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McCarthy

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(54) **LIFT APPARATUS FOR DRIVING A DOWNHOLE RECIPROCATING PUMP**

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E21B 47/00 (2012.01)
(Continued)

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CPC ***E21B 43/129*** (2013.01); ***E21B 47/0007*** (2013.01); ***F04B 1/324*** (2013.01);
(Continued)

(58) **Field of Classification Search**

CPC E21B 43/12; E21B 43/126–43/129; E21B 47/0007
See application file for complete search history.

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(57) **ABSTRACT**

A lift apparatus and method for driving a downhole reciprocating pump is disclosed. The apparatus includes a hydraulic cylinder having a piston and a hydraulic fluid port, the piston being coupled to a rod for driving the reciprocating pump, the piston being moveable between first and second ends of the cylinder in response to a flow of hydraulic fluid through the hydraulic fluid port. The apparatus also includes a variable displacement hydraulic pump coupled to receive a substantially constant rotational drive from a prime mover for operating the hydraulic pump, the hydraulic pump having an outlet and being responsive to a displacement control signal to draw hydraulic fluid from a reservoir and to produce a controlled flow of hydraulic fluid at the outlet. The apparatus also includes a hydraulic fluid line connected to deliver hydraulic fluid from the outlet of the hydraulic pump through the hydraulic fluid port to the cylinder for causing the piston to move through an upstroke away from the first end and toward the second end of the cylinder. The apparatus further includes a valve connected between the hydraulic fluid port and the reservoir, the valve

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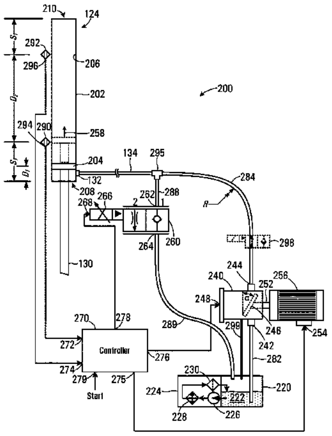

being responsive to a valve control signal for controlling discharge of hydraulic fluid from the hydraulic fluid port of the cylinder back to the reservoir to facilitate movement of the piston through a downstroke away from the second end toward the first end of the cylinder. The valve is operable to prevent flow of hydraulic fluid through the valve during the upstroke and the hydraulic pump is operable to prevent flow of hydraulic fluid back into the outlet of the hydraulic pump during the downstroke.

26 Claims, 7 Drawing Sheets

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F04B 47/00	(2006.01)
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F04B 49/22	(2006.01)
F04B 1/32	(2006.01)
F04B 49/06	(2006.01)

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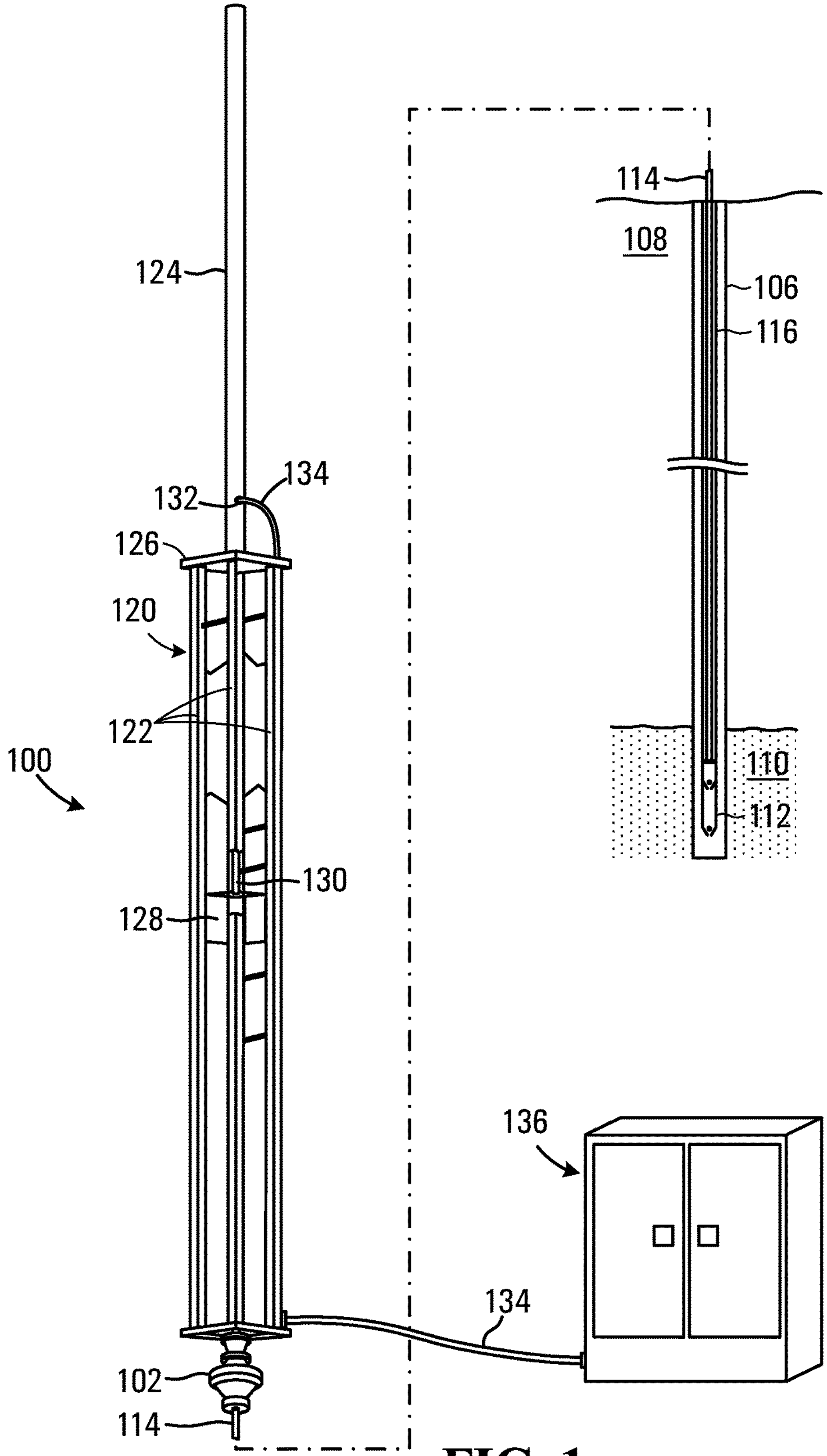
124
134
132
126
120
122
100
130
128
102
114
104
114
108
106
116
110
112
136
134

FIG. 1

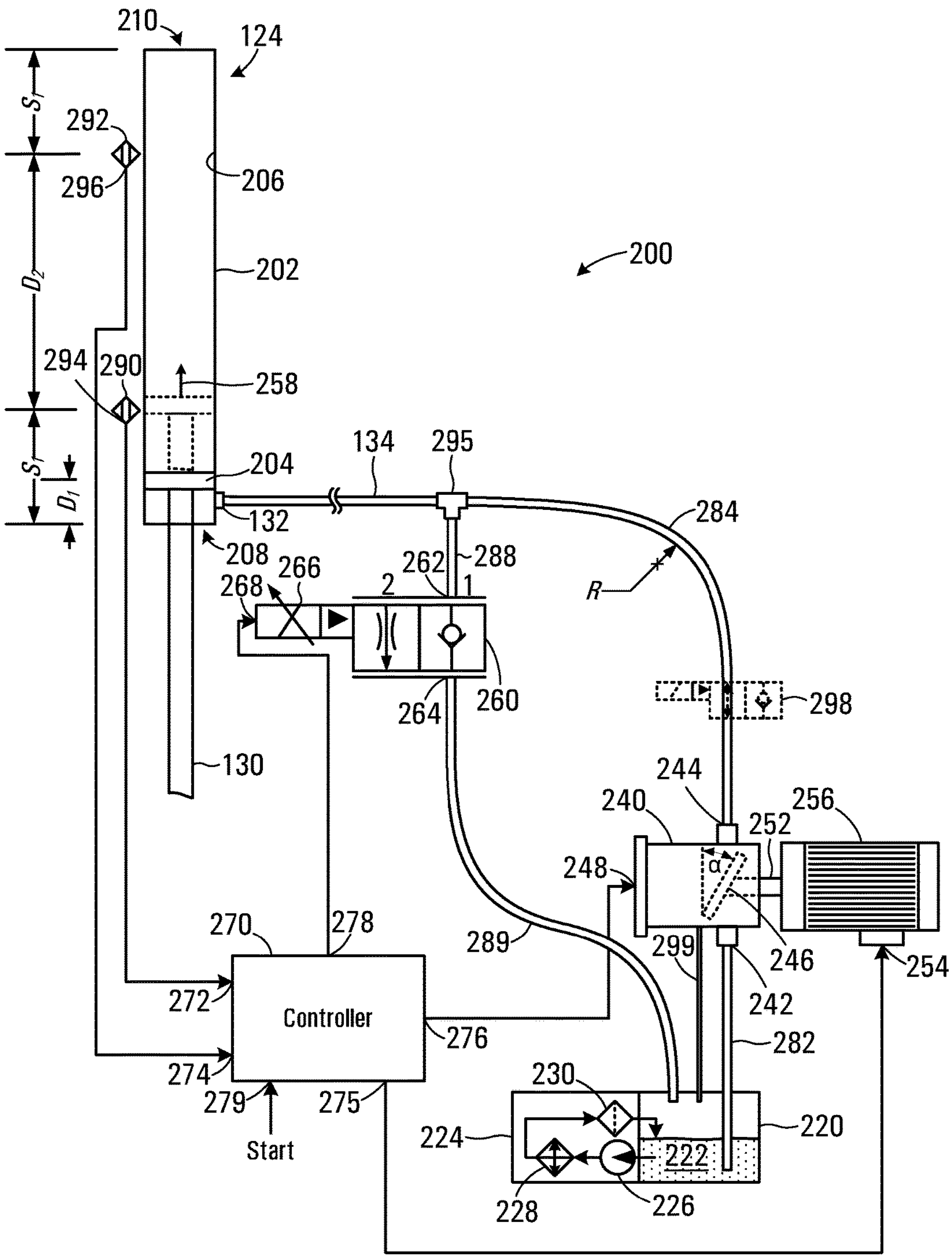
210
124
S1
292
296
206
200
202
D2
294
290
258
134
295
S1
204
D1
132
284
208
262
288
266
268
2
1
R
260
264
298
130
244
256
240
252
248
α
278
270
289
299
246
Controller
242
272
276
282
274
230
279
275
220
224
222
Start
228
226
254

FIG. 2

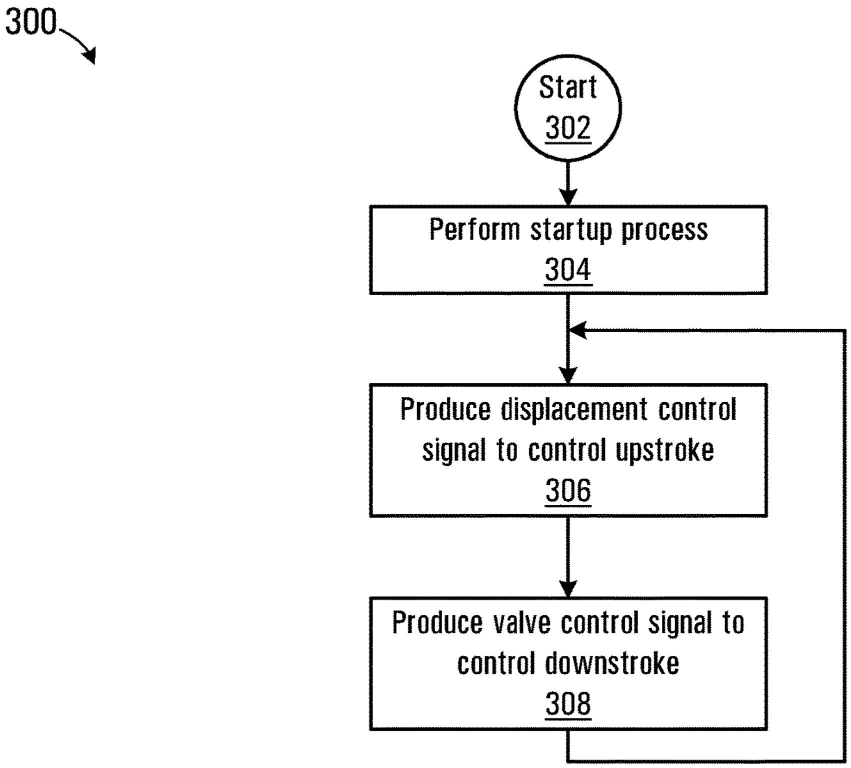
300
Start
302
Perform startup process
304
Produce displacement control signal to control upstroke
306
Produce valve control signal to control downstroke
308

FIG. 3

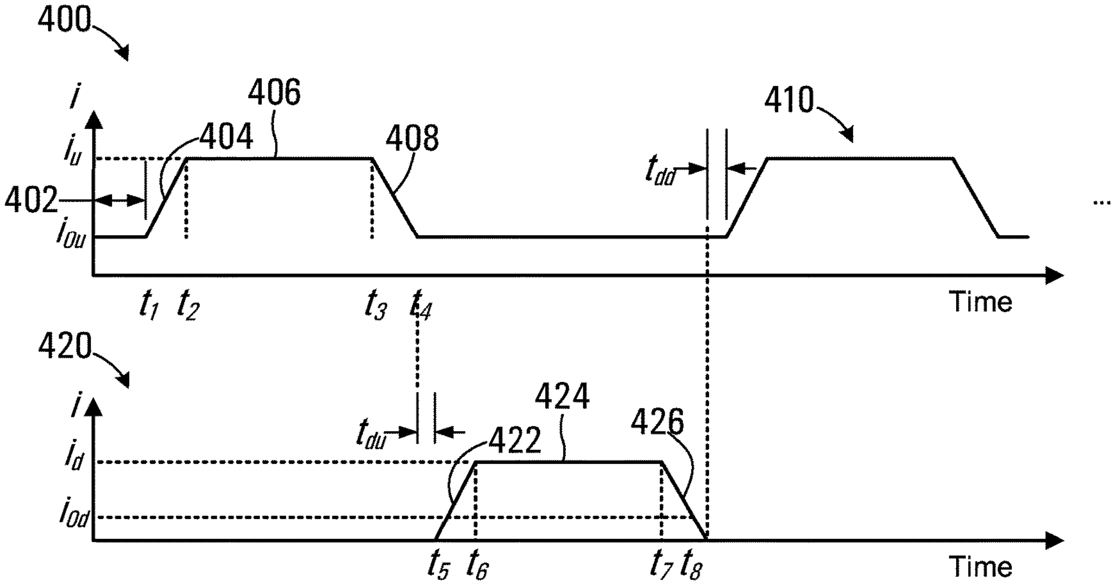
400
i
i_u
402
i_{0u}
404
406
408
410
t_{dd}
...
t_1
t_2
t_3
t_4
Time
420
i
i_d
i_{0d}
t_{du}
422
424
426
t_5
t_6
t_7
t_8
Time

FIG. 4

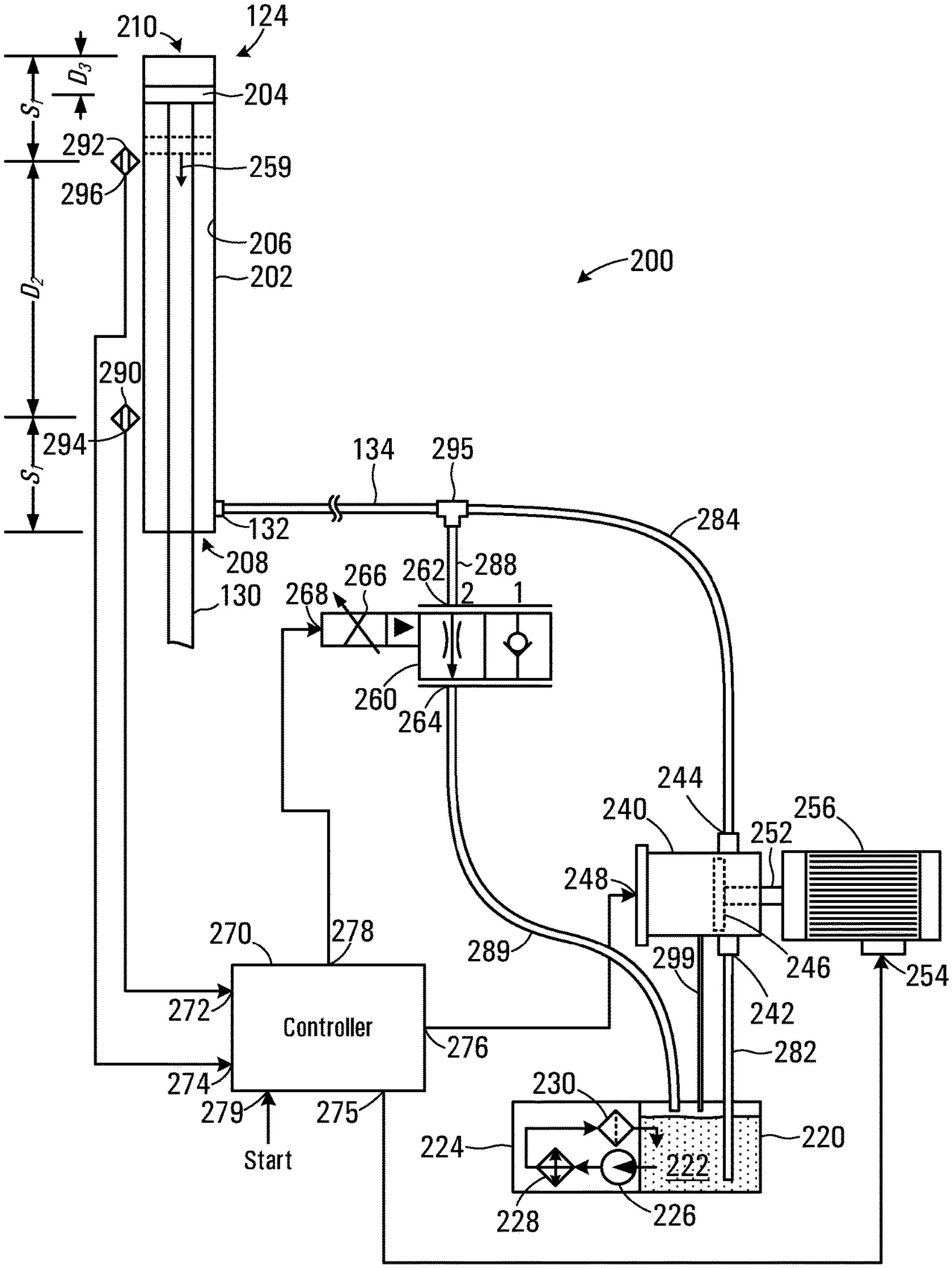
210
124
D_3
204
S_1
292
259
296
206
200
202
D_2
290
294
S_1
134
295
284
132
208
262
288
130
268
266
2
1
260
264
244
256
240
252
248
289
299
246
270
278
242
254
272
Controller
276
282
274
279
275
230
220
224
222
Start
228
226

FIG. 5

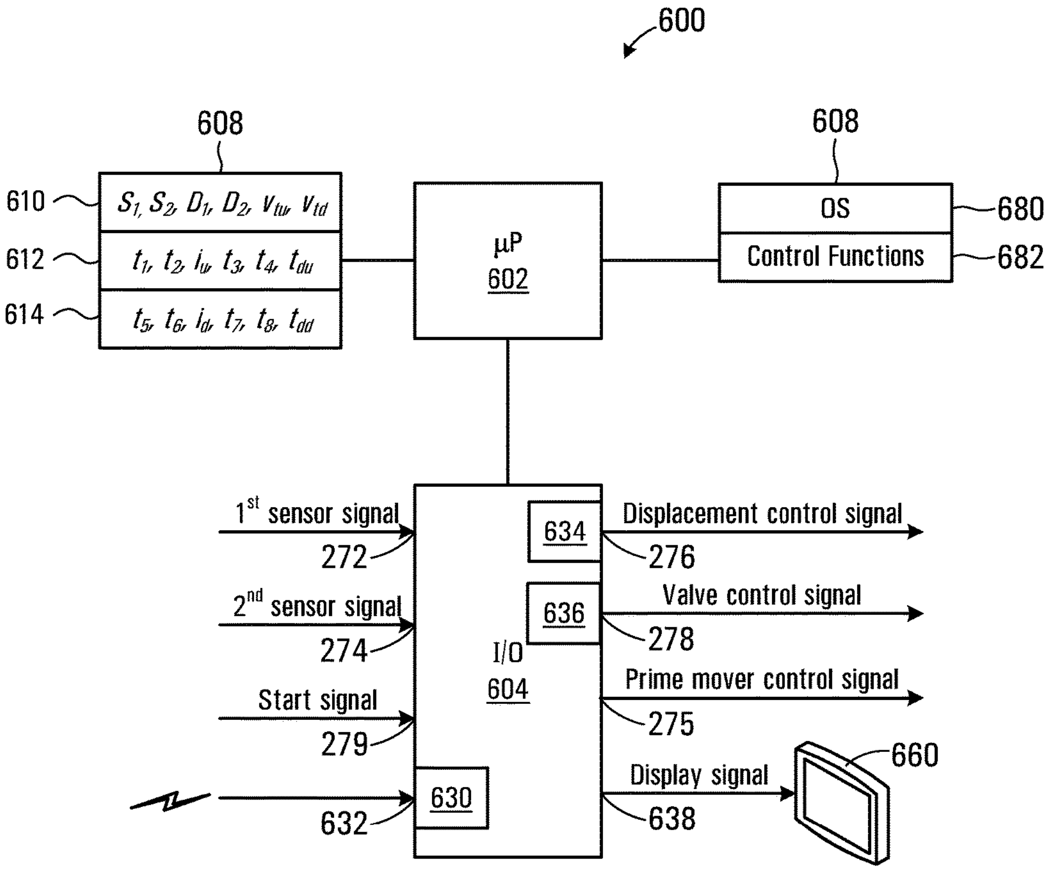
600
608
610
$S_1, S_2, D_1, D_2, v_{tu}, v_{td}$
612
$t_1, t_2, i_u, t_3, t_4, t_{du}$
614
$t_5, t_6, i_d, t_7, t_8, t_{dd}$
µP
602
608
OS
680
Control Functions
682
1st sensor signal
272
2nd sensor signal
274
Start signal
279
632
630
634
Displacement control signal
276
636
Valve control signal
278
I/O
604
Prime mover control signal
275
Display signal
638
660

FIG. 6

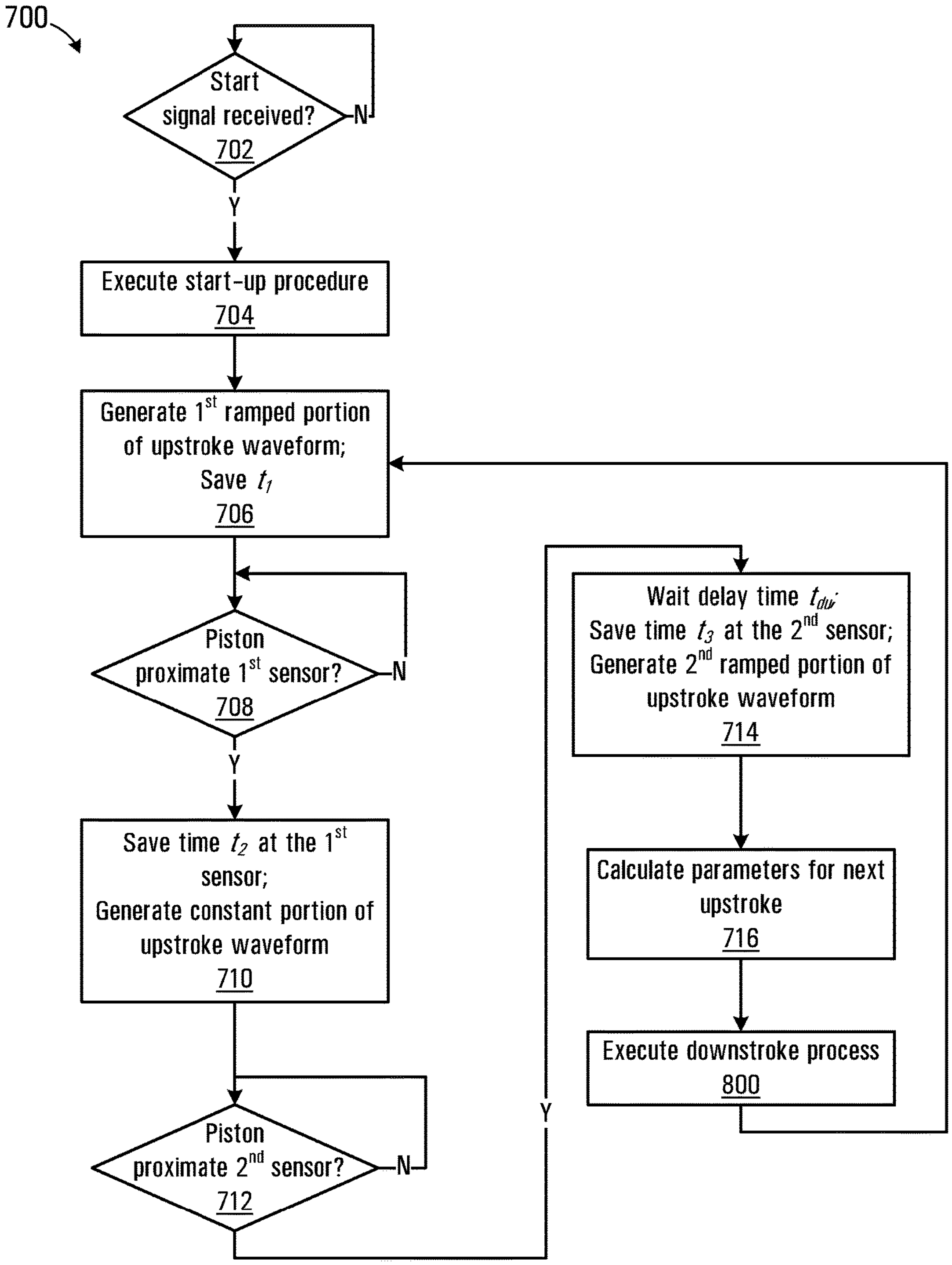
700
Start signal received? 702
N
Y
Execute start-up procedure 704
Generate 1st ramped portion of upstroke waveform; Save t1 706
Piston proximate 1st sensor? 708
N
Y
Save time t2 at the 1st sensor; Generate constant portion of upstroke waveform 710
Piston proximate 2nd sensor? 712
N
Y
Wait delay time tdu; Save time t3 at the 2nd sensor; Generate 2nd ramped portion of upstroke waveform 714
Calculate parameters for next upstroke 716
Execute downstroke process 800

FIG. 7

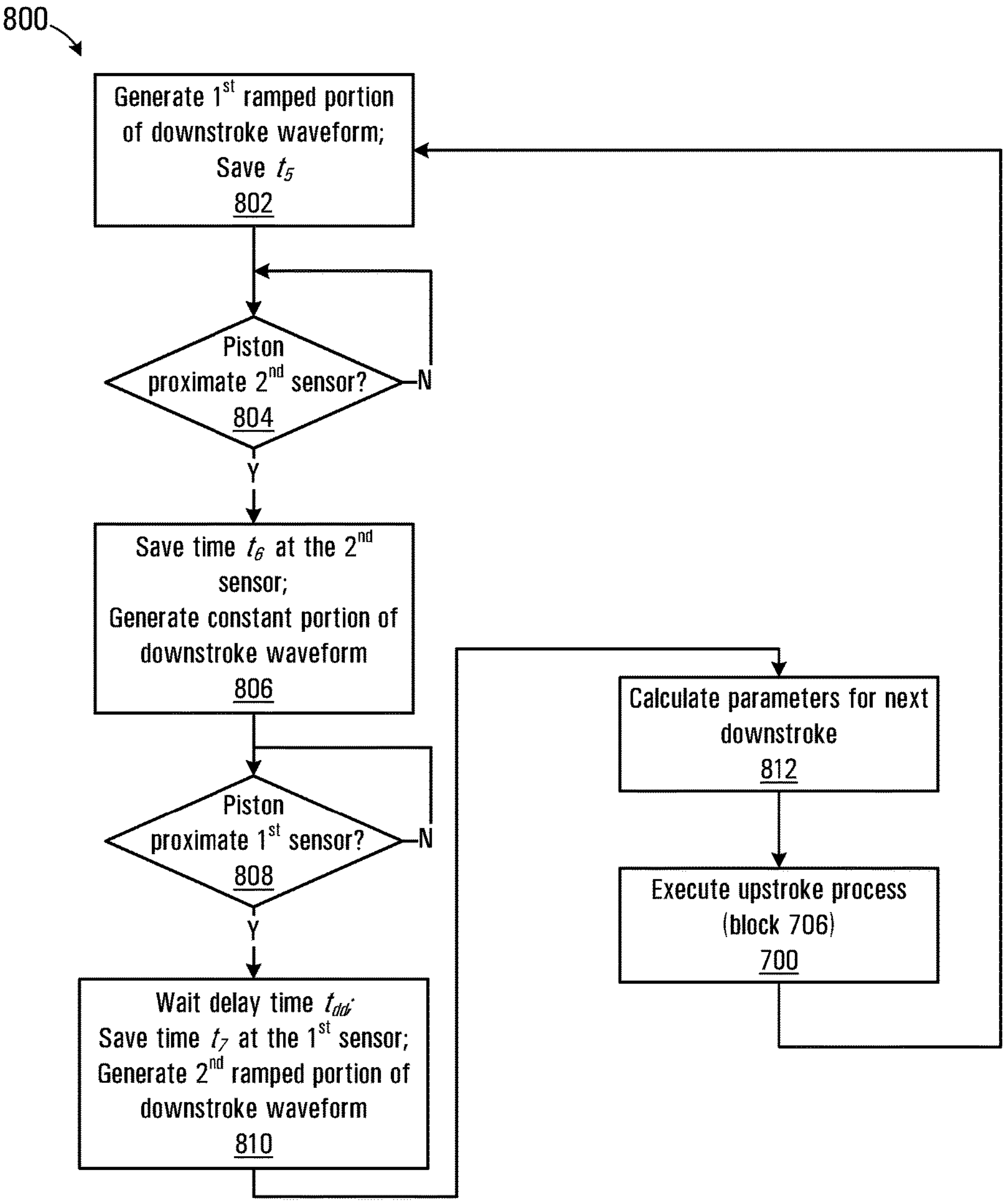
800
Generate 1st ramped portion of downstroke waveform; Save t_5
802
Piston proximate 2nd sensor?
804
N
Y
Save time t_6 at the 2nd sensor; Generate constant portion of downstroke waveform
806
Piston proximate 1st sensor?
808
N
Y
Wait delay time t_{dd}; Save time t_7 at the 1st sensor; Generate 2nd ramped portion of downstroke waveform
810
Calculate parameters for next downstroke
812
Execute upstroke process (block 706)
700

FIG. 8

LIFT APPARATUS FOR DRIVING A DOWNHOLE RECIPROCATING PUMP

BACKGROUND

1. Field

This disclosure relates generally to driving a downhole reciprocating pump and more particularly to a lift apparatus for driving a downhole reciprocating pump.

2. Description of Related Art

Downhole reciprocating pumps may be used to pump fluids from a borehole or well to the surface. In hydrocarbon recovery operations, conventional rocking arm pumpjacks have been used to drive downhole pumps. In some implementations hydraulic lift systems have replaced rocking arm pumpjacks. Hydraulic lift systems may include a cylinder having a movable piston responsive to a flow of a driving fluid, wherein movement of the piston drives the downhole reciprocating pump. There remains a need for alternative lift systems for driving downhole pumps.

SUMMARY

In accordance with one disclosed aspect there is provided a lift apparatus for driving a downhole reciprocating pump. The apparatus includes a hydraulic cylinder having a piston and a hydraulic fluid port, the piston being coupled to a rod for driving the reciprocating pump, the piston being moveable between first and second ends of the cylinder in response to a flow of hydraulic fluid through the hydraulic fluid port. The apparatus also includes a variable displacement hydraulic pump coupled to receive a substantially constant rotational drive from a prime mover for operating the hydraulic pump, the hydraulic pump having an outlet and being responsive to a displacement control signal to draw hydraulic fluid from a reservoir and to produce a controlled flow of hydraulic fluid at the outlet. The apparatus also includes a hydraulic fluid line connected to deliver hydraulic fluid from the outlet of the hydraulic pump through the hydraulic fluid port to the cylinder for causing the piston to move through an upstroke away from the first end and toward the second end of the cylinder. The apparatus further includes a valve connected between the hydraulic fluid port and the reservoir, the valve being responsive to a valve control signal for controlling discharge of hydraulic fluid from the hydraulic fluid port of the cylinder back to the reservoir to facilitate movement of the piston through a downstroke away from the second end toward the first end of the cylinder. The valve is operable to prevent flow of hydraulic fluid through the valve during the upstroke and the hydraulic pump is operable to prevent flow of hydraulic fluid back into the outlet of the hydraulic pump during the downstroke.

The hydraulic fluid port may include a first port for connecting to the hydraulic fluid line and a second port for connecting to the valve.

The hydraulic fluid line may include a common portion in communication with the hydraulic fluid port, the common portion carrying fluid flow from the hydraulic pump during the upstroke and to the valve during the downstroke.

The hydraulic fluid line may be routed between the outlet of the hydraulic pump and the hydraulic fluid port through at least one bend, the at least one bend having a bend radius of at least about 25 mm to reduce flow losses within the hydraulic fluid line.

The hydraulic pump may be configured to produce a unidirectional flow of fluid at the outlet having a flow rate ranging from a substantially no flow condition to a maximum flow rate in proportion to the displacement control signal.

The hydraulic pump may include a swashplate movable through a range of angles between 0° corresponding to the substantially no flow condition to a maximum angle corresponding to the maximum flow rate and the hydraulic pump may be configured to prevent the swashplate being angled at less than 0° for preventing flow back into the outlet and through the hydraulic pump.

The hydraulic fluid line may include a check valve disposed between the outlet of the pump and the hydraulic fluid port, the check valve being operable to permit flow from the outlet to the hydraulic fluid port during the upstroke while preventing flow of hydraulic fluid back into the outlet of the hydraulic pump during the downstroke.

The apparatus may include a first sensor located proximate the first end of the cylinder and operable to produce a first signal indicating a proximity of the piston to the first sensor, a second sensor located proximate the second end of the cylinder and operable to produce a second signal indicating a proximity of the piston to the second sensor, and a controller operably configured to generate the displacement control signal and the valve control signal in response to receiving the first signal and the second signal.

The first and second sensors are positioned proximate to but spaced inwardly from the respective first and second ends of the cylinder to cause the first and second signals to be generated in when the piston may be in proximity to the respective first and second ends of the cylinder.

The controller may be operably configured to generate a displacement control signal having a time varying waveform for controlling the upstroke, the waveform including a first ramped portion that causes the hydraulic pump to deliver an increasing flow of hydraulic fluid for accelerating the piston away from the first end of the cylinder, a constant portion that causes the hydraulic pump to deliver a substantially constant flow for moving the piston at a substantially constant velocity, and a second ramped portion that causes the hydraulic pump to deliver a reducing flow for decelerating the piston as the piston approaches the second end of the cylinder.

The controller may be operably configured to generate the constant portion of the waveform to target a desired velocity of the piston for the upstroke based on a calculated velocity of the piston during a previous upstroke of the piston, the velocity being calculated based on the first and second signals.

The controller may be operably configured to receive operator input of one of the desired velocity and an upstroke time.

The controller may be operably configured to, in response to receiving the second signal, commence the second ramped portion following a delay period.

The controller may be operably configured to calculate the delay period based on a calculated velocity of the piston between the first and second sensors during a current upstroke of the piston.

The controller may be operably configured to generate the first and second ramped portions of the waveform for the upstroke based on the first and second signals received during a previous upstroke of the piston.

The controller may be operably configured to generate a valve control signal having a time varying waveform for controlling the downstroke, the waveform including a first ramped portion that causes the valve to permit an increasing flow of hydraulic fluid permitting the piston to accelerate away from the second end of the cylinder, a constant portion that causes the valve to permit a substantially constant flow for moving the piston at a substantially constant velocity, and a second ramped portion that causes the valve to permit a reducing flow for decelerating the piston as the piston approaches the first end of the cylinder.

The controller may be operably configured to generate the constant portion of the waveform for targeting a desired velocity of the piston for the downstroke based on a calculated velocity of the piston during a previous downstroke of the piston, the velocity being calculated based on the first and second signals.

The controller may be operably configured to receive operator input of one of a desired velocity and a downstroke time.

The controller may be operably configured to, in response to receiving the first signal, commence the second ramped portion following a delay period.

The controller may be operably configured to calculate the delay period based on a calculated velocity of the piston between the second and first sensors during the downstroke of the piston.

The controller may be operably configured to generate the first and second ramped portions of the waveform for the downstroke based on the first and second signals received during a previous downstroke of the piston.

The valve may include an electrically controllable proportional throttle valve.

The hydraulic pump may include a swashplate pump an angle of the swashplate may be configurable over a range of angles in response to the displacement control signal and the range of angles is constrained to produce a unidirectional flow at the outlet.

In accordance with another disclosed aspect there is provided a method for operating a pumpjack lift including a hydraulic cylinder having a piston and a hydraulic fluid port, the piston being coupled to a rod for driving a down-hole reciprocating pump. The method involves producing a displacement control signal operable to cause a variable displacement hydraulic pump to draw hydraulic fluid from a reservoir and to produce a controlled flow of hydraulic fluid at an outlet of the hydraulic pump, the hydraulic pump being coupled to receive a substantially constant rotational drive from a prime mover. The method also involves delivering hydraulic fluid from the outlet through a hydraulic fluid line connected to the hydraulic fluid port of the cylinder to cause the piston to move through an upstroke away from a first end and toward a second end of the cylinder. The method further involves producing a valve control signal for controlling discharge of hydraulic fluid from the hydraulic fluid port of the cylinder through a valve connected between the hydraulic fluid port and the reservoir back to the reservoir to facilitate movement of the piston through a downstroke away from the second end and toward the first end of the cylinder. The method further involves preventing flow of hydraulic fluid through the valve during the upstroke and preventing flow of hydraulic fluid back into the outlet of the hydraulic pump during the downstroke.

Other aspects and features will become apparent to those ordinarily skilled in the art upon review of the following description of specific disclosed embodiments in conjunction with the accompanying figures.

BRIEF DESCRIPTION OF THE DRAWINGS

In drawings which illustrate disclosed embodiments,

FIG. **1** is a perspective view of a lift apparatus in accordance with one disclosed embodiment;

FIG. **2** is a schematic view of a fluid circuit of the lift apparatus of FIG. **1** while executing an upstroke process;

FIG. **3** is a flowchart of a process for operating the lift apparatus shown in FIG. **2**;

FIG. **4** is a graphical depiction of waveforms for controlling operation of components of the lift apparatus shown in FIG. **2**;

FIG. **5** is a schematic view of a fluid circuit of the lift apparatus of FIG. **1** while executing a downstroke process;

FIG. **6** is a schematic view of a processor circuit for implementing a controller of the lift apparatus shown in FIG. **2** and FIG. **5**;

FIG. **7** is a process flowchart showing blocks of code for directing the controller processor circuit shown in FIG. **6** to execute an upstroke process; and

FIG. **8** is a process flowchart showing blocks of code for directing the controller processor circuit shown in FIG. **6** to execute a downstroke process.

DETAILED DESCRIPTION

Referring to FIG. **1**, a lift apparatus according to one disclosed embodiment is shown generally at **100**. The lift apparatus **100** may be mounted at a wellhead **102** of a well shown in cross section at **104** as an insert. The well **104** has a well casing **106** extending downwardly through a land formation **108** to access a subterranean reservoir **110** from which it is desired to recover fluids such as hydrocarbons, natural gas, and/or water. In one embodiment the well casing may extend a few hundred meters into the land formation **108**. A down-hole reciprocating pump **112** is coupled to a sucker rod **114**, which is actuated by the lift apparatus **100** to produce the fluid upwardly through a tube **116** back to the wellhead **102**.

The lift apparatus **100** includes a frame **120** having a plurality of upright supports **122**. A hydraulic cylinder **124** is mounted on a platform **126** supported by the plurality of upright supports **122**. The lift apparatus **100** also includes a carriage **128** mounted for movement within the frame **120**. The hydraulic cylinder **124** includes a cylinder rod **130**, which is coupled to the carriage **128** (as shown in cut away view in FIG. **1**). The carriage **128** provides for coupling between the cylinder rod **130** and the sucker rod **114** and constrains lateral movement of the cylinder rod **130**, thus reducing wear of the hydraulic cylinder **124** during operation.

The hydraulic cylinder **124** includes a hydraulic fluid port **132** for coupling to a hydraulic fluid line **134**. The hydraulic fluid line **134** is routed through the frame **120** to an enclosure **136** that houses hydraulics and a controller (not shown in FIG. **1**), which together with the hydraulic cylinder **124** make up a hydraulic fluid circuit for driving the lift apparatus **100**.

The hydraulic fluid circuit is shown schematically in FIG. **2** at **200**. Referring to FIG. **2**, the hydraulic cylinder **124** includes a cylinder housing **202** and a piston **204**, disposed within a bore **206** of the cylinder housing. The hydraulic fluid port **132** is coupled to the hydraulic fluid line **134** and the piston **204** is movable between a first end **208** and a second end **210** of the cylinder housing **202** in response to receiving a flow of fluid at the hydraulic fluid port **132**. In the embodiment shown, the hydraulic cylinder **124** includes a single hydraulic fluid port **132**, but in other embodiments the cylinder may have more than one port.

The piston **204** is coupled to the cylinder rod **130** such that movement of the piston causes corresponding movement of the rod. In the embodiment shown in FIG. **1** the cylinder rod **130** is connected to the sucker rod **114** via the carriage **128**, but various other configurations may be implemented depending on the particular application.

In the embodiment shown, the reservoir **220** holds a hydraulic fluid **222**, which may be any suitable fluid that is substantially incompressible and suitable for driving the hydraulic cylinder **124**. The hydraulic fluid **222** may include anti-wear additives or constituents and provide for transfer heat from within fluid circuit **200** and the reservoir **220**. In some embodiments, the hydraulic fluid **222** may be SKYDROL™ airplane fluid, automatic transmission fluid, mineral oil, biodegradable hydraulic oil, and other synthetic and semi-synthetic fluids. The reservoir **220** further includes a sub-circuit **224** configured to cool and filter the hydraulic fluid **222**. In the embodiment shown, the sub-circuit **224** includes a pump **226**, a heater/cooler **228** and a filter **230**, which are connected to recirculate the hydraulic fluid **222** in the reservoir **220** while providing filtering and heating or cooling of the fluid. The heater/cooler **228** is operable to maintain the hydraulic fluid **222** within a desired temperature range, thus maintaining a desired viscosity. For example, in some embodiments, the heater/cooler **228** may be operable to cool the hydraulic fluid when the temperature goes above about 50° C. and to stop cooling when the temperature reduces below about 45° C. The heater/cooler **228** may further be operable to heat the hydraulic fluid when the temperature reduces below about −10° C. The hydraulic fluid may be selected to maintain a viscosity of between about 20 and about 40 mm^2s^{-1} over this temperature range. The filter **230** is operable to remove contaminants from the hydraulic fluid **222** and cooled and filtered hydraulic fluid **222** is returned to the reservoir **220**.

The hydraulic pump **240** includes an inlet **242** for drawing hydraulic fluid **222** from the reservoir **220** via a hydraulic fluid line **282** and an outlet **244** for delivering a pressurized flow of hydraulic fluid to a hydraulic fluid line **284**. The pump **240** is implemented using a variable-displacement hydraulic pump capable of producing a controlled flow hydraulic fluid at the outlet **244**. In one embodiment, the pump **240** may be an axial piston pump having a swashplate **246** that is configurable at a varying angle α. For example the pump **240** may be a HPV-02 variable pump manufactured by Linde Hydraulics GmBH & Co. KG of Germany, which is operable to deliver displacements of hydraulic fluid of up to about 281 cubic centimeters per revolution at pressures of up to about 500 bar. In other embodiments, the pump **240** may be any other variable displacement pump, such a variable piston pump or a rotary vane pump, for example. For the HPV-02 variable pump, the angle α of the swashplate **246** may be adjusted from between about 0°, corresponding to a substantially no flow condition, and a maximum angle of about 21°, which corresponds to a maximum flow rate condition at the outlet **244**. In the embodiment shown the swashplate **246** is constrained to positive angular displacements by preventing the swashplate from moving past $\alpha=0°$. As such fluid flow back through the pump **240** from the outlet **244** to the inlet **242** is restricted and when the angle α of the swashplate **246** is at 0°, the pump **240** produces no flow of hydraulic fluid at the outlet **244** and also substantially prevents backflow of hydraulic fluid though the pump **240** back to the reservoir **220**. The hydraulic pump **240** may thus be configured to produce a unidirectional flow of fluid at the outlet **244**. In some embodiments, the hydraulic pump **240** will permit a small amount of leakage when the swashplate **246** is at 0°.

In this embodiment the pump **240** includes an electrical input **248** for receiving a displacement control signal. The displacement control signal at the input **248** is operable to drive a coil of a solenoid (not shown) for controlling the displacement of the pump **240** and thus a hydraulic fluid flow rate produced at the outlet **244**. The electrical input **248** is connected to a 24 VDC coil within the hydraulic pump **240**, which is actuated in response to a controlled pulse width modulated (PWM) excitation current of between about 232 mA (i_{0u}) for a no flow condition and about 600 mA (i_u) for a maximum flow condition.

For the Linde HPV-02 variable pump, the swashplate **246** is actuated to move to an angle α only when the pressure at the port **244** has reached a threshold pressure, whereafter the angle α of the swashplate **246** is restricted by a level of the displacement control signal at the input **248**, thus controlling the flow rate produced at the outlet **244**. A version of the Linde HPV-02 pump has been supplied by the manufacturer including an internal spring to provide sufficient force (equivalent to a pressure of about 200 psi) for activating the swashplate when the pressure at the outlet **244** is less than the threshold pressure. This situation usually only arises when the lift apparatus **100** is first started up and the piston is not subjected to any pressure due to the load of the sucker rod **114** being supported by the frame **120**. During operation of the lift apparatus **100** the load pressure of the sucker rod **114** will generally be sufficient (typically greater than 200 psi) to provide the necessary threshold pressure at the outlet **244** for actuating the swashplate. In one embodiment, when the pressure at the port **244** is at least about 150 psi, the angle α of the swashplate **246** may be proportionally controlled between 0° and 21° in response to an electrical displacement control signal at the electrical input **248**. The corresponding flow rate at the outlet **244** thus ranges from no flow for a displacement control signal of at or below 232 mA and maximum flow for a displacement control signal of 600 mA. The Linde HPV-02 pump also has a load sense input for sensing a load pressure. However in this embodiment the load sense input is not used to limit the displacement of the pump and the load sense input is thus disabled.

In a swashplate pump, rotation of the swashplate drives a set of axially oriented pistons (not shown) to generate fluid flow. In the embodiment shown in FIG. **2**, the swashplate **246** of the pump **240** is driven by a rotating shaft **252**, which is coupled to the prime mover **256** for receiving a drive torque. In this embodiment the prime mover **256** is an electric motor but in other embodiments, the prime mover **256** may be implemented using a diesel engine, gasoline engine, or a gas driven turbine, for example. The prime mover **256** is responsive to a control signal received at a control input **254** to deliver a controlled substantially constant rotational speed and torque at the shaft **252**. The prime mover **256** may be selected to provide some torque margin so as to minimize any changes in rotational speed when higher loads are encountered on the sucker rod **114** during downhole pumping operations. While there may be some minor variations in rotational speed, the shaft **252** is driven at a speed that is substantially constant and produces a substantially constant flow of fluid at the outlet **244**. In one embodiment the prime mover **256** is selected and configured to deliver a rotational speed of about 1750 rpm which is controlled to be substantially constant within about ±1%.

The inlet **242** of the pump **240** is in fluid communication with the reservoir **220** via a fluid line **282**, and draws hydraulic fluid **222** from the reservoir **220**. When the swashplate **246** is angled at an angle $\alpha>0°$, a flow of fluid is delivered to the fluid line **284** via the outlet **244**. The hydraulic fluid line **284** is connected through a tee or wye coupling **295** to the fluid line **134**, which is in turn connected to the hydraulic fluid port **132** for delivering hydraulic fluid to the cylinder **124**.

The lift apparatus **100** also includes a valve **260** having ports **262** and **264**. The port **262** is connected via the fluid line **134** to the tee coupling **295**. In this embodiment the valve **260** is an electrically controllable proportional throttle valve, which is actuated by a solenoid **266** responsive to a valve control signal received at an input **268** for configuring the valve in a first state ("1") or a second state ("2"). The valve is shown configured in the first state in FIG. **2**, where the port **262** and **264** are connected through a check valve that prevents flow from port **262** through port **264** and back to the reservoir **220** via a fluid line **289**. In the second state the valve **260** is configured to function as a proportional throttle valve permitting a controlled flow in response to the valve control signal received at the input **268**. For example, the valve **260** may be operably configured to adjust the orifice size in response to a level of the valve control signal. The valve **260** may be implemented using a model FPJK valve made by Sun Hydraulics Corporation of United States of America, which is actuated by a 24 VDC solenoid coil responsive to a pulse width modulated (PWM) excitation current level between about 100 mA (i_{0d}) for a no flow condition and about 590 mA (i_d) for a maximum flow condition. The FPJK valve remains in the first state while the valve control signal provides a current i_{0d} of less than 100 mA, and configures in the second state to permit flow from port **262** to **264** in proportion to a current of between 100 mA and 590 mA received at the input **268**.

When the valve **260** is actuated to configure in the second state, hydraulic fluid flows out of the hydraulic fluid port **132** and through hydraulic fluid lines **134** and **288**, through the valve and fluid line **289** back to the reservoir **220**. In the embodiment shown, hydraulic fluid line **134** thus provides a common portion in communication with the hydraulic fluid port **132** for carrying fluid flow from the outlet **244** of the hydraulic pump **240** during the upstroke and to the valve **260** during the downstroke.

The hydraulic fluid circuit **200** also includes a first sensor **290** located proximate, but spaced apart from the first end **208** of the hydraulic cylinder **124** by a distance S_1, and a second sensor **292** located proximate, but spaced apart from the second end **210** by a distance of S_2. The sensors **290** and **292** are thus spaced apart from each other by a distance D_2. In one embodiment, the cylinder housing **202** may have a length of 150 inches (3.8 meters), S_1 may be about 36 inches (0.9 meters), S_2 may be about 33 inches (0.8 meters), and D_2 may be about 81 inches (2 meters). In this embodiment, the first and second sensors **290** and **292** are implemented using proximity sensors, which generate output signals at respective outputs **294** and **296** when the piston **204** is located proximate the respective sensors. In one embodiment the first and second sensors **290** & **292** may be implemented using inductive proximity sensors, such as model NI15-EM30E-YOX-H1141 sensors manufactured by Turck, Germany. These inductive sensors are operable to generate proximity signals responsive to the proximity of a metal portion of the carriage **128**.

The hydraulic fluid circuit **200** also includes a controller **270** that is operable to receive the proximity signal from the output **294** of the sensor **290** at an input **272** and the proximity signal from the output **296** of the sensor **292** at an input **274** of the controller. The controller **270** also produces the displacement control signal at an output **276** for controlling the pump **240** and produces the valve control signal at an output **278** for controlling the valve **260**. The controller **270** also includes an input **279** for receiving a start signal operable to cause the controller to start operation of the lift apparatus **100** and an output **275** for producing a control signal for controlling operation of the prime mover **256**. The start signal may be provided by a start button within the enclosure **136** that is depressed by an operator on site to commence operation. Alternatively, the start signal may be received from a remotely located controller, which may be communication with the controller via a wireless or wired connection. The controller **270** may be implemented using a microcontroller circuit although in other embodiments, the controller may be implemented as an application specific integrated circuit (ASIC) or other integrated circuit, a digital signal processor, an analog controller, a hardwired electronic or logic circuit, or using a programmable logic device or gate array, for example.

Referring to FIG. **3**, a process for operating the lift apparatus **100** is shown at **300**. The process **300** begins at **302** when an operator causes the lift apparatus **100** to start operation in response to receiving the start signal at the input **279**. As shown at **304**, the controller **270** then performs a startup process. In one embodiment the startup process involves producing a displacement control signal at the output **276**, which causes the swashplate **246** to adjust to angle $\alpha=0°$. The startup process also involves producing a valve control signal at the output **278** that causes the valve **260** to configure in the first state as shown in FIG. **1**. Once the valve **260** and hydraulic pump **240** are configured, the controller **270** generates a signal at the output **275** for starting the prime mover **256** such that a rotational torque is delivered to drive the shaft **252** at a substantially constant rotational speed. Under these conditions, hydraulic fluid is prevented from flowing into the outlet **244** of the hydraulic pump **240** due to the swashplate angle being at 0°. Similarly when configured in the first state, the valve **260** acts as a check valve between the valve ports **262** and **264** preventing flow of hydraulic fluid back to the reservoir **220**. The piston **204** thus remains at a position proximate the first end **208** of the hydraulic cylinder **124** during the startup process, as shown in FIG. **2**.

As shown at **306** the controller **270** then produces a displacement control signal for controlling the upstroke of the piston **204**. In one embodiment the displacement control signal has a waveform as shown at **400** in FIG. **4**. The startup functions shown at **304** are performed during a first time period **402**, following which the displacement control signal is set to a current level of i_{0u}, at a time t_1 and the upstroke commences. The controller **270** generates a first ramped portion **404** of the waveform that causes the angle α of the swashplate **246** to increase from 0° to a positive angle causing a hydraulic fluid flow at the outlet **244**. The valve control signal remains at or below a current level of i_{0d} preventing the fluid from flowing through the valve **260** back to the reservoir **220**. The weight of the cylinder rod **130** and sucker rod **114** on the piston **204** causes hydraulic fluid in the cylinder **124** to be pressurized causing a pressure at the outlet **244**, which should be sufficient to actuate movement of the swashplate **246** in response to the displacement control signal. A controlled flow of hydraulic fluid is thus generated at the outlet **244** and passes through the hydraulic fluid lines **284**, tee coupling **295**, and line **134** into the hydraulic fluid port **132** causing the piston **204** to move through an upstroke away from a first end **208** and toward a second end **210** of the cylinder in the direction indicated by arrow **258**. The movement **258** is controlled in proportion to the increasing current of the displacement control signal provided by the first ramped portion **404** of the waveform **400**. At a time t_2, the waveform **400** reaches a current level i_u and then remains at a constant current level for a constant portion **406** until a time t_3 is reached. During the constant portion **406**, the angle α of the swashplate **246** is held constant and the fluid flow rate at the outlet **244** is also substantially constant causing the piston **204** to move upwardly at a substantially constant velocity. At a time t_3 when the piston **204** is nearing the second end **210** a second ramped portion **408** of the waveform **400** begins. The second ramped portion **408** reduces the current, causing the fluid flow rate to reduce and decelerating the piston **204** until at i_{0u} the piston upstroke ends with the piston being located proximate the second end **210**. At t_4 the current of the waveform **400** is again at i_{0u} and the swashplate **246** angle α is adjusted to 0° such that hydraulic fluid is prevented from flowing back into the outlet **244** of the hydraulic pump **240** The piston **204**, cylinder rod **130**, and sucker rod **114** at the second end **210** of the cylinder **124** are thus held proximate the second end **210** of the hydraulic cylinder **124** for a delay period t_{du}.

As shown at **308** the controller **270** then produces the valve control signal for controlling the downstroke of the piston **204**. The valve control signal has a waveform as shown at **420** in FIG. **4**. At time t_5 the controller **270** generates a first ramped portion **422** of the waveform **420**, which causes the valve **260** to change configuration from the first state to the second state when the waveform reaches a current level of i_{0d}. Referring to FIG. **5**, the fluid circuit **200** is shown with the valve **260** configured in the second state.

The piston **204** is still positioned proximate the second end **210** following the upstroke and the orifice valve begins to open as the current level of the waveform **420** increases above i_{0d} permitting hydraulic fluid to flow through the hydraulic fluid line **134**, the tee coupling **295** and fluid line **288**, and through the valve via the fluid line **289** back to the reservoir **220**. In the meantime the waveform **400** of the displacement control signal remains at a current level i_{0u} thus causing the swashplate **246** to remain at angle $\alpha=0°$ preventing the flow of hydraulic fluid through the valve **260** and thus preventing the fluid from flowing back into the outlet **244** and through the hydraulic pump **240**. Proportional control of the orifice in response to the current level during a remaining portion of the first ramped portion of the waveform **420** permits the piston **204** to accelerate away from the second end **210** facilitating movement of the piston through a downstroke away from the second end **210** and toward the first end **208** of the cylinder in a direction indicated by the arrow **259**. Hydraulic fluid thus flows out of the hydraulic fluid port **132** and through the lines **134**, **288**, and **289** back to the reservoir **220**. At a time t_6, the current level of the waveform **400** reaches a constant current level i_d and remains at the constant current level for a constant portion **424** until a time t_7. During the constant portion **424**, the valve orifice opening size is maintained to permit a constant flow rate at the port **264** of the valve **260** allowing the piston **204** to move downwardly at a substantially constant velocity. At a time t_7 when the piston **204** is nearing the first end **208** a second ramped portion **426** of the waveform **420** begins. The second ramped portion **426** reduces in current level, thus causing the fluid flow rate to reduce thereby decelerating the piston **204**. At a time t_8 the waveform **420** reaches i_{0d} and the piston downstroke ends with the piston being located proximate the first end **208**. The current continues to decrease to 0 Amps, configuring the valve **260** in the first state and preventing further flow from the port **262** to the port **264** back to the reservoir **220**.

In the embodiment shown, there is a short delay period t_{du} between the end of the second ramped portion **408** of the waveform **400** at t_4 and the start of the first ramped portion **422** of the waveform **420** at t_5. Similarly there is a short delay period t_{dd} between the end of the second ramped portion **426** of the waveform **420** at t_8 and the start of the first ramped portion of a subsequent upstroke waveform **410**. In other embodiments the delay periods t_{du} and t_{dd} may be extended or omitted or may be calculated based on a calculated speed of the piston **204** during a previous upstroke or downstroke, for example.

The above described portions of the waveforms **400** and **420** respectively control the hydraulic pump **240** and the valve **260** to perform a single pumping cycle including an upstroke and a downstroke. As shown in FIG. **3**, the process steps **306** and **308** may then be repeated to cause a continuous reciprocation of the cylinder rod **130** for continuous operation of the down-hole reciprocating pump **112** and the waveform **400** thus repeats at **410**. Similarly the waveform **420** would also include repeating portions **422**, **424**, and **426**.

In general the times t_1 to t_8 and the currents i_u, i_{0u}, i_{0d} and i_d may be adjusted to produce target upstroke and downstroke times and velocities of the piston **204**. The times and current levels may be predetermined and set within the controller **270**.

In the embodiments shown in FIG. **2** and FIG. **5**, the hydraulic fluid lines **284** and **134** provide a direct connection between the pump **240** and the hydraulic cylinder **124**, which may be implemented using hydraulic fluid line having a 1 to 1.25 inch (25 to 32 millimeter) bore, for example. The tee coupling **295** may be configured to provide a smooth bore between the fluid lines **284** and **134** and the fluid lines have no additional restrictions along the lines, thus improving the flow efficiency between the pump and the cylinder **124**. In the embodiments shown, the fluid lines **284** and **134** do not cause the upstroke fluid flow to pass through the valve **260**, which may reduce an upstroke efficiency. Additionally, while the hydraulic fluid line **284** may include a bend as shown in FIGS. **2** and **5**, the bend may be configured to have a bend radius R that is sized to reduce flow losses within the hydraulic fluid line. For example, the bend radius may be at least about 1 inch or 25 millimeters. The hydraulic fluid lines **284**, **134**, and **288** may be implemented using steel lines or steel braided hydraulic lines with appropriate pressure rating and resistance to environmental factors such as UV exposure, high temperature and abrasion.

In some embodiments, an additional electrically actuated check valve **298** may be optionally disposed between the outlet of the pump **244** and the hydraulic fluid port **132**.

In some embodiments an optional additional check valve **298** may be disposed inline with the hydraulic fluid line **284**. During operation of the lift apparatus **100** the valve **298** will be configured fully open by the controller **270**, as shown in FIG. **2**. The check function of the valve **298** need only be actuated when it is required to hold the piston **204** under loading by the sucker rod **114** and down-hole reciprocating pump **112** while not supported by the frame **120**. The additional check valve **298** may be required in implementations where the pump **240** has significant leakage through the pump under load, which may flow back to the reservoir **220** via a line **299**. As an example, during an operating stoppage of the lift apparatus **100**, the valve **298** may be electrically actuated by the controller **270** to prevent flow of hydraulic fluid back into the outlet **244** of the hydraulic pump **240**.

As noted above, the hydraulic cylinder **124** may have separate hydraulic fluid ports and the portion **134** of the hydraulic fluid line is a common shared line for both upstroke and downstroke fluid flows. However in other embodiments the hydraulic fluid line **134** may be replaced by separate hydraulic fluid lines between the hydraulic pump **240** and the hydraulic cylinder **124** and between the valve **260** and the hydraulic cylinder.

In one embodiment the controller **270** may be implemented using a microcontroller circuit or other microprocessor based control circuit. Referring to FIG. **6**, a processor circuit for implementing the controller **270** is shown at **600**. The processor circuit **600** includes a microprocessor **602**, an input/output (I/O) **604**, a program memory **606**, and a parameter memory **608**, all of which are in communication with the microprocessor **602**. The microprocessor **602** executes program instructions stored in the program memory **606** to generate the displacement control signal and the valve control signal.

The I/O **604** includes the input **272** for receiving the first sensor signal from output **294** of the first sensor **290** and the input **274** for receiving the second sensor signal from output **296** of the second sensor **292**. Depending on the selected type of sensors, the sensor signals may be digital signals producing a binary "1" when the piston **204** is proximate the respective sensor and a "0" otherwise. Alternatively, if the proximity sensors **290** and **292** produce analog signals at the outputs **294** and **296**, the I/O **304** may include an analog-to-digital converter interface for converting the signals to a format that can be processed by the processor circuit **600**. The I/O **604** also includes the input **274** for receiving the start signal. In this embodiment the I/O **604** also includes a network interface **630** having a port **632** for connecting to a network such as a wireless 802.11 network, a cellular data network, or a wired network.

The I/O **604** also includes an interface **634** having the output **276** for producing the displacement control signal and an interface **636** having the output **278** for producing the valve control signal. In this embodiment, the interfaces **634** and **636** would generally be digital-to-analog converters operable to produce a 24 VDC pulse width modulated signal at the respective outputs **276** and **278** regulated to produce a controlled current for driving the input **248** of the hydraulic pump **240** or the input **268** of the solenoid **266** of the valve **260**. The I/O interface **302** also includes an output **275** for producing a prime mover control signal for controlling the prime mover **256**. The I/O interface **302** may further include an output **638** for generating a display signal for displaying information related to the operation of the lift apparatus **100** on a display **660**.

The program memory **606** has locations **680** storing codes for implementing an embedded controller operating system (OS) such as Linux®. The program codes may be generated using a visual programming language such as PLUS+1® GUIDE, produced by Danfoss A/S Denmark. The program memory **606** also includes locations **682** storing codes for causing the microprocessor **602** to implement functions related to controlling the lift apparatus **100**. The parameter memory **608** stores various parameters related to the functioning and configuration of the lift apparatus **100**. For example, in the embodiment shown, values of the parameters S_1 and S_2 defining the locations of the first and second sensors **290** and **292** and distances D_1, D_2, and D_3 related to the operating stroke of the piston **204** may be saved in a location **610** of the parameter memory **608**. A target piston velocity for the upstroke v_{tu} and downstroke v_{td} may also be saved in the location **610**. Parameter values for timing of the waveform **400** and parameter values for timing of the waveform **420** may be saved in the location **614** of the parameter memory **608**. In one embodiment the target piston velocity values of v_{tu} and v_{td} may be received through operator input via an input device connected to the (I/O) **604** or remotely via the network interface **630**. In other embodiments the desired piston upstroke and downstroke may be defining in terms of an upstroke time and downstroke time, which is essentially equivalent to the target piston velocity values.

Referring to FIG. **7**, a flowchart depicting blocks of code for directing the processor circuit **600** to control the upstroke of the lift apparatus **100** in accordance with one disclosed embodiment is shown generally at **700**. The blocks generally represent codes that may be read from the locations **682** of the program memory **606**. The actual codes for implementing each block may be written in any suitable program language, such as C, C++, C#, Java, and/or assembly code, for example.

The process **700** begins at block **702**, which directs the microprocessor **602** to determine whether a start signal has been received at the input **279**. If a start signal has not yet been received the processor circuit **600** remains in an idle state and the execution returns to the beginning of block **702**. When a start signal is received, block **702** directs the microprocessor **602** to block **704**, which directs the microprocessor **602** to execute the start-up process described above in connection with FIG. **3**, which involves directing the microprocessor to produce a displacement control signal having a current less than or equal to i_{0u}, at the output **276**, a valve control signal at the output **278** having a current less than or equal to i_{0d}, and to generate a prime mover control signal at the output **275** for causing the prime mover **256** to be started.

Block **704** may further direct the microprocessor **602** to initialize values for various operating parameters stored in the parameter memory **608**. For example, pre-determined initial values of the timing parameters t_1, t_2, t_3, and t_4 and the current level i_u for the waveform **400** shown in FIG. **4** may be stored in the location **612** of parameter memory **608**.

Block **706** then directs the microprocessor **602** to generate the first ramped portion **404** of the waveform **400** shown in FIG. **4**. In one embodiment the first ramped portion **404** is generated based on the timing parameters t_1, t_2 and the current level i_u stored in the location **612** of parameter memory **608**. Block **706** directs the microprocessor **602** to calculate a rate of increase of the first ramped portion **404** as follows:

$$\Delta i_1 = \frac{i_u}{t_2 - t_1} \qquad \text{Eqn 1}$$

where Δi_1 is calculated in units of Amps/second. In one embodiment t_1-t_2 is about 1500 milliseconds. Block **706** thus directs the microprocessor **602** to cause the interface **634** to produce a first ramped portion **404** of the displacement control signal at the output **276** that increases at a rate of Δi_1 Amps/second. Referring back to FIG. **2**, the first ramped portion **404** causes the swashplate **246** to be progressively angled at a greater angle α, causing an increasing flow rate at the outlet **244** that accelerates the piston **204** upwardly away from the first end **208** and towards the sensor **292**.

Block **706** also directs the microprocessor **602** to write the time t_1 at the actual start of the first ramped portion **404** to the location **612** of the parameter memory **608** and then directs the microprocessor to block **708**.

Block **708** directs the microprocessor **602** to determine whether a signal has been received from the first sensor **290** indicating that the piston **204** is proximate the sensor. If no signal has been received from the first sensor **290**, the microprocessor **602** is directed to repeat block **708**. If a signal is received from the first sensor **290**, the microprocessor **602** is directed to block **710**. Block **710** directs the microprocessor **602** to write a value for the time at which the proximity signal was received as a new value of t_2 in the location **612** of the parameter memory **608**. The time t_2 thus represents a time at which the piston is located at a distance S_1 from the first end **208** of the hydraulic cylinder **124**. Block **710** further directs the microprocessor **602** to cause the interface **634** to produce a constant displacement control signal having a current level i_u at the output **276** for generating the constant portion **406** of the waveform **400**. The current i_u may be initially set to a slow default level for producing an initially slow and safe average velocity of the piston while starting up operations. Under these conditions, the swashplate **246** is held at a constant angle α and the fluid flow rate at the outlet **244** of the hydraulic pump **240** is thus also substantially constant, causing the piston **204** to move at substantially constant velocity over the distance D_2 in the direction **258**.

The process **700** then continues at block **714**, which directs the microprocessor **602** to determine whether a signal has been received from the second sensor **292** indicating that the piston **204** is proximate the sensor. If no signal has been received from the second sensor **292**, the microprocessor **602** is directed to repeat block **712**. If a signal is received from the second sensor **292**, the piston **204** is located proximate the second sensor **292** and microprocessor **602** is directed to block **714**. Block **714** directs the microprocessor to read a value for a delay period t_{du} from the location **612** of the parameter memory **608** and to cause the interface **634** to continue to produce the constant output current level i_u for a further period of time t_{du}. Block **714** then directs the microprocessor **602** to generate the second ramped portion **408** of the waveform **400** shown in FIG. **4**. In this embodiment the second ramped portion **408** is generated based on the timing parameters t_3, t_4, and i_u having values stored in the location **612** of parameter memory **608**. Block **714** directs the microprocessor **602** to calculate a rate of decrease of the second ramped portion **408** as follows:

$$\Delta i_2 = \frac{i_u}{t_4 - t_3} \qquad \text{Eqn 2}$$

where Δi_2 will be a negative value calculated in units of Amps/second. Block **714** thus directs the microprocessor **602** to cause the interface **634** to produce a second ramped portion **408** of the displacement control signal at the output **276** that reduces at a rate of Δi_2 Amps/second. In one embodiment t_4-t_3 is about 600 milliseconds The delay period t_{du} and the times t_3 and t_4 are initially calculated to ensure that the fluid flow at the outlet **244** of the hydraulic pump **240** is reduced to zero before the piston **204** reaches the second end **210** of the hydraulic cylinder **124**. In one embodiment the delay period t_{du} and the times t_3 and t_4 are calculated to cause the piston **204** to stop about 6 inches (15 centimeters) from the second end **210** for a margin of safety to reduce the chance of the piston **204** topping out in the cylinder **124**, which could cause damage to the cylinder. In some embodiments, the delay period t_{du} may be eliminated.

The process **700** then continues at block **716**, which directs the microprocessor **602** to recalculate parameters for the upstroke based on the calculated velocity of the piston **204** during the current upstroke and to update these values for a subsequent upstroke. In one embodiment the following calculations may be performed:

$$\Delta v = \frac{D}{T_4 - T_1} - v_{tu} \qquad \text{Eqn 3}$$

where v_{tu} is a target average velocity for the upstroke, D is the total piston travel distance ($D=D_1+D_2+D_3$) shown in FIGS. **2** and **5**, and Δv is the velocity variance from the target average velocity. The target average velocity v_{tu} is saved in the location **610** of parameter memory **608**. An updated constant current level i_u is then calculated as follows:

$$i'_U = i_U\left[1 - \frac{\Delta v}{v_d}\right] \qquad \text{Eqn 4}$$

where i_u' is the constant current level based on the previous upstroke to be used for the next upstroke. The constant current level i_u' is thus increased if the previous upstroke was slower than the target average velocity v_{tu} and decreased if the previous upstroke was faster than the target average velocity v_{tu}. Block **714** directs the microprocessor **602** to save the updated the constant current value i_u' in the location **612** of parameter memory **608** as the constant current level i_u for the next upstroke. Block **716** then directs the microprocessor **602** to block **800**, which causes the microprocessor **602** to execute a downstroke process (shown in detail in FIG. **8**). Following the downstroke process **800**, the microprocessor **602** is directed back to block **706** for the next upstroke and blocks **706**-**714** are repeated. At blocks **706**, **710**, and **714**, the updated value of i_u is used to calculate the first and second ramped portions **404** and **408** and the constant portion **406**, thus targeting the target velocity v_{tu} for the upstroke. For each successive upstroke, the actual average velocity of the piston should therefor converge toward the target average velocity v_{tu}. Additionally, should the load conditions downhole change, the controller processor circuit **600** of the lift apparatus **100** will automatically adapt to the changing conditions and return to operation at or near the target average velocity v_{tu} for the upstroke. The processor circuit **600** is thus operably configured to generate the first and second ramped portions **404** and **408** of the waveform for the upstroke based on the first and second signals received from the first and second sensors **290** and **292** during a previous upstroke of the piston. In other embodiments the target average velocity v_{tu} may be based on a desired number of strokes per minute or spm (upstroke and downstroke).

Referring to FIG. **8**, a flowchart depicting blocks of code for directing the processor circuit **600** to control the downstroke of the lift apparatus **100** in accordance with one disclosed embodiment is shown generally at **800**. The process **800** begins at block **802**, which directs the microprocessor **602** to generate the first ramped portion **422** of the waveform **420** shown in FIG. **4**. In this embodiment the first ramped portion **422** is generated based on the timing parameters t_5, t_6, and the current level i_d stored in the location **614** of parameter memory **608**. Block **802** directs the microprocessor **602** to calculate a rate of increase of the first ramped portion **422** as follows:

$$\Delta i_3 = \frac{i_d}{t_6 - t_5} \qquad \text{Eqn 5}$$

where Δi_3 is calculated in units of Amps/second. Block **802** thus directs the microprocessor **602** to cause the interface **636** to produce a first ramped portion **422** of the valve control signal at the output **278** that increases at a rate of Δi_3 Amps/second. In one embodiment t_6-t_5 is about 2400 milliseconds Referring back to FIG. **5**, when the first ramped portion **422** reaches the current level i_{0d}, the valve **260** changes state from the checkvalve state "1" to the orifice valve state "2" and the orifice valve permits a flow of hydraulic fluid from the hydraulic cylinder **124** through the hydraulic fluid port **132** and lines **134**, **288** through the valve **260** and back to the reservoir **220** via the fluid line **289**. A rate of flow is determined by the current level of the first ramped portion **422**, which increases at the rate Δi_3 allowing the piston **204** to accelerate away from the first end **208** toward the second end **210**. The sucker rod **114** and downhole reciprocating pump **112** act as a significant load on the piston **204** for causing the downward motion. Block **802** also directs the microprocessor **602** to write the time t_5 at the actual start of the first ramped portion **422** to the location **614** of the parameter memory **608** and then directs the microprocessor to block **804**.

Block **804** directs the microprocessor **602** to determine whether a signal has been received from the second sensor **292** indicating that the piston **204** is proximate the sensor. If no signal has been received from the second sensor **292**, the microprocessor **602** is directed back to repeat block **804**. If a signal is received from the second sensor **292**, the microprocessor **602** is directed to block **806**.

Block **806** directs the microprocessor **602** to write a value for the time at which the proximity signal was received as a new value of t_6 in the location **614** of the parameter memory **608**. The time t_6 thus represents a time at which the piston is located at a distance S_2 from the second end **210** of the hydraulic cylinder **124**. Block **806** further directs the microprocessor **602** to cause the interface **636** to produce a constant valve control signal having a current level i_d at the output **278** for generating the constant portion **424** of the waveform **420**. Under these conditions, the orifice of the valve **260** is held at a constant opening and the fluid flow rate at the port **264** is thus restricted to a substantially constant flow rate, causing the piston **204** to move at substantially constant velocity over the distance D_2 in the downward direction **259**.

The process **800** then continues at block **808**, which directs the microprocessor **602** to determine whether a signal has been received from the first sensor **290** indicating that the piston **204** is proximate the sensor. If no signal has been received from the first sensor **290**, the microprocessor **602** is directed to repeat block **808**. If a signal is received from the first sensor **290**, the piston **204** is located proximate the first sensor and microprocessor **602** is directed to block **810**.

Block **810** directs the microprocessor to read a value for a delay period t_{dd} from the location **614** of the parameter memory **608** and to cause the interface **636** to continue to produce the constant output current level i_d for a further period of time t_{dd}. Block **810** then directs the microprocessor **602** to generate the second ramped portion **426** of the waveform **400** shown in FIG. **4**. In this embodiment the second ramped portion **426** is generated based on the timing parameters t_7, t_8, and i_d having values stored in the location **614** of parameter memory **608**. Block **810** further directs the microprocessor **602** to calculate a rate of decrease of the second ramped portion **426** as follows:

$$\Delta i_4 = \frac{i_d}{t_8 - t_7} \qquad \text{Eqn 6}$$

where Δi_4 will be a negative value calculated in units of Amps/second. Block **810** thus directs the microprocessor **602** to cause the interface **636** to produce a second ramped portion **426** of the displacement control signal at the output **278** that reduces at a rate of Δi_4 Amps/second. In one embodiment t_8-t_7 is about 1500 milliseconds The delay period t_{dd} and the times t_7 and t_8 are initially calculated to ensure that the fluid flow at the port **264** of the valve **260** is reduced to zero before the piston **204** reaches the first end **208** of the hydraulic cylinder **124**. In one embodiment the delay period t_{dd} and the times t_7 and t_8 are calculated to cause the piston **204** to stop about 3 inches (7.5 centimeters) from the first end **208** for a margin of safety to reduce the chance of the piston **204** bottoming out in the cylinder **124**, which could cause damage to the cylinder. In some embodiments, the delay period t_{dd} may be eliminated.

The process **800** then continues at block **812**, which directs the microprocessor **602** to recalculate parameters for the downstroke based on the calculated velocity of the piston **204** during the current downstroke and to update these values for a subsequent downstroke. In one embodiment the following calculations may be performed:

$$\Delta v = \frac{D}{t_8 - t_7} - v_{td} \qquad \text{Eqn 7}$$

where v_{td} is a target average velocity for the downstroke, D is the total piston travel distance, and Δv is the velocity variance from the target average velocity v_{td}. The target average velocity v_{td} is saved in the location **610** of parameter memory **608**. An updated constant current level i_d is then calculated as follows:

$$i_d' = i_d\left[1 - \frac{\Delta v}{v_{td}}\right] \qquad \text{Eqn 8}$$

where i_d' is the constant current level of the waveform **420** based on the previous downstroke to be used for the next downstroke. The constant current level i_d' is thus increased if the previous downstroke was slower than the target average velocity v_{td} and decreased if the previous downstroke was faster than the target average velocity v_{td}. Block **812** also directs the microprocessor **602** to save the updated constant current value i_d in the location **614** of parameter memory **608** as the constant current value i_d for the next downstroke. Block **812** then directs the microprocessor **602** to block **700**, which causes the microprocessor **602** to again execute the downstroke process starting at block **706** (as shown in FIG. **7**). Following the next upstroke, the microprocessor **602** is directed back to block **802** for the next downstroke and blocks **802**-**812** are again repeated. At blocks **802**, **806**, and **810** the updated value of i_d is used to calculate the first and second ramped portions **422** and **426** and the constant portion **424**, thus converging on the target velocity v_{td} for the next downstroke. For each successive downstroke, the actual average velocity of the piston should therefor get closer to the target average velocity v_{td}. Additionally, should the load conditions downhole change, the controller processor circuit **600** of the lift apparatus **100** will automatically adapt to the changing conditions and return to operation at or near the target average velocity v_{td} for a subsequent downstroke. The processor circuit **600** is thus operably configured to generate the first and second ramped portions **422** and **426** of the waveform **420** for the downstroke based on the first and second signals received from the first and second sensors **290** and **292** during a previous downstroke of the piston.

In one embodiment, conditions such as load, viscosity, temperature and friction etc. are compensated by the processes **700** and **800** such that the operation reaches a desired stroke per minute (spm) within about 30 strokes of the lift apparatus **100**. While the above upstroke process **7090** and downstroke process **800** have been described as performing average velocities v_{tu} and v_{td}, other calculations for providing feedback based on a pervious upstroke or downstroke may be performed for adjusting the parameters for the next upstroke or downstroke. Alternatively, the waveforms **400** and **420** may be adjusted during an upstroke, for example by transitioning from the first ramped portion **404** to the constant portion **406** when the proximity signal is received from the first sensor **290**, thus performing near real-time control of the upstroke and downstroke rather than the learning based approach described above. The signals produced by the first sensor **290** and second sensor **292** indicating proximity of the piston may thus be used to generate the displacement control signal and the valve control signal.

Since the hydraulic pump **240** is connected to the hydraulic cylinder **124** directly through the hydraulic fluid lines **284**, and **134** and not though a valve (such as the valve **260**), the disclosed lift apparatus **100** provides less flow resistance during the upstroke, thus reducing flow losses within the apparatus. Further, driving the pump **240** using a substantially constant rotational drive prime mover **256** reduces complexity associated with controlling the speed of prime mover to control the upstroke. The necessary control is provided by the variable displacement pump, which produces a controlled constant flow in response to receiving a constant displacement control signal. The upstroke of the piston **204** is controlled via the hydraulic pump **240** using a single displacement control signal and the downstroke of the piston is controlled by controlling the valve **260** through a single valve control signal, reducing control complexity for the disclosed lift apparatus **100**.

While specific embodiments have been described and illustrated, such embodiments should be considered illustrative of the invention only and not as limiting the invention as construed in accordance with the accompanying claims.

What is claimed is:

1. A lift apparatus for driving a downhole reciprocating pump, the apparatus comprising:

a hydraulic cylinder having a piston and a hydraulic fluid port, the piston being coupled to a rod for driving the reciprocating pump, the piston being moveable between first and second ends of the cylinder in response to a flow of hydraulic fluid through the hydraulic fluid port;

a variable displacement hydraulic pump coupled to receive a substantially constant rotational drive from a prime mover for operating the hydraulic pump, the hydraulic pump having an outlet and being responsive to a displacement control signal to draw hydraulic fluid from a reservoir and to produce a controlled flow of hydraulic fluid at the outlet;

a hydraulic fluid line connected to deliver the controlled flow of hydraulic fluid from the outlet of the hydraulic pump through the hydraulic fluid port to the cylinder for causing the piston to move through an upstroke away from the first end and toward the second end of the cylinder;

a valve connected between the hydraulic fluid port and the reservoir, the valve being responsive to a valve control signal for controlling discharge of hydraulic fluid from the hydraulic fluid port of the cylinder back to the reservoir to facilitate movement of the piston through a downstroke away from the second end toward the first end of the cylinder; and

wherein:

the hydraulic fluid line bypasses the valve such that the flow of hydraulic fluid during the upstroke does not pass through the valve;

the valve is operable to prevent flow of hydraulic fluid through the valve during the upstroke; and

the hydraulic pump is operable to prevent flow of hydraulic fluid back into the outlet of the hydraulic pump during the downstroke.

2. The apparatus of claim **1** wherein the hydraulic fluid line comprises a common portion in communication with the hydraulic fluid port, wherein the common portion carries fluid flow from the hydraulic pump during the upstroke and to the valve during the downstroke.

3. The apparatus of claim **1** wherein the hydraulic fluid line is routed between the outlet of the hydraulic pump and the hydraulic fluid port through at least one bend, the at least one bend having a bend radius of at least about 25 mm to reduce flow losses within the hydraulic fluid line.

4. The apparatus of claim **1** wherein the hydraulic pump is configured to produce a unidirectional flow of fluid at the outlet having a flow rate ranging from a substantially no flow condition to a maximum flow rate in proportion to the displacement control signal.

5. The apparatus of claim **4** wherein the hydraulic pump comprises a swashplate movable through a range of angles between 0° corresponding to the substantially no flow condition to a maximum angle corresponding to the maximum flow rate and wherein the hydraulic pump is configured to prevent the swashplate being angled at less than 0° for preventing flow back into the outlet and through the hydraulic pump.

6. The apparatus of claim **1** wherein the hydraulic fluid line includes a check valve disposed between the outlet of the pump and the hydraulic fluid port, the check valve being operable to permit flow from the outlet to the hydraulic fluid port during the upstroke while preventing flow of hydraulic fluid back into the outlet of the hydraulic pump during the downstroke.

7. The apparatus of claim **1** further comprising:

a first sensor located proximate the first end of the cylinder and operable to produce a first signal indicating a proximity of the piston to the first sensor;

a second sensor located proximate the second end of the cylinder and operable to produce a second signal indicating a proximity of the piston to the second sensor; and

- a controller operably configured to generate the displacement control signal and the valve control signal in response to receiving the first signal and the second signal.

8. The apparatus of claim **7** wherein the first and second sensors are positioned proximate to but spaced inwardly from the respective first and second ends of the cylinder to cause the first and second signals to be generated in when the piston is in proximity to the respective first and second ends of the cylinder.

9. The apparatus of claim **7** wherein the controller is operably configured to generate a displacement control signal having a time varying waveform for controlling the upstroke, the waveform including:

- a first ramped portion that causes the hydraulic pump to deliver an increasing flow of hydraulic fluid for accelerating the piston away from the first end of the cylinder;
- a constant portion that causes the hydraulic pump to deliver a substantially constant flow for moving the piston at a substantially constant velocity; and
- a second ramped portion that causes the hydraulic pump to deliver a reducing flow for decelerating the piston as the piston approaches the second end of the cylinder.

10. The apparatus of claim **9** wherein the controller is operably configured to generate the constant portion of the waveform to target a desired velocity of the piston for the upstroke based on a calculated velocity of the piston during a previous upstroke of the piston, the velocity being calculated based on the first and second signals.

11. The apparatus of claim **10** wherein the controller is operably configured to receive operator input of one of the desired velocity and an upstroke time.

12. The apparatus of claim **9** wherein the controller is operably configured to, in response to receiving the second signal, commence the second ramped portion following a delay period.

13. The apparatus of claim **12** wherein the controller is operably configured to calculate the delay period based on a calculated velocity of the piston between the first and second sensors during a current upstroke of the piston.

14. The apparatus of claim **9** wherein the controller is operably configured to generate the first and second ramped portions of the waveform for the upstroke based on the first and second signals received during a previous upstroke of the piston.

15. The apparatus of claim **7** wherein the controller is operably configured to generate a valve control signal having a time varying waveform for controlling the downstroke, the waveform including:

- a first ramped portion that causes the valve to permit an increasing flow of hydraulic fluid permitting the piston to accelerate away from the second end of the cylinder;
- a constant portion that causes the valve to permit a substantially constant flow for moving the piston at a substantially constant velocity; and
- a second ramped portion that causes the valve to permit a reducing flow for decelerating the piston as the piston approaches the first end of the cylinder.

16. The apparatus of claim **15** wherein the controller is operably configured to generate the constant portion of the waveform for targeting a desired velocity of the piston for the downstroke based on a calculated velocity of the piston during a previous downstroke of the piston, the velocity being calculated based on the first and second signals.

17. The apparatus of claim **16** wherein the controller is operably configured to receive operator input of one of a desired velocity and a downstroke time.

18. The apparatus of claim **15** wherein the controller is operably configured to, in response to receiving the first signal, commence the second ramped portion following a delay period.

19. The apparatus of claim **18** wherein the controller is operably configured to calculate the delay period based on a calculated velocity of the piston between the second and first sensors during the downstroke of the piston.

20. The apparatus of claim **15** wherein the controller is operably configured to generate the first and second ramped portions of the waveform for the downstroke based on the first and second signals received during a previous downstroke of the piston.

21. The apparatus of claim **1** wherein the valve comprises an electrically controllable proportional throttle valve.

22. The apparatus of claim **1** wherein the hydraulic pump comprises a swashplate pump in which an angle of the swashplate is configurable over a range of angles in response to the displacement control signal and wherein the range of angles is constrained to produce a unidirectional flow at the outlet.

23. A method for operating a pumpjack lift, the pumpjack comprising a hydraulic cylinder having a piston and a hydraulic fluid port, the piston being coupled to a rod for driving a downhole reciprocating pump, the method comprising:

- producing a displacement control signal operable to cause a variable displacement hydraulic pump to draw hydraulic fluid from a reservoir and to produce a controlled flow of hydraulic fluid at an outlet of the hydraulic pump, the hydraulic pump being coupled to receive a substantially constant rotational drive from a prime mover;
- delivering the controlled flow of hydraulic fluid from the outlet of the hydraulic pump through a hydraulic fluid line connected to the hydraulic fluid port of the cylinder to cause the piston to move through an upstroke away from a first end and toward a second end of the cylinder;
- producing a valve control signal for controlling discharge of hydraulic fluid back to the reservoir from the hydraulic fluid port of the cylinder through a valve connected between the hydraulic fluid port and the reservoir to facilitate movement of the piston through a downstroke away from the second end and toward the first end of the cylinder, wherein the hydraulic fluid line bypasses the valve such that the flow of hydraulic fluid during the upstroke does not pass through the valve; and
- preventing flow of hydraulic fluid through the valve during the upstroke and preventing flow of hydraulic fluid back into the outlet of the hydraulic pump during the downstroke.

24. The method of claim **23** wherein producing the displacement control signal comprises:

- receiving a first signal indicating a proximity of the piston to a first sensor located proximate the first end of the cylinder;
- receiving a second signal indicating a proximity of the piston to a second sensor located proximate the second end of the cylinder; and
- causing a controller operably to generate the displacement control signal and the valve control signal in response to receiving the first signal and the second signal.

25. The method of claim **24** wherein producing the displacement control signal comprises causing the controller to generate a displacement control signal having a time varying waveform for controlling the upstroke, the waveform including:

a first ramped portion that causes the hydraulic pump to deliver an increasing flow of hydraulic fluid for accelerating the piston away from the first end of the cylinder;

a constant portion that causes the hydraulic pump to deliver a substantially constant flow for moving the piston at a substantially constant velocity; and

a second ramped portion that causes the hydraulic pump to deliver a reducing flow for decelerating the piston as the piston approaches the second end of the cylinder.

26. The method of claim **24** wherein producing the valve control signal comprises causing the controller to generate a valve control signal having a time varying waveform for controlling the downstroke, the waveform including:

a first ramped portion that causes the valve to permit an increasing flow of hydraulic fluid permitting the piston to accelerate away from the second end of the cylinder;

a constant portion that causes the valve to permit a substantially constant flow for moving the piston at a substantially constant velocity; and

a second ramped portion that causes the valve to permit a reducing flow for decelerating the piston as the piston approaches the first end of the cylinder.

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