configuration is known as "inside impinged". Alternatively, the pistons may be connected to a fluid supply lying nearer the external tappet 104 so that the outer ends of the pistons are arranged to draw in fluid from this reservoir.

The connection of the pistons to the fluid supply may comprise a valve such that fluids may only flow through the connection in one direction. An inside impinged pump may have two valved openings on the inside ends of each piston. For example, the inner end 112 of the first piston 106 may have an opening with a valve that allows fluid to enter the first piston but not to leave the piston, and the outer end 114 of the first piston may have an opening with a valve that allows fluid to leave the first piston but not to enter. When the piston is expanding, fluid enters through the first opening. When the piston is compressed, fluid leaves only through the second opening, as the valve on the first opening does not allow fluid to exit.

Summary of the Disclosure

According to an aspect of the present disclosure, there is described: a gearbox for a pump, the gearbox comprising: a ring gear; a sun gear; and one or more planet gears arranged between the ring gear and the sun gear, the planet gears being arranged to move around the sun gear along a continuous path; wherein the ring gear, the sun gear, and the planet gears are arranged so that a radius of the path varies as the planet gears move along the path.

The variation in the radius of the path of the planet gears may be used to drive a pump.

Preferably, at least two of the ring gear, the sun gear, and the at least one planet gear have non-circular profiles (and/or non-circular pitch circumferences and/or non-constant pitch circle diameters).

5 The sun gear may have a non-circular pitch circumference and/or a non-circular profile, and the ring gear may also have a non-circular pitch circumference and/or a non-circular profile. The diameter, circumference, and/or the profile of the ring gear may be dependent on the diameter, circumference, and/or the profile of the sun gear. For example, the diameter of the ring gear may equal the sum of the diameter of the sun gear plus twice the diameter of a single planet gear. Advantageously, this allows the ring gear to mesh with the planet gears, and the planet gears to mesh with the sun gear, without imposing significant strain on the gears.

10 The gearbox may comprise a plurality of planet gears. The gearbox may comprise a pair of planet gears. Preferably, the pair of planet gears are arranged symmetrically about a centre of the path and/or a centre of rotation of the gearbox. Preferably, the gearbox comprises a plurality of pairs of planet gears.

15 The gearbox may comprise at least two planet gears, at least four planet gears, at least eight planet gears, and/or at least ten planet gears.

20 The gearbox may comprise a number of planet gears that is no greater than (and/or is equal to) an order of rotational symmetry of the gearbox. The gearbox may comprise a number of planet gears that is no greater than an order of rotational symmetry of the combination of the sun gear and the ring gear. When the gearbox comprises a number of planets that is not greater than the order of rotational symmetry of the combination of the sun gear and the ring gear, the planets may each be positioned so as to follow a path of equally varying width as they orbit the sun. Each planet may be positioned so as to follow a path, the width of which remains constant throughout the planet's orbit; this allows each planet to remain meshed with the sun and ring gear without experiencing significant compression at any points in the orbit.

The planet gears may be evenly spaced along the path.

25 The gearbox may comprise a carrier, and the planet gears may be attached to the carrier.

The width of the path the planet travels between the sun and ring gear may be substantially constant. The sun gear and the ring gear may be arranged such that a radial distance between the sun gear and the ring gear at the point of contact of each of the planet gears remains constant as said planet gears move along the path.

30 Each of the planet gears may have a circular profile. Each planet gear may be similar. The ring gear and the sun gear may each have non-circular profiles.

One or more of (e.g. each of) the sun gear, the ring gear, and the planet gears may comprise a plurality of teeth. Preferably, each of the gears has a similar spacing of teeth. Preferably, the teeth are arranged regularly about the profile of a corresponding gear.

35 The gearbox may comprise at least one piston, wherein the piston is arranged so that an amount of compression of the piston changes as the planet gears move along the path, preferably so that a radial compression of the piston changes as the planet gears move along the path. This radial compression may be used to cause a change in pressure of the piston as the planet moves along the path, which may be used to drive a pump. A first end of the piston may be associated with (e.g. attached to) a planet gear. A first end of the piston may be attached to a carrier.

40 The gearbox may comprise a plurality of pistons, wherein a first end of each piston may be associated with a respective planet gear.

A second end of each piston may be connected to a further component of the gearbox such that the first end of that piston moves relative to the second end of the piston as the planet gear moves along the path, preferably such that the first end of the piston moves towards and/or away from the second end of the piston as the planet gear moves along the path.

- 5 A second end of the piston may be connected to a further planet gear. Preferably, the second end of the piston is connected to an opposing planet gear that is located at an opposite point along the path to the gear (e.g. wherein the planet gear and the opposing planet gear are spaced along the path by 180° as each of the gears moves along the path).

- 10 The second end of the piston may be connected to one or more of: the sun gear; the ring gear; a carrier; and a point near to, and/or at, the centre of the path and/or a centre of rotation of the gearbox.

One or more of (e.g. each of) the pistons may be attached to a carrier.

The ring gear may be arranged to remain stationary (e.g. relative to a housing of the gearbox) as the planet gears move along the path. The sun gear may be arranged to remain stationary (e.g. relative to a housing of the gearbox) as the planet gears move along the path.

- 15 One or more of (e.g. each of) the sun gear and the ring gear may be arranged to rotate (e.g. relative to a housing of the gearbox) as the planet gears move along the path.

The gearbox may comprise a motor for driving a movement (e.g. a rotation) of one or more of: the sun gear; the ring gear; one or more of the planet gears; and a carrier associated with one or more of the planet gears.

- 20 The sun gear may comprise one or more minimum points, wherein the radius of the sun gear at said minimum points is less than an average radius of the sun gear. For example, the radial distance from the centre of the sun gear to the base of a tooth of the gear may be lower at a minimum point than the average value of the radial distance between the centre of the sun gear and the base of a tooth of the sun gear.

- 25 The sun gear may comprise one or more maximum points, wherein the radius at said maximum points is greater than an average radius of the sun gear. For example, the radial distance from the centre of the sun gear to the base of a tooth of the gear may be greater at a maximum point than the average value of the radial distance between the centre of the sun gear and the base of a tooth of the sun gear.

- 30 The ring gear may comprise one or more minimum points, wherein the radius of the ring gear (e.g. the distance from the ring gear to the centre of rotation of the ring gear and/or the gearbox) at said minimum points is less than an average radius of the ring gear. For example, the radial distance from the centre of the ring gear to the base of a tooth of the gear may be lower at a minimum point than the average value of the radial distance between the centre of the ring gear and the base of a tooth of the ring gear.

- 35 The ring gear may comprise one or more maximum points, wherein the radius of the ring gear (e.g. the distance from the ring gear to the centre of rotation of the ring gear and/or the gearbox) at said maximum points is greater than an average radius of the ring gear. For example, the radial distance from the centre of the sun gear to the base of a tooth of the gear may be greater at a maximum point than the average value of the radial distance between the centre of the sun gear and the base of a tooth of the sun gear.

- 40 The ring gear may be rotationally symmetric. Alternatively and/or additionally, the sun gear may be rotationally symmetric. Preferably, both the sun and ring gear are rotationally symmetric. This allows a plurality of planet gears to be positioned such that a radial distance between the sun gear and the ring gear at the point of contact of each of the planet gears remains constant as said planet gears move along the path.

The sun gear may comprise an equal number of minima and maxima; and/or the ring gear may comprise an equal number of minima and maxima.

The number of minima of the ring gear may be the same as the number of minima of the sun gear; and/or the number of maxima of the ring gear may be the same as the number of maxima of the sun gear.

The number of minima of the ring gear may be greater than the number of minima of the sun gear; and/or the number of maxima of the ring gear may be greater than the number of maxima of the sun gear.

- 5 An amplitude of the minima of the sun gear (e.g. a distance between an average radius of the sun gear and a radius of the sun gear at the minima) may be equal to an amplitude of the maxima of the sun gear (e.g. a distance between an average radius of the sun gear and a radius of the sun gear at the maxima).

- Similarly, an amplitude of the minima of the ring gear (e.g. a distance between an average radius of the ring gear and a radius of the ring gear at the minima) may be equal to an amplitude of the maxima of the ring gear (e.g. a distance between an average radius of the sun gear and a radius of the ring gear at the maxima).
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Preferably, a variation in amplitude of the minimum points of the sun gear (e.g. from an average radius of the sun gear) is equal to a variation in amplitude of the maximum points of the sun gear.

- Preferably, a variation in amplitude of the minimum points of the ring gear is equal to a variation in amplitude of the maximum points of the ring gear.
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Preferably, the variation in amplitude of the minimum points of the sun gear is equal to the variation in amplitude of the maximum points of the ring gear.

Preferably, the variation in amplitude of the maximum points of the sun gear is equal to the variation in amplitude of the minimum points of the ring gear.

- 20 The sun gear may have a wavy profile, and/or the ring gear may have a wavy profile.

The sun gear may have a profile that comprises a sinusoidal wave superimposed onto an ellipse, preferably a sinusoidal wave superimposed onto a circle; and/or the ring gear may have a profile that comprises a sinusoidal wave superimposed onto an ellipse, preferably a sinusoidal wave superimposed onto a circle.

- The profile of the sun gear and/or the ring gear (and preferably, the profile of each of the sun gear and the ring gear) may be defined by the equation:
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$$r(t) = \frac{P}{2} + a \cdot \sin(ft)$$

- where: t is a parametric variable with values from 0 to 2π ; r is a radius of the gear (e.g. of the profile of the gear) at a value t ; P is an average (e.g. pitch circle) diameter of the gear (e.g. of the profile of the gear); a is a wave amplitude (e.g. an amplitude of the sinusoidal wave and/or an amplitude of a variation of a minima and/or or a maxima of the gear from the average diameter); and f is a wave frequency (e.g. a number of waves of the gear).
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The ring gear may comprise a different number of minima and/or maxima than the sun gear. Preferably, the ring gear comprises a greater number of minima and/or maxima than the sun gear and/or f_{ring} is greater than f_{sun} .

- 35 The amplitude of the minima and/or maxima of the sun gear may be substantially equal to the amplitude of the minima and/or maxima of the ring gear, and/or a_{ring} may be equal to a_{sun} . When a_{ring} is equal to a_{sun} , it is possible to configure the gears such that a radial distance between the sun gear and the ring gear at the point of contact of each of the planet gears remains constant as said planet gears move along the path.

- The ring gear and/or the sun gear may comprise one or more waves, a wave being a sinusoidal section (e.g. a cycle) of a perimeter of the gear and/or a wave comprising a minima and a maxima. Preferably, the
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ring gear and/or the sun gear comprises a whole number of waves. The ring gear may comprise a greater number of waves than the sun gear.

The diameters and numbers of waves of the sun gear and the ring gear may be linked by the equation:

$$\frac{P_{sun}}{f_{sun}} = \frac{P_{ring}}{f_{ring}}$$

- 5 where: P_{sun} is an average (e.g. pitch circle) diameter of the sun gear; P_{ring} is an average (e.g. pitch circle) diameter of the ring gear; f_{sun} is a wave frequency (e.g. a number of waves) of the sun gear; and f_{ring} is a wave frequency (e.g. a number of waves) of the ring gear.

The sun gear may comprise eight waves (e.g. $f_{sun} = 8$). The ring gear may comprise ten waves (e.g. $f_{ring} = 10$).

- 10 The (e.g. pitch circle) diameter of the sun gear may be at least 100mm, at least 200mm, and/or at least 500mm. The (e.g. pitch circle) diameter of the sun gear may be no more than 1000mm, no more than 800mm, and/or no more than 500mm.

The diameter of the planet gears may be at least 50mm, at least 100mm, and/or at least 200mm. The diameter of the planet gears may be no more than 500mm, no more than 400mm, and/or no more than 300mm.

- 15 The pump may comprise a radial pump and/or a radial hydraulic pump. The pump may be arranged to pump a fluid through the pistons; and/or to pump a fluid in a radial direction of the gearbox (e.g. perpendicular to an axis of rotation of the gearbox); and/or to pump a fluid in a direction of an axis of rotation of the gearbox (e.g. of the sun gear and/or the ring gear).

- 20 The pump may comprise a shaft, wherein one or more of (preferably each of): the sun gear; the ring gear; and a carrier are arranged to rotate around the shaft.

According to another aspect of the disclosure, there is provided a (e.g. computer-implemented) method of operating the gearbox and/or the pump of any embodiment of the first aspect. The method may comprise driving one or more of: the sun gear, the ring gear, and one or more of the planet gears. The method may comprise driving said gear(s) in dependence on a desired pumping force.

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According to another aspect of the disclosure, there is provided a method of manufacturing the gearbox and/or the pump of the first aspect.

According to another aspect of the disclosure, there is provided a kit of parts for the gearbox of any preceding claim, the kit of parts comprising: the ring gear; the sun gear; and one or more planet gears.

- 30 According to another aspect of the disclosure, there is described: a computer program product (and/or a machine readable medium) comprising computer-executable instructions, which when executed, cause a processor to control the gearbox and/or the pump of any preceding claim.

Any feature in one aspect of the disclosure may be applied to other aspects of the invention, in any appropriate combination. In particular, method aspects may be applied to apparatus aspects, and vice versa.

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Furthermore, features implemented in hardware may be implemented in software, and vice versa. Any reference to software and hardware features herein should be construed accordingly.

Any apparatus feature as described herein may also be provided as a method feature, and vice versa. As used herein, means plus function features may be expressed alternatively in terms of their corresponding structure, such as a suitably programmed processor and associated memory.

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It should also be appreciated that particular combinations of the various features described and defined in any aspects of the disclosure can be implemented and/or supplied and/or used independently.

The disclosure also provides a computer program and a computer program product comprising software code adapted, when executed on a data processing apparatus, to perform any of the methods described
5 herein, including any or all of their component steps.

The disclosure also provides a computer program and a computer program product comprising software code which, when executed on a data processing apparatus, comprises any of the apparatus features described herein.

The disclosure also provides a computer program and a computer program product having an operating
10 system which supports a computer program for carrying out any of the methods described herein and/or for embodying any of the apparatus features described herein.

The disclosure also provides a computer readable medium having stored thereon the computer program as aforesaid.

The disclosure also provides a signal carrying the computer program as aforesaid, and a method of
15 transmitting such a signal.

The disclosure extends to methods and/or apparatus substantially as herein described with reference to the accompanying drawings.

The disclosure will now be described, by way of example, with reference to the accompanying drawings.

Description of the Drawings

20 Figure 1 shows a conventional radial piston pump according to the prior art.

Figure 2 shows a system comprising a pump.

Figure 3 shows an epicyclic gearbox.

Figures 4a and 4b show an epicyclic gearbox according to the present disclosure.

Figures 5a and 5b show exemplary gears.

25 Figure 6 shows a further embodiment of an epicyclic gearbox according to the present disclosure.

Figure 7 shows another embodiment of an epicyclic gearbox according to the present disclosure.

Description of the Preferred Embodiments

Referring to Figure 2, there is shown a system envisaged by the present disclosure. Figure 2 shows a fluid source 252, for example a water source. This fluid source is connected to a pump 254 at a fluid inlet 262.
30 The pump takes in fluid from the fluid source through the fluid inlet and subsequently expels the fluid through a fluid outlet. This fluid outlet is connected to a fluid output. Typically, the inlet and the outlet of the pump are associated with one-way valves to prevent any flows in the reverse direction through the system, e.g. from the fluid output back into the pump, or from the pump back into the fluid source.

The present disclosure relates to a gearbox that is suitable for use in a pump, in particular a radial hydraulic pump. More specifically, the present disclosure relates to an epicyclic (or planetary) gearbox that may be
35 used in a pump.

Referring to Figure 3, there is described a conventional epicyclic gearbox 300 that comprises a sun gear 310, a first planet gear 320 and a second planet gear 325, and a ring gear 330. Each of the gears comprises a series of teeth and grooves, so that the gears mesh together. More specifically, each planet gear meshes
40 with both of the sun gear and the ring gear so that as the planet gears move they roll without slip relative to the sun gear and the ring gear. Typically, the planet gears are supported by a carrier (which is not shown

in Figure 3). Therefore, a movement of the planet gears causes a movement (e.g. a rotation) of the carrier, which movement can be used to power another component.

An epicyclic gearbox can be operated by driving one or more of: the sun gear 310, the ring gear 330, the carrier (not shown), and one or more of the planet gears 320, 325. For example, a motor may be attached to one of these components and used to cause a movement of said component. In operation, driving the sun gear around its central axis causes the planet gears to move in an orbit around the sun gear 310. If the ring gear 330 is held stationary (e.g. stationary relative to a housing of the gearbox), then the meshed contact between the ring gear and the planet gears causes the planet gears to rotate around their respective axes (and thus causes a movement of the carrier). Equally, for example, the ring gear may be held stationary, with the planet gears being driven. Such movement of the planet gears then causes a movement of the sun gear.

Conventional epicyclic gearboxes comprise a circular sun gear 310, circular planet gears 320, 325, and a circular ring gear 330. As shown in Figures 4a and 4b, the present disclosure considers an epicyclic gearbox 400 with a non-circular ring gear 402 and a non-circular sun gear 404.

This epicyclic gearbox 400 of the present disclosure further comprises one or more planet gears 406, 408, which planet gears are located between the ring gear 402 and the sun gear 404 and are arranged to move along a path around the sun gear. Typically, each of the ring gear, the sun gear, and the planet gears comprises a series of teeth and grooves so that the gears mesh together (as has been described above) to promote such movement.

The planet gears 406, 408 are arranged to move along a (e.g. non-circular) continuous path defined by the ring gear 402 and the sun gear 404. Therefore, as the planet gears move along the path, a distance between the planet gears and an axis of rotation 410 of the sun gear (and of the epicyclic gearbox) changes. This may be viewed as a radius of the path of the planet gears changing as the planet gears move along that path.

The sun gear 404 comprises one or more troughs (or minima) and one or more peaks (or maxima), where the sun gear has a greater radius at the peaks than at the troughs. These troughs and/or peaks cause the aforementioned change in the radius of the path of the planet gears 406, 408 as the planet gears move about the sun gear.

The ring gear 402 typically comprises similar maxima and minima (e.g. peaks and troughs), where typically the peaks of the sun gear 404 are arranged to coincide with troughs of the ring gear during normal rotation of the planet gears 406, 408, so as to define a path of substantially constant width between the sun gear and the ring gear. Therefore, as the planet gears move around the sun gear, they move through the peaks and the troughs so as to alter a radius of the path of the planet gears.

The maxima/peaks of the sun 404 gear may be considered to be the points of the sun gear that are furthest from the axis of rotation of the sun gear (or the axis of rotation of the epicyclic gearbox), with the minima/troughs of the sun gear being the points of the sun gear that are closest from the axis of rotation of the sun gear.

Conversely, the maxima/peaks of the ring gear 402 may be considered to be the points of the ring gear that are closest to the axis of rotation 410 of the sun gear 404 (or the axis of rotation of the epicyclic gearbox), with the minima/troughs of the ring gear being the points of the ring gear that are furthest from the axis of rotation of the sun gear.

Typically, each planet gear 406, 408 is sized so as to fit between a peak of the sun gear 404 and a trough of the ring gear 402, or between a trough of the sun gear and a peak of the ring gear.

The above-described change in the radius of the path of the planet gears 406, 408 can be used to implement a radial pump. Specifically, a pump may comprise the epicyclic gearbox 400 and one or more pistons, with each of the pistons being connected to (or more generally associated with) one of the planet gears 406, 408 of the epicyclic gearbox. Driving any of the gears of the epicyclic gearbox causes a relative movement between the planet gears and the sun gear 402 that, due to the changing radius of the path of the planet gears, causes a change in volume in the pistons (e.g. a compression and/or decompression) and thus a change in pressure in the pistons.

As used herein the term 'piston' is used to refer to any component that provides a force in dependence on a compression and/or an extension so that the piston is able to provide a pumping force. Therefore, while the piston typically comprises a piston head that is arranged to move so as to alter a volume in the piston (and thereby provide a pumping force), the piston may equally comprise, for example, a solid material such as a spring or a rubber component, where the compression and extension of this material can be used to provide a pumping force.

The pistons are each associated with (e.g. connected to) one of the planet gears 406, 408 at a first end. In order to cause the aforementioned change in pressure, the second end of each piston may be connected to one or more of: another planet gear, the sun gear, and/or another external component that moves relative to the planet gears as the planet gears move along their path.

As shown in Figures 4a and 4b, in some embodiments the piston is connected to a first planet gear 406 and a second planet gear 408, where these planet gears are typically arranged symmetrically about the (e.g. axis of rotation of the) sun gear. The planet gears being arranged symmetrically about the sun gear comprises the planet gears being arranged on opposite sides of the sun gear and/or at opposite points of the path.

The embodiment of Figures 4a and 4b shows ring and sun gears 402, 404 with a regular arrangement of peaks and troughs and with a plurality of ring gears. It will be appreciated that more generally the sun gear and/or the ring gear may comprise any number of peaks and troughs (e.g. a single peak and trough) and that the epicyclic gearbox 400 may comprise any number of planet gears (e.g. a single planet gear). Furthermore, while the embodiment shown in Figures 4a and 4b comprises a rotationally symmetric sun gear and a rotationally symmetric ring gear, it will be appreciated that a change in radius may be achieved with an asymmetric sun gear and/or ring gear (e.g. with a sun gear that comprises a single short trough and a single long peak). However, rotationally symmetric gears are typically used, since these can be more easily used to provide a regular change in the radius of the path of the planet gears and therefore a consistent pumping force.

Referring to Figures 4a and 4b, this embodiment comprises a first planet gear 406 and a second planet gear 408 that are arranged to move along a (regularly) oscillating (e.g. sinusoidal) path, where each gear moves through a series of peaks and troughs, or through a series of points of maximal radius and points of minimal radius. As the gears move along this path, a radial distance between the planet gears and the axis of rotation 410 of the sun gear changes and a radial distance between the planet gears changes. In this regard, the pair of planet gears is typically arranged so as to simultaneously pass through a pair of peaks and/or so as to simultaneously pass through a pair of troughs so as to ensure that there is such a change in radial distance between the planet gears.

This movement causes a change in a volume of a piston connected to one or more of the planet gears (e.g. via a carrier connected to the planet gears). As has been explained above, such a change in volume causes a corresponding change in pressure, and this change in pressure can be used to apply a pumping force to a fluid.

Typically, the epicyclic gearbox 400 comprises a plurality of planet gears 406, 408, and/or a plurality of pairs of planet gears. Typically, each pair of planet gears is arranged symmetrically about the axis of rotation 410 of the sun gear 404.

Typically, the planet gears 406, 408 are evenly spaced along the path defined by the sun gear and the planet gear 402, where this enables the provision of a regular pressure and a regular pumping force. Typically, each of the planet gears is similar, where this also enables the provision of a regular pressure and a regular pumping force.

Typically, one or more of (and/or each of) the planet gears 406, 408 is associated with a piston, where a first end of the piston is arranged to move along with the associated planet gear so as to cause a compression or extension of the piston. A second end of the piston is typically connected to one or more of: another planet gear (e.g. the other planet gear of a pair of planet gears) or the sun gear 404.

The second end of the piston may be connected to a component of the sun gear 404 and/or the planet gear that is arranged to rotate relative to the sun gear and/or the planet gear so as to avoid collisions between various pistons. In particular, the connection of the second end of a piston to the sun gear and/or the planet gear may be arranged to rotate so as to remain radially aligned with the planet gear associated with the piston (while the axial distance between the second end of the piston and the planet gear changes). Attaching each piston to a pair of planet gears enables an arrangement in which numerous pistons can be provided with the circumferential distance between each piston remaining the same (since all of the planet gears and thus all of the pistons are rotating at the same rate. This enables the use of a combined piston carrier on which a plurality of pistons are mounted, where this piston carrier is arranged to rotate with the planet gears and to only allow radial movements of the pistons.

To provide a pump, the first end and/or the second end of each piston may be connected to a fluid source (e.g. the fluid source 252 of Figure 2) so that the changes in pressure in the pistons causes a pumping of this fluid. The connection of the piston to the fluid source may be a direct connection, where the piston draws in a fluid from the fluid source and then expels the fluid, or may be indirect, where the change in pressure in the piston is used to drive a movement of the fluid out of the fluid source (e.g. perpendicular to the direction of the piston). For example, the second end of the piston may be connected to the sun gear, and the change in pressure within the piston may be used to drive a working fluid along an axis aligned with the axis of rotation of the sun gear.

30 Parametric profiles

Typically, both of the ring gear 402 and the sun gear 404 have non-circular (e.g. parametric) profiles. Specifically, each of the ring gear and the sun gear typically has a profile that comprises a sinusoidal wave superimposed onto an ellipse (e.g. a circle).

Such a profile can be defined by the following parametric equations:

$$x(t) = \frac{P}{2} \cos(t) + a \cdot \sin(f \cdot t) \cdot \cos(t)$$

$$y(t) = \frac{P}{2} \sin(t) + a \cdot \sin(f \cdot t) \cdot \sin(t)$$

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These cartesian equations can equally be written as a polar equation:

$$r(t) = \frac{P}{2} + a \cdot \sin(ft)$$

Where, t is a parametric variable, and t goes from 0 to 2π .

It will be appreciated that this polar equation (and the associated cartesian equations) could equally be written as:

$$r(t) = \frac{P}{2} + a \cdot \cos(ft)$$

$$x(t) = \frac{P}{2} \cos(t) + a \cdot \cos(f \cdot t) \cdot \cos(t)$$

$$y(t) = \frac{P}{2} \sin(t) + a \cdot \cos(f \cdot t) \cdot \sin(t)$$

In the above equations:

P is an average (e.g. pitch circle) diameter of a gear about the centre of rotation 410 of the epicyclic gearbox (e.g. so that $\frac{P}{2}$ defines the average radius of a gear, and the sinusoidal term(s) define a variation of the radius of said gear about this average radius).

The diameter of the sun gear 404 is smaller than the diameter of the ring gear 402, with the planet gears 406, 408 being sized so as to fit between these diameters.

a is a wave amplitude that defines an amplitude of maxima and minima (e.g. peaks and troughs) of a gear. That is a defines a variation of a profile of the gear from the average diameter P . The value of a may depend on the available space for the epicyclic gearbox 400 and/or the pump, and/or the required pumping force/volume.

f is a wave frequency that defines a number of maxima and minima (e.g. peaks and troughs) of a gear. In this regard a single cycle of a sine wave (from a maxima to a subsequent maxima) can be considered to be a wave, where each gear has f waves.

The ring gear and the sun gear typically both have profiles that comprise both a constant radial term and a variable (e.g. sinusoidal) radial term. This leads to a non-circular gear profile, where the use of a sinusoidal radial term leads to a regular (albeit still non-circular) gear profile. Typically, the gear profiles are each rotationally symmetric, where such rotational symmetry can be obtained by using a whole number for the wave frequency f).

The gears typically comprise a plurality of teeth so that any adjacent pair of gears is able to mesh together. And due to these teeth each of the gears is typically not perfectly circular. In this regard, a gear can be considered to comprise a friction wheel with teeth, where a pitch circle of the gear corresponds to an outer circumference of the friction wheel so that the pitch circle provides a reference circle for determining the pitch of the gear teeth. Specifically, the circular pitch of a gear, which is the distance from one tooth centerline to the next, can be calculated by dividing the circumference of the pitch circle by the number of teeth of that gear.

The term pitch circle diameter is therefore used to identify that gears typically comprise a series of teeth located around an otherwise circular gear. References herein to the gears being non-circular refers to the gears being non-circular due to factors other than the teeth of the gears. The disclosures herein are applicable to non-circular gears generally, so it should be appreciated that while the detailed description refers to gears with non-constant pitch circle diameters (e.g. where a profile of the gears comprises a superposition of a circular profile with a sinusoid), more generally the present disclosures relate to the provision of gears with a non-circular pitch circumference.

As used herein, the 'profile' of a gear refers to the shape of the gear excluding teeth. For example, Figures 4a and 4b show a ring gear 402 and a sun gear 404, each of which have non-circular profiles as well as a pair of planet gears 406, 408, which planet gears have circular profiles. In practice, each gear typically

comprises a plurality of teeth so that, for example, the planet gears may be similar to the planet gears 320, 325 of the conventional epicyclic gearbox Figure 3. These planet gears may be considered to comprise a series of teeth that are arranged about a circular profile. Similarly, the ring gear and the sun gear may be considered to comprise a series of teeth that are arranged about a non-circular profile.

- 5 The above variables are shown by Figures 5a and 5b.

Referring to Figure 5a, there is shown an embodiment of a conventional gear with a circular profile. This gear has a pitch circle diameter P , where the gear further comprises a series of teeth arranged about this pitch circle diameter. Such a gear may, for example, be used for the planet gears 406, 408 of the epicyclic gearbox 400 of Figures 4a and 4b. While the gear comprises teeth such that the gear is not strictly circular, the gear can be considered to have a circular profile, where the teeth are arranged about this circular profile.

- 10 the gear can be considered to have a circular profile, where the teeth are arranged about this circular profile.

Referring to Figure 5b, there is shown an embodiment of a ring gear and a sun gear according to the present disclosure. The ring gear comprises twelve waves (e.g. $f_{ring} = 12$) and the sun gear comprises six waves ($f_{sun} = 6$). The ring gear and the sun gear each have non-circular profiles, where the embodiment of Figure 5b shows a sun gear with a profile that is composed of a sinusoidal wave superimposed onto a circle, so that the sun gear comprises a series of maximum points with a radius equal to $\frac{P}{2} + a_{sun}$ and a series of minimum points with a radius equal to $\frac{P}{2} - a_{sun}$. Typically, the sun gear and the ring gear each comprise a series of teeth that are arranged about their non-circular profiles.

- 15 the sun gear comprises a series of maximum points with a radius equal to $\frac{P}{2} + a_{sun}$ and a series of minimum points with a radius equal to $\frac{P}{2} - a_{sun}$. Typically, the sun gear and the ring gear each comprise a series of teeth that are arranged about their non-circular profiles.

With the embodiment of Figure 5b, $a_{sun,minima} = a_{sun,maxima}$. It will be appreciated that the gears may equally be provided with differing values of $a_{sun,minima}$ and $a_{sun,maxima}$.

- 20 As mentioned above, typically each of the ring gear and the sun gear further comprises a series of teeth arranged around the circumference of these gears. These teeth are not shown in the figures.

In the example shown, the ring gear 402 is defined with $f_{ring} = 10$, while the sun gear 404 is defined with $f_{sun} = 8$. It will be appreciated that various other combinations of wave frequencies may be applied.

- 25 In order to avoid damaging the planet gears 406, 408 as they move along the path defined by the ring gear 402 and the sun gear 404, typically the epicyclic gearbox 400 is arranged such that during use of the epicyclic gearbox, the width of this path is substantially constant. Values that provide such a path of substantially constant width are provided below. In some embodiments, the sun gear, the ring gear, and/or the planet gears may be flexible to reduce any damage that might occur due to (small) variations in the width of the path.

- 30 As has been described above, when the sun gear 404 is driven (e.g. by a motor associated with the sun gear), the planet gears 406, 408 are urged into orbit around the sun gear due to the interlocking teeth of each of the gears. As the planet gears rotate, they are urged towards maxima and minima (e.g. peaks and troughs) of the parabolic curves defining the sun gear and the ring gear 402. Figure 4a shows the planet gears when they are each located at maxima of parabolic curves defining the sun gear and the ring gear.
- 35 At this point, the distance between the planet gears is at a maximum. A piston fixed between the planet gears will therefore be at a point of maximum extension, and maximum volume, at this point in the cycle.

- Figure 4b shows the planet gears 406, 408 when they are each located at minima of parabolic curves defining the sun gear 404 and ring gear 402. At this point, the distance between the planet gears is at a minimum. A piston fixed between the planet gears will therefore have a maximum compression, and
- 40 minimum volume, at this point in the cycle.

Conventional radial hydraulic pumps – as shown in Figure 1 – have exactly one maximum and one minimum of extension for each piston per drive ring cycle; therefore, rapid cycling of the pump requires rapid rotation of the drive ring. This means that the translation of an external rotational force from, for example, a large

turbine, into pumping action requires extensive additional gearing to increase the rotational speed of the drive ring compared to the driving turbine. This additional gearing reduces the overall efficiency of the system. By using the epicyclic gearbox 400 of the present disclosure, it is possible to provide a radial hydraulic pump that has a plurality of extension cycles for each piston per drive ring cycle. This enables the efficient translation of an external rotational force into a pumping action. For example, Figures 4a and 4b show an embodiment of the gearbox in which a piston connected to the first planet gear 406 and the second planet gear 408 is driven through multiple maxima and minima over a single full rotation of the sun gear 404.

In order to achieve an efficient and reliable epicyclic gearbox arrangement, in some embodiments a number of constraints are enforced on the proportions and parameters defining the sun gear 404, the ring gear 402, and the planet gears 406 and 408. These constraints can be used to ensure the planet gears remain meshed in contact with the sun gear and ring gear throughout their orbit.

In some embodiments, these constraints relate to the values for P , α , and f in the above equations, where certain values are found to provide particularly effective gearboxes.

Typically, the sun gear 404 and the ring gear 402 are shaped such that the planet gears 406, 408 remain in contact with both the sun gear and the ring gear at all points along its path around the sun gear. Such a constraint requires that at every point in a planet gear's path around the sun at which the sun gear profile is at a maximum point, e.g. at every peak of the sun gear, the ring gear must have a corresponding minimum point. Likewise, at every point at which the sun gear profile is at a minimum point, e.g. at every trough of the sun gear, the ring gear must have a corresponding maximum point.

In some embodiments, in order to ensure this consistent contact, the sun gear and the ring gear comprise different numbers of maxima and minima (e.g. peaks and troughs). In some embodiments, the sun gear and the ring gear have different numbers of maxima and minima (e.g. peaks and troughs), where the sun gear and/or the ring gear may be arranged to rotate as the planet gears move along the path so that the planet gears remain in contact with the sun gear and the ring gear despite the differing number of maxima and minima.

Parametric dimensions

There are three primary curves that define the operation of the epicyclic gearbox 400: the curve defined by the radius of the ring gear 402 ($r_{ring}(t)$), the curve defined by the radius of the sun gear 404 ($r_{sun}(t)$), and the curve defined by the radius of the path of the planet gears 406, 408 ($r_{planet\ path}(t)$). The value for each curve is typically determined in dependence on the values of one or more other curves where a value is selected for one of the curves (e.g. based on a desired size of the epicyclic gearbox) and the values for the other curves are then determined based on this selected value. In particular, values for the dimensions of the ring gear may be determined based on selected dimensions of the sun gear (or *vice versa*).

In a preferred embodiment, the pitch circle diameter of the planet gears and the pitch circle diameter of the planet gear path are determined in dependence on the pitch circle diameters of the ring gear and sun gear. This allows values to be chosen for the planet gear that allow the planet gear to mesh with both the sun gear and the ring gear.

The pitch circle diameter for each planet gear 406, 408 may be determined using the equation:

$$\frac{P_{planet}}{2} = \frac{P_{ring} - P_{sun}}{2}$$

The pitch circle diameter of the path of the planet gears 406, 408 may be determined using the equation:

$$\frac{P_{planet\ path}}{2} = \frac{P_{ring} + P_{sun}}{2}$$

To calculate constraints on the ring gear 402 and the sun gear 404 that ensure a constant width of the path, it is possible to derive equations regarding the angular travel of the components.

Firstly, considering the motion of the components with the ring held stationary between a first position and a second position. The sun gear is rotated by an angle ω_s . As a consequence of this rotation, the planet gear rotates through an angle ω_p , and a carrier attached to the centre of the planet rotates through an angle ω_c . The contact point between the planet gear and the sun, measured along the surface of the sun gear, moves a total of $N_s\omega_s + N_p\omega_c$, where N_s is the number of teeth on the sun gear, because the contact point moves both due to a rotation by the sun gear, and the movement of the contact with the planet due to the planet's orbit,

The contact point between the planet gear and the sun, measured along the surface of the planet gear, moves a total of $N_p\omega_p - N_p\omega_c$, where N_p is a number of teeth of the planet gear, due to the rotation of the planet gear being accompanied by a change in the contact point with the sun gear,

Since the distance moved by the contact point on the sun and planet gears must be the same, we can derive the following equation:

$$N_s\omega_s + N_p\omega_p - (N_s + N_p)\omega_c = 0$$

Similarly, by considering only motion of the ring and planets, with the sun held still, we can derive the following equation:

$$N_r\omega_r - N_p\omega_p - (N_r - N_p)\omega_c = 0$$

Rearrangement of the second equation may be used to write $N_p\omega_p$ in terms of the other variables. This may then be substituted into the first equation to give:

$$N_s\omega_s + N_r\omega_r - (N_r - N_p)\omega_c - (N_s + N_p)\omega_c = 0$$

This may be rearranged to give:

$$\omega_c = \frac{N_s}{N_r + N_s}\omega_s + \frac{N_r}{N_r + N_s}\omega_r$$

If the ring is considered to be fixed, then the above equation may be further simplified to:

$$\omega_c = \frac{N_s}{N_r + N_s}\omega_s$$

Note that the number of teeth of the gear is directly proportional to the pitch circle diameter of the gear, which is proportional to the orbital path length L.

As discussed earlier, typically the profiles of the sun and ring gears are described by the following equations:

$$x(t) = \frac{P}{2}\cos(t) + a \cdot \sin(f \cdot t) \cdot \cos(t)$$

$$y(t) = \frac{P}{2}\sin(t) + a \cdot \sin(f \cdot t) \cdot \sin(t)$$

For the maxima and minima of the ring and sun gears 402, 404 to match up during rotation, the sun gear must rotate by an amount $\omega_s = \frac{1}{f_s} + \frac{1}{f_r}$ when a planet moves from one maximum of the ring to the next maximum of the ring, e.g. when the planet gear (or equivalently, the carrier) moves $\frac{1}{f_r}$ along its orbital path.

Substituting these two conditions into the equation for ω_c gives:

$$\frac{1}{f_r} = \frac{N_s}{N_r + N_s} \left(\frac{1}{f_s} + \frac{1}{f_r} \right)$$

This equation may be further rearranged to give:

$$\frac{f_s}{f_r + f_s} = \frac{N_s}{N_r + N_s}$$

As noted earlier, N is proportional to P , where P is the pitch circle diameter, or to the orbital path length. Therefore, the equation may equally be rewritten in the following terms.

$$\frac{f_{sun}}{f_{sun} + f_{ring}} = \frac{P_{sun}}{P_{sun} + P_{ring}} = \frac{l_{sun}}{l_{sun} + l_{ring}}$$

Where f = wave frequency; P = pitch circle diameter; l = parametric curve length.

For any chosen vales of f for the ring and sun gear, diameters may then be chosen using the above equation to allow the planet to travel a path of constant width. The use of a path of constant width ensures that the planet gear is not compressed during the cycle, and is able to mesh with the sun and ring gears at all points along the path.

Rearranging the above equation gives the equation:

$$P_{ring} = P_{sun} * \frac{f_{ring}}{f_{sun}}$$

Therefore, given a selected diameter of the sun gear 404 and a selected ratio of wave frequencies of the ring gear and the sun gear 402, it is possible to determine a suitable diameter for the ring gear.

Turning then to lengths, the perimeter (or parametric curve length) l of each gear may be determined as:

$$l = \int_0^{2\pi} \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2} dt$$

Equally, this length may be determined as:

$$l = \int_0^{2\pi} \sqrt{r^2 + \left(\frac{dr}{dt}\right)^2} dt$$

Where: $r(t) = \frac{p}{2} + a \sin(ft)$, $\frac{dr}{dt} = af \cos(ft)$

As can be seen from this equation, when $f = 0$ (e.g. there is no peak and the sun gear and ring gear are circular), the perimeter length of each gear is simply the perimeter of a circle ($\int_0^{2\pi} \frac{p}{2} dt$). According to the present disclosure, $f_{ring} > 0$ and $f_{sun} > 0$ so that the perimeter length of each gear is greater than the length of a circular gear of equivalent diameter.

The parametric equations used to determine the length of each gear have three variables, the pitch circle diameter P , the wave frequency f , and the wave amplitude a .

As described above, given a selected diameter of the sun gear 404 and a selected ratio of wave frequencies of the ring gear and the sun gear 402, it is possible to determine a suitable diameter for the ring gear. Notably, this diameter does not depend on the wave amplitude of either gear. Instead, this wave amplitude is independent of the relationship between the pitch circle diameters and the wave frequencies. Therefore,

the wave amplitude a can be adjusted independently. As the value of a increases, the change in radius as the planet gears 406, 408 move between the maxima and minima of the ring gear 402 and the sun gear 404 increases. Therefore, increasing the value of a increases the pressure changes that can be driven by the gearbox. However, increasing a also increases the resistance of the system. This tends to form a limit on a useable value of a (which limit depends on, for example, the materials used in the epicyclic gearbox 400 and the mechanical properties associated with these materials).

To ensure a constant connection between the ring gear 402 and the sun gear 404, the epicyclic gearbox 400 is typically arranged so that the width of the path followed by the planet gears 406, 408 is substantially constant. To achieve this, the ring gear and the sun gear are typically arranged so that the radial distance between the ring gear and the sun gear remains roughly constant. Therefore, typically, $a_{sun} = a_{ring}$.

A further constraint may be applied by the space available to the planet gears 406, 408, where this space must not exceed the space available within the confines of the ring gear 402 and the sun gear 404. To ensure that enough space is available, the gearbox is typically arranged so that:

$$\frac{length_{planet\ path}}{n_{planet}} > P_{planet}$$

Where n_{planet} is the number of planet gears. To provide a gearbox with maximal pumping power for an available space, the number of planet gears is typically selected to be equal to the sum of the number of waves of the sun gear and the number of waves of the ring gear, that is:

$$n_{planet} = f_{sun} + f_{ring}$$

It will be appreciated that fewer planet gears may be provided.

Given input values that are: a selected pitch circle diameter of the sun gear 404; a selected wave amplitude of the sun gear; and a selected wave frequency of the sun gear, appropriate values of the remaining components can be determined using the equations given above.

In an example that uses the following input values:

Parameter	Value	Source
Sun PCD	264mm	Input
Sun Wave Amplitude	5mm	Input
Sun Wave Frequency	8	Input
Ring Wave Frequency	10	Input

The above equations can be satisfied by using the following values.

Parameter	Value
Planet Path Parametric Curve Length	≈958.927mm
Planet Path Arclength	≈95.8927mm
Sun Rotation from Maxima to Maxima	≈1.414 radians
Ring PCD	330mm
Planet Path PCD	297mm
Sun Parametric Curve Length	≈848.089mm

Ring Parametric Curve Length	≈1060.089mm
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In this example, $f_{ring} = 10$ and $f_{sun} = 8$. Therefore, for the rotation of the sun to the next maximum to match the next ring maximum, the sun gear 104 must rotate through $\frac{2\pi}{f_{ring}} + \frac{2\pi}{f_{sun}}$, which when $f_{ring} = 10$ and $f_{sun} = 8$ results in a required sun gear rotation of roughly 1.414 radians between maxima.

- 5 It will be appreciated that these values are merely an example and that a variety of different values may be selected in order to obtain a desired pumping force.

For example, Figure 6 illustrates a gearbox with a ring gear and sun gear that are similar to the ring gear and sun gear of Figures 4a and 4b ($f_{ring} = 10$ and $f_{sun} = 8$). With the embodiment of Figure 5, the system comprises 18 planet gears.

- 10 Another example is embodiment of a gearbox according to the present disclosure is shown in Figure 7, which shows an epicyclic gearbox according to the present disclosure that has values $f_{ring} = 10$ and $f_{sun} = 4$.

Alternatives and modifications

- 15 It will be understood that the present invention has been described above purely by way of example, and modifications of detail can be made within the scope of the invention.

For example, the gearbox may have any number of planet gears, provided that this number of planet gears is capable of fitting between the ring and sun gear such that no planets touch each other. For example, the gearbox may have one, two, four, or eight planet gears.

- 20 In some embodiments, the gearbox has a number of planet gears that is no greater than an order of rotational symmetry of the gearbox (e.g. of the combination of the sun gear 404 and the ring gear 402). For example, if the gearbox has a rotational symmetry of order two (as in the example where $f_{ring} = 10$ and $f_{sun} = 8$), the gearbox may comprise one or two planet gears. If the system has a rotational symmetry of order four (for example if $f_{ring} = 16$ and $f_{sun} = 8$), the gearbox may comprise one, two, three or four planet gears. Such embodiments ensure that all the planet gears may be positioned at points at which the radial distance between the sun and the ring gear is equal to a constant value, said constant value being preferably the diameter of the planet gear.

Similarly, although the example above employed frequency values $f_{ring} = 10$ and $f_{sun} = 8$, it will be appreciated that many other combinations of values would satisfy the above constraints.

- 30 Similarly, although the sun and ring gear in the example above could be modelled by the parametric equations given in equations 1 and 2, in other embodiments these gears could be modelled by alternative parametric equations.

Likewise, although the detailed description primarily considered the use of circular planet gears, in alternative embodiments the planet gears could have non-circular profiles. For example, the planet gear profiles could be elliptical. In this case, one of the sun and ring gears could have a circular profile.

- 35 In general, a plurality of the (types of) gears have non-circular profiles. More specifically, typically two of: the ring gear 402, the sun gear 404, and the planet gear(s) 406, 408 have non-circular profiles.

The piston may be attached with a connection to the centre of the planet gear. Equally, the piston may be attached to a point that is not central to the planet gear. For example, if the planet gear is elliptical, the piston could be attached to a focus of the ellipse.

While the detailed description has primarily considered embodiments in which the sun gear 404 is driven, equally the ring gear 402, the planet gears 406, 408, and/or the carrier may be driven, instead of or in addition to driving of the sun gear. Equally, any one of the sun gear, the ring gear, and the carrier may be fixed, or alternatively none of the gears may be fixed.

- 5 Typically, the epicyclic gearbox 400 and/or the pump comprises a control unit and/or is associated with a control unit, where the control unit is arranged to drive one or more of the gears of the gearbox (e.g. the sun gear 402) in dependence on a desired pumping force. In this regard, the pumping force is typically relates to the torque provided to the gearbox and/or the speed of movement of the planetary gears 406, 408.

- 10 While in the example above, a single carrier was disclosed, in other embodiments there may be multiple carriers, with each carrier associated with a respective subset of the planets.

The pistons may be integral to or separate from the carrier. The pistons may be attached (directly or indirectly) to any one or more of the planet gears, the ring gears, a carrier, or the sun gear.

- 15 In some embodiments, the piston is connected at one end to the centre of the sun, and at a second end to the centre of the planet. In some embodiments, the piston is connected at one end to the centre of the sun, and at a second end to the carrier.

In some embodiments, each planet gear may be associated with a respective piston. In embodiments, each planet gear may be associated with a respective plurality (e.g. pair) of pistons.

- 20 In some embodiments, each piston may have a single opening to a fluid reservoir. In some embodiments, each piston may have a connection to each of a fluid reservoir and a fluid outlet.

Pumps may be used for a variety of applications. For example, heat pumps use the compression and expansion of the working fluid at different points in the pump cycle to cause heat energy to be taken in from the surroundings at one point in the cycle, and emitted at another point in the cycle. This may be used for cooling or heating a device, depending on the pump configurations.

- 25 Pumps may also be used for maintenance of pressure of a container. For example, a pump may be used to increase or decrease the pressure in a chamber to a desired level. This has application in devices such as scanning electron microscopes, which require low pressure in the operating chamber, as well as in simple devices such as bicycle tyres.

- 30 A further use for pumps arises in the transport of fluids. For example, pumps are used to transfer plastic melt out of the melting reactor during plastic processing. Pumps are also used to transfer water from inside to outside ships, and to move coolant around devices such as automotive engines.

- 35 Hydraulics refers generally to the use of liquid fluid power to perform work. However, the principles of operation of a hydraulic pump apply in general to pneumatic pumps, which use compressible gases as the working fluid. The epicyclic gearbox 400 disclosed herein may be used with a hydraulic pump, a pneumatic pump, or another type of pump.

Claims

1. A gearbox for a pump, the gearbox comprising:
 - a ring gear;
 - 5 a sun gear; and
 - one or more planet gears arranged between the ring gear and the sun gear, the planet gears being arranged to move around the sun gear along a continuous path;
 - wherein the ring gear, the sun gear, and the planet gears are arranged so that a radius of the path varies as the planet gears move along the path.
- 10 2. The gearbox of any preceding claim, comprising a piston, wherein the piston is associated with at least one planet gear such that an amount of compression of the piston changes as said planet gear moves along the path.
- 15 3. The gearbox of claim 2, wherein a second end of the piston is associated with a further component of the gearbox such that the first end of that piston moves relative to the second end of the piston as the planet gear moves along the path.
- 20 4. The method of claim 3, wherein the piston is arranged such that the first end of the piston moves towards and/or away from the second end of the piston as the planet gear moves along the path.
- 25 5. The gearbox of claim 3 or 4, wherein the second end of the piston is connected to one or more of:
 - the sun gear;
 - the ring gear;
 - a further planet gear; and
 - a carrier of the gearbox.
- 30 6. The gearbox of any preceding claim, comprising a plurality of pistons, wherein each piston is associated with a respective planet gear.
7. The gearbox of any preceding claim, wherein at least two of the ring gear, the sun gear, and the one or more planet gears have non-circular profiles.
- 35 8. The gearbox of claim 7, wherein each of the sun gear and the ring gear has a non-circular profile, preferably wherein the sun gear and the ring gear have corresponding non-circular profiles.
9. The gearbox of any preceding claim, wherein:
 - the sun gear has a profile that comprises a sinusoidal wave superimposed onto an ellipse, preferably a sinusoidal wave superimposed onto a circle; and/or
 - 40 the ring gear has a profile that comprises a sinusoidal wave superimposed onto an ellipse, preferably a sinusoidal wave superimposed onto a circle.
10. The gearbox of any preceding claim, wherein the profile of the sun gear and/or the profile of the ring gear, and preferably the pitch circle diameter of each of the sun gear and the ring gear, is defined by
 - 45 the equation:

$$r(t) = \frac{P}{2} + a \cdot \sin(ft)$$

where:

t is a parametric variable with values from 0 to 2π ;

r is a radius of the gear at a value t;
P is an average diameter of the gear;
a is a wave amplitude; and
f is a wave frequency.

5

11. The gearbox of any preceding claim, wherein the ring gear comprises a different number of minima and/or maxima than the sun gear.

10

12. The gearbox of claim 11, wherein the ring gear comprises a greater number of minima and/or maxima than the sun gear.

13. The gearbox of any preceding claim, wherein the average diameters and the numbers of waves of the sun gear and the ring gear are linked by the equation:

$$\frac{P_{sun}}{f_{sun}} = \frac{P_{ring}}{f_{ring}}$$

15

where:

P_{sun} is an average diameter of the sun gear;
 P_{ring} is an average diameter of the ring gear;
 f_{sun} is a wave frequency of the sun gear; and
 f_{ring} is a wave frequency of the ring gear.

20

14. The gearbox of any preceding claim, comprising a plurality of planet gears, preferably comprising at least one pair of planet gears, more preferably comprising a plurality of pairs of planet gears.

25

15. The gearbox of any preceding claim, comprising a number of planet gears that is equal to an order of rotational symmetry of the gearbox, preferably an order of rotational symmetry of the combination of the sun gear and the ring gear.

30

16. The gearbox of any preceding claim, wherein the planet gears are arranged symmetrically about a centre of rotation of the gearbox.

17. The gearbox of any preceding claim, wherein:
the ring gear is rotationally symmetric; and/or
the sun gear is rotationally symmetric.

35

18. The gearbox of any preceding claim, wherein the width of the path is substantially constant.

19. The gearbox of any preceding claim, wherein the sun gear, the ring gear, and the planet gears are arranged such that a radial distance between the sun gear and the ring gear at the point of contact of each of the planet gears remains constant as said planet gears move along the path.

40

20. The gearbox of any preceding claim, wherein one or more of the ring gear and the sun gear are arranged to remain stationary as the planet gears move along the path.

45

21. The gearbox of any of claims 1 to 19, wherein each of the sun gear and the ring gear are arranged to rotate as the planet gears move along the path.

22. The gearbox of any preceding claim, comprising a motor for driving a movement of one or more of:
the sun gear;
the ring gear;
one or more of the planet gears; and
5 a carrier associated with one or more of the planet gears,
preferably wherein the motor is arranged to operate in dependence on a desired pumping force.
23. The gearbox of any preceding claim, wherein:
the sun gear comprises one or more minimum points, wherein the radius of the sun gear at said
10 minimum points is less than an average radius of the sun gear; and/or
the sun gear comprises one or more maximum points, wherein the radius of the sun gear at said
maximum points is greater than an average radius of the sun gear.
24. The gearbox of any preceding claim, wherein:
15 the ring gear comprises one or more minimum points, wherein the radius of the ring gear at said
minimum points is less than an average radius of the ring gear; and/or
wherein the ring gear comprises one or more maximum points, wherein the radius of the ring gear
at said maximum points is greater than an average radius of the ring gear.
- 20 25. The gearbox of any preceding claim, wherein:
a variation in amplitude of the minimum points of the sun gear is equal to a variation in amplitude
of the maximum points of the sun gear; and/or
a variation in amplitude of the minimum points of the ring gear is equal to a variation in amplitude
25 of the maximum points of the ring gear;
26. The method of claim 25, wherein:
the variation in amplitude of the minimum points of the sun gear is equal to the variation in amplitude
of the maximum points of the ring gear; and/or
30 the variation in amplitude of the maximum points of the sun gear is equal to the variation in
amplitude of the minimum points of the ring gear.
27. The gearbox of any preceding claim, wherein the diameter of the sun gear is:
at least 100mm, at least 200mm, and/or at least 500mm, and/or
35 no more than 1000mm, no more than 800mm, and/or no more than 500mm.
28. The gearbox of any preceding claim, wherein the diameter of the planet gears is:
at least 50mm, at least 100mm, and/or at least 200mm, and/or
no more than 500mm, no more than 400mm, and/or no more than 300mm.
- 40 29. The gearbox of any preceding claim, wherein one or more of, and preferably each of, the sun gear, the
ring gear, and the planet gears may comprise a plurality of teeth, preferably wherein the teeth are
arranged regularly about the profile of said gear.
30. The gearbox of any preceding claim, comprising at least two planet gears, at least four planet gears, at
45 least eight planet gears, and/or at least ten planet gears.
31. A pump comprising the gearbox of any preceding claim.
32. The pump of claim 31, wherein the pump comprises a radial pump and/or a radial hydraulic pump.

33. A method of operating the gearbox of any of claims 1 to 30, wherein the method comprises driving one or more of: the sun gear, the ring gear, and one or more of the planet gears.
- 5 34. The method of claim 33, wherein the method comprises driving said gear(s) in dependence on a desired pumping force.
35. A computer program product comprising instructions that, when executed by a computer device, cause the computer device to perform the method of claim 33 or 34
- 10 36. A method of manufacturing the gearbox and/or the pump of any preceding claim.
37. A kit of parts for the gearbox of any preceding claim, the kit of parts comprising:
- 15 the ring gear;
the sun gear; and
one or more planet gears.