(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) **EP 3 748 155 A1**

(12) **EUROPEAN PATENT APPLICATION**

(43) Date of publication:
09.12.2020 Bulletin 2020/50

(21) Application number: **20178359.4**

(22) Date of filing: **04.06.2020**

(51) Int Cl.:
F04B 1/04 *(2020.01)*
F04B 1/06 *(2020.01)*
F04B 49/06 *(2006.01)*
F04B 1/053 *(2020.01)*
F04B 7/00 *(2006.01)*

(84) Designated Contracting States:
AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC MK MT NL NO PL PT RO RS SE SI SK SM TR
Designated Extension States:
BA ME
Designated Validation States:
KH MA MD TN

(30) Priority: **04.06.2019 EP 19178292**

(71) Applicants:
- **Danfoss Scotland Limited**
  6430 Nordborg (DK)
- **Artemis Intelligent Power Limited**
  Loanhead EH20 9TB (GB)

(72) Inventors:
- **Marshall, Paul**
  Loanhead, Lothian EH20 9TB (GB)
- **Lagarde, Jeremie**
  Loanhead, Lothian EH20 9TB (GB)
- **Stein, Uwe**
  Loanhead, Lothian EH20 9TB (GB)
- **Rampen, William**
  Loanhead, Lothian EH20 9TB (GB)

(74) Representative: **Hindles Limited**
Clarence House
131-135 George Street
Edinburgh, EH2 4JS (GB)

(54) HYDRAULIC MACHINES AND SYSTEMS

(57) A hydraulic system employing an electronically commutated fluid working machine having a plurality of working chambers, each having one or more electronically controllable valves which are actively controlled by at least one controller to regulate the net displacement of working fluid into or out of low- and high-pressure manifolds on a cycle by cycle basis, to meet a demand indicated by a demand signal. The high-pressure manifold has at least one additional outlet, regulated by an electronically controllable outlet valve, such as a proportional flow valve. If the demand indicated by the demand signal would be expected to cause pulsatile flow or vibrations which may excite resonant modes, the at least one controller causes the displacement of working fluid by the working chambers to be in excess of the demand indicated by the demand signal, and the at least one controller simultaneously (at least partially) opens an electronically controllable outlet valve to allow some of the excess flow to leave therethrough, such that the net displacement of fluid meets the demanded displacement of fluid, while mitigating the pulsatile flow or undesirable vibrations.

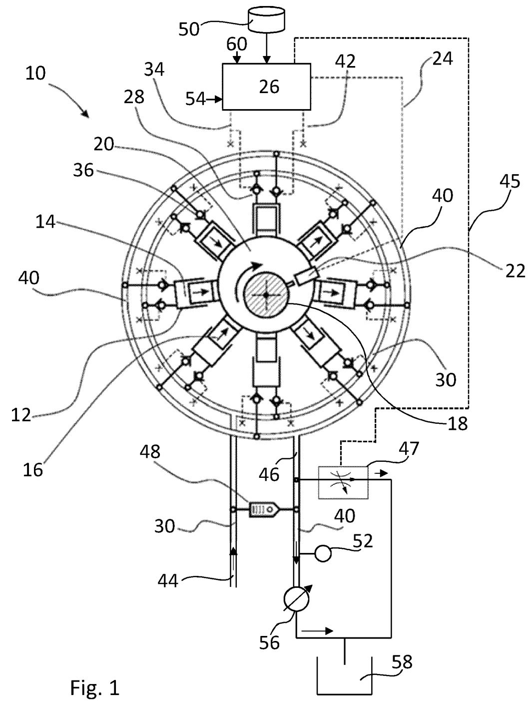

Fig. 1

EP 3 748 155 A1

Description

Field of the invention

[0001] The present invention relates to the field of electronically commutated hydraulic machines and hydraulic systems including such machines.

Background to the invention

[0002] Electronically commutated hydraulic machines (ECMs) include fluid-driven and/or fluid-driving machines with one or more working chambers of cyclically varying volume (e.g. piston cylinders). When a working chamber carries out a pumping cycle, a low-pressure manifold acts as a net source of fluid and a high-pressure manifold acts as a net sink for fluid. When a working chamber carries out a motoring cycle, a high-pressure manifold acts as a net source of fluid and a low-pressure manifold acts as a net sink for fluid. An ECM may have more than one low-pressure manifold and/or more than one high-pressure manifold.

[0003] The working chambers of ECMs have electronically controllable valves, which can be controlled on each cycle of working chamber volume to regulate the flow of fluid into and out of the working chamber from and into the low-pressure manifold, and in some embodiments, the high-pressure manifold.

[0004] In some ECMs, there is a single high-pressure manifold and all of the working chambers communicate with it and displace fluid into or out of the high-pressure manifold to meet a demand. However, it may be that there are multiple high-pressure manifolds in communication with different groups of one or more working chambers, and each group is controlled in response to a separate demand signal, such that the combined displacement of the working chambers in the group meets the demand. Thus, the individual groups of working chambers may function as independent pumps or motors.

[0005] The demand(s) are represented by demand signal(s) which may indicate a target pressure, flow rate, power output, or property (e.g. position) of a hydraulic actuator coupled directly or indirectly to the relevant high-pressure manifold. In order to meet the demand, the controller of the ECM makes decisions as to whether each cycle of working chamber volume should be an active cycle, in which there is a net displacement of working fluid, or an inactive cycle, in which there is no net displacement of working fluid. This leads to a pattern of working chamber actuations (active or inactive cycles) and a pattern of flow into or out of the respective high-pressure manifold. In this way, changes in demand can be responded to rapidly. Typically, output does not match demand perfectly from one moment to the next but over a short time average, the net output tends to the demand. Such machines are efficient and highly responsive.

[0006] However, some patterns of cylinder actuation can give rise to vibrations within a hydraulic machine. Some frequencies of vibration may cause the excitation of resonant modes within the hydraulic machine, which can cause damage to machine components and discomfort to users. This can arise when the frequency spectrum of the pattern of whether working chambers carry out active or inactive cycles, to meet the demand, has large components at frequencies which can excite resonances.

[0007] At low flow levels, the displacement of fluid may be highly pulsatile. If output is 5% of maximum displacement fraction it may be that there are repeating patterns of an active cycle every 20 cycles with inactive cycles therebetween. This again can lead to vibration, discomfort to users and a risk of damage to the machine. Similarly, when hydraulic machines are operated at low rates of flow, their operation can become inefficient.

[0008] Accordingly, the present invention seeks to reduce or mitigate some or all of the above disadvantages of existing electronically commutated hydraulic machines.

Summary of the invention

[0009] According to a first aspect of the invention there is provided a hydraulic system comprising;

a hydraulic machine, the hydraulic machine comprising a rotatable shaft, a low-pressure manifold and a high-pressure manifold, and one or more working chambers having a volume which varies cyclically with rotation of the rotatable shaft, each working chamber having both a low-pressure valve which regulates communication between the low-pressure manifold and the working chamber, and a high-pressure valve which regulates communication between the high-pressure manifold and the working chamber, wherein for each working chamber at least one of the respective low-pressure valve and the respective high-pressure valve is an electronically controllable working chamber valve;

the high-pressure manifold extending between the one or more said working chambers and one or more actuator ports and one or more additional outlets;

one or more hydraulic actuators which are fluidly connected to said high-pressure manifold through the one or more actuator ports and thereby hydraulically driven by the hydraulic machine;

one or more electronically controllable outlet valves which regulate the opening or closing of the one or more additional outlets; and

at least one controller configured to control the one or more electronically controllable working chamber valves and the one or more electronically controllable outlet valves;

wherein the at least one controller is operable to receive a demand signal and to regulate the one or more electronically controllable working chamber valves in phased relationship to cycles of working chamber volume to thereby regulate the net displacement of working fluid by each working chamber on each cycle of working chamber volume, and to concurrently regulate the one or more electronically controllable outlet valves, to thereby regulate the net displacement of working fluid into or out of the high-pressure manifold allowing for the flow of working fluid out of the high-pressure manifold through the one or more additional outlets, when one or more additional outlet is open, to meet a demand indicated by the demand signal.

[0010] Thus, the loss of hydraulic fluid through the one or more additional outlets is regulated by at least one controller and the net displacement of working fluid into (when pumping) or out of the high-pressure manifold (when motoring) is regulated to meet the demand taking into account both the net displacement of working fluid by each working chamber and the loss of hydraulic fluid through the one or more additional outlet(s). The high-pressure manifold comprises one or more actuator ports connected to one or more actuators which act as sinks or sources of hydraulic fluid. Typically, fluid which flows out of the one or more additional outlets does not travel between the working chambers and the actuator ports. Typically, fluid which flows out of the one or more additional outlets bypasses the one or more said actuators connected to the actuator ports (although in some embodiments the pressurised fluid lost through the one or more additional outlets is used to drive one or more other actuators, to minimise wasted energy). Typically, the demand relates to the supply of hydraulic fluid through the one or more actuator ports, between the working chamber(s) and the actuator(s).

[0011] Hydraulic machines of the type described have a very fast response time to changes in demand as the electronically controllable valves can be controlled to vary the net displacement of working fluid for each cycle of working chamber volume. Accordingly, it is usual to match the net displacement of working fluid by successive working chambers to a time-varying demand signal. Providing, in addition, one or more additional outlet(s) through which (e.g. excess) working fluid can be lost from the high-pressure manifold is counter-intuitive because it appears to waste energy.

[0012] Within this description and the appended claims, the terms "high-pressure manifold" and "low-pressure manifold" refer to manifolds with higher and lower pressures relative to each other. The pressure difference between the high- and low-pressure manifolds, and the absolute values of the pressure in the high- and low-pressure manifolds will vary with time and will depend on the application.

[0013] In some embodiments, the at least one controller is configured to control the electronically controllable working chamber valves to cause the hydraulic machine to displace working fluid in excess of the demand indicated by the demand signal and to cause one or more (or all) of the outlet valves to be open, the net displacement of working fluid into the high-pressure manifold from the one or more working chambers through the high-pressure valves being thereby regulated to meet the demand indicated by the demand signal after allowing for the flow of working fluid out of the high-pressure manifold through the one or more additional outlets.

[0014] Allowing for the flow of working fluid out of the high-pressure manifold through the one or more additional outlets may comprise (e.g. the at least one controller) calculating

i) a revised demand signal adjusted for the flow out of the high-pressure manifold through the one or more additional outlets; or

ii) subtracting a demand related to the flow of working fluid out of the high-pressure manifold through the one or more additional outlets.

[0015] Said flow is under the control of the at least one controller because the at least one controller controls the one or more electronically controllable outlet valves. It may be that the at least one controller is configured to control the electronically controllable working chamber valves to cause the hydraulic machine to displace working fluid in excess of the demand indicated by the demand signal and to cause the one or more outlet valves to be open in only some circumstances. The at least one controller may also take into account any expected leakage from the high-pressure manifold. Such leakage may originate from a control valve (e.g. in the wheel motor, or for control of other actuators and/or work functions). Thus, the one or more electronically controllable working chamber valves and the one or more electronically controllable outlet valves are controlled to meet the demand indicated by the demand signal.

[0016] Typically, the at least one controller is configured such that, under some other circumstances, and typically by default, the electronically controllable working chamber valves are controlled to cause the hydraulic machine to displace working fluid to match the demand indicated by the demand signal and to cause the outlet valve to be closed, such that the working fluid does not flow out of the high-pressure manifold through the additional outlet.

[0017] In some embodiments, one or more said outlet valve(s) (e.g. the or each outlet valve) is a variable flow control valve, for example a proportional flow valve, and the at least one controller controls the variable flow control valve across a range of positions.

[0018] In this case, the range of positions is typically continuous. The or each outlet valve is typically controlled to a plurality of, e.g. a continuous range of, positions between closed and a fully open position. By open we refer to any position which is not closed.

[0019] It may be that the adjustment of the position of one or more (or the or each) said outlet valve takes place without synchronisation to the phase of cycles of working chamber volume. It may be that the outlet valve takes longer than a cycle of working chamber volume to open or close. It may be that the outlet valve remains open for an average (mean) of 10 or more, or 100 or more cycles of working chamber volume.

[0020] However, in some embodiments, at least one controller is configured to open and close a said outlet valve in phased relationship to cycles of working chamber volume. In this case, the said outlet valve is typically a solenoid valve which is actively controlled to move directly from an open position to a closed position or vice versa without stopping. Thus, it is either open or closed or moving between these positions (an on-off valve), and is not a proportional flow valve which is configured to be maintainable (and maintained in use) at a variable position between open or closed. Thus, with the on-off valve, flow through the said outlet valve is regulated by opening and closing the valve, for example regulating the fraction of time for which the outlet valve is open. The said outlet valve may have an opening time and a closing time of less than 10ms, preferably less than 5ms. The said outlet valve is typically openable against a pressure gradient.

[0021] In this case, the timing of the opening and closing of the outlet valve can be controlled by the at least one controllerto (e.g. selectively) reduce pressure ripples in the high-pressure manifold. This may occur when the displacement of the hydraulic machine is below a threshold, for example less than 10%, or less than 5%, of the maximum displacement of working fluid by the hydraulic machine per rotation of the rotatable shaft and/or when a peak in the pressure in high-pressure manifold and/or a soliton is detected or predicted (for example as a result of a pattern of active and inactive cycles of working chamber volume determined by at least one controller in response to the demand signal) and/or when the ratio of active to inactive cycles of working chamber volume is below a threshold, which may be 1:9 or less. This may be considered as a ripple reduction operating mode of the at least one controller. The ripple reduction operating mode of the at least one controller functions to attenuate pressure pulses in the high-pressure manifold.

[0022] Typically, at least one controller is configured such that in the ripple reduction operating mode the outlet valve is opened and closed once per active cycle of working chamber volume. Typically, the at least one controller is configured such that each opening and subsequent closing of the at least one outlet valve overlaps with a single cycle of working chamber volume. Typically the outlet valve is opened before the peak of fluid pressure arising from an active cycle of working chamber volume and closed after the peak of fluid pressure arising from an active cycle of working chamber volume. The opening and closing of the outlet valve may have the effect of reducing or clipping the peak pressure arising from an individual active cycle of a working chamber. The opening and closing of the outlet valve may have the effect of reducing the pressure ripple arising from an individual active cycle of a working chamber. It may be that the at least one controller is configured that in at least some circumstances, typically where the ratio of active cycles to inactive cycles is high for example, above a threshold, which may be greater than 9:1, the outlet valve is held open (throughout consecutive active cycles) but closed and then opened again during inactive cycles. This maintains pressure during inactive cycles, when the majority of cycles are active cycles, and so reduces pressure ripple in these circumstances.

[0023] In some embodiments, the high-pressure manifold is in communication with a higher-pressure working fluid source (i.e. a source having working fluid at a higher pressure than the high-pressure manifold, e.g. an accumulator or higher-pressure manifold) through an inlet valve and at least one controller is configured to close and open the inlet valve in phased relationship with cycles of working chamber volume, to reduce pressure ripple. In this case, working fluid is admitted through the inlet valve into the high-pressure manifold (from the high-pressure working fluid source) at least some of the time and this supply of working fluid is temporarily closed off (by closing and then reopening the inlet valve) during an active cycle of working chamber volume. Thus the additional flow of working fluid compensates for any shortfall or deficiency in the supply of working fluid between active cycles of working fluid, reducing pressure ripple. The inlet valve will typically be closed before the point of maximum fluid flow during a cycle of working chamber volume and reopened after the point of maximum fluid flow during the cycle of working chamber volume. This ripple reduction mode may occur when the displacement of the hydraulic machine is below a threshold, for example less than 10%, or less than 5% of the maximum displacement of working fluid by the hydraulic machine per rotation of the rotatable shaft and/or when a peak in the pressure in high-pressure manifold and/or a soliton is detected or predicted (for example as a result of a pattern of active and inactive cycles of working chamber volume determined by at least one controller in response to the demand signal) and/or when the ratio of active to inactive cycles of working chamber volume is below a threshold, which may be 1:9 or less. It may be that when the at least one controller is not in the ripple reduction mode, the inlet valve remains closed. It may be that when the at least one controller is in the ripple reduction mode, the inlet valve is open by default and closed and reopened by the at least one controller once per active cycle of working chamber volume.

[0024] The at least one controller may transmit a pulse width modulated signal (typically generating a corresponding solenoid current) to the outlet (and/or inlet) valve (e.g. to the solenoid actuator of the outlet valve) to actively control the opening and closing of the outlet (and/or inlet) valve, typically in phased relationship to cycles of working chamber volume.

[0025] The at least one controller may vary the timing of the opening and/or closing of the outlet (and/or inlet) valve, in phased relationship to cycles of working chamber volume, responsive to measurements or calculations of one or more of: (a) the demand signal, (b) the volume of working fluid displaced by the hydraulic machine per revolution of the rotatable shaft and/or per second, (c) the speed of rotation of the rotatable shaft, (d) the compliance of the high-pressure manifold (variation in system pressure with volume of working fluid in the high-pressure manifold), (e) operating mode of the hydraulic system, for example whether the at least one controller is regulating displacement in response to the demand signal in a feedback, feedforward and/or open-loop control mode, (f) the temperature of the working fluid.

[0026] In some embodiments, one or more said additional outlets extend from the high-pressure manifold to the low-pressure manifold such that one or more outlet valves regulate the flow of working fluid out of the high-pressure manifold to the low-pressure manifold through one or more said additional outlets.

[0027] Optionally, one or more additional outlets extend(s) from the high-pressure manifold to a further manifold, such that the respective one or more outlet valves regulate(s) the flow of working fluid out of the high-pressure manifold to the further manifold through the one or more said additional outlets.

[0028] In some embodiments, the further manifold is a pressurised manifold, for example a manifold in fluid communication with one or more (typically other) actuators. This arrangement is advantageous because potential energy stored in the working fluid which flows out of the high-pressure manifold to the pressurised further manifold in fluid communication with one or more (typically other) actuators is at least in part retained (and can optionally be used to do work). The further manifold may be a boost line to a hydraulic motor or other actuator. Boost lines provide a required minimum back-pressure to an actuator. This boost line may be connected to the low-pressure port of a hydrostatic steering mechanism.

[0029] In some embodiments, the one or more additional outlets extend(s) from the high-pressure manifold to a further manifold with one or more compliant regions (e.g. flexible hoses or accumulator(s)) which may store energy from the pressurisation of the working fluid as potential energy.

[0030] Optionally, the high-pressure manifold may be part of a closed-circuit hydraulic arrangement and the further manifold may be part of an open-circuit hydraulic arrangement, or vice versa.

[0031] Typically, the hydraulic system comprises a prime mover coupled to the hydraulic machine to provide power to cause the hydraulic machine to pump working fluid from the low-pressure manifold to the high-pressure manifold and wherein the hydraulic system further comprises a second hydraulic machine driven by the prime mover, or one or more further working chambers of the (first) hydraulic machine configured to pump working fluid from a low-pressure manifold (the same or another low-pressure manifold) to the further manifold, such that the prime mover powers both the open-circuit and closed-circuit hydraulic arrangements (i.e. where the high-pressure manifold is part of an open-circuit and the further manifold is part of a closed-circuit or vice versa).

[0032] The hydraulic machine may be one or more electronically commutated machines (ECM). By an ECM we refer to a hydraulic fluid working machine comprising a rotatable shaft and one or more working chambers (e.g. chambers defined by cylinders, within which pistons reciprocate in use) having a volume which varies cyclically with rotation of the rotatable shaft, each working chamber having a low-pressure valve which regulates the flow of hydraulic fluid between the working chamber and a low-pressure manifold and a high-pressure valve which regulates the flow of hydraulic fluid between the working chamber and a high-pressure manifold. The reciprocation of the pistons may be caused by direct interaction with an eccentric on the rotatable shaft, or with a second rotatable shaft, the second rotatable shaft being rotatably connected to the rotatable shaft. A plurality of ECMs with linked rotatable shafts (e.g. common shafts) driven by a prime mover may function together as the hydraulic machine.

[0033] The hydraulic system may be a hydraulic vehicle, typically an industrial or off-highway vehicle, for example a fork lift truck.

[0034] The capacity of the various components will be selected depending on the application. In an example the electronically controllable outlet valve may be configured to allow a flow of at least 20 litres per minute, or at least 25 litres per minute. The electronically controllable outlet valve may be configured to allow a nominal flow of 15 litres per minute.

[0035] The electronically controllable outlet valve may be a solenoid actuated (e.g. electro-proportional) flow control valve. The electronically controllable outlet valve may be an electromagnetic proportional valve. Alternately, a manually adjustable flow control valve or an orifice could be used in combination (typically in series) with an electrically controllable on/off valve, together functioning as the electronically controllable outlet valve.

[0036] At least one controller typically comprises one or more hardware processors which together process a demand signal and control the one or more electronically controllable outlet valves. Typically a first hardware processor determines both the net displacement of the one or more working chambers and the intended flow of hydraulic fluid out of the one or more outlets. It may be that one or more second hardware processors generate the control signals which actively control the electronically controllable working chamber valves. The first hardware processor may receive a demand signal and transmit one or more adjusted demand signals (taking into account the flow of working fluid out of the high-pressure manifold through the one or more outlet valves) to one or more second hardware processors. The or each second hardware processor may generate valve control signals to actively control the electronically controllable working chamber valves to implement a displacement of working fluid by the one or more working chambers indicated by the adjusted demand signals.

[0037] According to a second aspect of the invention there is provided a method of operating a hydraulic system, the hydraulic system comprising a hydraulic machine, the hydraulic machine comprising a rotatable shaft, a low-pressure manifold and a high-pressure manifold, and one or more working chambers having a volume which varies cyclically with rotation of the rotatable shaft, each working chamber having a low-pressure valve which regulates communication between the low-pressure manifold and the working chamber and a high-pressure valve which regulates communication between the high-pressure manifold and the working chamber, wherein for each working chamber at least one of the respective low-pressure valve and high-pressure valve is an electronically controllable working chamber valve;

the high-pressure manifold extending between the one or more said working chambers and one or more actuator ports and one or more additional outlets;
one or more hydraulic actuators which are fluidly connected to said high-pressure manifold through one or more said actuator ports and thereby hydraulically driven by the hydraulic machine,
one or more electronically controllable outlet valves which regulate the opening or closing of the one or more additional outlets; and
the method comprising receiving a demand signal and, responsive thereto, regulating the one or more electronically controllable working chamber valves in phased relationship to cycles of working chamber volume to thereby regulate the net displacement of working fluid by each working chamber on each cycle of working chamber volume, and concurrently regulating the one or more electronically controllable outlet valves, to thereby regulate the net displacement of working fluid into or out of the high-pressure manifold allowing for the flow of working fluid out of the high-pressure manifold through the one or more additional outlets, when one or more additional outlet is open, to meet a demand indicated by the demand signal.

[0038] In some embodiments, the electronically controllable working chamber valves are controlled to cause the hydraulic machine to displace working fluid in excess of the demand indicated by the demand signal and one or more electronically controllable outlet valves is controlled to be open, such that the net displacement of working fluid into the high-pressure manifold from the one or more working chambers is regulated to meet the demand indicated by the demand signal after allowing for the flow of working fluid out of the high-pressure manifold through the one or more additional outlets.

[0039] Under some other circumstances, and typically by default, the electronically controllable working chamber valves are controlled to cause the hydraulic machine to displace working fluid to match the demand indicated by the demand signal and to cause the one or more outlet valves to be closed, such that the working fluid does not flow out of the high-pressure manifold through the one or more additional outlets.

[0040] The demand signal may comprise, or be used to calculate, a fraction of maximum displacement (Fd). Typically, displacement, in volume flow terms, is proportional to the fraction of maximum displacement and the speed of rotation of the rotatable shaft. Optionally, the demand signal may be an adjusted demand signal, for example where the at least one controller receives a demand signal and determines that the received demand signal is associated with pulsatile flow, it may calculate an adjusted demand signal (typically a demand signal that would be indicative of a higher flow demand).

[0041] In some embodiments of the method, when the demand is below a threshold, the electronically controllable working chamber valves may be controlled to cause the hydraulic machine to displace working fluid at a predetermined minimum fraction of maximum displacement, or in a predetermined pattern of working chambers carrying out active or inactive cycles of working chamber volume,

and wherein the one or more outlet valves are controlled to cause hydraulic fluid to flow out of the high-pressure manifold such that the overall displacement of working fluid into the high-pressure manifold meets the demand.

[0042] This is useful, for example, to avoid undesirable effects of the highly pulsatile flow which would arise at low demands if the demand was met using only occasional active cycles of working chamber volume.

[0043] Typically, (for example, towards the lower end of an operating range of flow rates) the at least one controller is operable to intersperse idle cycles in which there is no net displacement of fluid and partial cycles in which a part of the maximum stroke volume of the working chamber is displaced, even where a demand signal remains constant. Typically, within a portion of the operating range of flow rates the at least one controller is operable to intersperse idle cycles in which there is no net displacement of fluid, and partial cycles in which a part of the maximum stroke volume of the working chamber is displaced, and full cycles in which the maximum stroke volume of the working chamber is displaced, even where a demand signal remains constant.

[0044] The at least one outlet valve may be opened and closed without synchronisation to the phase of cycles of working chamber volume. The outlet valve may remain open for an average (mean) of 10 or more, or 100 or more cycles of working chamber volume. However, it may be that the method comprises opening and closing a said outlet valve in phased relationship to cycles of working chamber.

[0045] In this case, the timing of the opening and closing of the outlet valve may be controlled to (e.g. selectively) reduce pressure ripples in the high-pressure manifold. This may occur when the displacement of the hydraulic machine is below a threshold, for example less than 10%, or less than 5% of the maximum displacement of working fluid by the hydraulic machine per rotation of the rotatable shaft and/or when a peak in the pressure in high-pressure manifold and/or a soliton is detected or predicted (for example as a result of a pattern of active and inactive cycles of working chamber volume determined by at least one controller in response to the demand signal) and/or when the ratio of active to inactive cycles of working chamber volume is below a threshold, which may be 1:9 or less. This may be considered as a ripple reduction operating mode, which attenuates pressure pulses in the high-pressure manifold.

[0046] It may be that (in the ripple reduction operating mode), the outlet valve is opened and closed once per active cycle of working chamber volume. Typically, each opening and subsequent closing of the at least one outlet valve overlaps with a single cycle of working chamber volume. Typically the outlet valve is opened before the peak of fluid pressure arising from an active cycle of working chamber volume and closed after the peak of fluid pressure arising from an active cycle of working chamber volume.

[0047] In some embodiments, the high-pressure manifold is in communication with a higher-pressure working fluid source through an inlet valve and the method comprises closing and opening the inlet valve in phased relationship with cycles of working chamber volume, to reduce pressure ripple. In this case, working fluid is admitted through the inlet valve into the high-pressure manifold (from the high-pressure working fluid source) at least some of the time and this supply of working fluid is temporarily closed off during an active cycle of working chamber volume. Thus the additional flow of working fluid compensates for any shortfall or deficiency in the supply of working fluid between active cycles of working fluid, reducing pressure ripple. This ripple reduction mode may occur when the displacement of the hydraulic machine is below a threshold, for example less than 10%, or less than 5% of the maximum displacement of working fluid by the hydraulic machine per rotation of the rotatable shaft and/or when a peak in the pressure in high-pressure manifold and/or a soliton is detected or predicted (for example as a result of a pattern of active and inactive cycles of working chamber volume determined by at least one controller in response to the demand signal) and/or when the ratio of active to inactive cycles of working chamber volume is below a threshold, which may be 1:9 or less. It may be that when the apparatus is not in the ripple reduction mode, the inlet valve remains closed. It may be that when the apparatus is in the ripple reduction mode, the inlet valve is open by default and closed and reopened once per active cycle of working chamber volume.

[0048] The timing of the opening and/or closing of the outlet (and/or inlet) valve, in phased relationship to cycles of working chamber volume, responsive to measurements or calculations of one or more of: (a) the demand signal, (b) the hydraulic machine rate of displacement (per revolution of the rotatable shaft) or flow rate, (c) the speed of rotation of the rotatable shaft, (d) the compliance of the high-pressure manifold (variation in system pressure with volume of working fluid in the high-pressure manifold), (e) operating mode of the hydraulic system, for example whether at least one controller is regulating displacement in response to the demand signal in a feedback, feedforward and/or open-loop control mode, (f) the temperature of the working fluid.

[0049] Optionally, under at least some circumstances the electronically controllable working chamber valves may be controlled to cause the hydraulic machine to displace working fluid at one of a plurality of discrete fractions of maximum displacement, or in one of a plurality of predetermined patterns of working chambers carrying out active or inactive cycles of working chamber volume,

> wherein the electronically controllable working chamber valves are controlled to cause the working chambers to displace one of the plurality of discrete fractions of maximum displacement in excess of the displacement required to meet the demand indicated by the received demand signal, or to carry out one of the plurality of predetermined patterns which causes the combined displacement of the one or more working chambers to exceed the displacement required to meet the demand,
> and wherein the one or more outlet valves are controlled to cause hydraulic fluid to flow out of the high-pressure manifold such that the overall displacement of working fluid into the high-pressure manifold meets the demand.

[0050] In some embodiments of the method, the electronically controllable working chamber valves may be controlled to cause the hydraulic machine to displace working fluid in excess of the flow required to meet the demand indicated by the demand signal and to cause one or more of the outlet valves to be open, responsive to determination that the demand is such that if

> i) the one or more additional outlets were closed and
> ii) demand was met only using working fluid displaced by the one or more working chambers,

there would be an undesirable response (e.g. resonance) arising from the pattern of selection of working chambers to carry out active or inactive cycles to meet the demand.

[0051] It may be that when the demand is below a threshold, the electronically controllable working chamber valves are controlled to cause only a predetermined number of working chambers to carry out active cycles and the other working chambers of the one or more working chambers to carry out inactive cycles. It may be that, below the threshold, only working chambers which are phased apart by a predetermined amount carry out active cycles and the remainder carry out inactive cycles. The predetermined amount may be 360°/n where n is an integer and in particular it may be 120°, or 120°/n where n is an integer because this provides relatively low ripple output flows.

[0052] It may be that in at least some circumstances, for example when the demand is below a threshold, or for any demand, the electronically controllable working chamber valves are controlled to cause the hydraulic machine to displace working fluid which is at least a predetermined margin in excess of the flow required to meet the demand.

[0053] Typically, the method further comprises measuring or calculating a current rate of flow of working fluid through the one or more additional outlets, optionally comprising measuring the pressure in the high-pressure manifold.

[0054] The electronically controllable outlet valve may also be opened temporarily to do one or more of: allow air to be bled out of the high-pressure manifold, for example during filling of the machine with working fluid; drain hot working fluid, e.g. from a crankcase, to avoid overheating; or warm the working fluid (which may be oil), for example in an initial phase after start-up and before normal operation.

[0055] It will be understood that, any feature of any one or more embodiments of any aspect of the invention may be combined or used with any other feature in any other one or more embodiments of any other aspect of the invention.

Description of the Drawings

[0056] An example embodiment of the present invention will now be illustrated with reference to the following Figures in which:

Figure 1 is a schematic diagram of an electronically commutated machine;

Figures 2A through 2E are a series of plots indicating the response of an electronically commutated machine according to the invention;

Figure 3 is a hydraulic schematic of an electronically controllable outlet valve applied to a hydraulic machine according to an example embodiment of the invention;

Figure 4 is a flow chart of a procedure for implementing the invention;

Figures 5A-5E are a series of plots indicating the relationships between vehicle speed and flow in various embodiments;

Figure 6 is a plot of demanded flow, pumped flow, outlet valve flow (upper y-axis) and outlet valve control signal current (lower y-axis) with time (x-axis);

Figure 7A is a plot of pressure variation as a function of time without pressure ripple suppression and Figure 7B is a plot of pressure variation as a function of time in a ripple reduction operating mode; and

Figure 8 is a schematic diagram of an electronically controlled machine further comprising an inlet valve.

Detailed Description of an Example Embodiment

First Example

[0057] Figure 1 is a schematic diagram of an electronically commutated machine (ECM) 10 comprising a plurality of working chambers in the form of cylinders 12 which have working volumes 14 defined by the interior surfaces of the cylinders and pistons 16 which are driven from a rotatable shaft 18 by an eccentric cam 20 and which reciprocate within the cylinders to cyclically vary the working volume of the cylinders 12. The rotatable shaft 18 is driven by a prime mover (not shown). A shaft position and speed sensor 22 determines the instantaneous angular position and speed of rotation of the rotatable shaft 18, and through a signal line 24 informs the machine controller 26, which enables the ECM controller 26 to determine the instantaneous phase of the cycles of each cylinder 12. The ECM controller 26 is typically a microprocessor or microcontroller, (or a plurality of microprocessors or microcontrollers which may be distributed) which executes a stored program in use.

[0058] The working chambers are each associated with low-pressure valves (LPVs) in the form of electronically actuated face-sealing poppet valves 28, which have an associated working chamber and are operable to selectively seal off a channel extending from the working chamber to a low-pressure hydraulic fluid manifold (LPM) 30, which may connect one or several working chambers, or indeed all as is shown here, to the LPM 30 of the ECM 10. The LPVs 28 are normally open solenoid actuated valves which open passively when the pressure force on the poppet from within the working chamber is less than or equal to the pressure force on the poppet from within the LPM 30 plus the spring force of the LPV spring, i.e. during an intake stroke, to bring the working chamber into fluid communication with the LPM 30, but are selectively closable under the active control of the ECM controller 26 via LPV control line 34 to bring the working chamber out of fluid communication with the LPM 30. The valves may alternatively be normally closed valves.

[0059] The working chambers are each further associated with a respective high-pressure valve (HPV) 36 in the form of a pressure actuated delivery valve. The HPVs 36 open outwards from their respective working chambers and are each operable to seal off a respective channel extending from the working chamber to a high-pressure hydraulic fluid manifold (HPM) 40, which may connect one or several working chambers, or indeed all as is shown here, to a port 46 in HPM 40. In a similar manner, the LPVs are operable to seal off a respective channel extending from the working chamber to a low-pressure hydraulic fluid manifold (LPM) 30, which may connect one or several working chambers, or indeed all as is shown here, to a port 44 in LPM 30. The HPVs 36 function as normally-closed pressure-opening check valves which open passively when the pressure within the working chamber exceeds the pressure within the HPM 40. The same HPVs 36 may be solenoid actuated check valves which the machine controller 26 may selectively hold open via HPV control line 42 once the HPV 36 is opened by pressure within the associated working chamber. The solenoid actuation can be used, depending on its configuration, to open or close, or to hold open or closed the HPV 36.

[0060] As well as determining whether or not to close or hold open the LPVs 28 or HPVs 36 on a cycle by cycle basis, the machine controller 26 is operable to vary the precise timing (e.g. phasing) of the closure of the LPVs 28 and HPVs 36 with respect of the varying working chamber volume. Arrows indicate hydraulic fluid flow in the pumping mode; in the motoring mode the flow is reversed. A pressure relief valve 48 may protect the hydraulic machine from over-pressure damage. Fluid in the HPM 40 drives a motor 56 (being an example of an actuator) which, when operating in closed-circuit mode (not shown) then flows back to the LPM 30 or, in open-circuit mode (as shown) flows to the tank 58.

[0061] The ECM 10 also has an electronically controllable outlet valve 47 which can be opened or closed by the machine controller or another system controller. When open the electronically controllable outlet valve allows some fluid to leave the HPM 40 other than via the actuator 56. The electronically controllable outlet valve 47 is typically a proportional flow valve, i.e. a valve which can be opened partially, in contrast to valves which are binary in the sense that they may only be stable when completely opened or completely closed. As such, the machine controller 26 can select not only whether the electronically controllable outlet valve 47 is open or closed, but also how open or how closed the electronically controllable outlet valve 47 is.

[0062] Inputs to the machine controller 26 include a demand signal 60, (which may be a fraction of maximum displacement, Fd), the speed and position of the shaft as measured by the shaft speed and position sensor 24, and the pressure 54 of the HPM 40 as measured by a pressure sensor 52 (pressure sensor signal line not shown). In some examples the pressure 54 of the HPM 40 may be used as a feedback signal as part of a pressure control system, along with a demand signal 60, however this is not necessarily the case and one skilled in the art will appreciate that other demand signals may be used. In addition, the machine controller 26 may be able to read (and/or receive data from) a database 50 of disallowed frequencies (for example, Fd values which lead to patterns of cylinder actuations that give rise to frequencies that are unfavourable). Outputs include valve control signals through LPV and HPV control lines 34 and 42, as well as a control signal (via control line 45) to an electronically controllable outlet valve 47.

[0063] In some example embodiments, the ECM 10 may also have one or more vibration sensors (for example an accelerometer) and the machine controller 26 may be operable to receive information from the vibration sensors and to determine the frequency and amplitude of any vibrations detected by the vibration sensors. In which case, the machine controller 26 is typically also operable to write vibration data to the database 50. In some cases, the machine controller 26 may also execute a machine learning algorithm operable to determine patterns of cylinder actuation and/or Fd values, that give rise to frequencies and/or amplitudes of vibrations that are unfavourable, in which case the machine controller 26 is typically also operable to write output information from the machine learning algorithm to the database 50.

[0064] Although in Figure 1 all of the working chambers are connected to the same HPM 40, in some embodiments, such as the second example below, there are a plurality of groups of one or more of the working chambers (coupled to the same shaft) which are connected to a respective plurality of HPMs (and thereby to sources or sinks of hydraulic fluid, e.g. hydraulic actuators or motors). Each group may be controlled according to a separate demand signal for the respective group. In some embodiments, the allocation of working chambers to groups can be dynamically changed during operation, for example using one or more electronically controllable switching valves.

[0065] An advantage of using ECMs is that the fluid flow output of respective ECMs can be varied in rapid response to varying demands, on a cycle-by-cycle basis. With suitable control of the LPVs 28 and HPVs 36 in phased relationship with cycles of working chamber volume, the machine controller 26 can control the net displacement (from the LPM 30 to the HPM 40 or vice versa) of each chamber on each cycle of working chamber volume. Each working chamber may, on a given cycle of working chamber volume, undergo an active cycle with a net displacement of working fluid or an inactive (idle) cycle with no net displacement of working fluid. Active cycles can be pumping mode cycles, in which there is a net displacement of working fluid from the LPM 30 to the HPM 40, driven by the rotation of the rotatable shaft 18, or motoring mode cycles in which there is a net displacement of working fluid from the HPM 40 to the LPM 30 (driving the rotation of the shaft). Inactive cycles can be achieved by holding a valve (typically an LPV) open throughout a cycle so that the working chamber remains in communication with a manifold throughout the cycle. A decision is made on a cycle by cycle basis as to whether to carry out active or inactive cycles in order that the net displacement follows a target demand indicated by a demand signal 60. The demand signal 60 may be a demand for a pressure of hydraulic fluid, or a flow rate of hydraulic fluid, or a total displaced volume of hydraulic fluid, or a power output, or the position of an actuator hydraulically linked to the hydraulic fluid, etc.

[0066] In a pumping mode cycle, the machine controller 26 selects the net rate of displacement of hydraulic fluid from the working chamber to the HPM 40 by the hydraulic motor 56 by actively closing one or more of the LPVs 28, typically near the point of maximum volume in the associated working chamber's cycle, closing the path to the LPM 30 and thereby directing hydraulic fluid out through the associated HPV 36 on the subsequent contraction stroke (but does not actively hold open the HPV 36). The machine controller 26 selects the number and sequence of LPV closures (and HPV openings) to produce a flow, or create a shaft torque, or power, to thereby meet or exceed a demand signal 60 (which may be a demand signal 60 associated with the selected net rate of displacement).

[0067] In a motoring mode of operation, the hydraulic machine controller 26 selects the net rate of displacement of hydraulic fluid to be displaced by the hydraulic machine, via the HPM 40, by actively closing one or more of the LPVs 28 shortly before the point of minimum volume in the associated working chamber's cycle. This closes the path to the LPM 30 which causes the hydraulic fluid in the working chamber to be compressed by the remainder of the contraction stroke. The associated HPV 36 opens when the pressure across it equalises and a small amount of hydraulic fluid is directed out through the associated HPV 36, which is held open by the hydraulic machine controller 26. The machine controller 26 then actively holds open the associated HPV 36, typically until near the maximum volume in the associated working chamber's cycle, admitting hydraulic fluid from the HPM 40 to the working chamber and applying a torque to the rotatable shaft 18.

[0068] In use, the machine controller 26 typically receives the demand signal 60 in the form of a displacement fraction (Fd) signal and executes an algorithm to determine whether or not to carry out an active cycle. The controller may compare accumulated actual displacement with accumulated demand and carry out an active cycle if the difference between the two exceeds a threshold. Thus, the net displacement by the group of working chambers connected to the HPM is regulated to thereby meet this demand.

[0069] However, in some circumstances and for certain values of Fd (e.g. those associated with low flow rates, pulsatile flow, or resonance) the machine controller 26 will instead cause the net displacement of the working chamberto be greaterthan would be required to meet the demand, thus avoiding patterns of working chamber actuation which may cause excessively pulsatile flow, or resonance. In such circumstances, the machine controller 26 also causes the electronically controllable outlet valve 47 to be (e.g. at least partially) open. The volume of fluid that is displaced into the HPM 40 (when pumping) beyond that required as indicated by the demand signal 60 (i.e. the excess Fd) is thereby allowed to leave via the electronically controllable outlet valve 47 and may either return to the LPM 30 in closed-circuit mode, or else may be diverted to tank 58 in open-circuit mode. This provides the advantage that low flow rates, and rates of flow which are pulsatile (and are therefore likely to cause resonance) are avoided and thus potential damage to the vehicle, machine, or machine parts is mitigated, as is potential user discomfort, however the net displacement of working fluid into the HPM 40, after allowing for the loss of working fluid through outlet valve 47, meet the required demand, in this case for the motor 56.

[0070] Figures 2A through 2E are a series of plots showing the operation of an electronically commutated machine 10 according to the invention. Figure 2A is a plot of flow demand 60 as a function of time; Figure 2B is a plot of Fd 102 as a function of time; Figure 2C is a plot of the position 104 of the electronically controllable outlet valve 47 as a function of time; Figure 2D is a plot of the loss 106 (i.e. the flow out of the HPM via the additional outlet, controlled by the electronically controllable outlet valve 47) as a function of time; and Figure 2E is a plot of the net flow 108 as a function of time.

[0071] At time ti, the demand signal received by the controller changes to a new level, in this case indicating a reduced demand. The controller determines that if this demand were met with a normal pattern of active and inactive cycles (i.e. if the demand were met by causing ECMs to output the amount of flow which corresponds to the demanded flow using the controller's algorithm to select active or inactive cycles on each cycle of working chamber volume) and with outlet valve 47 closed, this would potentially lead to pulsatile flow. As a result, the machine controller 26 causes the cylinders connected to the HPM 40 to produce flow in excess of the decreased flow demand (although this may still be (and typically will be) a reduction in total flow when compared to the total flow output before the machine controller 26 receives the demand signal 60 indicating a decreased flow demand). A higher proportion of cylinders connected to the HPM undergo active (instead of inactive) cycles than would otherwise take place in response to the demand signal 60. At the same time, the electronically controllable outlet valve 47 opens to a controlled partially open position such that a portion of the output flow, corresponding to the amount of excess flow produced, can leave via the electronically controllable outlet valve 47. In the open-circuit arrangement shown in figure 1, the excess flow which leaves via the electronically controllable outlet valve 47 is directed to the tank 58. Accordingly, the net flow (output flow from the working chambers minus excess flow from the working chambers) meets the demanded flow, while pulsatile flow from the working chambers is reduced or avoided. When the flow demand changes to a level which would not cause unwanted resonance or pulsatile flow, the electronically controllable outlet valve 47 is closed and the cylinders implement demand, Fd (although this is not the case for shown in Figure 5D where the outlet valve 47 is always at least partially open).

Second Example

[0072] Figure 3 is a diagram of the control circuit of a vehicle 200, with hydraulic transmission, according to the invention (in this example, the vehicle is a fork lift truck). The vehicle 200 comprises a fluid working machine 150 and an engine 152 which acts as prime mover and which drives the fluid working machine through a rotatable shaft 154. Said shaft may be directly or indirectly connected (i.e. through a torque connecting member or a gear train) to the output shaft of the prime mover. The fluid working machine has a machine controller 156, which is in electronic communication with a vehicle controller 158, and three groups of working chambers which are controlled as independent pumps 160, 162, 164 (first, second, third pumps), are each in communication with respective high-pressure manifolds 166, 168 and 170 (first, second, third high-pressure manifolds). A separate fixed displacement pump 172 is also coupled to the rotatable shaft 154. The working chambers are in communication with a low-pressure manifold 174 which extends to tank 176. The fluid working machine may be formed with a single housing including the groups of working chambers controlled as independent pumps or there may be a plurality of housings. The machine controller and vehicle controller function as the at least one controller. The third high-pressure manifold functions as the high-pressure manifold of the invention.

[0073] The first high-pressure manifold 166 drives one or more actuators 178 in an open-circuit hydraulic arrangement. Actuators may include a travel motor, lift, tilt, side-arm, single or double acting rams, e.g. a stick ram, a bucket ram, and/or other hydraulic working devices, depending on the type of vehicle 200 and its intended uses. The third high-pressure manifold 170 is used to drive wheel motor(s) 180 which in turn drive respective wheels 182 via a propel system manifold (PSM) block 184 including directional control valve group 186 with a directional control valve (DCV), which comprises two, 2-way solenoid operated direction control valves which provide the pump high-pressure line to one side of the bi-directional motor at a time. A single wheel motor may drive multiple wheels or just one wheel. There may be an intermediate gearbox between the wheel motor and wheel(s). The connection from the third hydraulic manifold to the directional control valve group functions as the actuator port 196. The third high-pressure manifold also has an outlet 188 (functioning as an additional outlet) through a proportional control valve 190, functioning as the electronically controlled outlet valve, which leads to the output line 194 of a hydrostatic steering unit 192 which is powered by the fixed displacement pump 172. The output line 194 is above tank pressure and so some potential energy is retained and reused. The wheel motors are supplied with hydraulic fluid in a closed circuit. The electronically controlled outlet valve is typically connected in series with a check valve, to prevent flow of hydraulic fluid into the high-pressure manifold 170 through the additional outlet. A switching valve 165 switches the second high-pressure manifold, and therefore the output of the second pump, between the first and third high-pressure manifolds 166, 170, which it may thereby switchably assist. Although the engine 152 typically drives the pumps 160, 162, 164 and 172, in some circumstances, for example during regenerative breaking or when lowering a load and reclaiming gravitational potential energy, some or all of pumps 160, 162, 164 may carry out motoring cycles instead of pumping cycles, while the rotatable shaft continues to rotate in the same direction. Pumps 160, 162 and 164 are typically different groups of working chambers within a single fluid working machine with an integrated controller 156 but they may be discrete pumps. The fixed displacement pump 172 is typically a separate device, though it may also be formed of a group of working chambers within the fluid working machines which may use only check valves instead of electronically controlled valves.

[0074] The vehicle controller 158 is in electronic communication with the ECM controller 156 and the electronic switching valve 165. The ECM controller is operable to independently control the working chambers of the individual pumps in response to respective received demand signals. For the actuators 178, these may be signals concerning the pressure in the first high-pressure manifold 166, or after one or more switching valves, or a position or speed of movement of an actuator. The working chambers of the first pump are controlled according to known algorithms to implement the respective demand.

[0075] With reference to Figure 4, for the third high-pressure manifold, a demand signal is received or calculated from the requirements of the wheel motors. The requirements typically vary with the speed of the vehicle, and this signal is used to calculate 252 a required displacement fraction, Fd for the third pump 164. The displacement fraction which is required depends on the speed of rotation of the rotatable shaft as the actual rate of displacement of working fluid in volumetric terms is proportional to both the displacement fraction and the speed of rotation of the rotatable shaft. The vehicle controller next determines whether this displacement fraction is likely to cause a problem, that is to say whether the pattern of working chamber active and inactive cycles which the fluid working machine controller will implement in response to the displacement fraction signal (Fd) will cause vibrations, pulsatile flow etc. If no problem is predicted 254 then the calculated displacement fraction for the third pump is simply passed to the fluid working machine controller 156 to implement. However, if a problem is predicted then, instead, the vehicle controller calculates a revised displacement fraction, Fd', which is higher than Fd, and which is selected to mitigate the predicted problem, and also calculates a valve open position, for the proportional flow valve 190, which will give a net displacement of working fluid into the third high-pressure manifold 170 to meet the demand after allowing for the flow of some hydraulic fluid out of the third high-pressure manifold 170 through the electronically controlled proportional flow valve 190. The vehicle controller then transmits the revised displacement fraction, Fd' to the fluid working machine controller 156 and also transmits a control signal to the proportional flow valve 190. The fluid working machine controller 156 receives the revised demand signal, Fd', and executes its algorithm to determine whether each cycle should be active or inactive to meet the demand signal which it receives.

[0076] In this example, the electronically controllable outlet valve 190 is connected between the third high-pressure manifold and the low-pressure side of the steering mechanism, however it may regulate an outlet from the high-pressure manifold to a low-pressure manifold or tank, or to a different high-pressure manifold. Although in this example, the electronically controllable outlet valve 47 is within the PSM block (184), it may be external to the PSM block.

[0077] Accordingly, in some embodiments, the displacement of the third pump 164 may be restricted (e.g. via the vehicle controller) to certain allowable levels, e. g. only certain displacements may be allowed, or certain displacements may be disallowed. These restricted allowable displacements may vary with the speed of rotation of the rotatable shaft. When the received demand is not to be implemented, a higher demand is implemented and the electronically controllable outlet valve 190 is controlled as appropriate so that the wheel motors receive the required fluid.

[0078] There are numerous different ways in which the actual displacement of the individual pumps and the electronically controllable outlet valve 190 may be controlled and some examples are shown in Figures 5A through 5E. In these figures the y-axis represents flow (volume per second) with vehicle speed (x-axis). Demanded flow is shown with a dotted line 300; the net flow displaced by pump 164 and perhaps 162 is shown with a solid line 302, and leakage flow through the electronically controlled outlet valve 190 is shown with a dashed line 304. In these embodiments, the demanded flow is the sum of the net displacement of the pump minus the leakage flow.

[0079] The various embodiments shown in Figures 5A through 5E each address the problem of pulsatile flow at low flow rates and the embodiments of Figures 5B, 5C and 5D address the problem of avoiding generating patterns of active and inactive working chamber actuations at undesirable secondary frequencies.

[0080] In the example embodiment of Figure 5A, the controller maintains a minimum pump flow F_A when the vehicle speed is between zero and a threshold vehicle speed S_A. Between zero speed and S_A speed, the demand displacement fraction, Fd, is low, leading to occasional active cycles interspersed between more frequent inactive cycles, causing pulsatile flow and/or resonance. This region or range pulsatile flow (or resonance) is avoided by the vehicle controller maintaining pump flow of F_A, which lies outside the problematic region or range, thereby overriding the demanded displacement fraction, Fd. At the same time, the electronically controllable outlet valve 190 is regulated to be at least partially open. At flow F_A working chambers are used which provide smooth flow, for example three working chambers which are mutually phased apart by 120°.

[0081] The excess flow 304 then leaves manifold 170 via the outlet valve 190. As the vehicle speed increases from 0 to S_A, the demanded flow approaches a point X where directly matching the demand would no longer be associated with pulsatile flow and/or resonance and the portion of flow which leaves manifold 170 via the electronically controllable outlet valve 190 decreases to zero. At point X, and for speeds above S_A, the calculated demand Fd is implemented without modification.

[0082] In the embodiment of Figure 5B in order to obtain the demanded flow 300, the actual pump flow 302 takes one of a series of equally spaced discrete values A, B, C, D, E in dependence on vehicle speed. These discrete flow values are selected to avoid resonances or other issue related to undesirable vibrations or pulsatile flow. At the bottom end of the speed range associated with each discrete flow, the electronically controllable outlet valve 190 is closed, and it is opened progressively as the speed increases, until it is fully open, whereupon the actual pump flow increases to the next discrete level and the electronically controllable outlet valve is closed again.

[0083] In the embodiment of Figure 5C, at the majority of vehicle speeds, there is at least some leakage flow through outlet valve 190. The pumped flow 302, is the same as the demanded flow 300 between speeds S_A and S_B and again between Sc and S_D, or above S_E. These are speed regions where this pumped flow is not expected to cause undesirable vibrations or pulsatile flow. The other speed regions, which may be expected to cause undesirable vibrations or pulsatile flow, are shown in this figure as flow ranges 1 and 2, and from zero flow to level F_A. These flow ranges correspond to between speed 0 and S_A, and between speed S_B and Sc, and again between speed S_D and S_E, the pumped flow has a predetermined value (F_A, Fc or F_E respectively) which is selected to exceed the demanded flow and the electronically controlled outlet valve is correspondingly regulated to cause leakage flow 304 such that the demand flow 300 is met. Again, the minimum flow, F_A, is selected to avoid vibrations arising from pulsatile flow. From speed S_A to speed S_B, the pump flow increases from F_A to F_B, with the outlet valve closed and then, from speed S_B to S_C, the flow is maintained at F_C. At speed S_B the amount of leakage flow is at a maximum, F_{l2} and it then drops to 0 linearly through this range. There is no leakage flow and the pump flow increases linearly with speed from speed Sc to S_D and then again from speed S_D to S_E, the pump flow is maintained at a fixed level, F_E, with maximum leakage flow F_{l1}, which decreases from speed S_D to S_E, selected to obtain the desired net flow into the high-pressure manifold 170.

[0084] In the embodiment of Figure 5D, the leakage flow 304 has a minimum baseline value of F_{A0} which is always present through the speed range, and is provided by the one or more said outlet valve(s) being at least partially open. The net flow into the high-pressure manifold 40, 170 after allowing for leakage flow of 304, always meets the demand flow 300. The pump may be operated at any one of the distinct, discrete 'step' levels F_A, F_B, F_C, F_D, F_E, etc, selected to provide smooth pumped flow. It should be noted that the size of each step is equal (i. e. the flows associated with F_B, F_C, F_D, F_E, etc. are simple multiples of flow F_A), and as the flow level F_A is chosen to given smooth flow, thus multiples of this flow level are in theory likely also to yield smooth flow. At speeds S_A, S_B, S_C, S_D, S_E respectively, only leaked flow of F_{A0} is produced. At other speeds there is additional leaked flow according to line 304. Leakage flow 304 increases discontinuously and then decreases smoothly in a sawtooth pattern as vehicle speed increases. Point 'X' corresponds to a minimum flow level F_A, at which the pump alone provides an acceptably smooth level of flow without undesirable frequencies.

[0085] In the embodiment of Figure 5E, as the vehicle speed increases from speed 0 to S_A, the leakage flow is held constant at flow F_A. Leakage flow is switched off above speed S_A, however pumped flow does increase from flow F_A to higher flow F_B as vehicle speed increases in the range from 0 to S_A. This enables the net flow to increase with vehicle speed without pumped flow ever being below a minimum threshold F_A where there would be pulsatile flow. Again, X corresponds to a minimum flow level F_A, at which the pump alone provides an acceptably smooth level of flow without undesirable frequencies.

[0086] In the above example, the third hydraulic manifold, driven by the third pump 164, is regulated according to the invention without any contribution from the second pump 162. If the electronic switching valve 165 is switched so that the second pump 162 contributes to the flow of hydraulic fluid to the wheel-motor propel hydraulic circuit, then instead of regulating the displacement of the cylinders which make up the third pump 164 alone, the second and third manifolds 168 and 170 together form a high-pressure manifold (the high-pressure manifold) and the combined displacement of the cylinders which make up the third pump 164 and second pump 162 is regulated. In some embodiments, more than one outlet is provided, each having a separate electronically controlled outlet valve.

[0087] The invention is also operable where the actuators instead supply fluid to the third pump 164, acting instead as a motor for example during a regenerative process. The additional outlet valve can be opened or closed as required to control flow to either or both of pumps 162 and 164. The loss of hydraulic fluid through the additional outlet valve would be taken into account, and the calculations of flow consumed by the pump, and lost through the additional outlet valve need only take into account the sign/direction of fluid flow.

[0088] In the above example, the invention is employed to control the flow of hydraulic fluid to the wheel-motor propel hydraulic circuit, by regulating the flow of third pump 164 and the position of proportional flow valve 190. However, the invention may also be employed to control the flow of hydraulic fluid to one or more actuators 178 by the first pump 160 by providing an additional outlet from manifold 166 regulated by a further electronically controlled valve in the same way and controlling the displacement of pump 160 and the position of the further electronically controlled valve in concert. The invention would be useful for example for providing hydraulic fluid to hydraulic rams of a hydraulic vehicle (e.g. fork lift truck) tilt function.

Third Example

[0089] In the first and second examples, the outlet valve 47, 190 is typically a proportional flow valve which is opened and closed, or adjusted, relatively slowly. Even if it were a digital valve, which is either open or closed or transiting therebetween, it is typically opened or closed relatively slowly or at least infrequently, compared with the solenoid operated LPVs 28 and HPVs 36 of the ECM. Furthermore, it is typically controlled asynchronously with the cycles of working chamber volume.

[0090] In a third example, illustrated with reference to Figure 8, the apparatus corresponds generally to Figure 1, with a first outlet valve 47 which is a proportional flow valve that is controlled as described above, with the addition of a second outlet valve, 62, which regulates an outlet path from the HP manifold to tank, and which is a solenoid operated valve that is digitally operated between open or closed, typically with a transit time in the range of 1-4ms, and which is controlled in phased relationship to the cycles of working chamber volume, through a control line 45 in the same way as the LPVs 28 and HPVs 36 of the ECM.

[0091] This is used in part to provide a further controlled flow of working fluid to leave the HP manifold 40, through the outlet valve so that the net flow to the high-pressure manifold meets the demand, and partially to attenuate pressure ripples and/or solitons in the high-pressure manifold. Pressure ripples are a significant problem at low fractions of maximum displacement. At a displacement demand of say 5% of maximum demand, the ECM will typically cause every 20^{th} working chamber in the sequence to execute an active cycle with the intervening cycles being inactive cycles. Accordingly, the flow of fluid to the HP manifold is highly pulsatile in nature.

[0092] With reference to Figure 6, when this occurs or is predicted, the machine controller 26 varies the control signal to the second outlet valve 62 to cause the second outlet valve to open before the time of peak flow from an individual working chamber into the HP manifold and close again after the peak flow. This has the effect of reducing the peak pressure, and thereby attenuating pressure ripples. In addition, there will be a loss of working fluid from the HP manifold, which is a function of the time for which the valve is open and the pressure difference across the respective valve while it is open, and which should be summed with any flow out of the HP manifold through the first outlet valve when calculating net flow into the HP manifold to meet demand.

[0093] Figure 6 shows the demand signal 400 which is constant in the short period of time shown, the flow of working fluid into the high-pressure manifold 402 during an active cycle of working chamber volume and the control signal to the valve 404 causing it to open in response to the rising edge of the signal and close in response to the closing edge and a pulse of fluid 406 to flow through the valve for a period of time 408. The person skilled in the art can determine experimentally or by calculation the precise timings required taking into account the opening or closing speed of the second outlet valve and the time required for pressure waves from the working chambers to propagate to the location of the second outlet valve.

[0094] The electronically controllable second outlet valve is open for the duration of the control pulse 404. Longer pulse lengths result in more flow leaving via the second outlet valve (and this thus corresponds to higher loss of flow and loss of efficiency as more fluid flows to the tank). Pulses of shorter duration result in correspondingly lower losses of flow but increased pressure variations. The pulse start time or phase (relative to cycles of working chamber volume) and pulse width (time or phase of cycles of working chamber volume), is selected to obtain a desired level of attenuation and fluid outflow characteristics.

[0095] The control signal to the second outlet valve typically takes the form of a current directed to a solenoid actuator of the valve. This signal is typically varied by pulse width modulation. The precise moment at which the second outlet valve opens or closes will be affected by factors such as the strength of a spring holding the valve in either a closed or open position (in a normally closed or normally open valve), the instantaneous pressure in the working chamber and so forth. More generally, the opening time or phase and the pulse width (expressed as time or phase) will be varied depending on measurements or calculations of one or more of:

a) the demand signal,

(b) the hydraulic machine rate of displacement, or flow rate;

(c) the speed of rotation of the rotatable shaft;

(d) the compliance of the high-pressure manifold (variation in system pressure with volume of working fluid in the high-pressure manifold);

(e) operating mode of the hydraulic system, for example whether the controller is regulating displacement in response to the demand signal in a feedback, feedforward and/or open-loop control mode; and

(f) the temperature of the working fluid.

[0096] Although typically a pulse is timed to be coincident with a peak in output flow, in some embodiments of the invention pulses may be offset in time (e.g. advanced or retarded with respect to a peak in output flow). This presents options for optimisation as will be appreciated by the person skilled in the art.

[0097] Figure 7A is a plot of pressure as a function of time in an example without application of the invention. As can be seen from this figure, there are significant variations in pressure overtime, and the amplitude of the pressure varies between pulses. Figure 7B is a plot of pressure as a function of time with application of the invention. As can be seen from this figure, the amplitude of the pressure ripples is reduced, in this example from 20-25 bar to about 15 bar.

[0098] Although in this example the second outlet valve 62 is controlled by the machine controller 26, it may be controlled by another controller such as a vehicle controller 158, although typically the controller generating the outlet valve control signals requires to receive a signal (such as shaft position) indicative of the phase of cycles of working chamber volume and typically also information about the sequence of active and inactive cycles of working chamber volume generated by the machine controller responsive to the demand signal. The second outlet valve will more typically lead to the LP manifold or tank, generally as shown in Figure 1, than to another manifold.

[0099] Typically, an outlet valve provided for the purpose of smoothing pressure ripples has a relatively high flow capacity and is only opened and closed during active cycles of working chamber volume. A relatively high flow capacity is required to significantly attenuate pressure ripples and if such a valve was left open for a larger proportion of the time, as may be required for the purpose of controlling net demand as described with reference to example 1 and example 2, losses would be quite substantial. Accordingly, the outlet valve for the purpose of smoothing pressure ripples is typically provided in addition to an outlet valve for the purpose of regulating net demand as shown in Figure 1. Nevertheless, a single outlet valve may be used to both regulate outflow of working fluid to obtain the desired net flow into the HP manifold and also to attenuate pressure ripple.

Fourth example

[0100] In a fourth example, shown in Figure 9, apparatus according to Figure 1 has a digital solenoid actuated inlet valve 64, through which the HP manifold 40 is connected to a source 66 of higher-pressure fluid, such as a charged fluid accumulator. The machine controller 26 opens the inlet valve between active cycles of working chamber volume and closes the inlet valve during at least a peak flow region of active cycles of working chamber volume. Accordingly, fluid is admitted from the higher-pressure fluid source 64 between times of peak flow into the working chamber to compensate for any shortfall or deficiency in the supply of working fluid between active cycles, i.e. during pressure minima and again to reduce pressure ripple. Where the higher pressure fluid source is an accumulator it may be filled with fluid from the high pressure manifold when it is above a threshold, through a check valve. The line from the accumulator through the inlet valve to the high-pressure manifold includes a restrictor to prevent excessive flow.

Claims

1. A hydraulic system comprising;

a hydraulic machine, the hydraulic machine comprising a rotatable shaft, a low-pressure manifold and a high-pressure manifold, and one or more working chambers having a volume which varies cyclically with rotation of the rotatable shaft, each working chamber having both a low-pressure valve which regulates communication between the low-pressure manifold and the working chamber, and a high-pressure valve which regulates communication between the high-pressure manifold and the working chamber, wherein for each working chamber at least one of the respective low-pressure valve and the respective high-pressure valve is an electronically controllable working chamber valve;
the high-pressure manifold extending between the one or more said working chambers and one or more actuator ports and one or more additional outlets;
one or more hydraulic actuators which are fluidly connected to said high-pressure manifold through the one or more actuator ports and thereby hydraulically driven by the hydraulic machine;
one or more electronically controllable outlet valves which regulate the opening or closing of the one or more additional outlets; and
at least one controller configured to control the one or more electronically controllable working chamber valves and the one or more electronically controllable outlet valves;
wherein the at least one controller is operable to receive a demand signal and to regulate the one or more electronically controllable working chamber valves in phased relationship to cycles of working chamber volume to thereby regulate the net displacement of working fluid by each working chamber on each cycle of working chamber volume, and to concurrently regulate the one or more electronically controllable outlet valves, to thereby regulate the net displacement of working fluid into or out of the high-pressure manifold allowing for the flow of working fluid out of the high-pressure manifold through the one or more additional outlets, when one or more additional outlet is open, to meet a demand indicated by the demand signal.

2. A hydraulic system according to claim 1, wherein the at least one controller is configured to control the electronically controllable working chamber valves to cause the hydraulic machine to displace working fluid in excess of the demand indicated by the demand signal and to cause one or more outlet valves to be open, the net displacement of working fluid into the high-pressure manifold from the one or more working chambers through the high-pressure valves being thereby regulated to meet the demand indicated by the demand signal after allowing for the flow of working fluid out of the high-pressure manifold through the one or more additional outlets.

3. A hydraulic system according to any one preceding claim, wherein one or more said outlet valve(s) is a variable flow control valve, and the at least one controller controls the variable flow control valve across a range of positions.

4. A hydraulic system according to any one preceding claim, wherein at least one controller is configured to open and close a said outlet valve in phased relationship to cycles of working chamber volume to reduce pressure ripples in the high-pressure manifold.

5. A hydraulic system according to any one preceding claim, wherein the high-pressure manifold is in communication with a higher-pressure working fluid source through an inlet valve and at least one controller is configured to close and open the inlet valve in phased relationship with cycles of working chamber volume, to reduce pressure ripple.

6. A hydraulic system according to any one preceding claim, wherein one or more said additional outlets extend from the high-pressure manifold to the low-pressure manifold such that one or more outlet valves regulate the flow of working fluid out of the high-pressure manifold to the low-pressure manifold through one or more said additional outlets.

7. A hydraulic system according to any one of claims 1 to 3, wherein one or more said additional outlets extend from the high-pressure manifold to a further manifold, such that the respective one or more outlet valves regulate the flow of working fluid out of the high-pressure manifold to the further manifold through the one or more said additional outlets.

8. A hydraulic system according to claim 7, wherein the further manifold is a pressurised manifold in fluid communication with one or more actuators.

9. A hydraulic system according to claim 7 or claim 8, wherein the high-pressure manifold is part of a closed-circuit hydraulic arrangement and the further manifold is part of an open-circuit hydraulic arrangement, or vice versa.

10. A hydraulic system according to claim 9, wherein the hydraulic system comprises a prime mover coupled to the hydraulic machine to provide power to cause the hydraulic machine to pump working fluid from the low-pressure manifold to the high-pressure manifold and wherein the hydraulic system further comprises a second hydraulic machine driven by the prime mover, or one or more further working chambers of the hydraulic machine configured to pump working fluid from the or another low-pressure manifold, to the further manifold, such that the prime mover powers both the open-circuit and closed-circuit hydraulic arrangements.

11. A hydraulic system according to any one preceding claim, which is a hydraulic vehicle, for example a fork lift truck.

12. A method of operating a hydraulic system, the hydraulic system comprising;

a hydraulic machine, the hydraulic machine comprising a rotatable shaft, a low-pressure manifold and a high-pressure manifold, and one or more working chambers having a volume which varies cyclically with rotation of the rotatable shaft, each working chamber having a low-pressure valve which regulates communication between the low-pressure manifold and the working chamber and a high-pressure valve which regulates communication between the high-pressure manifold and the working chamber, wherein for each working chamber at least one of the respective low-pressure valve and high-pressure valve is an electronically controllable working chamber valve;
the high-pressure manifold extending between the one or more said working chambers and one or more actuator ports and one or more additional outlets;
one or more hydraulic actuators which are fluidly connected to said high-pressure manifold through one or more said actuator ports and thereby hydraulically driven by the hydraulic machine,
one or more electronically controllable outlet valves which regulate the opening or closing of the one or more additional outlets; and
the method comprising receiving a demand signal and, responsive thereto, regulating the one or more electronically controllable working chamber valves in phased relationship to cycles of working chamber volume to thereby regulate the net displacement of working fluid by each working chamber on each cycle of working chamber volume, and concurrently regulating the one or more electronically controllable outlet valves, to thereby regulate the net displacement of working fluid into or out of the high-pressure manifold allowing for the flow of working fluid out of the high-pressure manifold through the one or more additional outlets, when one or more additional outlet is open, to meet a demand indicated by the demand signal.

13. A method according to claim 12, wherein the electronically controllable working chamber valves are controlled to cause the hydraulic machine to displace working fluid in excess of the demand indicated by the demand signal and one or more electronically controllable outlet valves is controlled to be open, such that the net displacement of working fluid into the high-pressure manifold from the one or more working chambers is regulated to meet the demand indicated by the demand signal after allowing for the flow of working fluid out of the high-pressure manifold through the one or more additional outlets.

14. A method according to claim 13, wherein when the demand is below a threshold, the electronically controllable working chamber valves are controlled to cause the hydraulic machine to displace working fluid at a predetermined minimum fraction of maximum displacement, or in a predetermined pattern of working chambers carrying out active or inactive cycles of working chamber volume,
and wherein the one or more outlet valves are controlled to cause hydraulic fluid to flow out of the high-pressure manifold such that the overall displacement of working fluid into the high-pressure manifold meets the demand.

15. A method according to claim 13 or claim 14, wherein under at least some circumstances the electronically controllable working chamber valves are controlled to cause the hydraulic machine to displace working fluid at one of a plurality of discrete fractions of maximum displacement, or in one of a plurality of predetermined patterns of working chambers carrying out active or inactive cycles of working chamber volume,

wherein the electronically controllable working chamber valves are controlled to cause the working chambers to displace one of the plurality

of discrete fractions of maximum displacement in excess of the displacement required to meet the demand indicated by the received demand signal, or to carry out one of the plurality of predetermined patterns which causes the combined displacement of the one or more working chambers to exceed the displacement required to meet the demand,
and wherein the one or more outlet valves are controlled to cause hydraulic fluid to flow out of the high-pressure manifold such that the overall displacement of working fluid into the high-pressure manifold meets the demand.

16. A method according to any one of claims 13 to 15, wherein the electronically controllable working chamber valves are controlled to cause the hydraulic machine to displace working fluid in excess of the flow required to meet the demand indicated by the demand signal and to cause one or more of the outlet valves to be open, responsive to determination that the demand is such that if,

i) the one or more additional outlets were closed, and
ii) demand was met only using working fluid displaced by the one or more working chambers,

there would be an undesirable response from the system arising from the pattern of selection of working chambers to carry out active or inactive cycles to meet the demand.

17. A method according to any one or claims 13 to 16, comprising measuring or calculating a current rate of flow of working fluid through one or more said additional outlets, optionally comprising measuring the pressure in the high-pressure manifold.

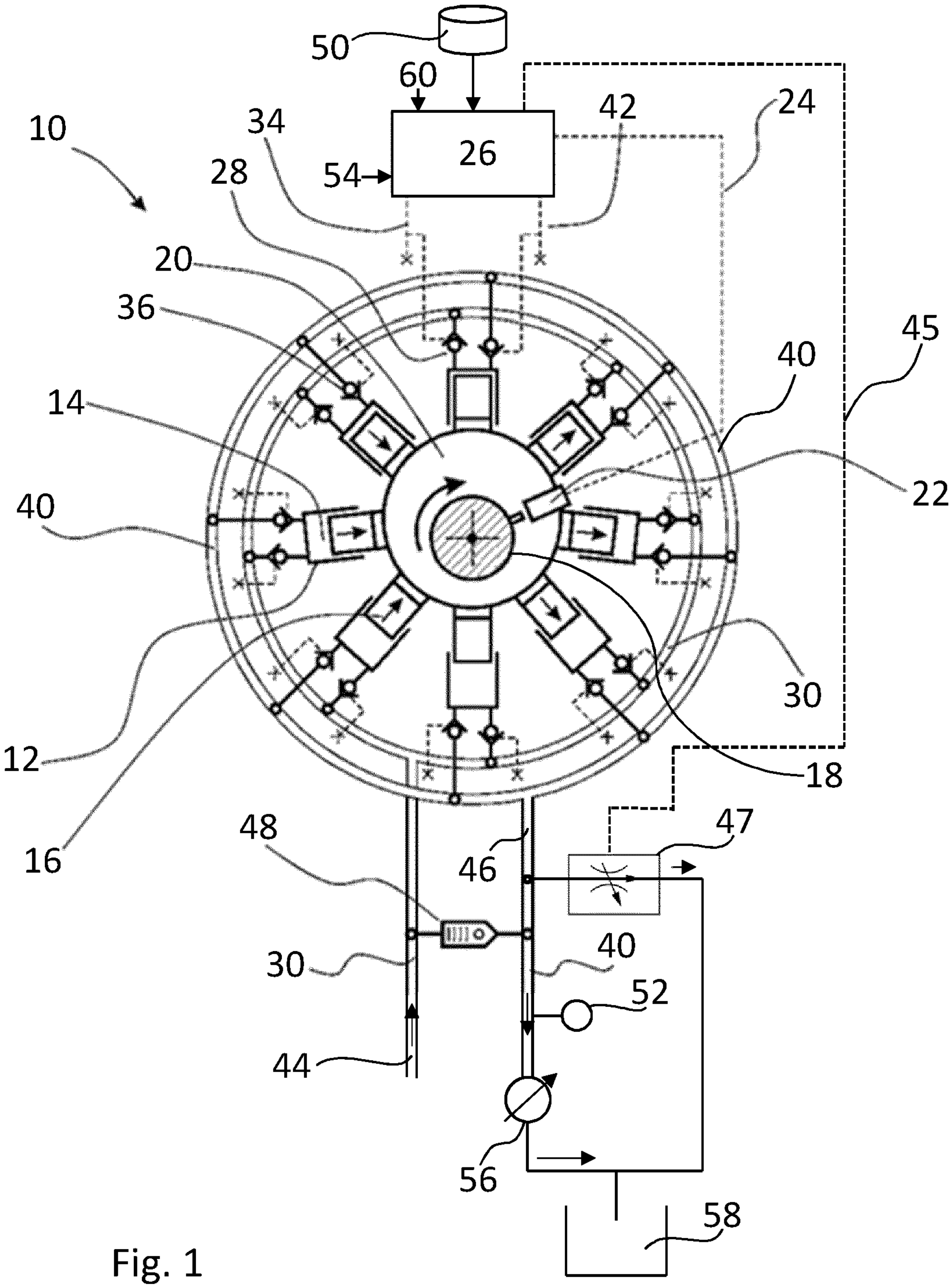
50
60
10
34
26
42
24
54
28
20
36
14
40
45
40
22
30
12
18
16
48
46
47
30
40
52
44
56
58

Fig. 1

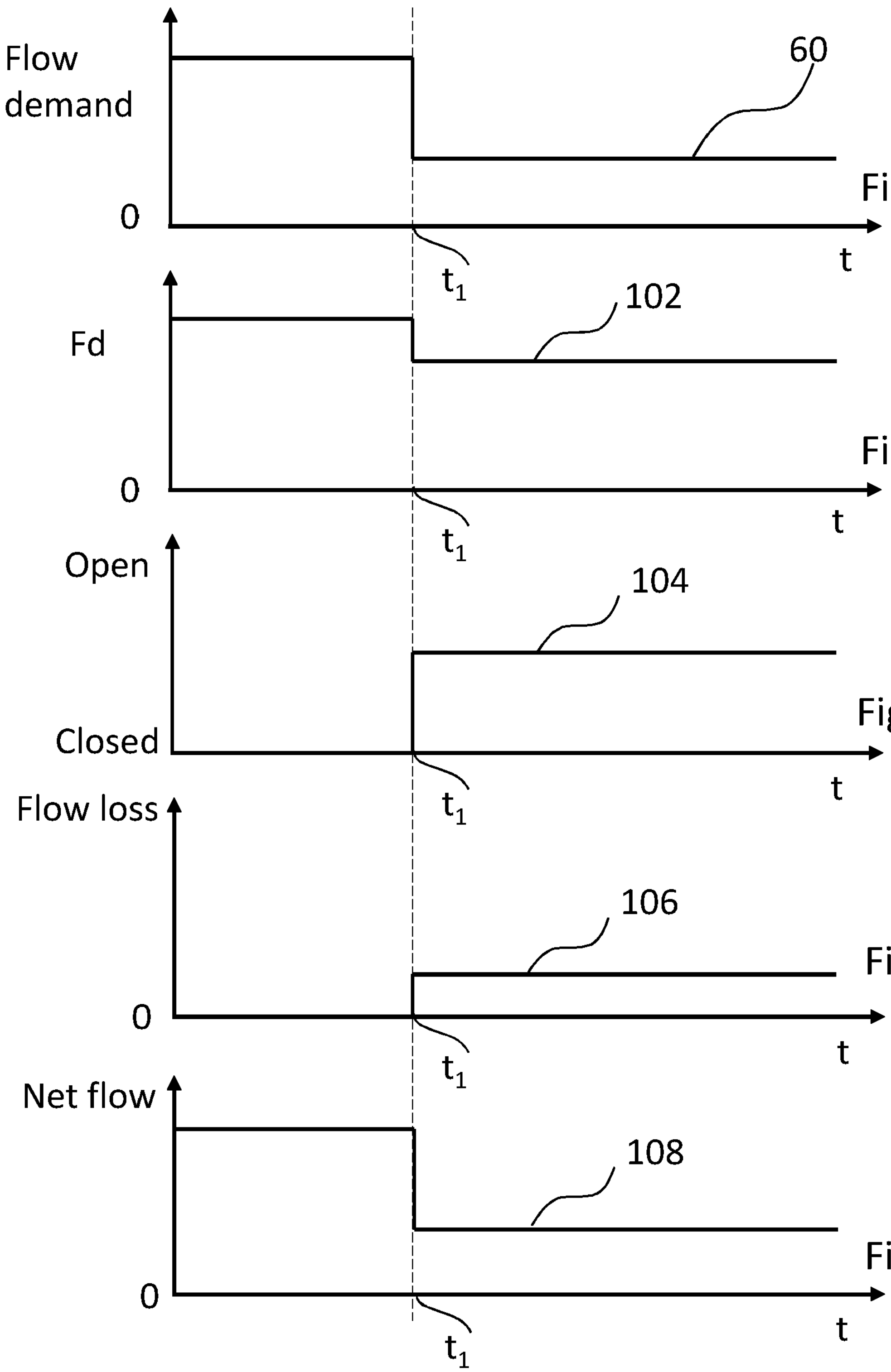

Fig. 2A

Fig. 2B

Fig. 2C

Fig. 2D

Fig. 2E

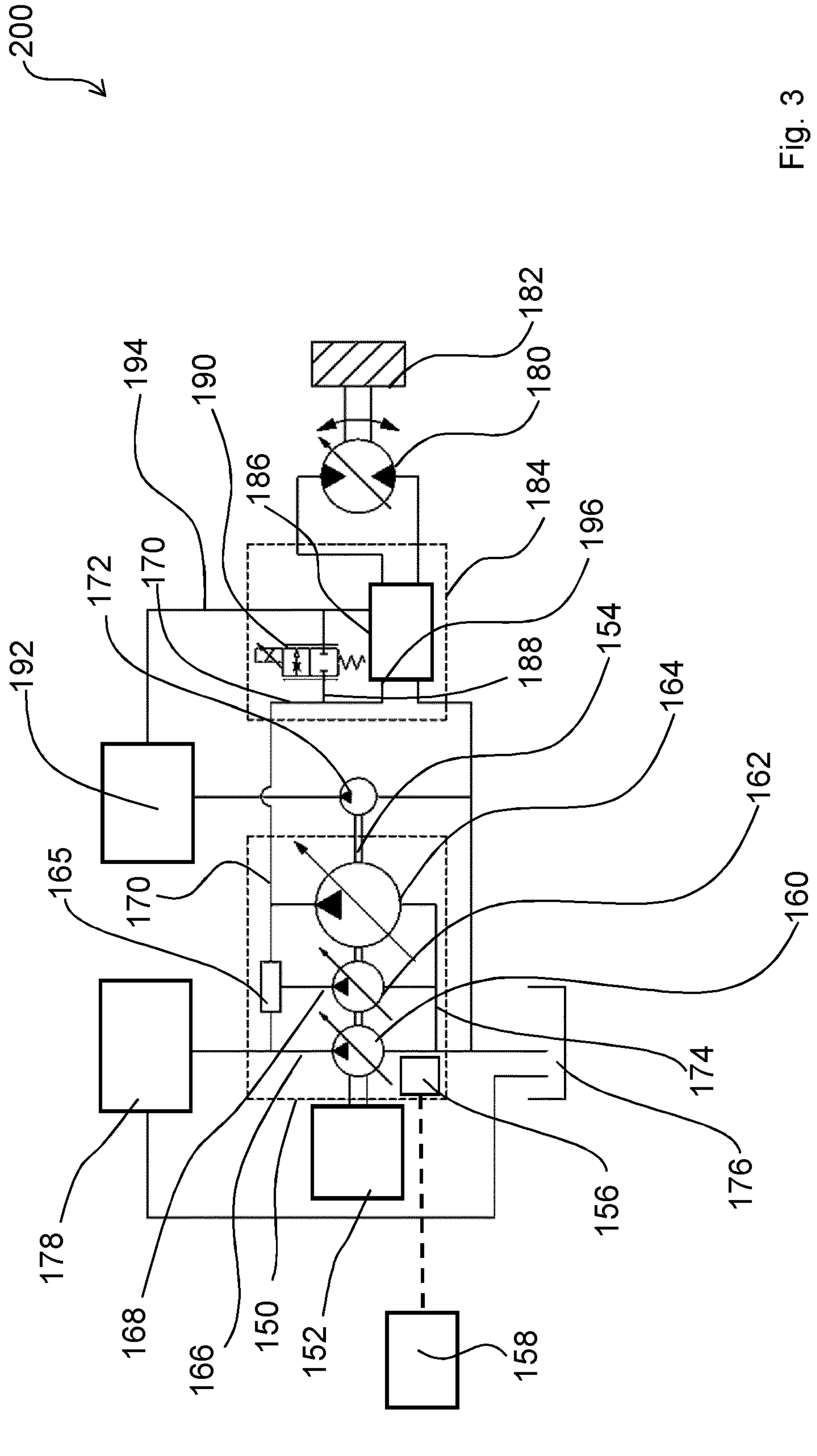
200
182
180
194
190
186
184
196
172
170
192
154
188
164
162
165
170
160
174
176
156
178
168
166
150
152
158

Fig. 3

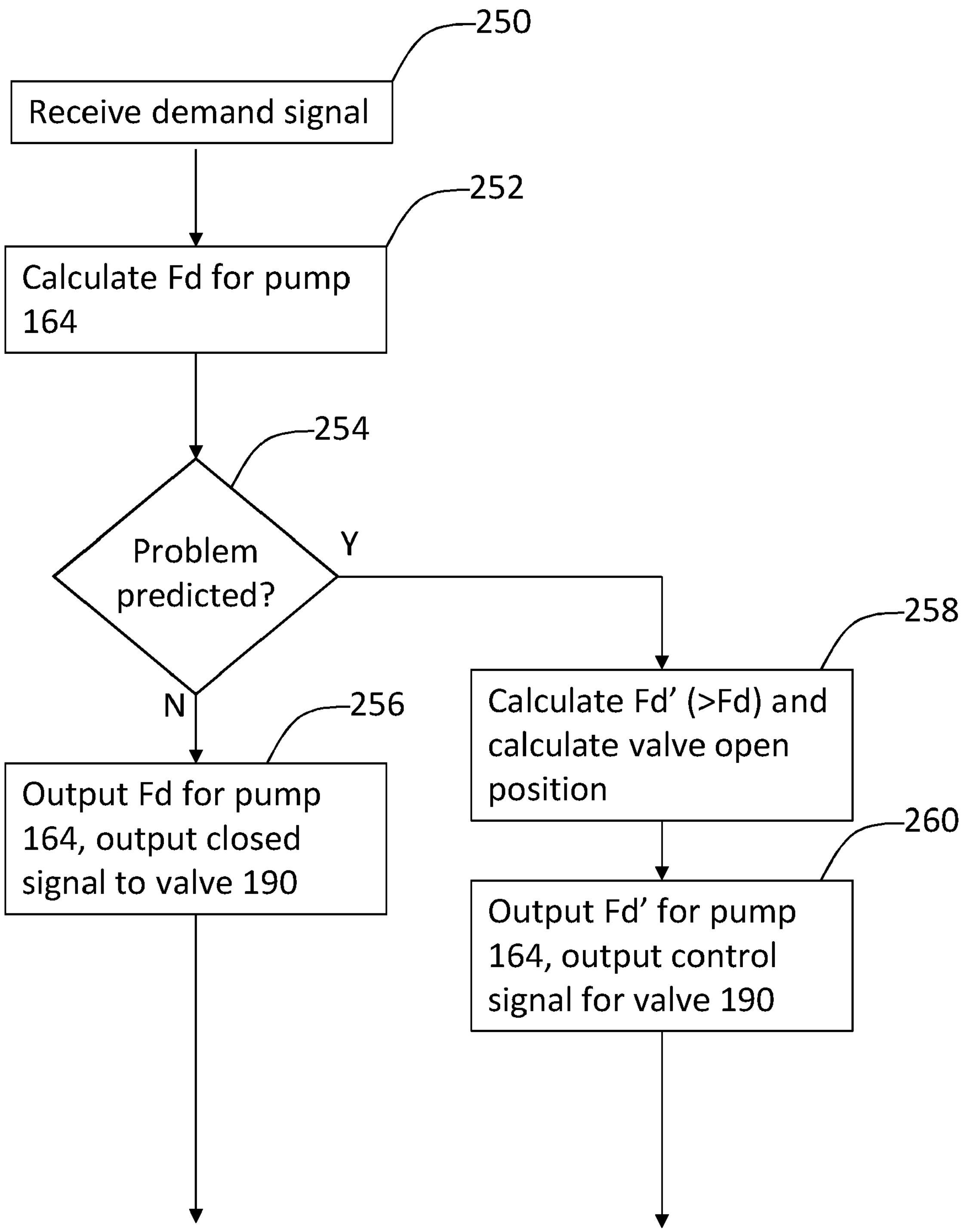
250
Receive demand signal
252
Calculate Fd for pump 164
254
Problem predicted?
Y
N
256
Output Fd for pump 164, output closed signal to valve 190
258
Calculate Fd' (>Fd) and calculate valve open position
260
Output Fd' for pump 164, output control signal for valve 190

Fig. 4

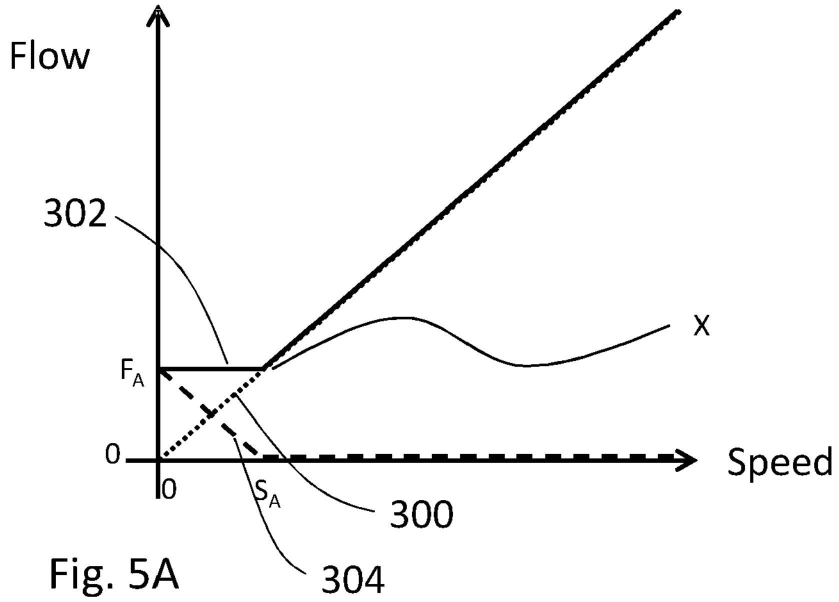
Flow
302
X
F_A
0
Speed
0
S_A
300
304

Fig. 5A

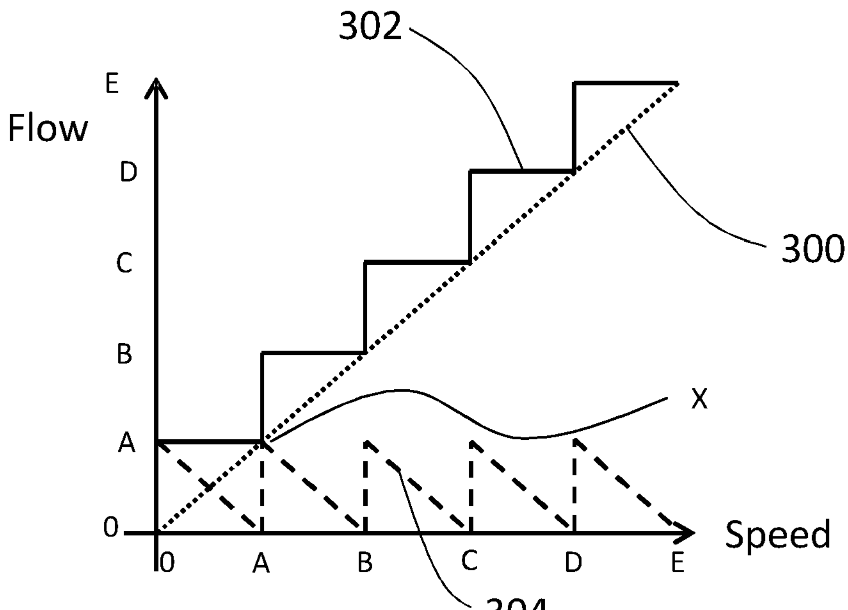
302
E
Flow
D
C
B
A
0
300
X
Speed
0
A
B
C
D
E
304

Fig. 5B

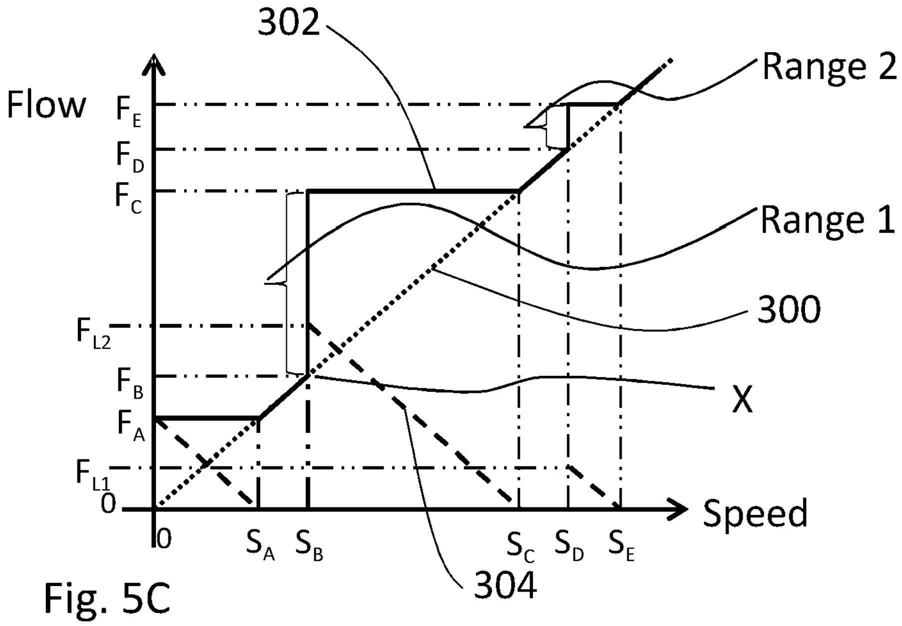
302
Range 2
Flow
F_E
F_D
F_C
Range 1
300
F_{L2}
F_B
X
F_A
F_{L1}
0
Speed
0
S_A
S_B
S_C
S_D
S_E
304

Fig. 5C

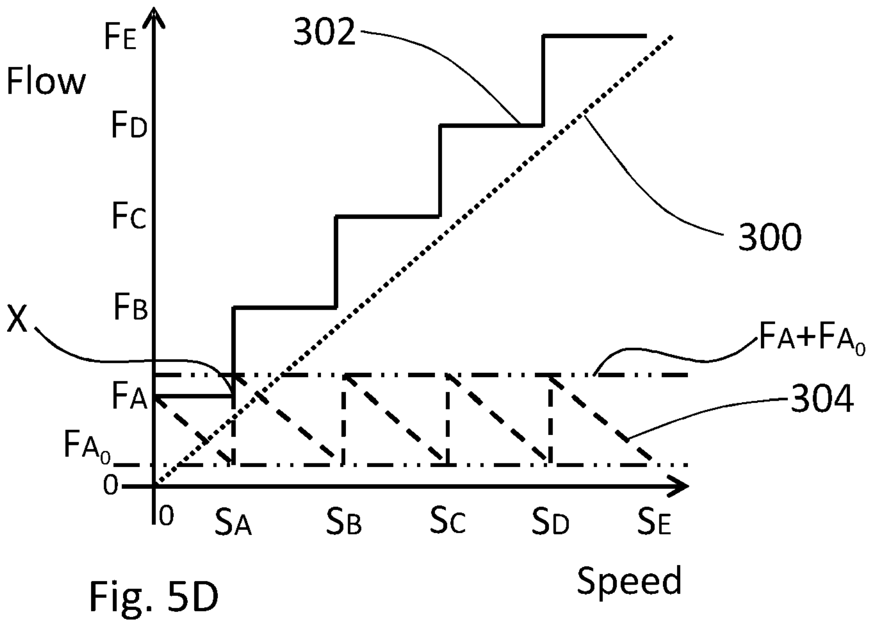
FE
302
Flow
FD
FC
300
FB
X
FA+FA0
FA
304
FA0
0
0
SA
SB
SC
SD
SE
Speed

Fig. 5D

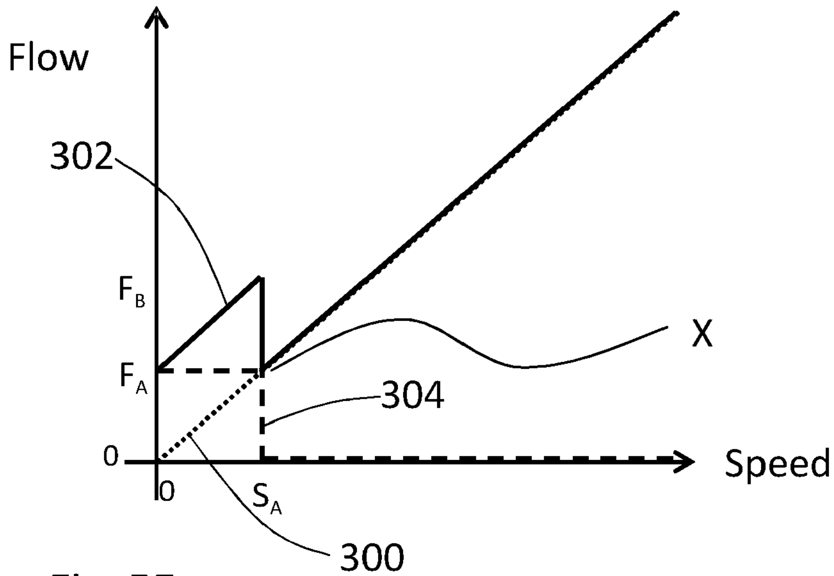
Flow
302
F_B
F_A
X
304
0
0
S_A
Speed
300

Fig. 5E

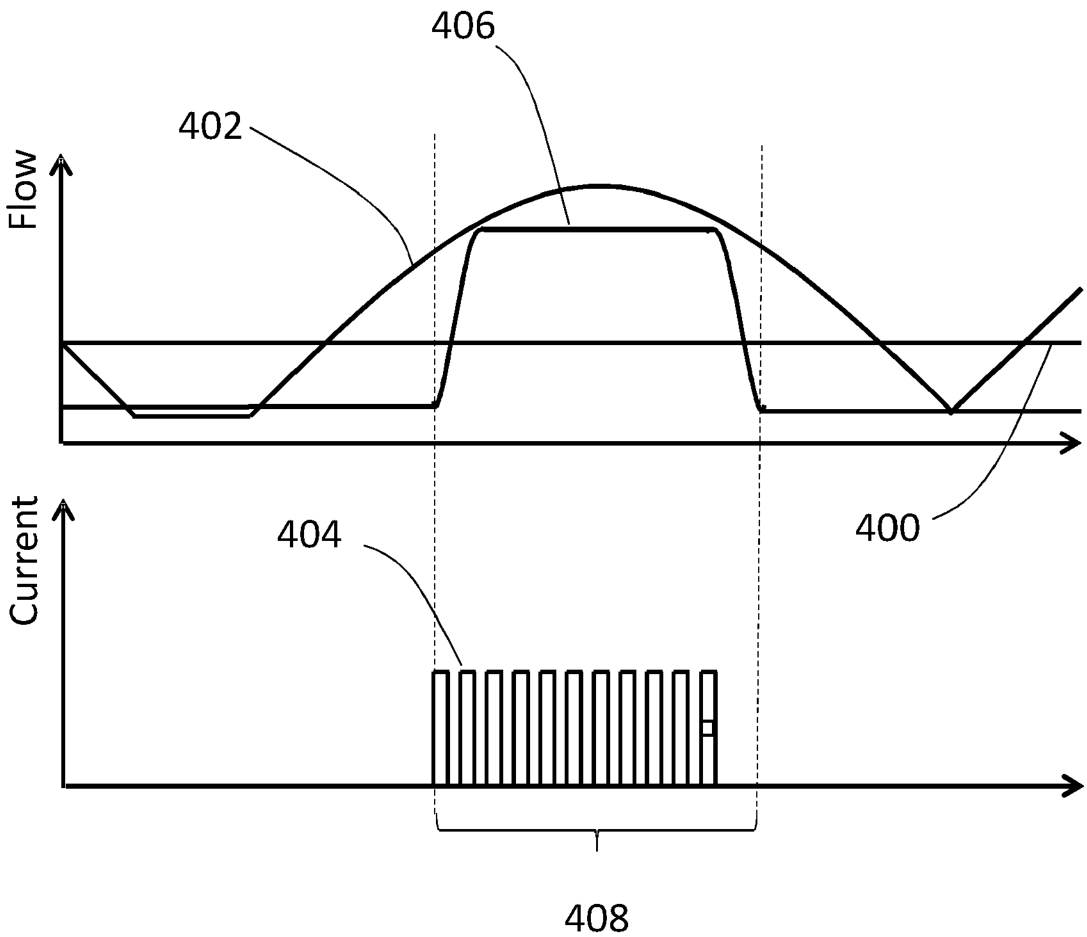
406
402
Flow
Current
404
400
408

Fig. 6

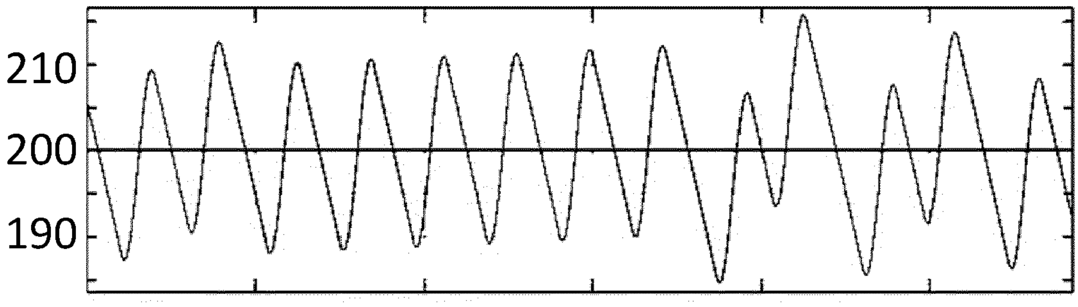

Fig. 7A

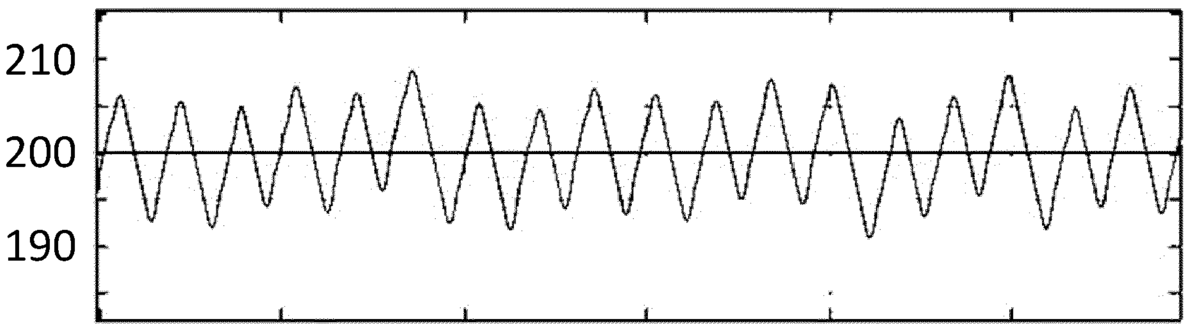

Fig. 7B

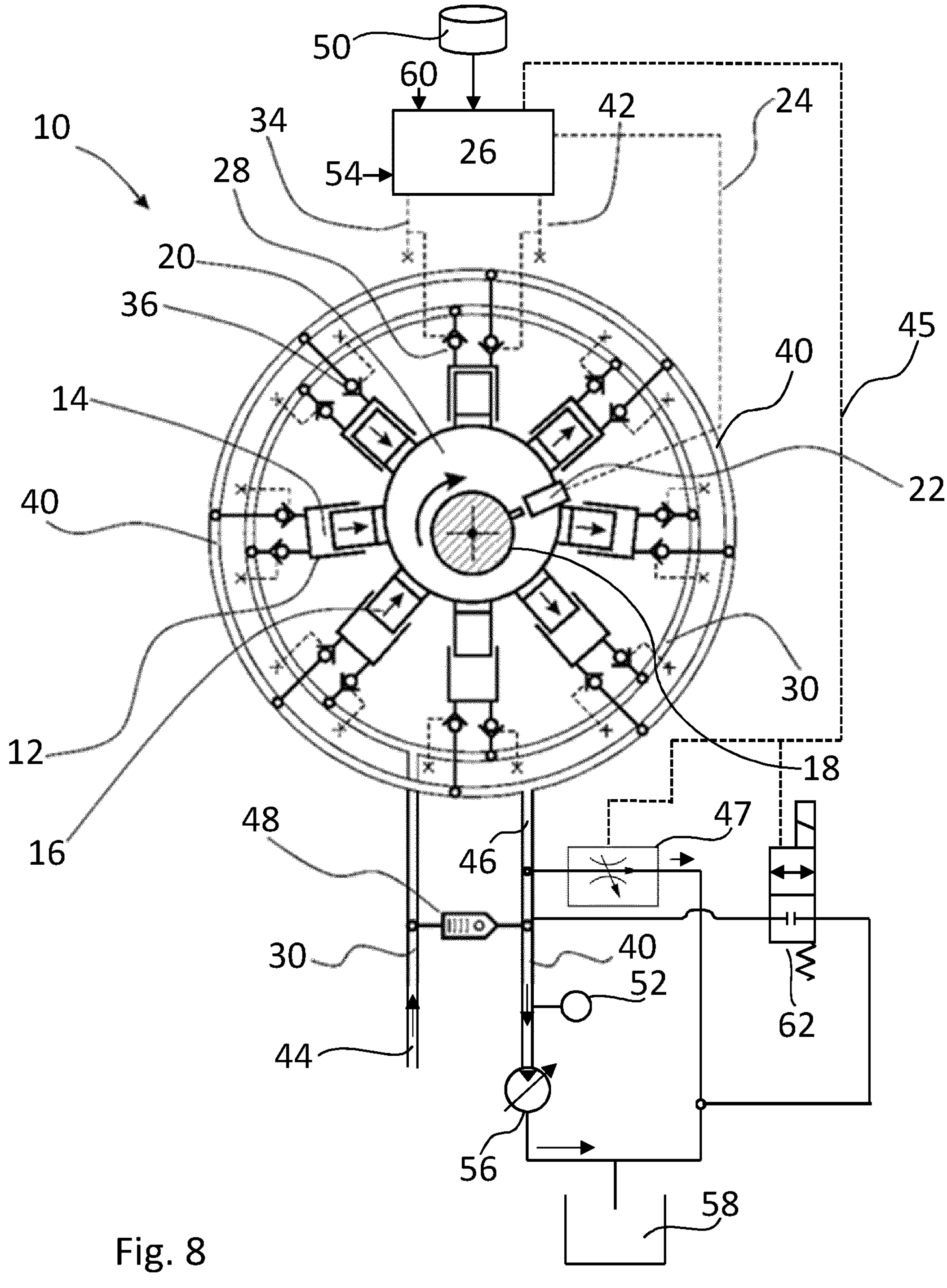
50
60
10
34
26
42
24
54
28
20
36
14
40
45
40
22
12
30
18
16
48
46
47
30
40
52
62
44
56
58

Fig. 8

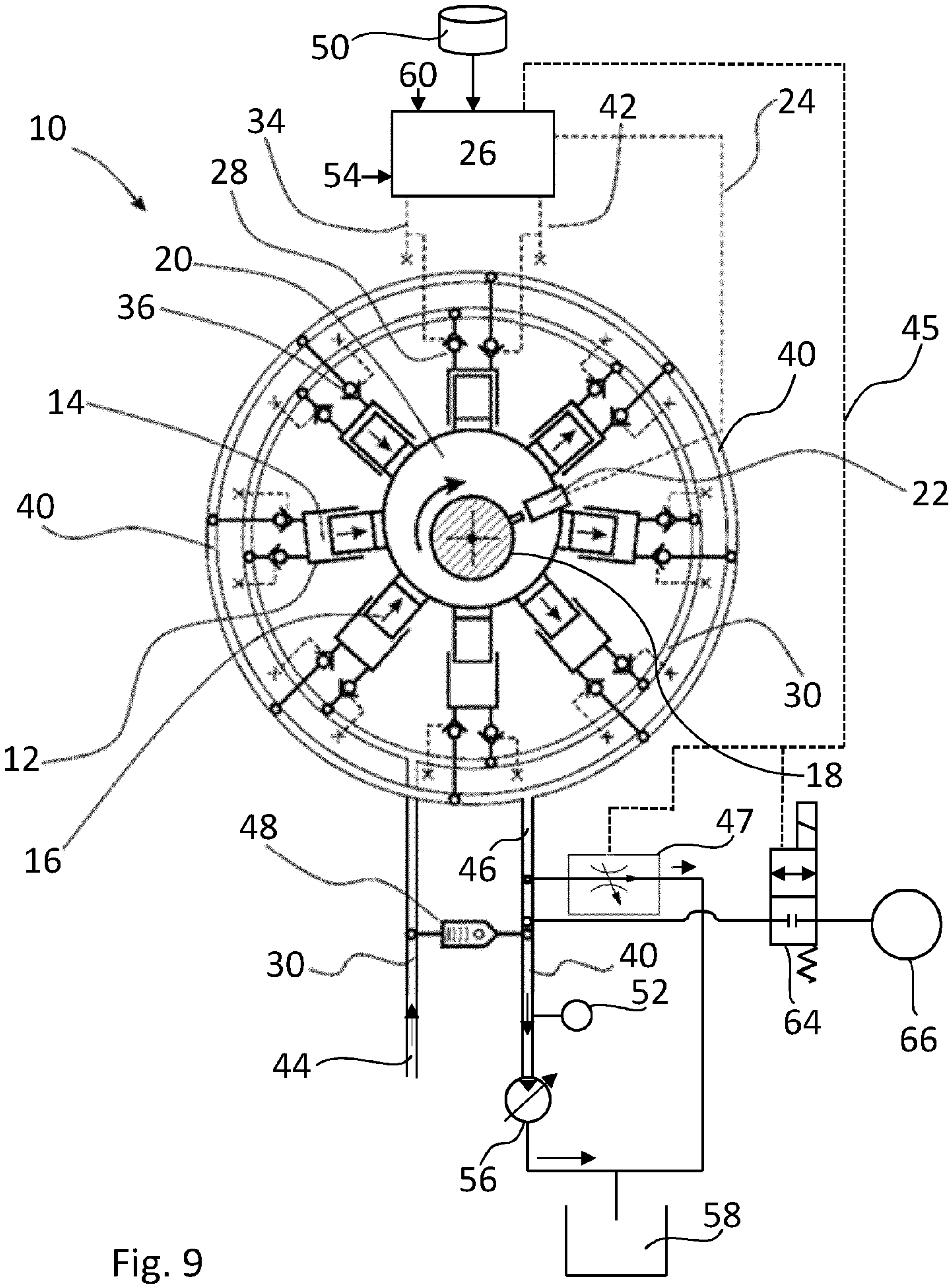
50
60
42
24
10
34
26
54
28
20
36
45
40
14
22
40
30
12
18
16
48
47
46
30
40
52
64
66
44
56
58

Fig. 9

Europäisches Patentamt
European Patent Office
Office européen des brevets

EUROPEAN SEARCH REPORT

Application Number
EP 20 17 8359

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
A	US 2012/141303 A1 (CALDWELL NIALL JAMES [GB] ET AL) 7 June 2012 (2012-06-07) * paragraphs [0047] - [0057]; figure 4 * -----	1-17	INV. F04B1/04 F04B1/053 F04B1/06 F04B7/00 F04B49/06
A	US 2019/010965 A1 (GREEN MATTHEW [GB] ET AL) 10 January 2019 (2019-01-10) * paragraph [0122]; figure 27 * -----	1-17	
A	DE 10 2010 046217 A1 (BOSCH GMBH ROBERT [DE]) 22 March 2012 (2012-03-22) * paragraph [0005] * -----	1-17	

TECHNICAL FIELDS SEARCHED (IPC)
F04B

The present search report has been drawn up for all claims

2

Place of search	Date of completion of the search	Examiner
Munich	10 September 2020	Ziegler, Hans-Jürgen

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons

& : member of the same patent family, corresponding document

EPO FORM 1503 03.82 (P04C01)

ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 20 17 8359

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report. The members are as contained in the European Patent Office EDP file on
The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

10-09-2020

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2012141303 A1	07-06-2012	DE 112010003287 T5	27-12-2012
		GB 2484847 A	25-04-2012
		JP 5688083 B2	25-03-2015
		JP 2013501889 A	17-01-2013
		JP 2015061985 A	02-04-2015
		KR 20120085744 A	01-08-2012
		US 2012141303 A1	07-06-2012
		WO 2011018660 A1	17-02-2011
US 2019010965 A1	10-01-2019	CN 108474362 A	31-08-2018
		EP 3402985 A1	21-11-2018
		GB 2546485 A	26-07-2017
		JP 2019503455 A	07-02-2019
		US 2019010965 A1	10-01-2019
		WO 2017122024 A1	20-07-2017
DE 102010046217 A1	22-03-2012	DE 102010046217 A1	22-03-2012
		GB 2498156 A	03-07-2013
		US 2014147293 A1	29-05-2014
		WO 2012038050 A1	29-03-2012

EPO FORM P0459

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82