



US 20170146007A1

(19) **United States**(12) **Patent Application Publication**
ROBISON et al.(10) **Pub. No.: US 2017/0146007 A1**(43) **Pub. Date: May 25, 2017**(54) **OPERATIONAL CONTROL OF WELLSITE
PUMPING UNIT WITH DISPLACEMENT
DETERMINATION****F04B 53/16** (2006.01)**E21B 43/12** (2006.01)**F04B 9/103** (2006.01)(71) Applicant: **WEATHERFORD TECHNOLOGY
HOLDINGS, LLC**, Houston, TX (US)(52) **U.S. Cl.**CPC **F04B 49/12** (2013.01); **E21B 43/126**(2013.01); **E21B 33/06** (2013.01); **F04B 19/22**(2013.01); **F04B 9/103** (2013.01); **F04B 47/02**(2013.01); **F04B 49/22** (2013.01); **F04B 53/16**(2013.01); **F04B 49/20** (2013.01); **F04B****2203/0903** (2013.01); **F04B 2203/0209**

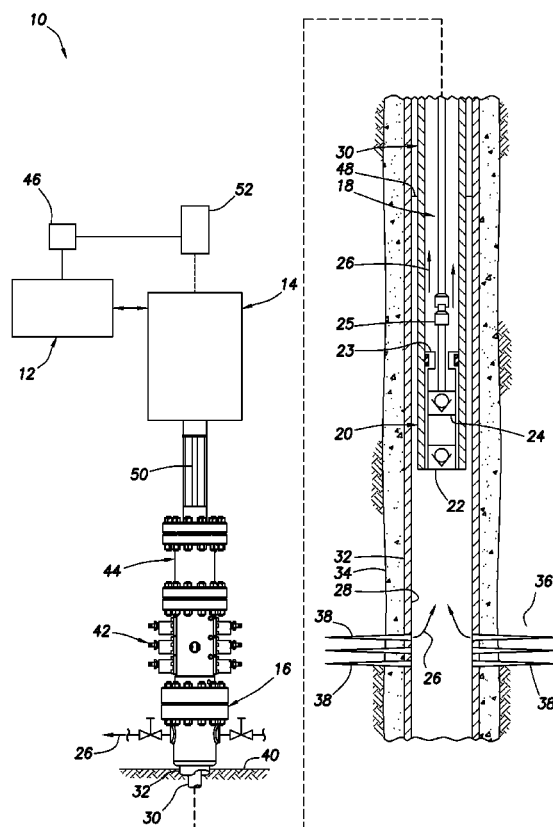
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(21) Appl. No.: **14/991,253**(22) Filed: **Jan. 8, 2016****Related U.S. Application Data**(63) Continuation-in-part of application No. 14/947,839,
filed on Nov. 20, 2015.**Publication Classification**(51) **Int. Cl.****F04B 49/12** (2006.01)**E21B 33/06** (2006.01)**F04B 19/22** (2006.01)**F04B 49/20** (2006.01)**F04B 47/02** (2006.01)**F04B 49/22** (2006.01)

(57)

ABSTRACT

A well pumping system can include an actuator that reciprocally displaces a rod string, a flowmeter that measures flow of a fluid between a power source and the actuator, and a control system that modifies reciprocal displacement of the rod string by the actuator, in response to an output of the flowmeter. A well pumping method can include reciprocally displacing a rod string, continuously determining a velocity profile of the rod string, and modifying the velocity profile while the rod string reciprocally displaces, in response to an output of a flowmeter. Another well pumping method can include reciprocally displacing a rod string with an actuator, continuously determining displacement in response to an output of a flowmeter, and modifying reciprocating displacement of the rod string by the actuator, in response to the output of the flowmeter.



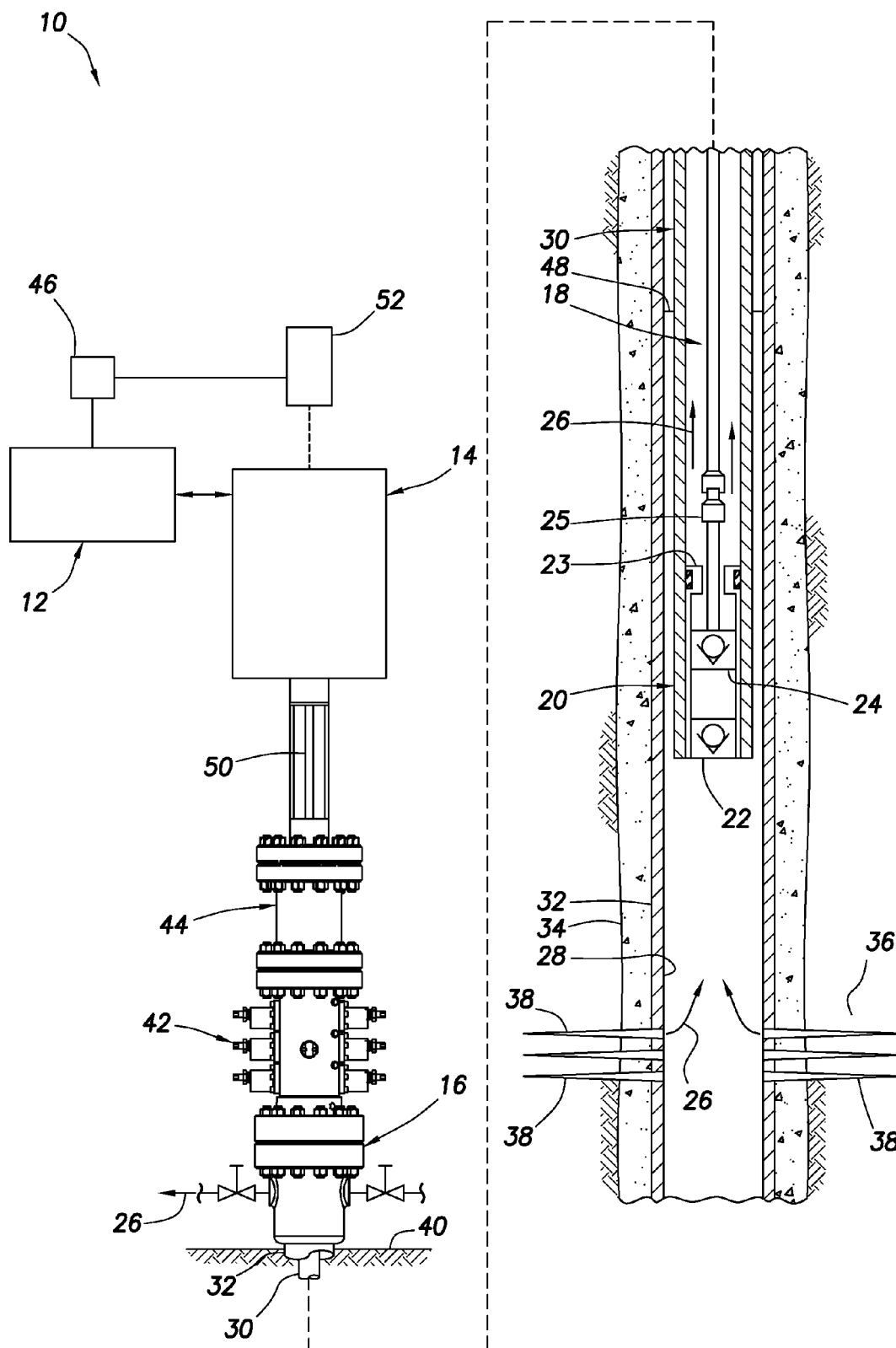


FIG.1

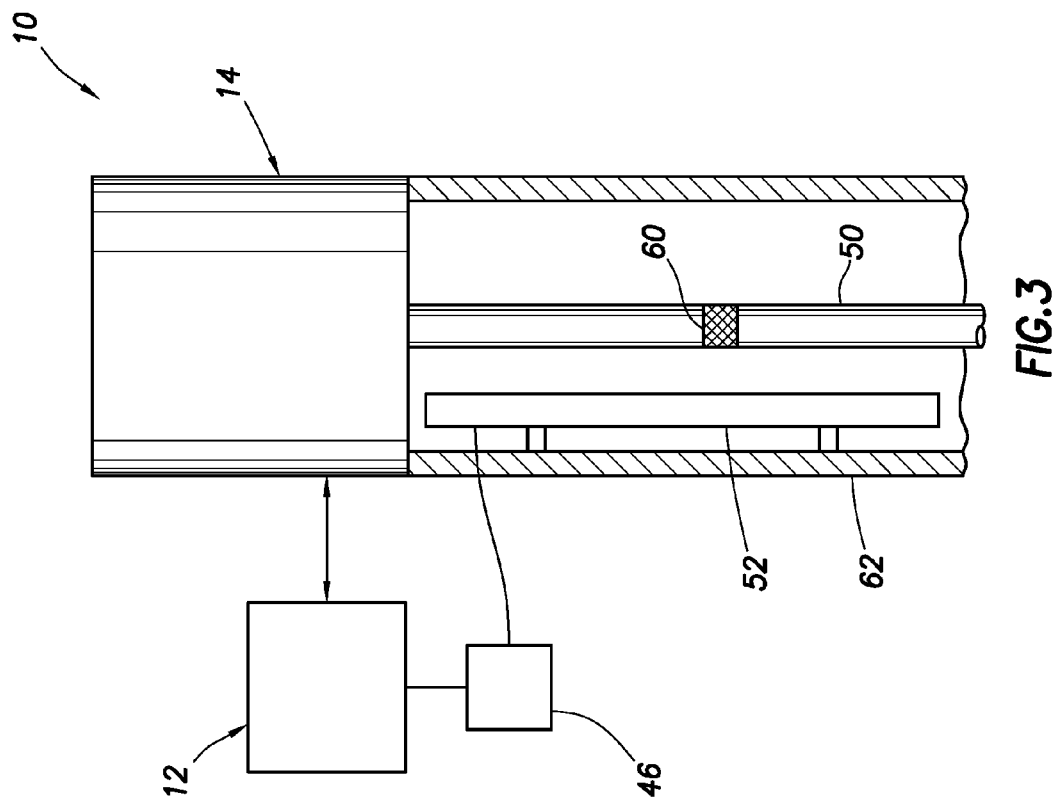


FIG. 2

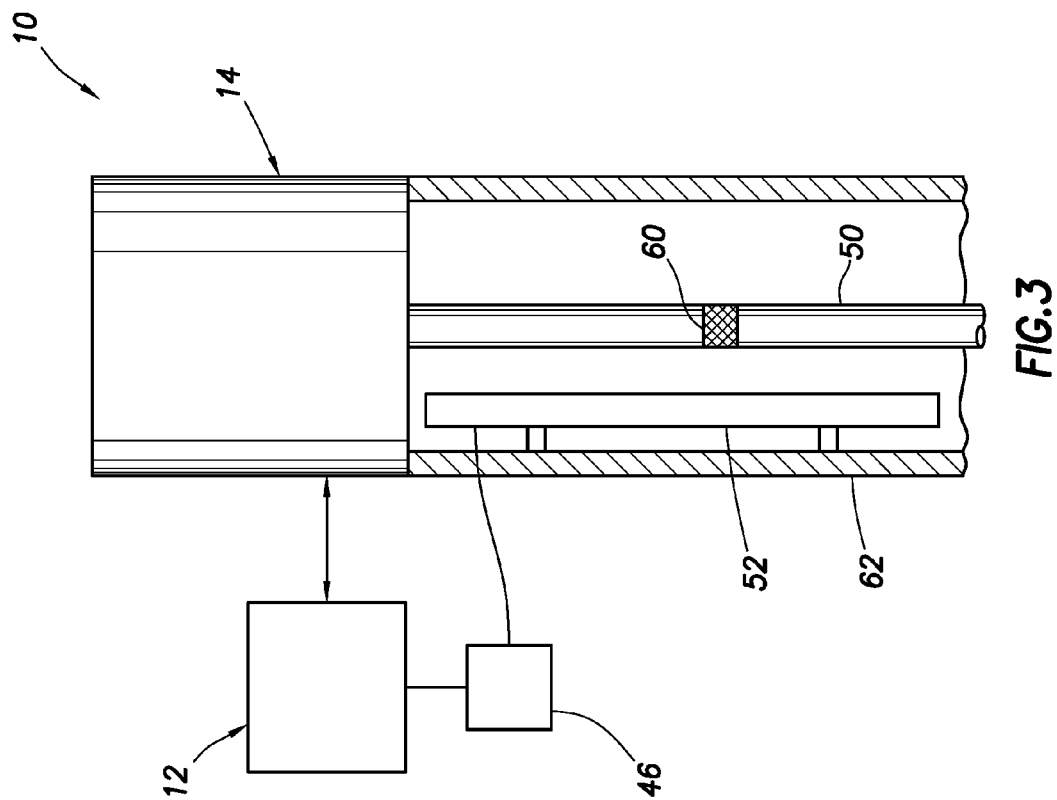
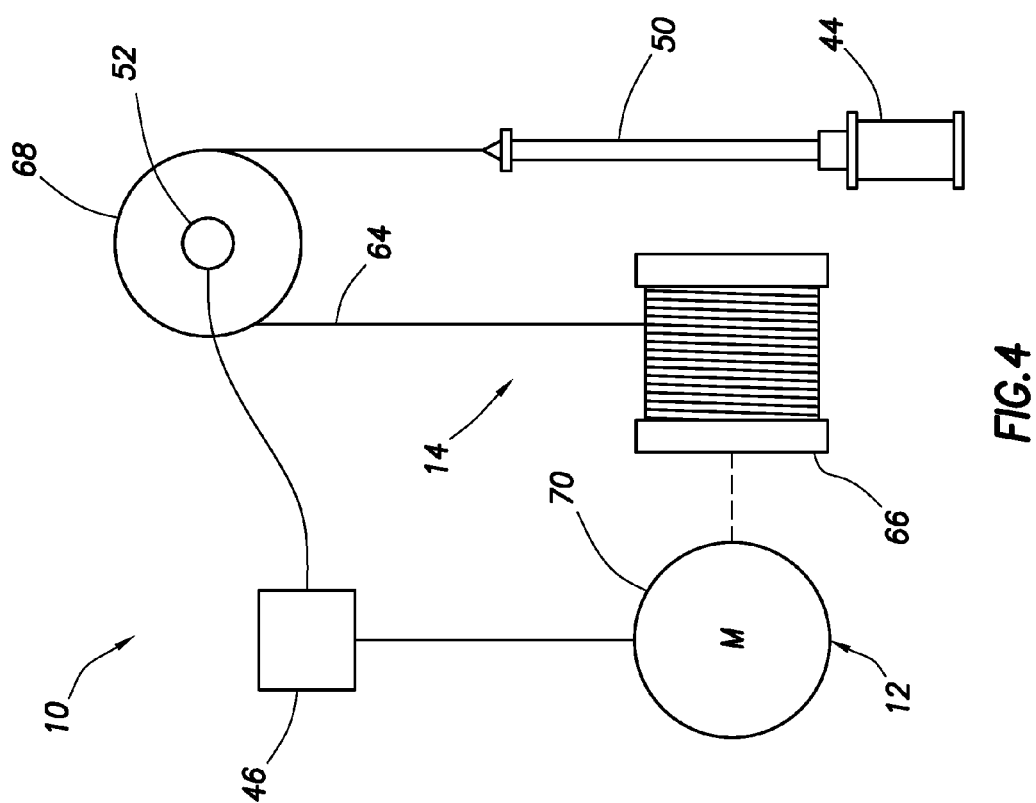
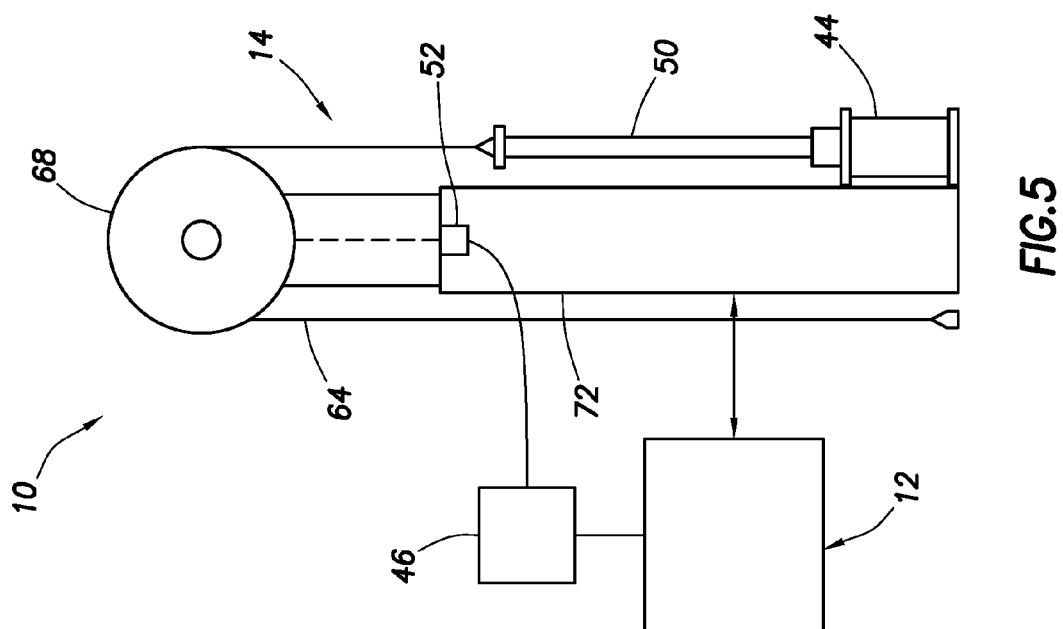


FIG. 3



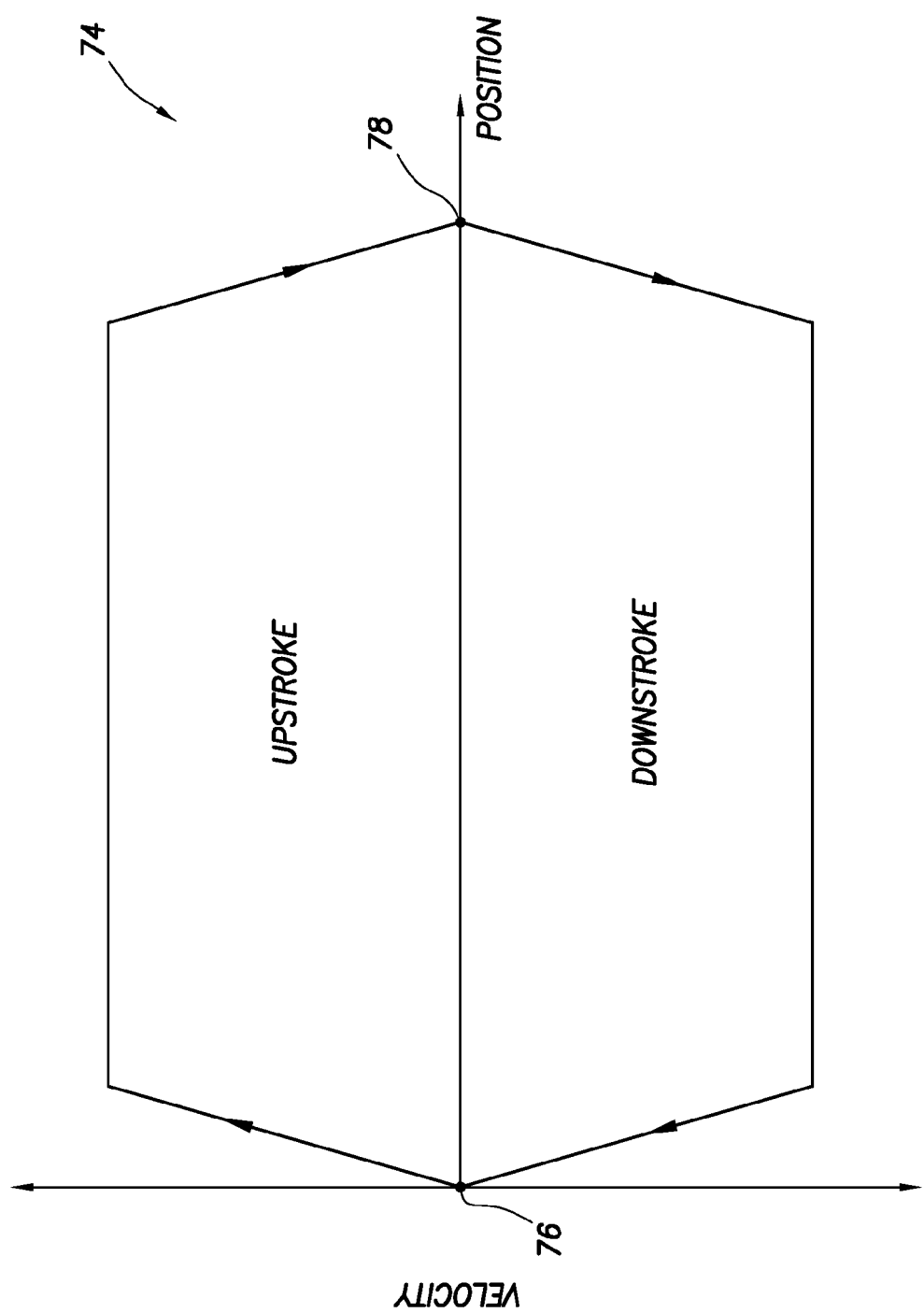


FIG.6

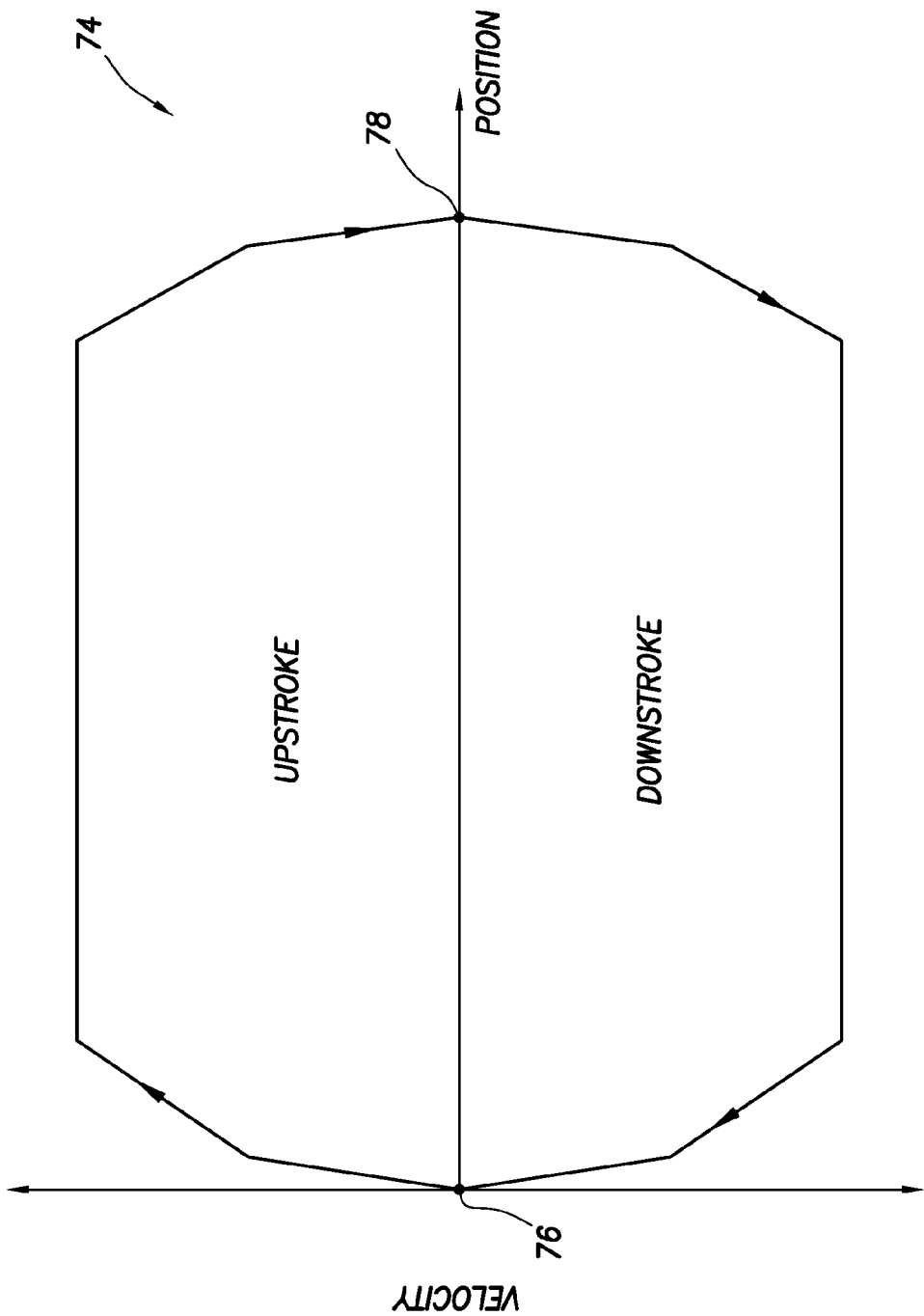


FIG. 7

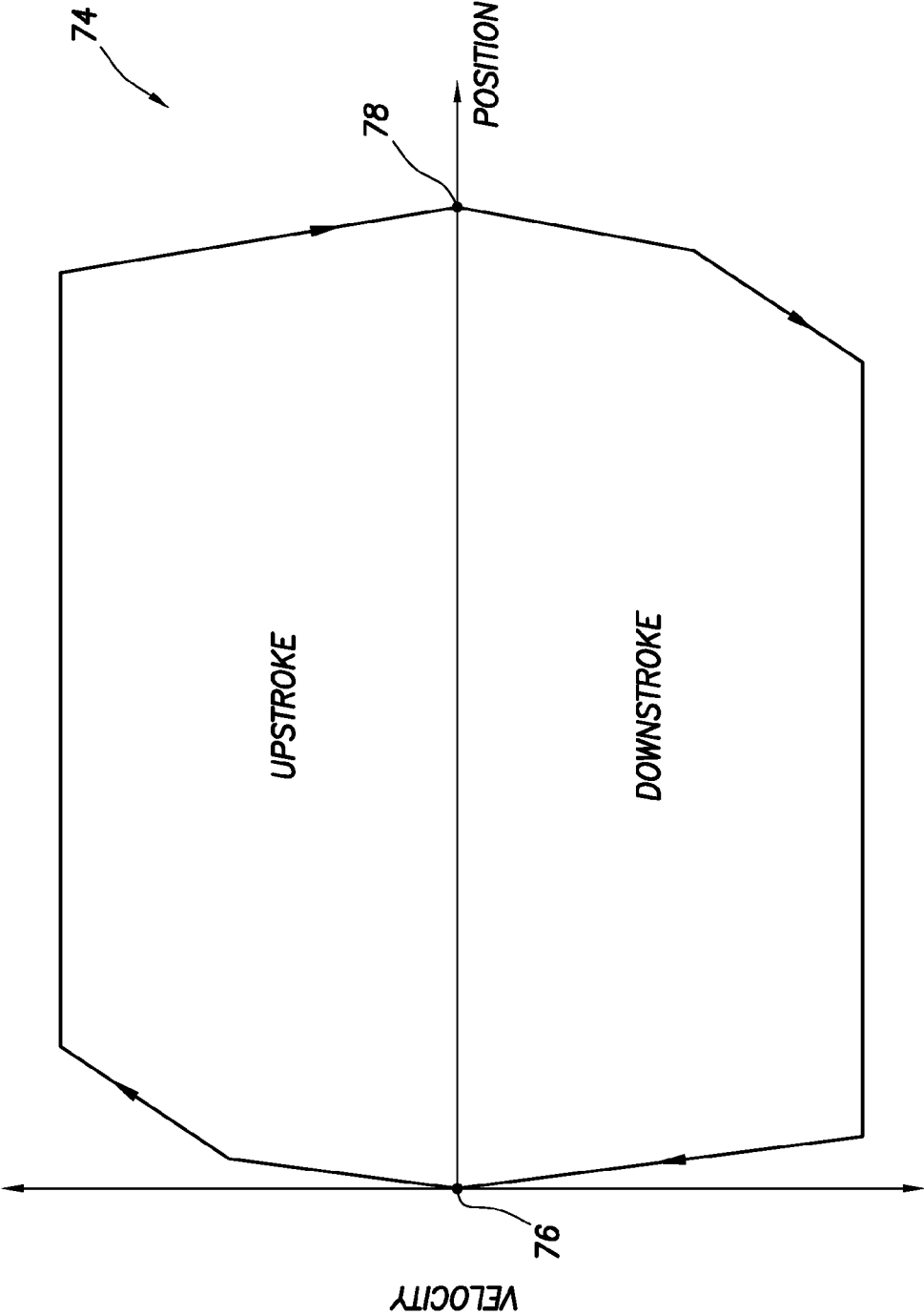


FIG.8

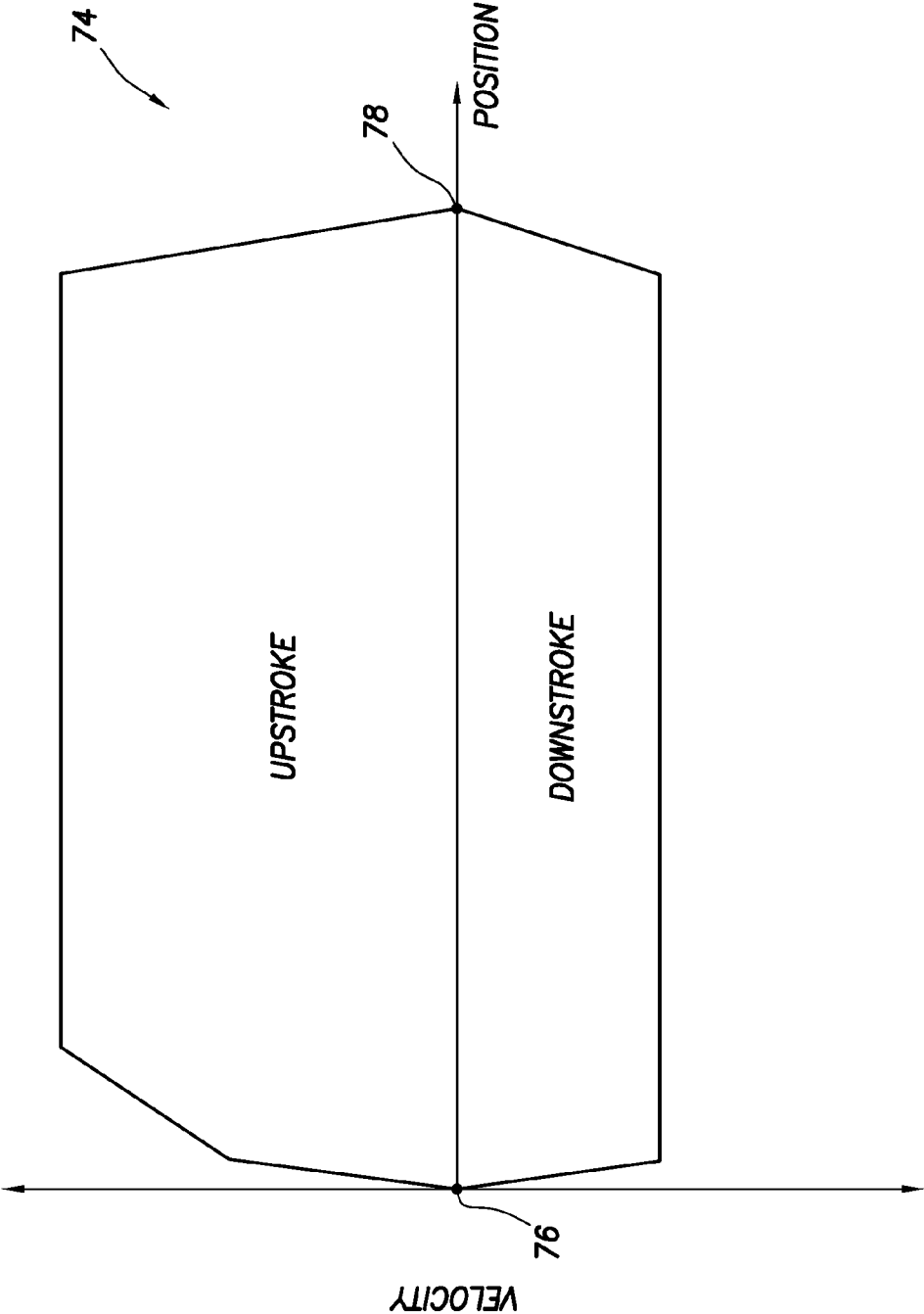


FIG.9

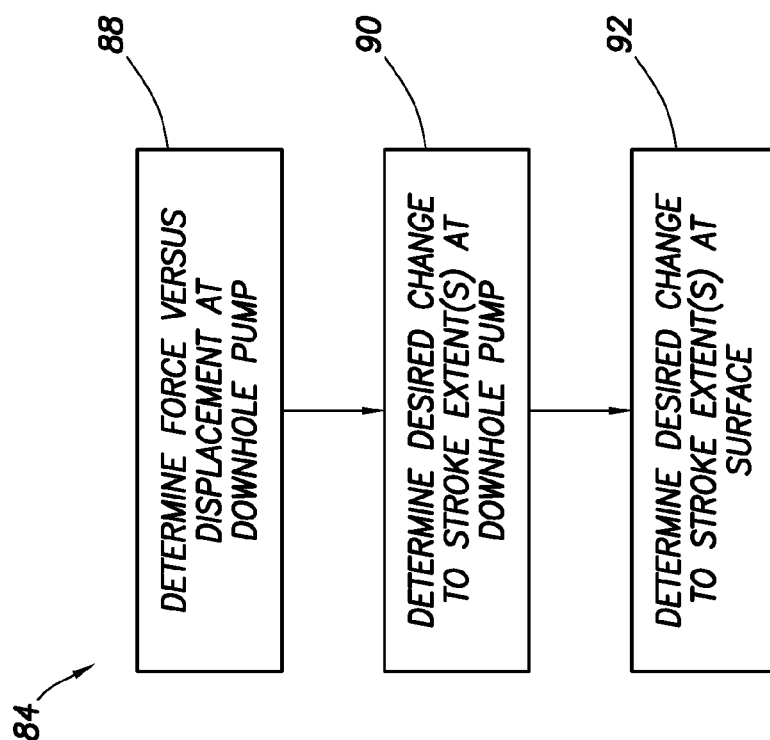


FIG.11

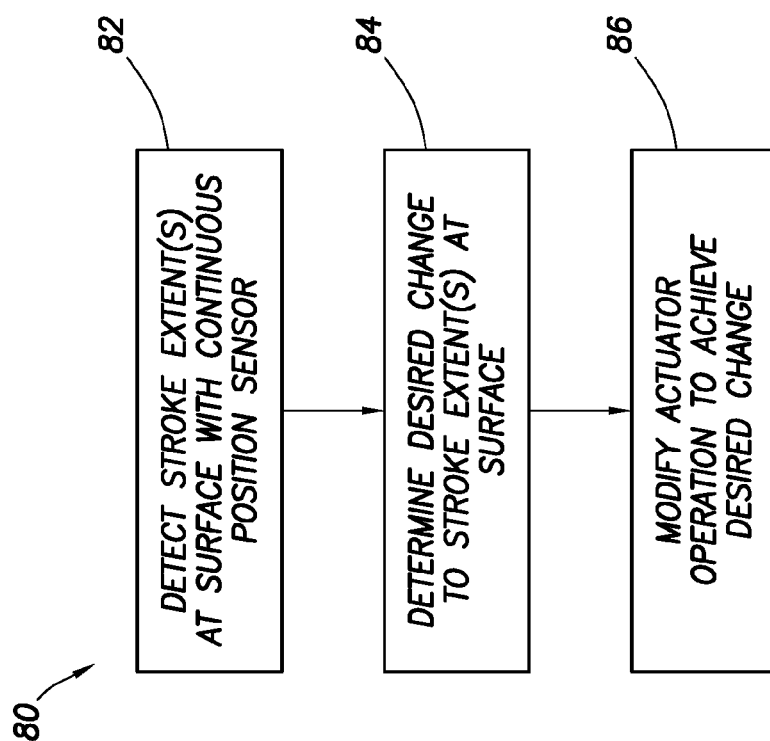


FIG.10

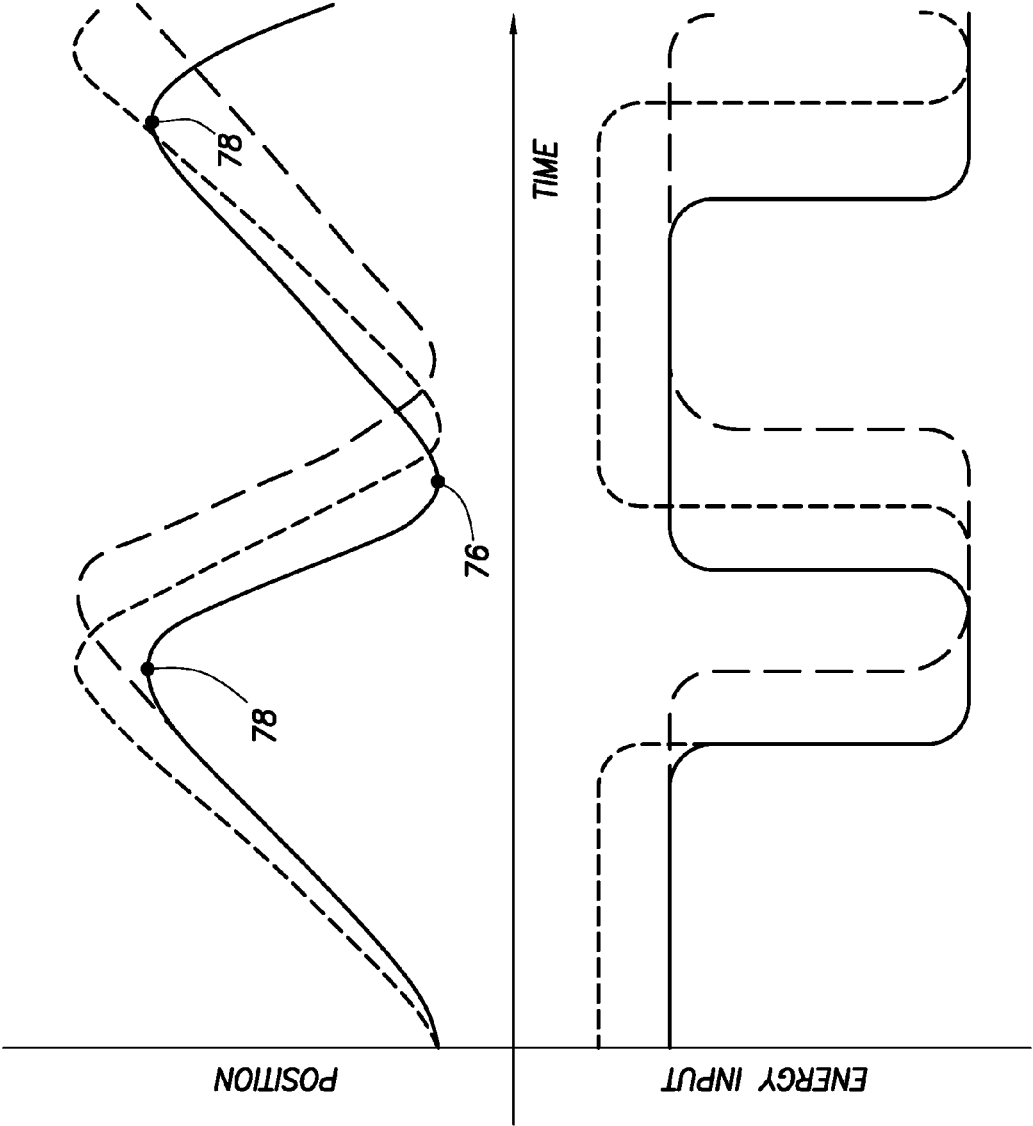


FIG.12

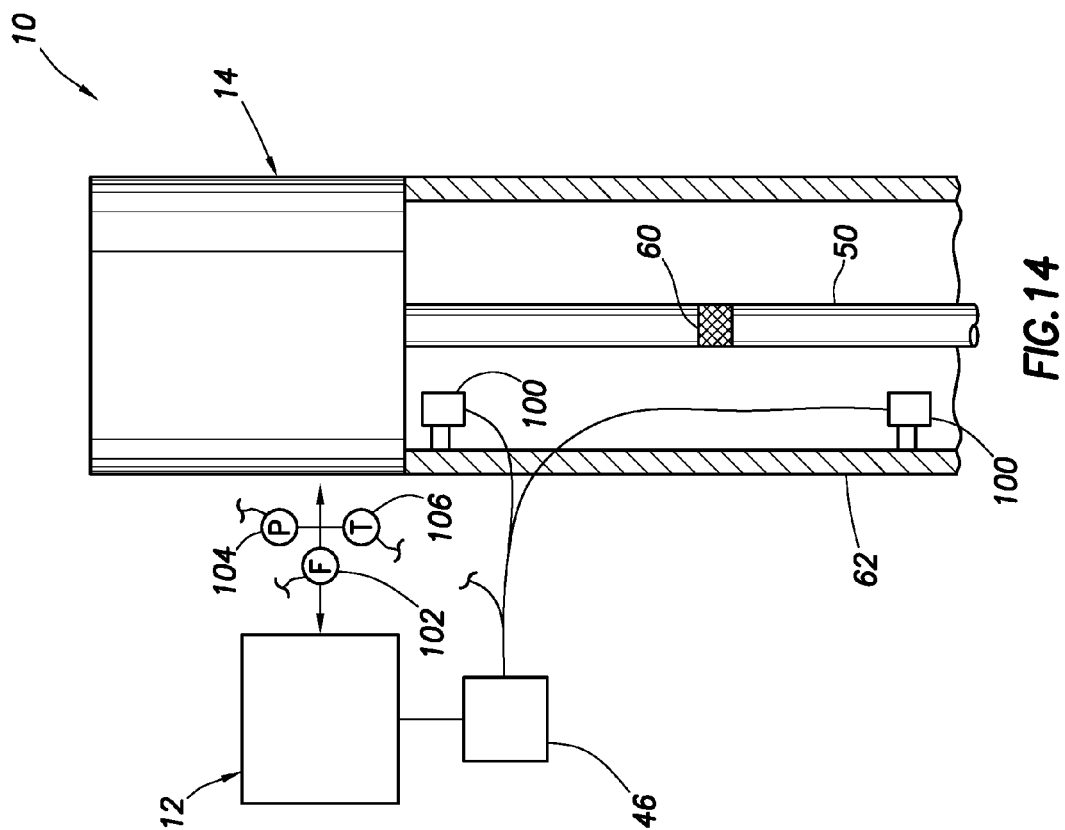


FIG. 13

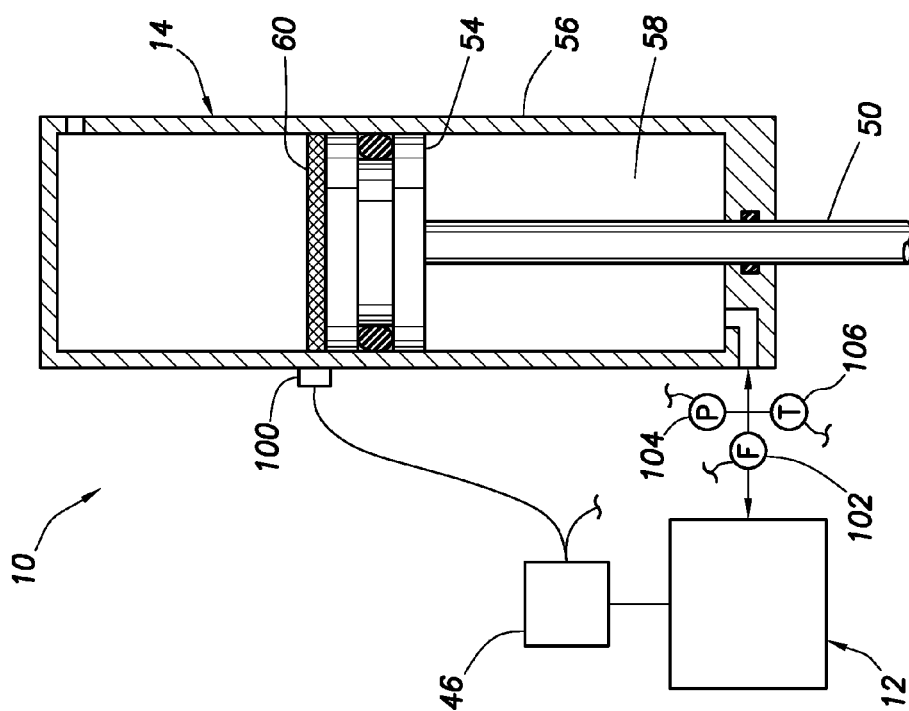


FIG. 14

OPERATIONAL CONTROL OF WELLSITE PUMPING UNIT WITH DISPLACEMENT DETERMINATION

BACKGROUND

[0001] This disclosure relates generally to equipment utilized and operations performed in conjunction with a subterranean well and, in one example described below, more particularly provides a well pumping system and associated method.

[0002] Reservoir fluids can sometimes flow to the earth's surface when a well has been completed. However, with some wells, reservoir pressure may be insufficient (at the time of well completion or thereafter) to lift the fluids (in particular, liquids) to the surface. In those circumstances, technology known as "artificial lift" can be employed to bring the fluids to or near the surface (such as a subsea production facility or pipeline, a floating rig, etc.).

[0003] Various types of artificial lift technology are known to those skilled in the art. In one type of artificial lift, a downhole pump is operated by reciprocating a string of "sucker" rods deployed in a well. An apparatus (such as, a walking beam-type pump jack or a hydraulic actuator) located at the surface can be used to reciprocate the rod string.

[0004] Therefore, it will be readily appreciated that improvements are continually needed in the arts of constructing and operating artificial lift systems. Such improvements may be useful for lifting oil, water, gas condensate or other liquids from wells, may be useful with various types of wells (such as, gas production wells, oil production wells, water or steam flooded oil wells, geothermal wells, etc.), and may be useful for any other application where reciprocating motion is desired.

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] FIG. 1 is a representative partially cross-sectional view of an example of a well pumping system and associated method which can embody principles of this disclosure.

[0006] FIGS. 2-5 are representative views of actuator examples and continuous position sensor examples.

[0007] FIGS. 6-9 are representative graphs of example velocity profiles.

[0008] FIGS. 10 & 11 are representative flowcharts for techniques of controlling operation of the well pumping system.

[0009] FIG. 12 is a representative example graph of position and energy input versus time, with modifications thereof.

[0010] FIGS. 13 & 14 are representative views of further actuator examples.

DETAILED DESCRIPTION

[0011] Representatively illustrated in FIG. 1 is a well pumping system 10 and associated method for use with a subterranean well, which system and method can embody principles of this disclosure. However, it should be clearly understood that the well pumping system 10 and method are merely one example of an application of the principles of this disclosure in practice, and a wide variety of other examples are possible. Therefore, the scope of this disclosure is not limited at all to the details of the system 10 and method as described herein or depicted in the drawings.

[0012] In the FIG. 1 example, a power source 12 is used to supply energy to an actuator 14 mounted on a wellhead 16. In response, the actuator 14 reciprocates a rod string 18 extending into the well, thereby operating a downhole pump 20.

[0013] The rod string 18 may be made up of individual sucker rods connected to each other, although other types of rods or tubes may be used, the rod string 18 may be continuous or segmented, a material of the rod string 18 may comprise steel, composites or other materials, and elements other than rods may be included in the string. Thus, the scope of this disclosure is not limited to use of any particular type of rod string, or to use of a rod string at all. It is only necessary for purposes of this disclosure to communicate reciprocating motion from the actuator 14 to the downhole pump 20, and it is therefore within the scope of this disclosure to use any structure capable of such transmission.

[0014] The downhole pump 20 is depicted in FIG. 1 as being of the type having a stationary or "standing" valve 22 and a reciprocating or "traveling" valve 24. The traveling valve 24 is connected to, and reciprocates with, the rod string 18, so that fluid 26 is pumped from a wellbore 28 into a production tubing string 30. However, it should be clearly understood that the downhole pump 20 is merely one example of a wide variety of different types of pumps that may be used with the well pumping system 10 and method of FIG. 1, and so the scope of this disclosure is not limited to any of the details of the downhole pump described herein or depicted in the drawings.

[0015] The wellbore 28 is depicted in FIG. 1 as being generally vertical, and as being lined with casing 32 and cement 34. In other examples, a section of the wellbore 28 in which the pump 20 is disposed may be generally horizontal or otherwise inclined at any angle relative to vertical, and the wellbore section may not be cased or may not be cemented. Thus, the scope of this disclosure is not limited to use of the well pumping system 10 and method with any particular wellbore configuration.

[0016] In the FIG. 1 example, the fluid 26 originates from an earth formation 36 penetrated by the wellbore 28. The fluid 26 flows into the wellbore 28 via perforations 38 extending through the casing 32 and cement 34. The fluid 26 can be a liquid, such as oil, gas condensate, water, etc. However, the scope of this disclosure is not limited to use of the well pumping system 10 and method with any particular type of fluid, or to any particular origin of the fluid.

[0017] As depicted in FIG. 1, the casing 32 and the production tubing string 30 extend upward to the wellhead 16 at or near the earth's surface 40 (such as, at a land-based wellsite, a subsea production facility, a floating rig, etc.). The production tubing string 30 can be hung off in the wellhead 16, for example, using a tubing hanger (not shown). Although only a single string of the casing 32 is illustrated in FIG. 1 for clarity, in practice multiple casing strings and optionally one or more liner strings (a liner string being a pipe that extends from a selected depth in the wellbore 28 to a shallower depth, typically sealingly "hung off" inside another pipe or casing) may be installed in the well.

[0018] In the FIG. 1 example, a rod blowout preventer stack 42 and a stuffing box 44 are connected between the actuator 14 and the wellhead 16. The rod blowout preventer stack 42 includes various types of blowout preventers (BOP's) configured for use with the rod string 18. For

example, one blowout preventer can prevent flow through the blowout preventer stack 42 when the rod string 18 is not present therein, and another blowout preventer can prevent flow through the blowout preventer stack 42 when the rod string 18 is present therein. However, the scope of this disclosure is not limited to use of any particular type or configuration of blowout preventer stack with the well pumping system 10 and method of FIG. 1.

[0019] The stuffing box 44 includes an annular seal (not visible in FIG. 1) about an upper end of the rod string 18. A reciprocating rod member 50 of the actuator 14 connects to the rod string 18 above the annular seal, although in other examples a connection between the rod member 50 and the rod string 18 may be otherwise positioned.

[0020] The power source 12 may be connected directly to the actuator 14, or it may be positioned remotely from the actuator 14 and connected with, for example, suitable electrical cables, mechanical linkages, hydraulic hoses or pipes. Operation of the power source 12 is controlled by a control system 46.

[0021] The control system 46 may allow for manual or automatic operation of the actuator 14 via the power source 12, based on operator inputs and measurements taken by various sensors. The control system 46 may be separate from, or incorporated into, the actuator 14 or the power source 12. In one example, at least part of the control system 46 could be remotely located or web-based, with two-way communication between the actuator 14, the power source 12 and the control system 46 being via, for example, satellite, wireless or wired transmission.

[0022] The control system 46 can include various components, such as a programmable controller, input devices (e.g., a keyboard, a touchpad, a data port, etc.), output devices (e.g., a monitor, a printer, a recorder, a data port, indicator lights, alert or alarm devices, etc.), a processor, software (e.g., an automation program, customized programs or routines, etc.) or any other components suitable for use in controlling operation of the actuator 14 and the power source 12. The scope of this disclosure is not limited to any particular type or configuration of a control system.

[0023] In operation of the well pumping system 10 of FIG. 1, the control system 46 causes the power source 12 to increase energy input to the actuator 14, in order to raise the rod string 18. Conversely, the energy input to the actuator 14 is reduced or removed, in order to allow the rod string 18 to descend. Thus, by alternately increasing and decreasing energy input to the actuator 14, the rod string 18 is reciprocated, the downhole pump 20 is actuated and the fluid 26 is pumped out of the well.

[0024] Note that, when energy input to the actuator 14 is decreased to allow the rod string 18 to displace downward (as viewed in FIG. 1), the energy input may not be decreased to zero. Instead, a "balance" energy level may be maintained in the actuator 14 to nominally offset a load due to the rod string 18 being suspended in the well (e.g., a weight of the rod string, taking account of buoyancy, inclination of the wellbore 28, friction, well pressure, etc.).

[0025] In this manner, the power source 12 is not required to increase energy input to the actuator 14 from zero to that necessary to displace the rod string 18 upwardly (along with the displaced fluid 26), and then reduce the energy input back to zero, for each reciprocation of the rod string 18. Instead, the power source 12 only has to increase energy input to the actuator 14 sufficiently greater than the balance

energy level to displace the rod string 18 to its upper stroke extent, and then reduce the energy input to the actuator 14 back to the balance energy level to allow the rod string 18 to displace back to its lower stroke extent.

[0026] Note that it is not necessary for the balance energy level in the actuator 14 to exactly offset the load exerted by the rod string 18. In some examples, it may be advantageous for the balance energy level to be somewhat less than that needed to offset the load exerted by the rod string 18. In addition, it can be advantageous in some examples for the balance energy level to change over time. Thus, the scope of this disclosure is not limited to use of any particular or fixed balance energy level, or to any particular relationship between the balance energy level, any other force or energy level and/or time.

[0027] A reciprocation speed of the rod string 18 will affect a flow rate of the fluid 26. Generally speaking, the faster the reciprocation speed at a given length of stroke of the rod string 18, the greater the flow rate of the fluid 26 from the well (to a point).

[0028] It can be advantageous to control the reciprocation speed, instead of reciprocating the rod string 18 as fast as possible. For example, a fluid interface 48 in the wellbore 28 can be affected by the flow rate of the fluid 26 from the well.

[0029] The fluid interface 48 could be an interface between oil and water, gas and water, gas and gas condensate, gas and oil, steam and water, or any other fluids or combination of fluids.

[0030] If the flow rate is too great, the fluid interface 48 may descend in the wellbore 28, so that eventually the pump 20 will no longer be able to pump the fluid 26 (a condition known to those skilled in the art as "pump-off"). On the other hand, it is typically desirable for the flow rate of the fluid 26 to be at a maximum level that does not result in pump-off. In addition, a desired flow rate of the fluid 26 may change over time (for example, due to depletion of a reservoir, changed offset well conditions, water or steam flooding characteristics, etc.).

[0031] A "gas-locked" downhole pump 20 can result from a pump-off condition, whereby gas is received into the downhole pump 20. The gas is alternately expanded and compressed in the downhole pump 20 as the traveling valve 24 reciprocates, but the fluid 26 cannot flow into the downhole pump 20, due to the gas therein.

[0032] In the FIG. 1 well pumping system 10 and method, the control system 46 can automatically control operation of the actuator 14 via the power source 12 to regulate the reciprocation speed, so that pump-off is avoided, while achieving any of various desirable objectives. Those objectives may include maximum flow rate of the fluid 26, optimized rate of electrical power consumption, reduction of peak electrical loading, etc. However, it should be clearly understood that the scope of this disclosure is not limited to pursuing or achieving any particular objective or combination of objectives via automatic reciprocation speed regulation by the control system 46.

[0033] As mentioned above, the power source 12 is used to variably supply energy to the actuator 14, so that the rod string 18 is displaced alternately to its upper and lower stroke extents. These extents do not necessarily correspond to maximum possible upper and lower displacement limits of the rod string 18 or the pump 20.

[0034] For example, it is typically undesirable for a valve rod bushing 25 above the traveling valve 24 to impact a

valve rod guide **23** above the standing valve **22** when the rod string **18** displaces downward (a condition known to those skilled in the art as “pump-pound”). Thus, it is preferred that the rod string **18** be displaced downward only until the valve rod bushing **25** is near its maximum possible lower displacement limit, so that it does not impact the valve rod guide **23**.

[0035] On the other hand, the longer the stroke distance (without impact), the greater the productivity and efficiency of the pumping operation (within practical limits), and the greater the compression of fluid between the standing and traveling valves **22**, **24** (e.g., to avoid gas-lock). In addition, a desired stroke of the rod string **18** may change over time (for example, due to gradual lengthening of the rod string **18** as a result of lowering of a liquid level (such as at fluid interface **48**) in the well, etc.).

[0036] In the FIG. 1 well pumping system **10** and method, the control system **46** can automatically control operation of the power source **12** to regulate the upper and lower stroke extents of the rod string **18**, so that pump-pound is avoided, while achieving any of various desirable objectives. Those objectives may include maximizing rod string **18** stroke length, maximizing production, minimizing electrical power consumption rate, minimizing peak electrical loading, etc. However, it should be clearly understood that the scope of this disclosure is not limited to pursuing or achieving any particular objective or combination of objectives via automatic stroke extent regulation by the control system **46**.

[0037] In the FIG. 1 example, the system **10** includes a continuous position sensor **52** in communication with the control system **46**. The continuous position sensor **52** is capable of continuously detecting a position of a reciprocating member of the actuator **14** (such as the rod member **50** or another member).

[0038] An output of the continuous position sensor **52** can be useful to achieve a variety of objectives, such as, controlling stroke distance, speed and extents to maximize production and efficiency, minimize electrical power consumption and/or peak electrical loading, maximize useful life of the rod string **18**, etc.

[0039] However, the scope of this disclosure is not limited to pursuing or achieving any particular objective or combination of objectives via use of a continuous position sensor.

[0040] As used herein, the term “continuous” is used to refer to a substantially uninterrupted sensing of position by the sensor **52**. For example, when used to continuously detect the position of the rod member **50**, the sensor **52** can detect the member’s position during all portions of its reciprocating motion, and not just at certain discrete points (such as, at the upper and lower stroke extents). However, a continuous position sensor may have a particular resolution (e.g., 0.001-0.1 mm) at which it can detect the position of a member. Accordingly, the term “continuous” does not require an infinitely small resolution.

[0041] Using the continuous position sensor **52**, the control system **46** can be provided with an accurate measurement of an actuator **14** member position at any point in the member’s reciprocation, thereby dispensing with any need to perform calculations based on discrete detections of position. It will be appreciated by those skilled in the art that actual continuous position detection can be more precise than such calculations of position, since various factors (including known and unknown factors, such as, temperature, fluid compressibility, fluid leakage, etc.) can affect the calculations. However, such calculations of position may be

used in keeping with the principles of this disclosure, either in conjunction with, or instead of, continuous position measurements.

[0042] By continuously sensing the position of a member of the actuator **14** at or near a top of the rod string **18**, characteristics of the rod string’s reciprocating displacement are communicated to the control system **46** at each point in the rod string’s reciprocating displacement. The control system **46** can, thus, determine whether the rod string’s **18** position, speed and acceleration correspond to desired preselected values.

[0043] If there is a discrepancy between the desired preselected values and the rod string’s reciprocating displacement as detected by the sensor **52**, the control system **46** can change how energy is supplied to the actuator **14** by the power source **12**, so that the reciprocating displacement will conform to the desired preselected values. For example, the control system **46** may change a level, timing, frequency, duration, etc., of the energy input to the actuator **14**, in order to change the rod string’s upper or lower stroke extent, or velocity or acceleration at any point in the rod string’s reciprocating displacement.

[0044] Note that the desired preselected values may change over time. As mentioned above, it may be desirable to change the upper or lower stroke extent, or the pumping rate, during the pumping operation, for example, due to the level of the fluid interface **48** changing, reservoir depletion over time, detection of a pump-off, pump-pound or gas-lock condition, etc.

[0045] Referring additionally now to FIGS. 2-5, examples of different actuators **14** that may be used with the system **10** and method are representatively illustrated. These examples are not limiting of the scope of this disclosure, but are instead provided to demonstrate that the principles disclosed herein are applicable to a wide variety of different actuator configurations.

[0046] In FIG. 2, the actuator **14** includes a piston member **54** sealingly and reciprocably disposed in a generally cylindrical housing **56**. The rod member **50** is connected to the piston member **54** and extends downwardly through a lower end of the housing **56**.

[0047] The power source **12** in this example comprises a hydraulic pressure source (such as, a hydraulic pump and associated equipment) for supplying energy in the form of fluid pressure to a chamber **58** in the housing **56** below the piston member **54**. To raise the piston member **54**, the rod member **50** and the rod string **18**, hydraulic fluid at increased pressure is supplied to the chamber **58** from the power source **12**. To cause the piston member **54**, rod member **50** and rod string **18** to descend, the pressure in the chamber **58** is reduced (with hydraulic fluid being returned from the chamber to the power source **12**).

[0048] In this example, the sensor **52** is attached externally to the housing **56**. In other examples, the sensor **52** could be positioned internal to, or in a wall of, the housing **56**. The scope of this disclosure is not limited to any particular position or orientation of the sensor **52**.

[0049] A magnet **60** is attached to, and displaces with, the piston member **54**. A position of the magnet **60** (and, thus, of the piston member **54**) is continuously sensed by the sensor **52** during reciprocating displacement of the piston member. A suitable magnet for use in the actuator **14** is a neodymium magnet (such as, a neodymium-iron-boron

magnet) in ring form. However, other types and shapes of magnets may be used in keeping with the principles of this disclosure.

[0050] A suitable linear position sensor (or linear variable displacement transducer) for use as the sensor **52** in the system **10** is available from Rota Engineering Ltd. of Manchester, United Kingdom. Other suitable position sensors are available from Hans Turck GmbH & Co. KG of Germany, and from Balluff GmbH of Germany. However, the scope of this disclosure is not limited to use of any particular sensor with the system **10**.

[0051] In the FIG. 3 example, the sensor **52** is not mounted external to the housing **56**, but is instead positioned internal to another housing **62** at a lower end of the actuator **14**. In this manner, the sensor **52** does not have to detect the position of the magnet **60** through a wall of the housing **62**, and can be in closer proximity to the magnet.

[0052] In addition, the magnet **60** in the FIG. 3 example is mounted to the rod member **50**, instead of to the piston member **54**. Thus, the position of any reciprocating member of the actuator **14** can be continuously detected using an appropriately configured sensor **52**. Note that the actuator **14** in the FIG. 3 example is not necessarily a hydraulic actuator.

[0053] In the FIG. 4 example, the actuator **14** comprises a cable, ribbon, tape, belt or other flexible member **64** stored on a spool **66**. The flexible member **64** extends upwardly about a sheave member **68** and downwardly to a connection with the rod member **50**.

[0054] The spool **66** is driven by an electric motor **70** of the power source **12**, so that the flexible member **64** is alternately wound and unwound about the spool, to thereby alternately raise and lower the rod member **50**. In this example, the power source **12** and the actuator **14** may be conveniently combined, with the control system **46** controlling operation of the motor **70** to achieve a desired reciprocating displacement of the rod member **50** and rod string **18** connected thereto (see FIG. 1).

[0055] The sensor **52** in the FIG. 4 example comprises a rotary encoder capable of continuously detecting a rotational position of the sheave member **68**. In this manner, the position, velocity and acceleration of the sheave member **68**, the flexible member **64** and the rod member **50** (and the upper end of the rod string **18**) can be continuously known.

[0056] The FIG. 5 example is similar in some respects to the FIG. 4 example, but the actuator **14** in the FIG. 5 example comprises a hydraulic cylinder **72** for alternately raising and lowering the sheave member **68** to thereby alternately raise and lower the rod member **50**. Similar to the FIG. 2 example, the FIG. 5 power source **12** comprises a hydraulic pressure source to alternately increase and decrease fluid pressure applied to the cylinder **72**.

[0057] The sensor **52** in the FIG. 5 example can comprise an infrared or ultrasonic sensor for sensing the position of the sheave member **68** as it reciprocates upward and downward. Alternatively, the sensor **52** could sense the position of another member of the actuator **14** as it reciprocally displaces.

[0058] Referring additionally now to FIGS. 6-9, examples of velocity profiles **74** that may be used with the system **10** and method are representatively illustrated as graphs of velocity versus position. The velocity profiles **74** may be used with other systems and methods, in keeping with the scope of this disclosure.

[0059] Since the position of a reciprocating member of the actuator **14** (or an upper end of the rod string **18**) can be detected at any point in the displacement of the member, the control system **46** can readily determine the velocity of the member at any point in the displacement of the member (velocity equals the derivative of position over time). This determination of velocity may be made by the control system **46**, or in some examples the sensor **52** may provide an output of instantaneous velocity, as well as position. In other examples, acceleration (equal to the derivative of velocity over time) may also be determined by the control system **46**, or may be provided as an output of the sensor **52**.

[0060] In the FIG. 6 example, an upstroke begins at zero velocity and at a lower stroke extent **76**. The velocity rapidly increases, and then levels off once the rod string **18** is displacing upward at a desired rate. Note that the entire rod string **18** does not displace as an infinitely rigid member. Instead, the rod string **18** has some elasticity and there are dampening effects present (such as, friction between the rod string **18** and the tubing string **30**, etc.), so that the reciprocating displacement of a lower end of the rod string at the downhole pump **20** is not the same as the reciprocating displacement of the upper end of the rod string at the surface.

[0061] Accordingly, a wave equation in the rod string **18** can be solved, so that the velocity profile **74** to be maintained at the surface corresponds to a desired velocity profile at the downhole pump **20**. The Everitt-Jennings algorithm may be used to solve the wave equation (see Everitt, T. A. and Jennings, J. W., *An Improved Finite-Difference Calculation of Downhole Dynamometer Cards for Sucker-Rod Pumps*, SPE 18189, February 1992). Although the full Everitt-Jennings algorithm produces a calculation of load versus position, the algorithm can be used to calculate velocity (and acceleration) as an intermediate step.

[0062] Thus, working “backward” from a desired velocity profile at the downhole pump **20**, solution of the wave equation produces a corresponding desired velocity profile at the surface (e.g., at a reciprocating member of the actuator **14**, or an upper end of the rod string **18**). The desired velocity profile (either the desired velocity profile at the surface, or the desired velocity profile at the downhole pump **20** if the wave equation is to be solved by the control system **46**) may be input to the control system, and the control system can then operate the power source **12** and the actuator **14**, so that any deviation of the velocity profile as detected by the sensor **52** from the desired velocity profile is minimized.

[0063] Referring again to the velocity profile **74** of FIG. 6, it will be appreciated that, when the velocity increases rapidly from the lower stroke extent **76**, the upper end of the rod string **18** will begin displacing before the lower end of the rod string. Thus, the rapid velocity increase can be used to obtain displacement of the lower end of the rod string **18** relatively quickly, and then the velocity can level off once the entire rod string is displacing.

[0064] Near an end of the upstroke, the velocity rapidly decreases to zero velocity at the upper stroke extent **78**. Note that there is desirably a slope to the profile **74** prior to the upper stroke extent **78**, instead of an abrupt reversal of direction, which would be inefficient and possibly damaging to system components. Similarly, although the profile **74** is depicted as being composed of straight line segments, in practice the profile would have smoother transitions.

[0065] The downstroke in the FIG. 6 example is a mirror image of the upstroke. However, it is not necessary for this to be the case and, as discussed more fully below, it can be beneficial for there to be differences in the velocity profile 74 between the upstroke and the downstroke.

[0066] In the FIG. 7 example, a slope of the velocity profile 74 changes multiple times on the upstroke after the lower stroke extent 76 and prior to the upper stroke extent 78. The downstroke is again a mirror image of the upstroke, and so the velocity profile slope changes multiple times on the downstroke after the upper stroke extent 78 and prior to the lower stroke extent 76.

[0067] Such changes in the velocity profile 74 may be used to account for the fact that progressively more of the rod string 20 is being displaced over time after the upper and lower stroke extents 78, 76, and that progressively more of the rod string is being slowed to zero velocity prior to the upper and lower stroke extents.

[0068] In the FIG. 8 example, the downstroke is a reversed mirror image of the upstroke, with multiple velocity profile slope changes after each of the lower and upper stroke extents 76, 78, and with a single velocity slope change prior to each of the lower and upper stroke extents. This example demonstrates that a wide variety of different shapes are possible for the velocity profile 74.

[0069] In the FIG. 9 example, a maximum velocity (absolute value) on the downstroke is much less than a maximum velocity on the upstroke. This velocity profile 74 can be beneficial in avoiding a gas-lock condition, since the reduced downstroke velocity can provide more time for the downhole pump 20 to fill, as well as provide more precise control over the lower stroke extent at the downhole pump (momentum effects on the downward moving rod string 18 are more controllable and predictable, as compared to the upstroke). In other examples, a reduced velocity may be provided on the upstroke to reduce stresses in the rod string 18. Thus, the scope of this disclosure is not limited to any particular velocity profile, or to any particular relationship between upstroke and downstroke velocity profiles.

[0070] Since the control system 46 knows the velocity at any point during reciprocating displacement (the velocity being provided by the continuous position sensor 52 output, or being calculated by the control system based on the sensor output), the control system can at any point during the reciprocating displacement compare the detected velocity to the desired velocity, and vary operation of the power source 12 and the actuator 14 as needed to minimize any discrepancies. In this manner, the control system 46 can maintain a preselected desired velocity profile at a member of the actuator 14, the rod string 18 at the surface, and the rod string at the downhole pump 20.

[0071] In addition, the velocity profile 74 can be changed as needed to achieve other objectives. For example, if it is desired to change the position of the lower and/or upper stroke extents 76, 78, the velocity profile 74 can be appropriately changed, and the control system 46 will accordingly change its operation of the power source 12 and the actuator 14. Similarly, the velocity profile 74 can be changed, if desired, to achieve increased efficiency, increased production, reduced rod string wear, increased rod string usable life, reduced electricity consumption or peak load, or in response to changed conditions (such as, depletion of a reservoir, pump-off, pump-pound, gas-lock, etc.).

[0072] Referring additionally now to FIGS. 10 & 11, an example technique or method 80 for controlling operation of the well pumping system 10 is representatively illustrated in flowchart form. In this method 80, it is desired to change one or both of the lower and upper stroke extents 76, 78 at the surface, in order to achieve a corresponding (although not necessarily equal) change in stroke extent(s) of the rod string 18 at the downhole pump 20.

[0073] Similar methods or techniques may be used to achieve other changes in the reciprocating displacement of the rod string 18 at the downhole pump 20. For example, similar methods may be used to change velocity, acceleration or stroke length of the rod string 18 at the downhole pump 20. Thus, the scope of this disclosure is not limited to any particular change made in the reciprocating displacement of the rod string 18.

[0074] In step 82 of the method 80, the stroke extents 76, 78 are detected at the surface (for example, using the continuous position sensor 52). The stroke extents 76, 78 in this example correspond to minimum and maximum displacement values detected by the sensor 52, and to positions at which the velocity is zero.

[0075] The continuous position sensor 52 may detect the position of a member of the actuator 14 (such as, the rod member 50, the piston member 54, the sheave member 68 or another member), or the upper end of the rod string 18 (for example, by positioning the sensor 52 in or on the stuffing box 44). The scope of this disclosure is not limited to the position of any particular component being detected by the continuous position sensor 52.

[0076] In step 84, a desired change to one or both of the stroke extents 76, 78 is determined. For example, it may be desired to increase a stroke distance by changing one or both of the stroke extents 76, 78, in order to increase the pumping rate. As another example, it may be desired to raise the lower stroke extent at the downhole pump 20, in order to alleviate a pump-pound condition. As yet another example, it may be desired to change one or both of the stroke extents at the downhole pump 20, in order to increase a work output of the system 10.

[0077] The determination of the desired change to one or both of the stroke extents 76, 78 may be made automatically by the control system 46 (for example, in response to detection of a pump-pound condition, detection of a pump-off condition, detection of a reduction in work output, etc.), or as part of a pre-programmed routine (for example, to periodically adjust the lower stroke extent, so that maximum compression is achieved on the downstroke to avoid gas-lock). Alternatively, the determination may be made elsewhere and then input to the control system 46 by a user.

[0078] In step 86, the control system 46 modifies the operation of the power source 12 and actuator 14 as needed to achieve the desired change. Since the continuous position sensor 52 provides to the control system 46 a continuous output of position during the reciprocating displacement in this example, the control system can make any appropriate changes in operation while the reciprocating displacement continues, and without any need to change the sensor's position relative to the actuator 14 or any other component of the system 10.

[0079] The control system 46 can change operation of the power source 12 and actuator 14, for example, by varying a duration, level, relative timing, frequency, etc., of energy

supplied to the actuator from the power supply 12. An example is described more fully below in relation to the graph illustrated in FIG. 12.

[0080] In FIG. 11, the step 84 of determining the desired change to the stroke extent(s) at the surface is more particularly expanded for a situation where it is desired to increase a work output at the downhole pump 20. For example, work output at the downhole pump 20 may be monitored over time, and a decrease in work output can be indicative of a pump-pound condition. Thus, if a decrease in work output at the downhole pump 20 is detected, the method 80 can be used to change the stroke extent(s) as needed to alleviate the pump-pound condition and thereby increase the work output.

[0081] As mentioned above, the Elliott-Jennings algorithm may be used to solve the wave equation in the rod string 18 and determine load (force) versus position (displacement) at the downhole pump 20. Since work equals force applied over a distance, a force versus displacement curve at the downhole pump 20 (also known to those skilled in the art as a “downhole card”) can be integrated to determine work output.

[0082] In one technique, the lower stroke extent of the rod string 18 at the downhole pump 20 can be incrementally raised by the control system 46 to thereby alleviate the pump-pound condition and increase the work output. Steps 88-92 can be repeated for each increment, until the work output is sufficiently increased.

[0083] For example, the control system 46 can monitor the work output in step 88. In step 90, a desired change in the lower stroke extent (the amount of the incremental raising) at the downhole pump 20 is determined. This desired change in the lower stroke extent at the downhole pump 20 may be determined separately for each occurrence of a pump-pound condition, or it may be preselected (for example, by user input or initial programming of the control system 46).

[0084] In step 92, a desired change in the lower stroke extent at the surface corresponding to the desired change in the lower stroke extent at the downhole pump 20 is determined. Again, the solution to the wave equation in the rod string 18 can be used to relate reciprocating displacement at the downhole pump 20 to reciprocating displacement at the surface (for example, using the Elliott-Jennings algorithm or another suitable algorithm), in order to determine the desired change in the lower stroke extent at the surface.

[0085] The control system 46 can then modify operation of the power source 12 and actuator 14 as needed to achieve the desired change (as in step 86). The continuous position sensor 52 output will confirm whether the modified operation in fact achieves the desired change, and the control system 46 will make further modifications as needed to minimize any discrepancies between the detected change and the desired change in lower stroke extent at the surface.

[0086] Referring additionally now to FIG. 12, an example graph of position and energy input versus time is representatively illustrated. The graph demonstrates how characteristics of the reciprocating displacement can be varied by modifying the energy input to the actuator 14 from the power source 12.

[0087] As discussed above, the control system 46 can control the energy input to the actuator 14 to achieve various objectives. In the FIG. 12 example, an upper stroke extent (e.g., of an actuator member, or the rod string 18 at the

surface or at the downhole pump) is desired to be raised, and two different ways of achieving this objective are depicted in FIG. 12.

[0088] In a solid line, the position (for example, as detected by the continuous position sensor 52 and optionally resulting from a solution of the wave equation in the rod string 18) is depicted over time prior to modification of the energy input to the actuator 14. The energy input over time is also depicted as a solid line prior to modification.

[0089] Note that the upper stroke extent 78 occurs after the energy input periodically decreases to a minimum level, and the lower stroke extent 76 occurs after the energy input periodically increases to a maximum level. This is due to inertia and friction effects on the rod string 18, so that the rod string does not immediately begin to displace upward when the energy input is increased, and the rod string does not immediately begin to displace downward when the energy input is decreased.

[0090] One technique of raising the upper stroke extent 78 is depicted in relatively long dashed lines in FIG. 12. In this technique, a duration of the maximum energy input level is increased, so that the rod string 18 displaces upward over a correspondingly increased duration. Since the rod string 18 displaces upward longer, the upper stroke extent 78 is raised.

[0091] Another technique of raising the upper stroke extent 78 is depicted in relatively short dashed lines in FIG. 12. In this technique, the maximum energy input level is increased, so that the acceleration and velocity of the rod string 18 on the upstroke is correspondingly increased. Since the rod string 18 displaces faster upward, the upper stroke extent 78 is raised.

[0092] The example of FIG. 12 demonstrates that a variety of different techniques and combinations of techniques may be used by the control system 46 to modify the reciprocating displacement characteristics of the rod string 18. Such techniques may be used to modify the velocity (including upstroke and downstroke velocity profiles), acceleration (including upstroke and downstroke acceleration profiles), lower and upper stroke extents, and stroke length of the rod string 18 at surface and at the downhole pump 20.

[0093] As mentioned above, use of the continuous position sensor 52 with the system 10 is not necessary. In further examples described below, other methods of determining the position of a member of the actuator 14 or an upper end of the rod string 18 are provided. However, it should be clearly understood that the scope of this disclosure is not limited to any particular method or technique for determining position, displacement, velocity, acceleration or any other characteristic of reciprocating motion.

[0094] Referring additionally now to FIG. 13, another example of the actuator 14 in the well pumping system 10 and associated method is representatively illustrated. The FIG. 13 example is similar in most respects to the FIG. 2 example, but the continuous position sensor 52 is not used in the FIG. 13 example. However, the continuous position sensor 52 could be used with the FIG. 13 example in keeping with the principles of this disclosure.

[0095] As depicted in FIG. 13, a discrete position sensor 100 is used to detect when the magnet 60 (and, thus, the piston member 54 or another reciprocating member of the actuator 14, or the upper end of the rod string 18) is at a particular position. The sensor 100 is shown as being disposed between the upper and lower stroke extents of the

piston **54**, but in other examples, the sensor **100** could be located at or near the upper or lower stroke extent.

[0096] Only a single sensor **100** is depicted in FIG. **13**. However, in other examples, other numbers of sensors may be used. For example, a sensor **100** could be located at or near the upper stroke extent, and another sensor **100** could be located at or near the lower stroke extent. The scope of this disclosure is not limited to use of any particular number or location of sensors in or on the actuator **14**.

[0097] A suitable magnetic field sensor for use as the sensor **100** is a Pepperl MB-F32-A2 magnetic flux sensing switch marketed by Pepperl+Fuchs North America of Twinsburg, Ohio USA. However, other magnetic field sensors or other types of discrete position sensors may be used in keeping with the principles of this disclosure.

[0098] The sensor **100** is used in conjunction with a flowmeter **102** in the FIG. **13** example to continuously determine the position of the piston member **54** (or another reciprocating member of the actuator **14**, or the upper end of the rod string **18**). The flowmeter **102** measures flow of fluid between the power source **12** and the actuator **14**.

[0099] The flowmeter **102** may be a volumetric or mass flowmeter. In this example, the flowmeter **102** is a positive displacement volumetric flowmeter.

[0100] However, other types of flow measurements may be made by the flowmeter **102** in keeping with the scope of this disclosure.

[0101] Assuming that the fluid displaced into and out of the chamber **58** is incompressible and there is no fluid leakage, a certain fluid volume will correspond to a certain displacement of the piston member **54** (displacement equals fluid volume divided by piston area). If a mass flowmeter is used, the fluid volume can be determined from the density of the fluid (volume equals mass divided by density).

[0102] Combined with the position sensing provided by the sensor **100**, the position of the piston member **54** at every point in its reciprocating displacement can be readily determined (current position equals previous position plus displacement). The sensor **100** can also be used for calibration of the flowmeter **102**, for example, to compensate for compressibility of the fluid, leakage of fluid, etc.

[0103] Thus, using the sensor **100** and flowmeter **102**, the position, displacement, velocity (derivative of displacement over time) and acceleration (derivative of velocity over time) of the piston member **54** can be known continuously during the reciprocation of the rod string **18**. The control system **46** can use this information as described above to control the reciprocating displacement of the rod string **18**.

[0104] If the assumption that the fluid is incompressible results in an unacceptable level of inaccuracy in calculating and controlling the reciprocating displacement, additional sensors may be used to improve accuracy. For example, a pressure sensor **104** can be used to monitor pressure in the chamber **58**, so that compressibility of the fluid can be compensated for in the displacement calculation. A temperature sensor **106** can also be used to monitor the temperature of the fluid, for example, in the event that a gas is entrained in the fluid (so that its volume changes substantially in response to temperature changes), or the fluid is of a type (such as silicone-based hydraulic fluid) that has a relatively high coefficient of thermal expansion. If a mass flowmeter is used for the flowmeter **102**, it will be appreciated that volume calculations will be aided by the temperature mea-

surements provided by the temperature sensor **106** (since for most fluids density changes in response to temperature changes).

[0105] Referring additionally now to FIG. **14**, another example of the actuator **14** in the system **10** is representatively illustrated. The FIG. **14** example is similar in most respects to the example of FIG. **3**, but in the FIG. **14** example multiple discrete position sensors **100** are used in place of the continuous position sensor **52**, and the flowmeter **102**, pressure sensor **104** and temperature sensor **106** are used for improved accuracy.

[0106] As depicted in FIG. **14**, one of the position sensors **100** is located at or near each of the upper and lower stroke extents of the magnet **60**. By detecting arrival of the magnet **60** at multiple relatively widely spaced apart locations, position calculations based on measurements made by the flowmeter **102** (with or without use of the other sensors **104**, **106**) are more readily calibrated. For example, it will be appreciated that the piston area of the piston member **54** multiplied by the known distance between the sensors **100** equals the change in volume of the chamber **58**. If the change in volume calculated based on the flowmeter **102** measurements does not equal the change in volume detected based on the output of the sensors **100**, an appropriate calibration coefficient can be applied as needed.

[0107] Another type of discrete position sensor that may be used for the sensors **100** in the FIG. **14** example is a photoelectric sensor. In that case, an optically discernible member (such as, a member having a color, texture, refractive index or other optical characteristic different from the surrounding environment) could be used in place of the magnet **60**. The scope of this disclosure is not limited to use of any particular type of sensor, or to any particular technique for detecting **20** position.

[0108] Although two position sensors **100** are depicted in FIG. **14**, any number of sensors may be used in keeping with the principles of this disclosure. Although the sensors **100** are described above as being located at or near the upper and lower stroke extents of the magnet **60**, the sensors may be otherwise located. Thus, the scope of this disclosure is not limited to any of the details of the sensor(s) **100** placement, quantity, configuration or arrangement as depicted in FIGS. **13** & **14**, or as described above.

[0109] Note that any of the sensors **52**, **100**, **102**, **104**, **106** described above may be used alone or in combination with any of the other sensors. For example, the flowmeter **102** could be used alone to determine the position, displacement, velocity and acceleration of a member of the actuator **14** (or the upper end of the rod string **18**) with acceptable accuracy in some situations. One discrete position sensor **100** would provide for convenient initialization and calibration of the displacement determinations, and multiple sensors **100** provide for enhanced accuracy, but use of these sensors is not necessary in keeping with the principles of this disclosure.

[0110] It may now be fully appreciated that the above disclosure provides significant advancements to the arts of monitoring and controlling operation of a well pumping system. In examples described above, the well pumping system **10** can be precisely controlled, in part by utilizing the continuous position sensor **52** to provide substantially continuous output of position to the control system **46** as the actuator **14** reciprocates the rod string **18**. In other examples, the flowmeter **102**, discrete position sensor(s) **100** and/or other sensors **104**, **106** may be used instead of, or in addition

to, the continuous position sensor **52** for determining displacement of a member of the actuator **14** or an upper end of the rod string **18**.

[0111] The above disclosure provides to the art a well pumping system **10**. In one example, the system **10** can include an actuator **14** that reciprocally displaces a rod string **18**, a flowmeter **102** that measures flow of a fluid between a power source **12** and the actuator **14**, and a control system **46** that modifies reciprocal displacement of the rod string **18** by the actuator **14**, in response to an output of the flowmeter **102**.

[0112] The well pumping system **10** can also include at least one discrete position sensor **100** that detects when a member (e.g., rod member **50**, piston member **54**, magnet **60**) of the actuator **14** or an upper end of the rod string **18** is at a predetermined position.

[0113] The control system **46** may modify a stroke extent of a member (e.g., rod member **50**, piston member **54**, magnet **60**) of the actuator **14**, or a stroke extent of the rod string **18** at surface or proximate a downhole pump **20**, in response to the output of the flowmeter **102**.

[0114] The control system **46** may maintain a preselected velocity profile **74** of a member of the actuator **14**, or of the rod string **18** at surface or at a downhole pump **20**, in response to the output of the flowmeter.

[0115] A well pumping method **80** is also provided to the art by the above disclosure. In one example, the method **80** can include reciprocally displacing a rod string **18**, continuously determining a velocity profile **74** of the rod string **18**, and modifying the velocity profile **74** while the rod string **18** reciprocally displaces, in response to an output of a flowmeter **102**.

[0116] The modifying step can comprise changing a duration of the velocity profile **74**. The changing may be performed while the rod string **18** reciprocally displaces.

[0117] The modifying step can comprise changing a position at which an actuator member velocity is zero, the position being detected based on the output of the flowmeter **102**. The changing may be performed while the rod string **18** reciprocally displaces.

[0118] The modifying step may comprise changing a position at which the rod string **18** velocity is zero at a downhole pump **20**. The changing can comprise solving a wave equation in the rod string **18**.

[0119] The modifying step may comprise minimizing differences between the detected velocity profile and a preselected velocity profile. The modifying step may comprise maintaining acceleration of the rod string **18** less than a preselected level.

[0120] Another well pumping method is disclosed above. In this example, the method comprises reciprocally displacing a rod string **18** with an actuator **14**, continuously determining displacement in response to an output of a flowmeter **102**, and modifying reciprocating displacement of the rod string **18** by the actuator **14**, in response to the output of the flowmeter **102**.

[0121] The determined displacement may be calibrated in response to an output of at least one discrete position sensor **100**.

[0122] The modifying step may comprise varying a periodic energy input to the actuator **14** relative to the reciprocating displacement of the rod string **18**. The varying can comprise varying a duration of the energy input and/or varying a level of the energy input.

[0123] The modifying step may comprise varying a stroke extent. The varying can include displacing the stroke extent until either: a) the stroke extent is positioned at a preselected stroke extent, or b) the stroke extent has displaced a preselected distance.

[0124] Although various examples have been described above, with each example having certain features, it should be understood that it is not necessary for a particular feature of one example to be used exclusively with that example. Instead, any of the features described above and/or depicted in the drawings can be combined with any of the examples, in addition to or in substitution for any of the other features of those examples. One example's features are not mutually exclusive to another example's features. Instead, the scope of this disclosure encompasses any combination of any of the features.

[0125] Although each example described above includes a certain combination of features, it should be understood that it is not necessary for all features of an example to be used. Instead, any of the features described above can be used, without any other particular feature or features also being used.

[0126] It should be understood that the various embodiments described herein may be utilized in various orientations, such as inclined, inverted, horizontal, vertical, etc., and in various configurations, without departing from the principles of this disclosure. The embodiments are described merely as examples of useful applications of the principles of the disclosure, which is not limited to any specific details of these embodiments.

[0127] In the above description of the representative examples, directional terms (such as "above," "below," "upper," "lower," "raised," "lowered," etc.) are used for convenience in referring to the accompanying drawings. However, it should be clearly understood that the scope of this disclosure is not limited to any particular directions described herein.

[0128] The terms "including," "includes," "comprising," "comprises," and similar terms are used in a non-limiting sense in this specification. For example, if a system, method, apparatus, device, etc., is described as "including" a certain feature or element, the system, method, apparatus, device, etc., can include that feature or element, and can also include other features or elements. Similarly, the term "comprises" is considered to mean "comprises, but is not limited to."

[0129] Of course, a person skilled in the art would, upon a careful consideration of the above description of representative embodiments of the disclosure, readily appreciate that many modifications, additions, substitutions, deletions, and other changes may be made to the specific embodiments, and such changes are contemplated by the principles of this disclosure. For example, structures disclosed as being separately formed can, in other examples, be integrally formed and vice versa. Accordingly, the foregoing detailed description is to be clearly understood as being given by way of illustration and example only, the spirit and scope of the invention being limited solely by the appended claims and their equivalents.

What is claimed is:

1. A well pumping system, comprising:
an actuator that reciprocally displaces a rod string;
a flowmeter that measures flow of a fluid between a power source and the actuator; and

a control system that modifies reciprocal displacement of the rod string by the actuator, in response to an output of the flowmeter.

2. The well pumping system of claim 1, further comprising at least one discrete position sensor that detects when a member of the actuator or an upper end of the rod string is at a predetermined position.

3. The well pumping system of claim 1, wherein the control system modifies a stroke extent of a member of the actuator, in response to the output of the flowmeter.

4. The well pumping system of claim 1, wherein the control system modifies a stroke extent of the rod string at surface, in response to the output of the flowmeter.

5. The well pumping system of claim 1, wherein the control system modifies a stroke extent of the rod string proximate a downhole pump, in response to the output of the flowmeter.

6. The well pumping system of claim 1, wherein the control system maintains a preselected velocity profile of a member of the actuator, in response to the output of the flowmeter.

7. The well pumping system of claim 1, wherein the control system maintains a preselected velocity profile of the rod string at surface, in response to the output of the flowmeter.

8. The well pumping system of claim 1, wherein the control system maintains a preselected velocity profile of the rod string proximate a downhole pump, in response to the output of the flowmeter.

9. A well pumping method, comprising:
reciprocally displacing a rod string;
continuously determining a velocity profile of the rod string; and
modifying the velocity profile while the rod string reciprocally displaces, in response to an output of a flowmeter.

10. The well pumping method of claim 9, wherein the modifying comprises changing a duration of the velocity profile.

11. The well pumping method of claim 10, wherein the changing is performed while the rod string reciprocally displaces.

12. The well pumping method of claim 9, wherein the modifying comprises changing a position at which an actuator member velocity is zero, the position being determined based on the output of the flowmeter.

13. The well pumping method of claim 12, wherein the changing is performed while the rod string reciprocally displaces.

14. The well pumping method of claim 9, wherein the modifying comprises changing a position at which the rod string velocity is zero at a downhole pump.

15. The well pumping method of claim 14, wherein the changing comprises solving a wave equation in the rod string.

16. The well pumping method of claim 9, wherein the modifying comprises minimizing differences between the detected velocity profile and a preselected velocity profile.

17. The well pumping method of claim 9, wherein the modifying comprises maintaining acceleration of the rod string less than a preselected level.

18. A well pumping method, comprising:
reciprocally displacing a rod string with an actuator;
continuously determining displacement in response to an output of a flowmeter; and
modifying reciprocating displacement of the rod string by the actuator, in response to the output of the flowmeter.

19. The well pumping method of claim 18, wherein the determined displacement is calibrated in response to an output of at least one discrete position sensor.

20. The well pumping method of claim 18, wherein the modifying comprises varying a periodic energy input to the actuator relative to the reciprocating displacement of the rod string.

21. The well pumping method of claim 20, wherein the varying comprises varying a duration of the energy input.

22. The well pumping method of claim 20, wherein the varying comprises varying a level of the energy input.

23. The well pumping method of claim 18, wherein the modifying comprises varying a stroke extent.

24. The well pumping method of claim 23, wherein the varying comprises displacing the stroke extent until either:
a) the stroke extent is positioned at a preselected stroke extent, or

b) the stroke extent has displaced a preselected distance.

25. The well pumping method of claim 18, wherein the modifying comprises modifying a stroke extent of the rod string at surface.

26. The well pumping method of claim 18, wherein the modifying comprises modifying a stroke extent of the rod string proximate a downhole pump.

27. The well pumping method of claim 26, wherein modifying the stroke extent of the rod string proximate the downhole pump comprises solving a wave equation in the rod string.

28. The well pumping method of claim 18, wherein the modifying comprises maintaining a preselected velocity profile of a member of the actuator.

29. The well pumping method of claim 18, wherein the modifying comprises maintaining a preselected velocity profile of the rod string at surface.

30. The well pumping method of claim 18, wherein the modifying comprises maintaining a preselected velocity profile of the rod string proximate a downhole pump.

31. The well pumping method of claim 30, wherein maintaining the preselected velocity profile of the rod string proximate the downhole pump comprises solving a wave equation in the rod string.

32. The well pumping method of claim 18, wherein the modifying comprises maintaining a preselected velocity profile, during the reciprocating displacement of the rod string.

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