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(71) Applicant: EATON CORPORATION [US/US]; Eaton Center, 1111 Superior Avenue, Cleveland, OH 44114-2584 (US).

(72) Inventors: YUAN, Qinghui; 6879 Timber Crest Drive, Mapple Grove, MN 55311 (US). SCHOTTLER, Christy, W.; 9206 Georgia Avenue, N., Brooklyn Park, MN 55445 (US). LEW, Jae, Y.; 19840 Waterford Place, Shorewood, MN 55331 (US).

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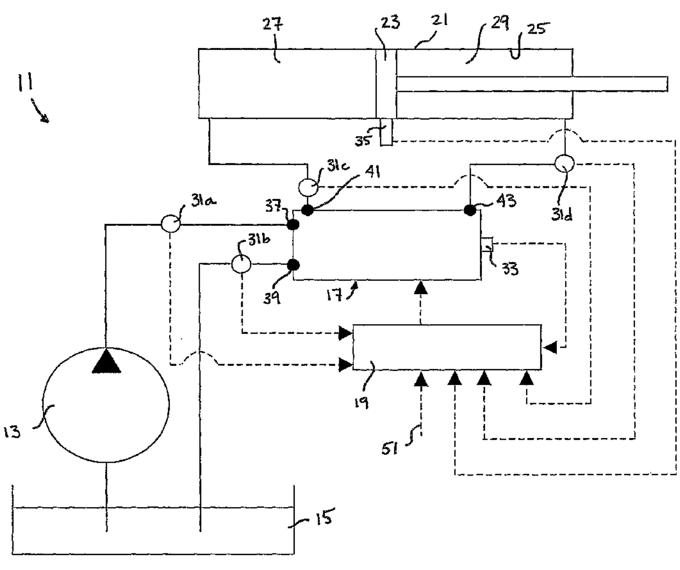

(57) Abstract: An actuator position control system comprises an actuator; at least one actuator position sensor mounted to the actuator; a flow control valve having at least one main stage spool, at least one spool position sensor that monitors the position of the main stage spool, a supply port, a tank port, a first control port, and a second control port, wherein the flow control valve is in fluid communication with the actuator; a plurality of fluid pressure sensors for monitoring pressure of fluid at the supply port, the tank port, the first control port, and the second control port of the flow control valve; and a controller being in electrical communication with the flow control valve, wherein the controller is configured to: - receive a desired actuator position input; - receive fluid pressure data signals from the plurality of fluid pressure sensors; - receive spool position signals from the spool position sensor; - receive actuator position data signals from the actuator position sensor; - determine corrected fluid flow rates to and from the actuator based on the fluid pressure data signals, the spool position signals, and an error-correction factor, wherein the error-correction factor is a function of the fluid pressure data signals and the spool position signals; - determine estimated actuator position, wherein the estimated actuator position determination includes a kinematic component, which is a function of the corrected fluid flow rates to and from the actuator, and a dynamic component, which is a function of a pressure of a chamber of the actuator; - apply adaptive gain factors to calibrate the estimated actuator position to the actuator position data signals from the actuator position sensor; - compare the estimated actuator position to the desired actuator position input; and - close the main stage spool valve to prevent fluid communication to the actuator.

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TITLE OF INVENTION

[0001] System and Method for Controlling Actuator Position.

BACKGROUND

1. FIELD OF THE INVENTION

[0002] The present invention relates to a system and method for controlling actuator position, and more particularly to an adaptive system and method that includes error correction.

2. DESCRIPTION OF THE RELATED ART

[0003] Fluid actuators are used in various hydraulic applications, including skid steer loaders, boom lifts, and mini excavators. The fluid actuators in these applications typically have a piston, which is encased by a cylinder, and a rod, which is attached to some accessory such as a bucket or a boom. In adjusting the position of the actuator, typically an operator of the application must manually actuate a joystick, which controls the position of the fluid actuator, and approximate the position of the actuator based on sight. If the operator's approximation is not correct, the operator must make minor adjustments to the position of the cylinder through the joystick. In some situations, the accurate positioning of the actuator could be critical, such as when positioning an actuator near electrical lines or near gas lines or water mains.

[0004] Some manufacturers have recommended using position sensors on the actuators. These position sensors typically require some type of marking on the rod so that the sensor can accurately sense the position of the actuator. While this would likely work in most applications, the sensors and the required markings on the rod significantly affect the cost of the actuator. As a result, most of the fluid actuators on these types of hydraulic applications do not use position sensors.

[0005] Information relevant to attempts to address the cost prohibitiveness of position sensing can be found in U.S. Patent Nos. 6,848,323 and 7,114,430. However, each one of these references suffers from the disadvantage of not being precise enough to provide an accurate location of the actuator.

BRIEF SUMMARY

[0006] An actuator position control system comprises an actuator and at least one actuator position sensor mounted to the actuator. The actuator position control system further includes a flow control valve, which is in fluid communication with the actuator, that has at least one main stage spool, at least one spool position sensor, a supply port, a tank port, a first control port, and a second control port. A plurality of pressure sensors are included to monitor pressure of fluid at the supply port, the tank port, the first control port, and the second control port of the flow control valve. A controller is in electrical communication with the flow control valve wherein the controller is configured to receive a desired actuator position input, fluid pressure data signals from the plurality of fluid pressure sensors, spool position signals from the spool position sensor, and actuator position data signals from the actuator position sensor. The controller is further configured to determine the corrected fluid flow rates to and from the actuator based on the fluid pressure data signals, the spool position signals, and an error-correction factor, wherein the error-correction factor is a function of fluid pressure data signals and the spool position signals. The controller than calculates an estimated actuator position, wherein the estimated actuator position calculation includes a kinematic component, which is a function of the corrected fluid flow rates to and from the actuator, and a dynamic component, which is a function of pressure in a chamber of the actuator. Adaptive gain factors are applied to calibrate the estimated actuator position to the actuator position data signals from the actuator position sensor. The controller makes a comparison between the estimated actuator position and the desired actuator position input and then closes the main stage spool valve to prevent fluid communication to the actuator.

[0007] A method for estimating actuator position comprises the steps of receiving fluid pressure data signals from the plurality of fluid pressure sensors, spool position signals from the spool position sensor, and actuator position data signals from the actuator position sensor. Corrected fluid flow rates to and from an actuator are determined based on the fluid pressure data signals, the spool position signals, and an error-correction factor, wherein the error-correction factor is a function of the fluid pressure data signals and the spool position signals. The estimated actuator position is calculated, wherein the estimated actuator position calculation includes a kinematic component, which is a function of the corrected fluid flow rates to and from the actuator, and a dynamic component, which is a function of pressure of a chamber of the actuator. Adaptive gain factors are applied to calibrate the estimated actuator position to the actuator position data signals from the actuator position sensor.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] The accompanying drawings are included to provide a further understanding of the present invention and are incorporated in and constitute part of this specification. The drawings illustrate exemplary embodiments of the present invention and together with the description serve to further explain the principles of the invention, wherein:

[0009] FIG. 1 is a schematic of an actuator position control system, which is made in accordance with the present invention.

[0010] FIG. 2a is a schematic of a flow control valve in a first position, which is made in accordance with the present invention.

[0011] FIG. 2b is a schematic of a flow control valve in a second position, which is made in accordance with the present invention.

[0012] FIG. 3 is a block diagram of a method for controlling actuator position in accordance with the present invention.

[0013] FIG. 4 is a block diagram of a method for estimating the position of an actuator in accordance with the present invention

[0014] FIG. 5 is a plot of actuator position versus time.

[0015] FIG. 6 is a block diagram of an alternate method for estimating the position of an actuator in accordance with the present invention.

[0016] FIG. 7 is a block diagram of an alternate method for estimating the position of an actuator in accordance with the present invention.

DETAILED DESCRIPTION

[0017] Referring now to the drawings, which are not intended to limit the invention, FIG. 1 illustrates a schematic representation of an actuator position control system, generally designated **11**. The actuator position control system **11** includes a fluid pump **13**, shown herein as a fixed displacement pump, a system reservoir **15**, a flow control valve, generally designated **17**, a controller **19**, and a linear actuator, or cylinder, **21**. The cylinder **21** includes a piston **23**, which separates an internal bore **25** of the cylinder **21** into a first chamber **27** and a second chamber **29**. While the actuator position control system **11** is described with regard to the cylinder **21**, it will be understood by those skilled in the art after reviewing the disclosure of the present invention that the scope of the present invention is not limited to linear actuators. The actuator position control system **11** and the methods described herein could also be used to determine the position of a rotary actuator. Therefore, the term "actuator" as used in the appended claims shall refer to both rotary and linear actuators.

[0018] The actuator position control system **11** also includes a plurality of fluid pressure sensors **31a**, **31b**, **31c**, **31d** that monitor the pressure of the fluid associated with the fluid pump **13**, the system reservoir **15**, the first chamber **27** of the cylinder **21**, and the second chamber **29** of the cylinder **21**, respectively. The actuator position control system **11** also includes at least one spool position sensor **33**, which will be described in more detail subsequently, and at least one actuator position sensor **35**. While the actuator position sensor **35** is shown in a center location of the cylinder **21**, it will be understood by those skilled in the art after reviewing the disclosure of the present invention that the location of the actuator position sensor **35** could be anywhere along the cylinder **21**. In addition, it will be understood by those skilled in the art after reviewing the disclosure of the present invention that multiple actuator position sensors **35** could be used in the actuator position control system **11**. However, increasing the number of actuator position sensors **35** would likely increase the cost of the actuator position control system **11**. In the subject embodiment, the actuator position sensor **35** is of a latch sensor type, which transmits a signal to the controller **19** when the piston **23** of the cylinder **21** is sensed by the actuator position sensor **35**. However, as there are various types of actuator position sensors **35** that would be adequate, the scope of the present invention is not limited to actuator position sensors **35** of the latch sensor type. Data from these sensors **31**, **33**, **35** is transmitted to the controller **19**.

[0019] Referring still to FIG. 1, the flow control valve **17** will now be described. In the subject embodiment, the flow control valve **17** includes a plurality of ports including a supply port **37**, which is in fluid communication with the fluid pump **13** and the pressure sensor **31a**, a tank port **39**, which is in fluid communication with the system reservoir **15** and the pressure sensor **31b**, a first control port **41**, which is in fluid communication with the first chamber **27** of the cylinder **21** and the pressure sensor **31c**, and a second control port **43**, which is in fluid communication with the second chamber **29** of the cylinder **21** and the pressure sensor **31d**. In the subject embodiment, when the flow control valve **17** allows fluid communication between the supply port **37** and the first control port **41** and between the tank port **39** and the second control port **43**, pressurized fluid from the fluid pump **13** flows through the flow control valve **17** into the first chamber **27** of the cylinder **21**, while fluid from the second chamber **29** flows to the system reservoir **15**. This fluid communication results in the extension of the cylinder **21**. In the alternative, when the flow control valve **17** allows fluid communication between the tank port **39** and the first control port

41, and between the supply port **37** and the second control port **43**, pressurized fluid from the fluid pump **13** flows through the flow control valve **17** into the second chamber **29** of the cylinder **21**, while fluid from the first chamber **27** flows to the system reservoir **15**. This fluid communication results in the retraction of the cylinder **21**.

[0020] FIGS. 2a and 2b provide schematic representations of an exemplary embodiment of the flow control valve **17**. In addition to the plurality of ports **37**, **39**, **41**, **43** described above, the flow control valve **17** further includes two pilot stage spools **45a**, **45b** and two main stage spools **47a**, **47b** associated with the cylinder **21**. It shall be understood by those skilled in the art, however, after reviewing the disclosure of the present invention that while the subject embodiment has shown the flow control valve **17** schematically in FIGS. 2a and 2b as having two pilot stage spools **45a**, **45b** and two main stage spools **47a**, **47b** in association with a single cylinder **21**, it is also within the scope of the present invention to have only one pilot stage spool **45** and one main stage spool **47** in association with a single cylinder **21**, or any combination thereof.

[0021] The positions of the pilot stage spools **45a**, **45b** are controlled by actuators **49a**, **49b**, respectively. While it is preferred that actuators **49a**, **49b** are of the electromagnetic type, such as voice coils, it will be understood by those skilled in the art after reviewing the disclosure of the present invention that actuators **49a**, **49b** could be of any type that is capable of providing linear motion to the pilot stage spools **45a**, **45b**. The positions of the pilot stage spools **45a**, **45b** control the positions of the main stage spools **47a**, **47b**, respectively, by regulating the fluid pressure that acts on either end of the main stage spools **47a**, **47b**. The positions of the main stage spools **47a**, **47b**, on the other hand, control the fluid flow rate to the cylinder **21**. In the subject embodiment, the spool position sensors **33a**, **33b** measures the positions of the main stage spools **47a**, **47b**, respectively, and transmit position data to the controller **19** for use by the controller **19** in determining an estimated actuator position, which will be described in greater detail subsequently. While many different types of spool position sensors **33a**, **33b** would be adequate for use in this system, Linear Variable Differential Transformers (LVDTs) are preferred. In FIG. 2a, the flow control valve **17** is in a first position in which the actuator **49a** positions the pilot stage spool **45a** such that the main stage spool **47a** provides fluid communication between the supply port **37** and the first control port **41**, while the actuator **49b** positions the pilot stage spool **45b** such that the main stage spool **47b** provides fluid communication between the tank port **39** and the second control port **43**. In the subject embodiment, this first position would result in the extension of the cylinder **21**. In FIG. 2b, the flow control valve **17** is in a second position in which the actuator **49a** positions the pilot stage spool **45a** such that the main stage spool **47a** provides fluid communication between the tank port **39** and the first control port **41**, while the actuator **49b** positions the pilot stage spool **45b** such that the main stage spool **47b** provides fluid communication between the supply port **37** and the second control port **43**. In the subject embodiment, this second position would result in the retraction of the cylinder **21**.

[0022] Referring again to FIG. 1, the pressure sensors **31** are shown external to the flow control valve **17**. However, the scope of the present invention is not limited to the pressure sensors **31** being external to the flow control valve **17**. In the preferred embodiment, the pressure sensors **31** would be integrated in the flow control valve **17**. Such an arrangement is described in UK Pat. No. GB2328524 and is incorporated herein by reference. In addition, the controller **19** is also shown schematically in FIG. 1 as being external to the flow control valve **17**. However, the scope of the present invention is not limited to the controller **19** being external to the flow control valve **17**. In the preferred embodiment, the controller **19** would also be integrated in the flow control valve **17**.

[0023] Referring now primarily to FIG. 3 with references made to elements introduced in FIGS. 1 and 2, a method **301** for controlling an actuator will be described. In step **303** of the method **301**, a desired actuator position **51**

(shown schematically in FIG. 1) is obtained by the controller **19**. The desired actuator position can be inputted in a variety of ways, including but not limited to a joystick used by an operator or through a keyboard. In step **305**, the controller **19** determines whether fluid is currently being provided to the cylinder **21**. This determination can be made by the controller from information received from the spool position sensors **33a**, **33b**. If there is no fluid being provided to the cylinder **21**, the controller **19** sends a signal to the actuators **49a**, **49b** to actuate the pilot stage spools **45a**, **45b**, which in turn actuate the main stage spools **47a**, **47b**, in step **307**. This allows for fluid communication to and from the appropriate chambers **27**, **29** of the cylinder **21**. If fluid is currently being communicated to and from the appropriate chambers **27**, **29** of the cylinder **21**, the method **301** proceeds to the next step. An estimated actuator position is then determined using a method **309** that will be described in greater detail subsequently. In step **311**, a comparison is made between the desired actuator position and the estimated actuator position determined by the method **309**. If these actuator positions are similar, a signal is communicated to the actuators **49a**, **49b** that results in the closing of the main stage spool valves **47a**, **47b**, which prevents further fluid communication to the cylinder **21**. It will be understood by those skilled in the art after reviewing the disclosure of the present invention that the step **311** could also include the step of communicating a signal to the actuators **49a**, **49b** to begin closing the main stage spool valves **47a**, **47b** as the desired actuator position and the estimated actuator position get closer in value. This step would avoid an abrupt stop in the movement of the cylinder **21**. If, however, the estimated actuator position and the desired position are not similar, the main stage spool valves **47a**, **47b** are left in position and the actuator position is again estimated using method **309**.

[0024] Referring now to FIG. 4, the method **309**, which estimates actuator position, will now be described in greater detail. In step **401**, a determination is made as to whether the controller **19** is receiving actual actuator position data from the actuator position sensor **35**. If no actual actuator position data has been received, a position, X_{Sp1}, of the main stage spool **47a**, which is associated with the first chamber **27** of the cylinder **21** and a position, X_{Sp2}, of the main stage spool **47b**, which is associated with the second chamber **29** of the cylinder **21**, is obtained in step **403** from the spool position sensors **33a**, **33b**. In step **405**, fluid pressure data corresponding to the pressure of the fluid at the fluid pump **13**, referred to hereinafter as P_S, the system reservoir **15**, referred to hereinafter as P_t, the first chamber **27** of the cylinder **21**, referred to hereinafter as P_1, and the second chamber **29** of the cylinder **21**, referred to hereinafter as P_2, is obtained from the fluid pressure sensors **31a**, **31b**, **31c**, **31d**. It will be understood by those skilled in the art that the order of steps **401**, **403**, and **405** are not critical to the scope of the present invention.

[0025] In steps **407** and **407'**, corrected flow rates, $Q_{1,C}$ and $Q_{2,C}$, are calculated with regard to fluid flowing to and from the cylinder **21**. The corrected flow rate is a flow rate calculation that reduces or "corrects" implicit errors in a theoretical flow rate equation by multiplying the theoretical flow rate by an error-correction factor. For ease of description, this calculation will be described with regard to the first chamber **27** of the cylinder **21** only. It will be understood by those skilled in the art after reviewing the disclosure of the present invention, however, that the calculation of the corrected flow rate, $Q_{2,C}$, associated with the second chamber **29** of the cylinder **21** is similar to the calculation of the corrected flow rate, $Q_{1,C}$, which is described below. The corrected flow rate equation, $Q_{1,C}$, associated with the first chamber **27** of the cylinder **21** is:

$$Q_{1,C} = K_1 \cdot Q_1,$$

where Q_1 is the estimated flow rate of fluid to or from the first chamber **27** of the cylinder **21**, and K_1 is the error-correction factor. A more detailed description of these terms is provided immediately below.

[0026] The estimated flow rate, Q_1, is a theoretical nonlinear function based on variables P_S, P_t, P_1, and X_{Sp1}. While there are a variety of equations that could be used to calculate the estimated flow rate, Q_1, two exemplary equations are provided below. The first equation would be used if the main stage spool **47a** of the flow control valve **17** was positioned such that the first control port **41** was in fluid communication with the supply port **37**. In other words, the following equation would be used when fluid is flowing from the fluid pump **13** to the first chamber **27** of the cylinder **21**, thereby resulting in the extension of cylinder **21**. It should be noted, however, that the following equation would also be used when the pressure of the fluid in the first chamber **27** is greater than the pressure of the fluid being output from the fluid pump **13**, even though this situation would create a backflow of fluid from the first chamber **27** to the fluid pump **13** which would result in the retraction of the cylinder **21**. In both of these scenarios, Q_1 may be calculated using the following equation:

$$Q_1 = C_d \cdot W \cdot X_{Sp1} \cdot \mathrm{sgn}(P_S - P_1) \cdot \sqrt{\frac{2 \cdot |P_S - P_1|}{\rho}},$$

where C_d is a discharge coefficient, X_{Sp1} is the position of the main stage spool **47a**, W is a differential of orifice area, which is a function of the main stage spool position, over a differential of the main stage spool position, $dA(X_{Sp1})/dX_{Sp1}$, (the orifice is shown in FIG. 2a by reference letter "$O_{1,S}$"), and ρ is the density of the fluid.

[0027] The second equation would be used if the main stage spool **47a** of the flow control valve **17** was positioned such that the first control port **41** was in fluid communication with the tank port **31**. In other words, the following equation would be used when fluid is flowing from the first chamber **27** of the cylinder **21** to the system reservoir **15**, thereby resulting in the retraction of the cylinder **21**. In this scenario, Q_1 may be calculated using the following equation:

$$Q_1 = C_d \cdot W \cdot X_{Sp1} \cdot \mathrm{sgn}(P_1 - P_t) \cdot \sqrt{\frac{2 \cdot |P_1 - P_t|}{\rho}},$$

where C_d is a discharge coefficient, X_{Sp1} is the position of the main stage spool **47a**, W is a differential of orifice area, which is a function of the main stage spool position, over a differential of the main stage spool position, $dA(X_{Sp1})/dX_{Sp1}$, (the orifice is shown in FIG. 2b by reference letter "$O_{1,t}$"), and ρ is the density of the fluid.

[0028] As stated above, the estimated flow rate, Q_1, is a theoretical equation. Due to multiple factors, including but not limited to fluid viscosity, fluid type, fluid temperature, etc., the estimated flow rate, Q_1, does not always correlate to a flow rate that is experimentally measured. Therefore, an error-correction factor, K_1, is used to reduce error associated with the theoretical equation. The error-correction factor, K_1, is defined by the following nonlinear function: $K_1 = f(P_s, P_1, P_t, X_{Sp1})$. As this function may be determined experimentally, a variety of equations could be used to correlate the independent variables to the correction factor. An example of such an equation is provided below:

$$K_1 = c_0 + c_1 \cdot X_{Sp1} + c_2 \cdot \sqrt{P_S - P_1} + c_3 \cdot X_{Sp1}{}^2 + c_4 \cdot (P_S - P_1),$$

where c_0, c_1, c_3, and c_4 are experimentally determined coefficients.

[0029] It will be understood by those skilled in the art after reviewing the disclosure of the present invention that the scope of the present invention does not require that these calculations be performed during the operation of the actuator position control system **11**. Rather, the values of the corrected flow rates, $Q_{1,C}$ and $Q_{2,C}$, could be contained in a look-up table, which are retrievable based on the values of input parameters P_S, P_t, P_1, P_2, X_{Sp1} and X_{Sp2}.

[0030] In steps **409** and **409'**, estimated actuator positions, $X_{1,Est}$ and $X_{2,Est}$, of the cylinder **21** are determined based on the corrected flow rates, $Q_{1,C}$ and $Q_{2,C}$, respectively. For ease of description, this determination will be described with regard to the corrected flow rate, $Q_{1,C}$, of the first chamber **27** of the cylinder **21** only. It will be understood by those skilled in the art after reviewing the disclosure of the present invention, however, that the determination of the estimated actuator position, $X_{2,Est}$, with regard to the corrected flow rate, $Q_{2,C}$, of the second chamber **29** of the cylinder **21** is similar. In the subject embodiment, the position of the cylinder **21** with regard to the corrected flow rate, $Q_{1,C}$, of the first chamber **27** is calculated by integrating an equation for the velocity of the piston **23**, $\dot{X}_{1,Est}$, over a period of time, where the equation for the velocity of the piston **23**, $\dot{X}_{1,Est}$, has a dynamic component and a kinematic component. An example of such an equation is provided below:

$$\dot{X}_{1,Est} = \left[\frac{1}{\beta_{Est} A} (-A\eta_1 X_{1,Est} - \eta_1 V_1) \right] + \left[\frac{1}{A} Q_{1,C} \right],$$

where β_{Est} is the estimated bulk modulus of the fluid; A is the area of the piston **23** that is subjected to pressurized fluid; V_1 is the volume of the first chamber **27** of the cylinder **21** when the piston **23** is fully retracted; $X_{1,Est}$ is an initial estimated actuator position; η_1 represents the variation in fluid pressure, P_1, in the first chamber **27** of the cylinder **21** over a given sample time that has been filtered to eliminate noise; and $Q_{1,C}$ is the corrected flow rate. The dynamic component of the above velocity equation is provided in the first set of square brackets and in the above equation is a function of the fluid pressure, P_1, in the first chamber **27** of the cylinder **21**. The kinematic component of the above velocity equation is provide in the second set of square brackets and is based on the corrected flow rate, $Q_{1,C}$, divided by the area of the piston **23** that is subjected to pressurized fluid.

[0031] In step **411**, the estimated positions, $X_{1,Est}$ and $X_{2,Est}$, of the cylinder **21** are compared. If those positions are different from each other, a determination of the estimated actuator position, X_{Est}, is made. This determination could be made by taking the arithmetic mean of the positions, $X_{1,Est}$ and $X_{2,Est}$, or by using some other weighted average function.

[0032] Referring now to FIG. 5, the importance of including both the dynamic and kinematic components in the determination of the estimated actuator positions, $X_{1,Est}$ and $X_{2,Est}$, is shown. Plots of actual actuator position **501**, estimated actuator position **503**, and kinematic actuator position **505**, which is based solely on the kinematic component of the velocity equation, are provided in FIG. 5. In this plot, the piston **23** of the cylinder **21** is oscillating while expanding. The oscillation could be caused an external condition, such as an outside force exerted against the cylinder **21**. The kinematic actuator position **505** is only able to capture the overall movement of the piston **23** and therefore does not capture the oscillations of the piston **23**. In the subject embodiment, and by way of example only, this results in the kinematic actuator position having an error of around 5%, although this error could be much larger depending on the outside force acting against the cylinder **21**. The estimated actuator position **503**, which includes the dynamic component and the kinematic component described above, on the other hand, closely approximates the actual actuator position **501**, including the oscillations of the piston **23** due to the outside force acting against the cylinder **21**.

[0033] Referring again to FIG. 4, the adaptivity of the method **309**, which estimates the actuator position, will now be described. If the controller **19** has received the actual actuator position, X_{Act}, from the actuator position sensor **35** in step **401** and the estimated actuator positions, $X_{1,Est}$ and $X_{2,Est}$, with respect to the first **27** and the second **29** chambers of the cylinder **21**, respectively, are different than the actual actuator position, X_{Act}, adaptive gain factors, δ_1 and δ_2, are determined in step **413** to calibrate the estimated actuator positions to the actual actuator position. Thus, the adaptive gain factors, δ_1 and δ_2, are based on the actuator position errors, $X_{1,Err}$ and $X_{2,Err}$, respectively, where $X_{1,Err} = X_{1,Est} - X_{Act}$ and $X_{2,Err} = X_{2,Est} - X_{Act}$. The adaptive gain factors, δ_1 and δ_2, are then applied as an adjustment to the determination of the corrected flow rates, $Q_{1,C}$ and $Q_{2,C}$. This adjustment to the corrected flow rates, $Q_{1,C}$ and $Q_{2,C}$, can be accomplished by multiplying the error-correction factors, K_1 and K_2, by the adaptive gain factors, δ_1 and δ_2, respectively.

[0034] A theoretical equation that represents the actuator position error, $X_{1,Err}$, will be briefly described in order to demonstrate how that adjustment to the error-correction flow rates are made. While only the actuator position error,

$X_{1,Err}$, with respect to the first chamber **27** of the cylinder **21** will be described, it will be understood by those skilled in the art after reviewing the disclosure of the present invention that the adjustment based on the actuator position error, $X_{2,Err}$, with respect to the second chamber **29** of the cylinder **21** is similar. The theoretical equation for the actuator position error, $X_{1,Err}$, is given below:

$$X_{1,Err}(t+1) = \left[\int^{t+1}\left(\frac{-\eta_1}{\beta_{Est}}X_{1,Err} + \frac{1}{\beta_{Err}}\left(-\eta_1 X_{1,Est} - \eta_1 V_1 \frac{1}{A}\right)\right)dt\right] + \left[\int^{t+1} -\frac{1}{A}Q_{1,Err}\,dt\right],$$

where $X_{1,Err}(t+1)$ is the actuator position error at sample time $t+1$, β_{Est} is the estimated bulk modulus of the fluid; β_{Err} is the error associated with the bulk modulus of the fluid which may be calculated using the following equation: $\frac{1}{\beta_{Err}} = \frac{1}{\beta_{Est}} - \frac{1}{\beta_{Act}}$; A is the area of the piston **23** that is subjected to pressurized fluid; V_1 is the volume of the first chamber **27** of the cylinder **21** when the piston **23** is fully retracted; $X_{1,Est}$ is an estimate of the actuator position; η_1 represents the variation in fluid pressure, P_1, in the first chamber **27** of the cylinder **21** over a given sample time that has been filtered to eliminate noise; and $Q_{1,Err}$ is the flow rate error which is calculated using the following equation: $Q_{1,C} - Q_1$.

[0035] It should be noted that all of the terms in the integral in the first set of square brackets in the theoretical equation for the actuator position error are multiplied by η_1, which represents the filtered variation in fluid pressure in the first chamber **27** of the cylinder **21**. This term η_1 could be positive or negative depending on the fluid pressure variations in the first chamber **27** over a given sample time. As these fluid pressure variations are largely the result of external conditions, such as an outside force exerted against the cylinder **21**, η_1 is a term that is somewhat unpredictable. As a result of this unpredictability, it would be difficult to correlate an adjustment to one of the terms in the integral in the first set of square brackets with the actuator position error, $X_{1,Err}$, with respect to the first chamber **27**. However, an adjustment to one of the terms in the integral in the second set of brackets in the above equation could be more readily correlated to the actuator position error, $X_{1,Err}$, due to the predictability of those terms. An example will be briefly explained to demonstrate how the error-correction factor, K_1, could be correlated to the actuator position error, $X_{1,Err}$. The integral in the second set of brackets can be simplified as: $\int^{t+1} \frac{Q_1 - K_1 \cdot Q_1}{A} dt$. Therefore, assuming that the actuator position error, $X_{1,Err}$, is governed by this integral, if the difference between the estimated actuator position, $X_{1,Est}$, and the actual actuator position, X_{Act}, is positive, the error-correction factor, K_1, should be increased. On the other hand, if the difference between the estimated actuator position, $X_{1,Est}$, and the actual actuator position, X_{Act}, is negative, the error-correction factor, K_1, should be decreased. Thus, if the main stage spool **47a** of the flow control valve **17** is positioned such that the first control port **41** is in fluid communication with the supply port **37** and the actuator position error, $X_{1,Err}$, is greater than zero, then the correction factor, K_1, is multiplied by an adaptive gain factor, δ_1, where $\delta_1 > 1$. In this example, the equation for the corrected flow rate, $Q_{1,c}$, would be $Q_{1,c} = \delta_1 \cdot K_1 \cdot Q_1$. If the main stage spool **47a** of the flow control valve **17** is positioned such that the first control port **41** is in fluid communication with the supply port **37** but the actuator position error is less than or equal to zero, then the error-correction factor, K_1, is multiplied by an adaptive gain factor $\frac{1}{\delta_1}$, where $\delta_1 > 1$. In this example, the equation for the corrected flow rate, $Q_{1,c}$, would be $Q_{1,c} = \frac{1}{\delta_1} \cdot K_1 \cdot Q_1$. If, however, the main stage spool **47a** of the flow control valve **17** is positioned such that the first control port **41** is in fluid communication with the tank port **39** and the actuator position error, $X_{1,Err}$, is greater than zero, then the correction factor, K_1, is multiplied by an adaptive gain factor, $\frac{1}{\delta_1}$, where $\delta_1 > 1$. In this example, the equation for the corrected flow rate, $Q_{1,c}$, would be $Q_{1,c} = \frac{1}{\delta_1} \cdot K_1 \cdot Q_1$. If the main stage spool **47a** of the flow control valve **17** is positioned such that the first control port **41** is in fluid communication with the tank port **39** but the actuator position error, $X_{1,Err}$, is less than or equal to zero, then the error-correction factor, K_1, is multiplied by an adaptive gain factor δ_1, where $\delta_1 > 1$. In this example, the equation for the corrected flow rate, $Q_{1,c}$, would be $Q_{1,c} = \delta_1 \cdot K_1 \cdot Q_1$.

[0036] In the preferred embodiment of the present invention, the adaptive gain factor, δ_1, is a function of the actual position error, $X_{1,Err}$. The larger the actuator position error, the more aggressive the change to the error-correction factor, K_1, will be. However, it will be understood by those skilled in the art after reviewing the disclosure of the present invention that the adaptive gain factor, δ_1, could be any real value. In order to prevent an overly aggressive change to the error-correction factor, K_1, in the preferred embodiment, the adaptive gain factor, δ, would be less than or equal to two.

[0037] Referring now to FIG. 6, an alternate method **309'** used by the controller to determine the estimated position of the cylinder **21** will be described. In this alternative method **309'**, method steps that are the same or similar as those in the method **309** will have the same reference number and will not be further described. Additional method steps, however, shall have reference numerals in excess of "600" and shall be described in detail.

[0038] Similar to the method **309**, in step **401** of the alternative method **309'**, a determination is made as to whether the controller **19** is receiving actual actuator position data from the actuator position sensor **35**. If no actual actuator position data has been received, positions, X_{Sp1} and X_{Sp2}, of the main stage spools **47a**, **47b** which are associated with the first and second chambers **27**, **29**, respectively, of the cylinder **21**, are obtained in step **403** from the spool position sensors **33a**, **33b**. In step **405**, fluid pressure data P_S, P_t, P_1, and P_2 is obtained from the fluid pressure sensors **31a**, **31b**, **31c**, **31d**, respectively. It will be understood by those skilled in the art that the order of steps **401**, **403**, and **405** are not critical to the scope of the present invention.

[0039] In steps **407** and **407'**, corrected flow rates, $Q_{1,C}$ and $Q_{2,C}$, are determined with regard to fluid flowing to and from the cylinder **21**, where the corrected flow rate determinations would be similar to those described in method **309**. In step **601**, a corrected flow rate, Q_C, is determined based on the corrected flow rates, $Q_{1,C}$ and $Q_{2,C}$. If the corrected flow rates, $Q_{1,C}$ and $Q_{2,C}$, are equal, then the corrected flow rate, Q_C, could equal $Q_{1,C}$ or $Q_{2,C}$. If, however, the corrected flow rates, $Q_{1,C}$ and $Q_{2,C}$, are different from each other, a determination of the corrected flow rate, Q_C, is made. This determination could be made by taking the arithmetic mean of the corrected flow rates, $Q_{1,C}$ and $Q_{2,C}$, or by using some other weighted average function. Following this determination, the estimated actuator position, X_{Est}, is calculated based on the corrected flow rate, Q_C, in a calculation that is similar to that described with regard to method **309**. The adaptivity of the method **309'** in step **413** is similar to that described in step **413** in method **309**.

[0040] An advantage to using the methods **309** and **309'** to determine actuator position is that the methods **309** and **309'** incorporate three ways in which errors associated with the theoretical calculations are minimized. The first way involves the use of the error-correction factors, K_1 and K_2. These error-correction factors, K_1 and K_2, minimize errors associated with the calculation of the theoretical flow rates, Q_1 and Q_2, by correlating the theoretical flow rates, Q_1 and Q_2, to experimentally measured flow rates. The second way involves the use of the adaptive gain factors, δ_1 and δ_2, which are multiplied to the error-correction factors, K_1 and K_2, respectively. These adaptive gain factors minimize errors between the estimated actuator position, X_{Est}, and the actual actuator position, X_{Act}. The third way in which errors associated with the theoretical calculations are minimized involves the use of two corrected flow rates, $Q_{1,C}$ and $Q_{2,C}$, in the determination of the estimated actuator position, X_{Est}. By using two corrected flow rates, $Q_{1,C}$ and $Q_{2,C}$, a discrepancy between the two corrected flow rates would be minimized by using some weighted mean function. This in turn would potentially reduce an error in the determination of the estimated actuator position.

[0041] Referring now to FIG. 7, an alternate method **309"** is illustrated, which provides an additional advantage to using two corrected flow rates, $Q_{1,C}$ and $Q_{2,C}$, in the determination of the estimated actuator position will be described. In the alternative method **309"**, method steps that are the same or similar as those in methods **309** and **309'** will have the same reference number and will not be further described. Additional method steps, however, shall have reference numerals in excess of "700" and shall be described in detail.

[0042] In the alternate method **309"**, a comparison is made between the two corrected flow rates, $Q_{1,C}$ and $Q_{2,C}$, in step **701**. If the corrected flow rates, $Q_{1,C}$ and $Q_{2,C}$, are similar in value, the estimated actuator position is determine in step **601**. If, however, the corrected flow rates, $Q_{1,C}$ and $Q_{2,C}$, are significantly different, a warning is sent to the operator in step **703**. In this way, the corrected flow rates, $Q_{1,C}$ and $Q_{2,C}$, are used as a type of fault detection for the actuator position control system **11**. For example, if the corrected flow rate, $Q_{1,C}$, for the first chamber **27** of the cylinder **21** is significantly different than the corrected flow rate, $Q_{2,C}$, for the second chamber **29** of the cylinder **21**, a warning is communicated to the operator in step **703** that there may be a problem with the actuator position control system **11**. The type of warning is not critical to the scope of the present invention and could include visual or audible warnings. While the significant discrepancy in the corrected flow rates, $Q_{1,C}$ and $Q_{2,C}$, could not isolate the problem to a specific component, such as one of the pressure sensors **31a**, **31b**, **31c**, **31d** or one of the spool position sensors **33a**, **33b**, in the actuator position control system **11**, it would notify the operator of a potential problem with the system as a whole. It will be understood by those skilled in the art after reviewing the disclosure of the present invention that placement order of step **701** is not critical to the scope of the present invention.

[0043] The invention has been described in great detail in the foregoing specification, and it is believed that various alterations and modifications of the invention will become apparent to those skilled in the art from a reading and understanding of the specification. It is intended that all such alterations and modifications are included in the invention, insofar as they come within the scope of the appended claims.

What is claimed is:

1. An actuator position control system comprising
an actuator;
at least one actuator position sensor mounted to the actuator;
a flow control valve having at least one main stage spool, at least one spool position sensor that monitors the position of the main stage spool, a supply port, a tank port, a first control port, and a second control port wherein the flow control valve is in fluid communication with the actuator;
a plurality of fluid pressure sensors for monitoring pressure of fluid at the supply port, the tank port, the first control port, and the second control port of the flow control valve; and
a controller being in electrical communication with the flow control valve, wherein the controller is configured to:
receive a desired actuator position input;
receive fluid pressure data signals from the plurality of fluid pressure sensors;
receive spool position signals from the spool position sensor;
receive actuator position data signals from the actuator position sensor;
determine corrected fluid flow rates to and from the actuator based on the fluid pressure data signals, the spool position signals, and an error-correction factor, wherein the error-correction factor is a function of the fluid pressure data signals and the spool position signals;
determine estimated actuator position, wherein the estimated actuator position determination includes a kinematic component, which is a function of the corrected fluid flow rates to and from the actuator, and a dynamic component,

which is a function of a pressure of a chamber of the actuator;

apply adaptive gain factors to calibrate the estimated actuator position to the actuator position data signals from the actuator position sensor;

compare the estimated actuator position to the desired actuator position input; and

close the main stage spool valve to prevent fluid communication to the actuator.

2. An actuator position control system as claimed in claim 1 wherein the controller is further configured to compare the corrected fluid flow rate to the actuator and the corrected fluid flow rate from the actuator and send a warning signal when there is a significant difference between the corrected fluid flow rates.

3. An actuator position control system as claimed in claim 2 wherein the warning signal is audible.

4. An actuator position control system as claimed in claim 2 wherein the warning signal is visual.

5. An actuator position control system as claimed in claim 1 wherein the actuator is a linear actuator.

6. An actuator position control system as claimed in claim 5 wherein the actuator is a cylinder.

7. An actuator position control system as claimed in claim 6 wherein the actuator position sensor is mounted at a center location on the cylinder.

8. An actuator position control system as claimed in claim 1 wherein the plurality of fluid pressure sensors are disposed in the flow control valve.

9. An actuator position control system as claimed in claim 1 wherein the controller is disposed in the flow control valve.

10. An actuator position control system as claimed in claim 1 wherein the flow control valve includes two main stage spools.

11. An actuator position control system as claimed in claim 10 wherein a pilot stage spool is associated with each main stage spool in the flow control valve.

12. An actuator position control system as claimed in claim 1 wherein the spool position sensor is a Linear Variable Differential Transformer.

13. An actuator position control system as claimed in claim 1 wherein the actuator position sensor is a latch sensor.

14. A method for estimating actuator position comprising the steps of
receiving fluid pressure data signals from a plurality of fluid pressure sensors;
receiving spool position signals from at least one spool position sensor;
receiving actuator position data signals from at least one actuator position sensor;
determining corrected fluid flow rates to and from an actuator with each corrected fluid flow rate based on the fluid pressure data signals, the spool position signals, and an error-correction factor, wherein the error-correction factor is a function of the fluid pressure data signals and the spool position signals;
determining an estimated actuator position, wherein the estimated actuator position determination includes a kinematic component, which is a function of the corrected fluid flow rates to and from the actuator, and a dynamic component, which is a function of a pressure of a chamber of the actuator; and
applying adaptive gain factors to calibrate the estimated actuator position to the actuator position data signals from the actuator position sensor.

15. A method for determining actuator position as claimed in claim 14 further comprising the step of comparing the corrected fluid flow rate to the actuator and the corrected fluid flow rate from the actuator.

16. A method for determining actuator position as claimed in claim 15 wherein a weighted function is applied to the corrected fluid flow rate to the actuator and the corrected fluid flow rate from the actuator in determining the estimated actuator position.

17. A method for determining actuator position as claimed in claim 15 wherein a warning signal is sent from a controller when there is a significant discrepancy between the corrected fluid flow rate to the actuator and the corrected fluid flow rate from the actuator.

18. A method for determining actuator position as claimed in claim 14 wherein the spool position sensor is a Linear Variable Differential Transformer.

19. A method for determining actuator position as claimed in claim 14 wherein the actuator displacement sensor is a latch sensor.

20. A method for determining actuator position as claimed in claim 14 wherein the actuator is a linear actuator.

21. A method for determining actuator position as claimed in claim 20 wherein the actuator is a cylinder.

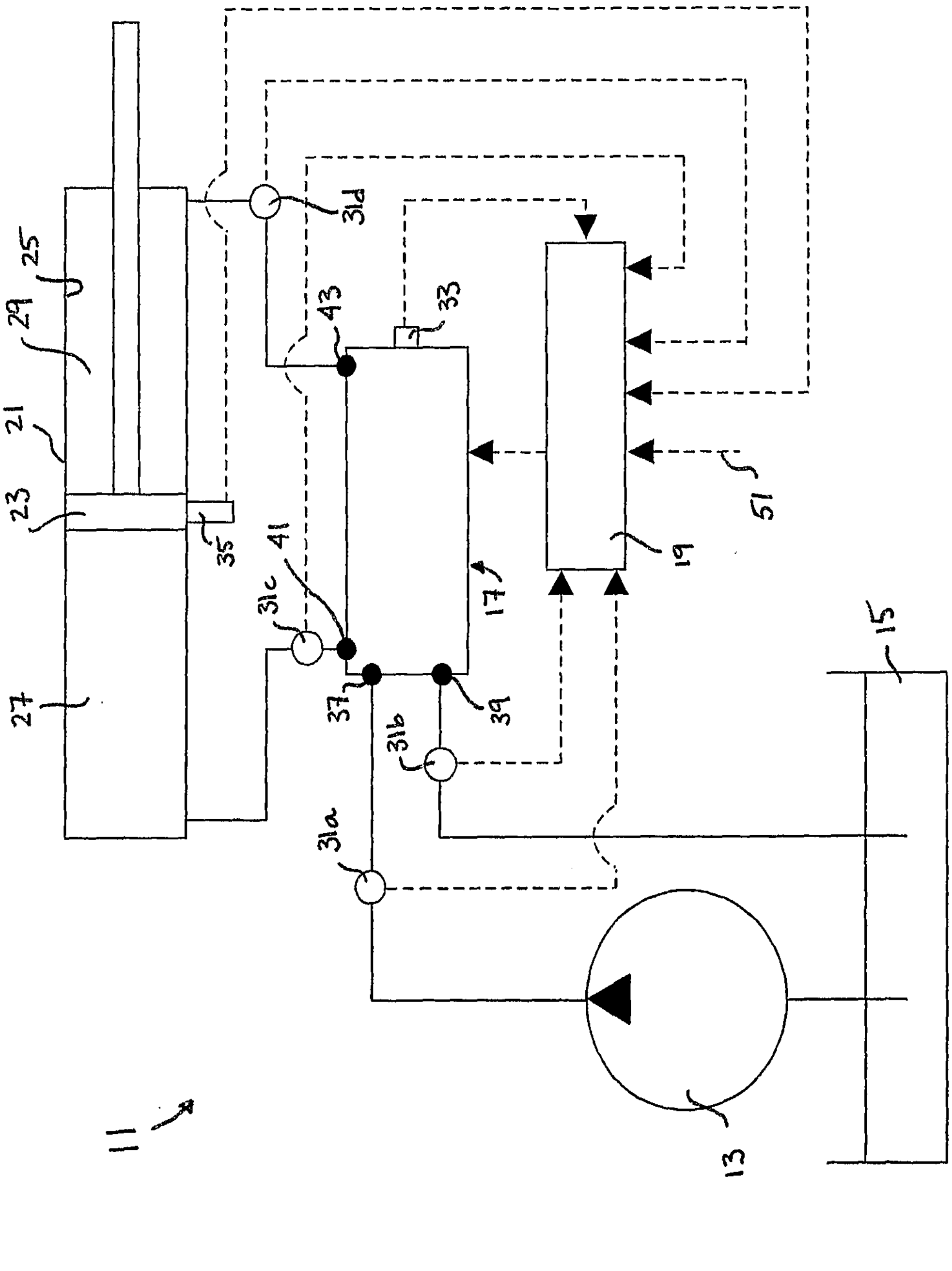

FIG. 1

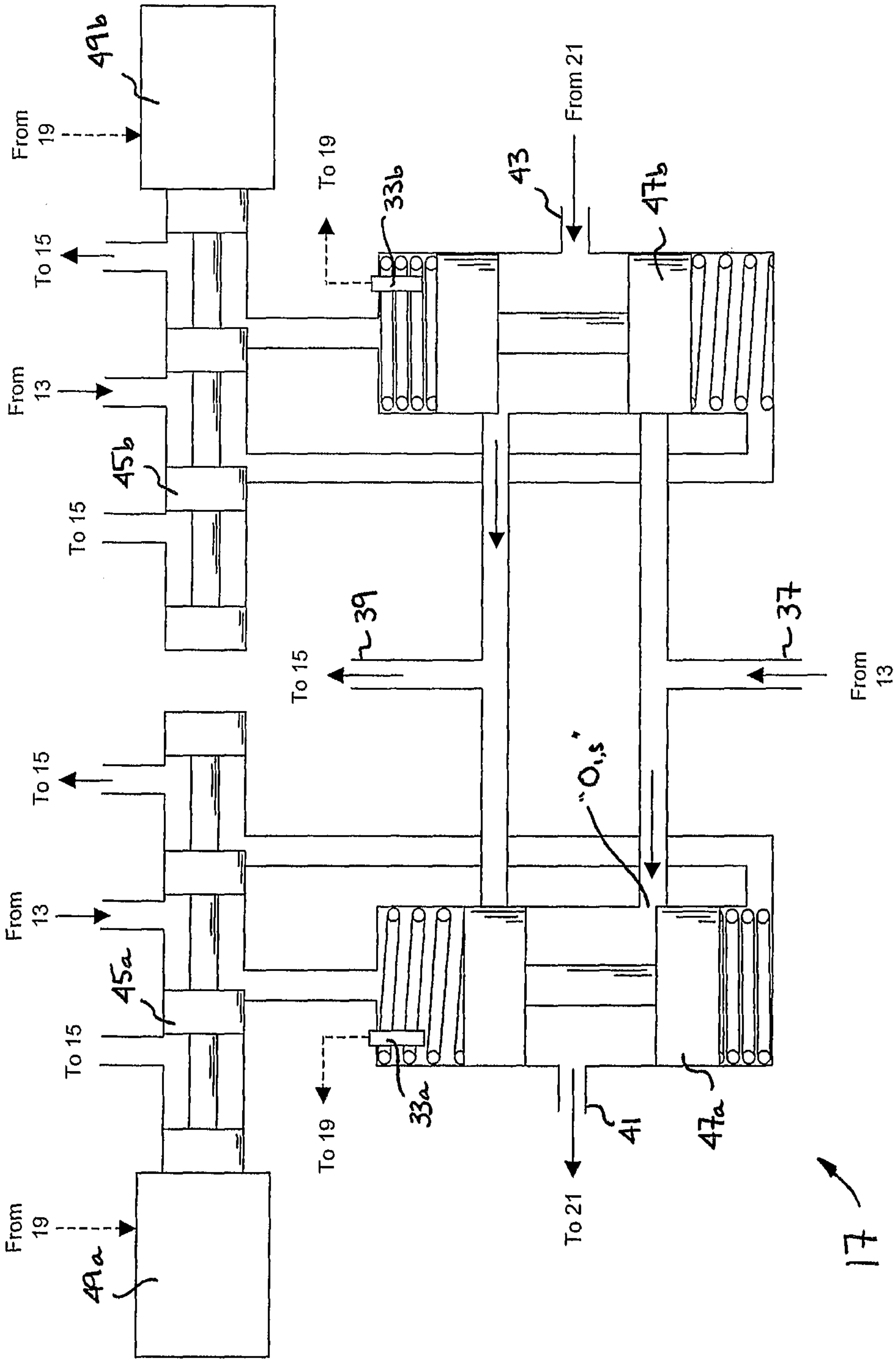
From 19
49b
To 15
From 13
45b
To 15
To 19
33b
43
From 21
47b
39
To 15
37
From 13
To 15
From 13
45a
To 15
To 19
33a
41
47a
To 21
From 19
49a
17

FIG. 2a

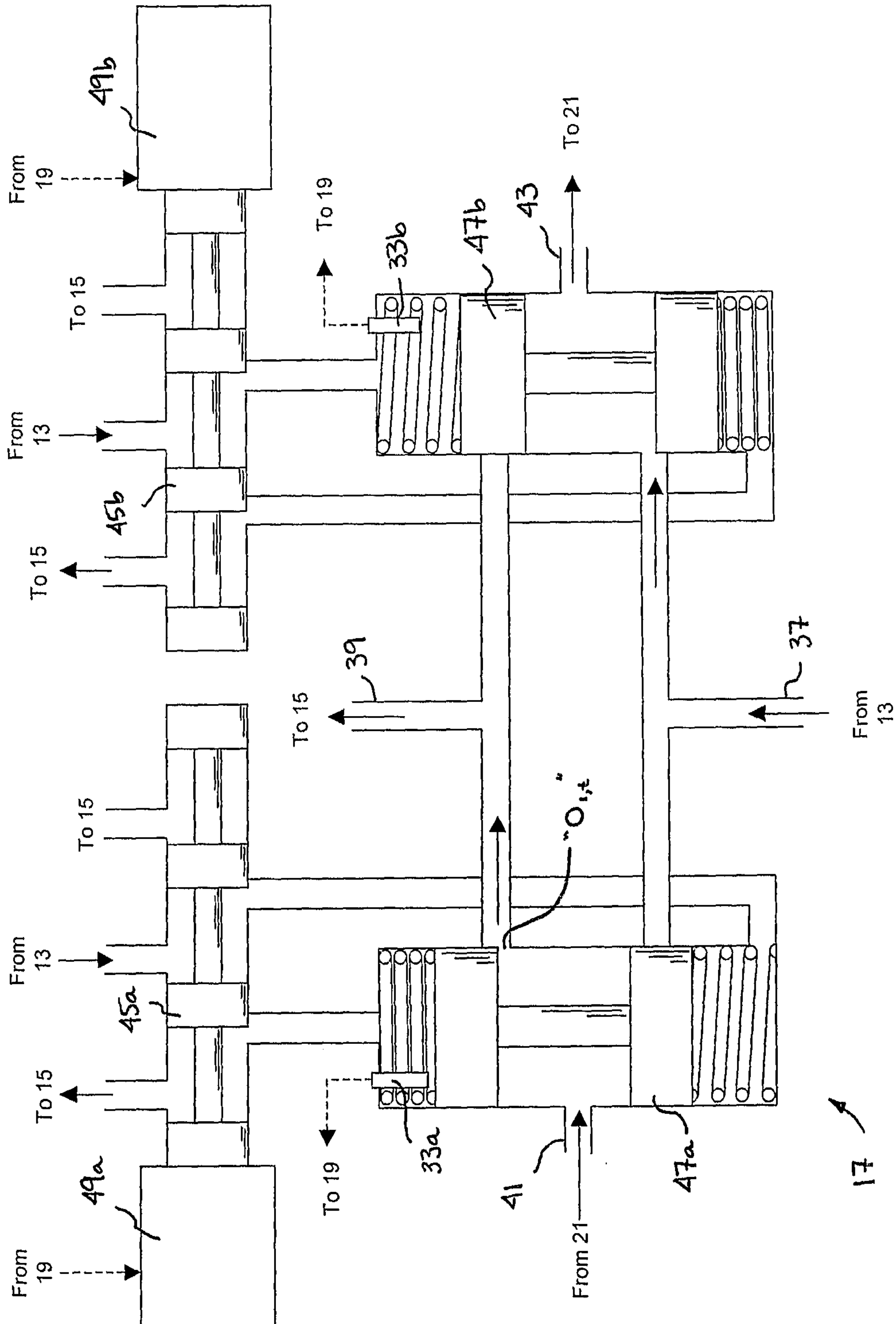
49b
From 19
To 15
From 13
45b
To 15
To 19
33b
47b
43
To 21
39
To 15
37
From 13
To 15
From 13
45a
To 15
49a
From 19
To 19
33a
41
From 21
47a
17

FIG. 2b

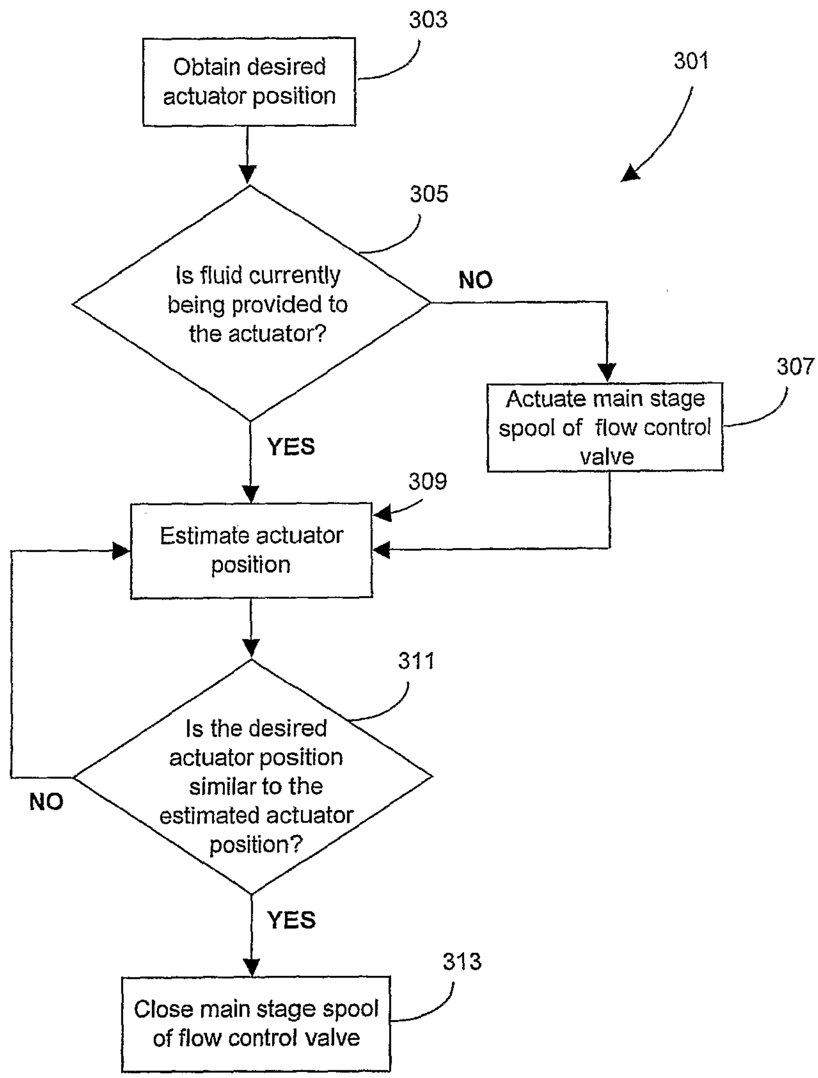
303
Obtain desired actuator position
301
305
Is fluid currently being provided to the actuator?
NO
307
Actuate main stage spool of flow control valve
YES
309
Estimate actuator position
311
Is the desired actuator position similar to the estimated actuator position?
NO
YES
313
Close main stage spool of flow control valve

FIG. 3

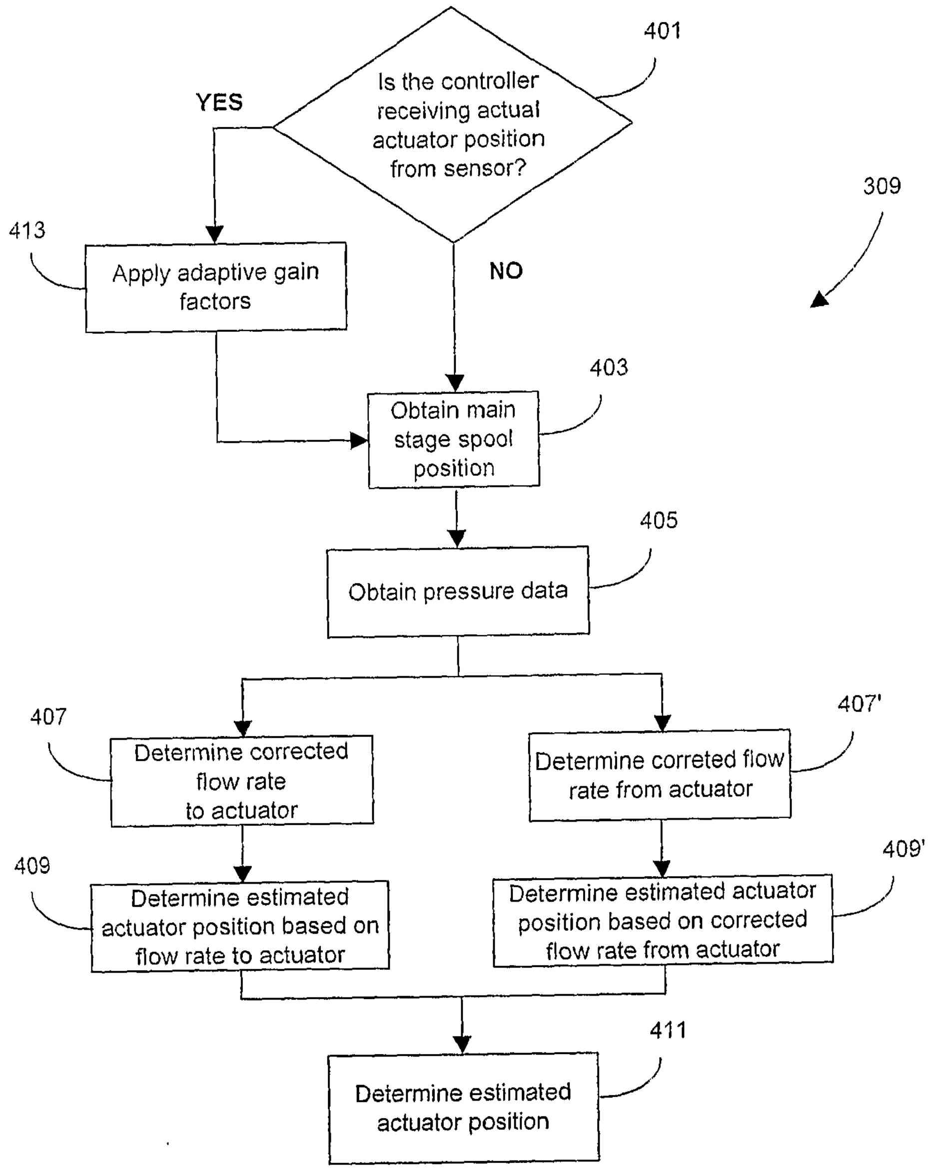
401
Is the controller receiving actual actuator position from sensor?
YES
NO
309
413
Apply adaptive gain factors
403
Obtain main stage spool position
405
Obtain pressure data
407
Determine corrected flow rate to actuator
407'
Determine correted flow rate from actuator
409
Determine estimated actuator position based on flow rate to actuator
409'
Determine estimated actuator position based on corrected flow rate from actuator
411
Determine estimated actuator position

FIG. 4

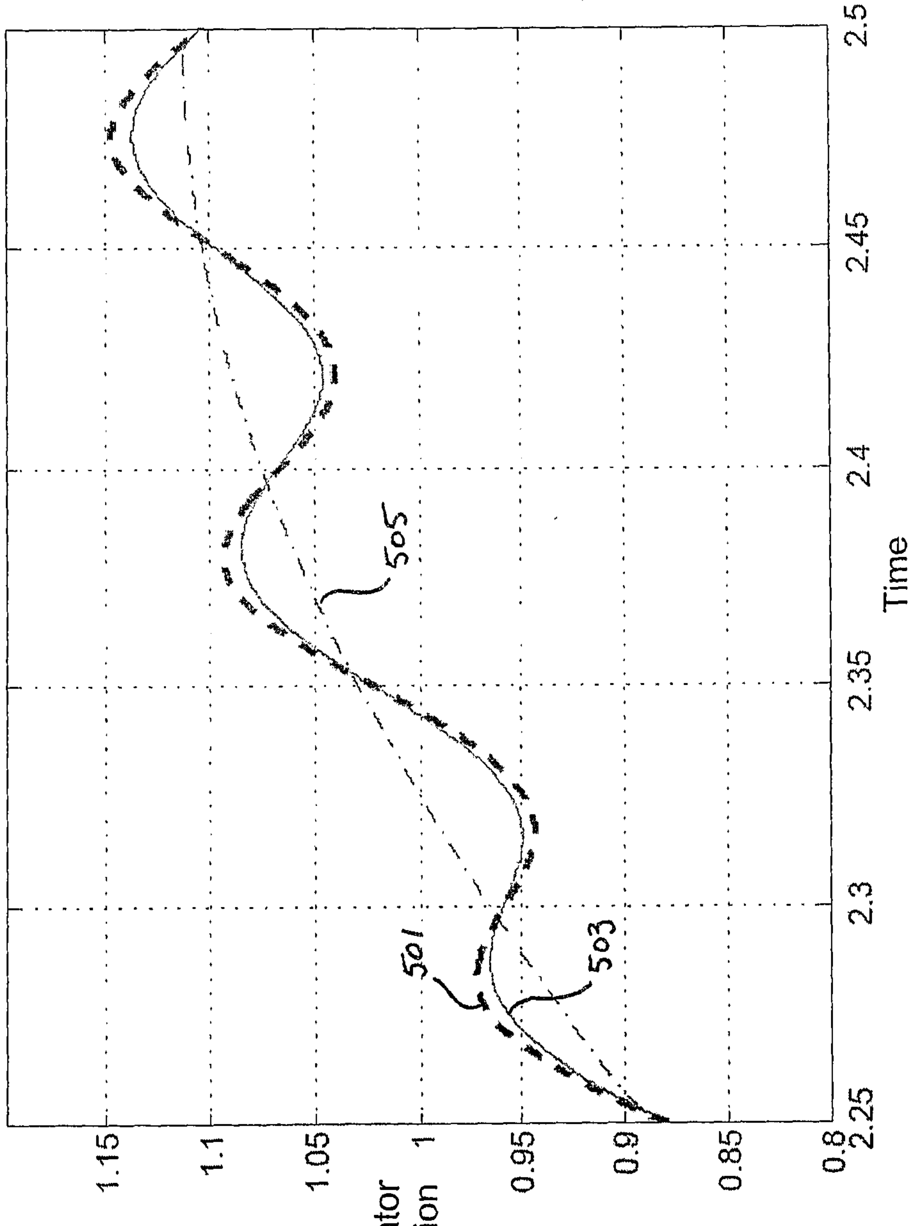
Actuator Position
Time
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
2.25
2.3
2.35
2.4
2.45
2.5
501
503
505

FIG. 5

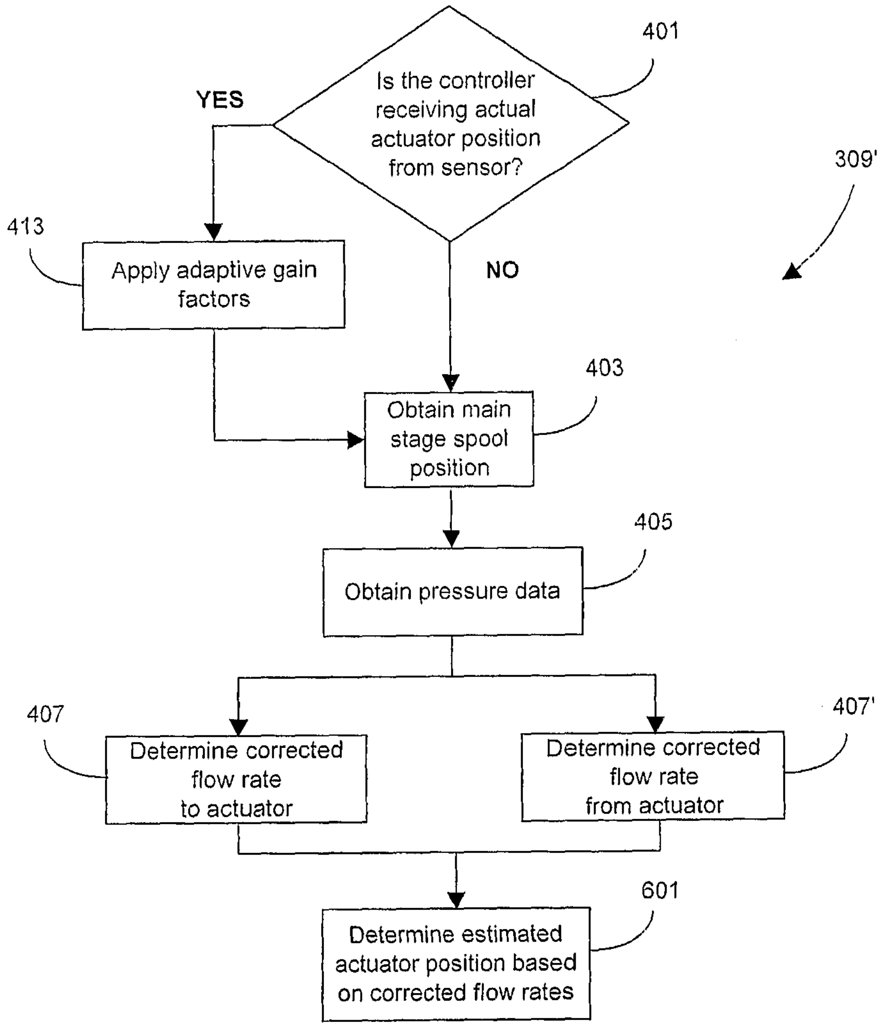
401
Is the controller receiving actual actuator position from sensor?
YES
NO
309'
413
Apply adaptive gain factors
403
Obtain main stage spool position
405
Obtain pressure data
407
Determine corrected flow rate to actuator
407'
Determine corrected flow rate from actuator
601
Determine estimated actuator position based on corrected flow rates

FIG. 6

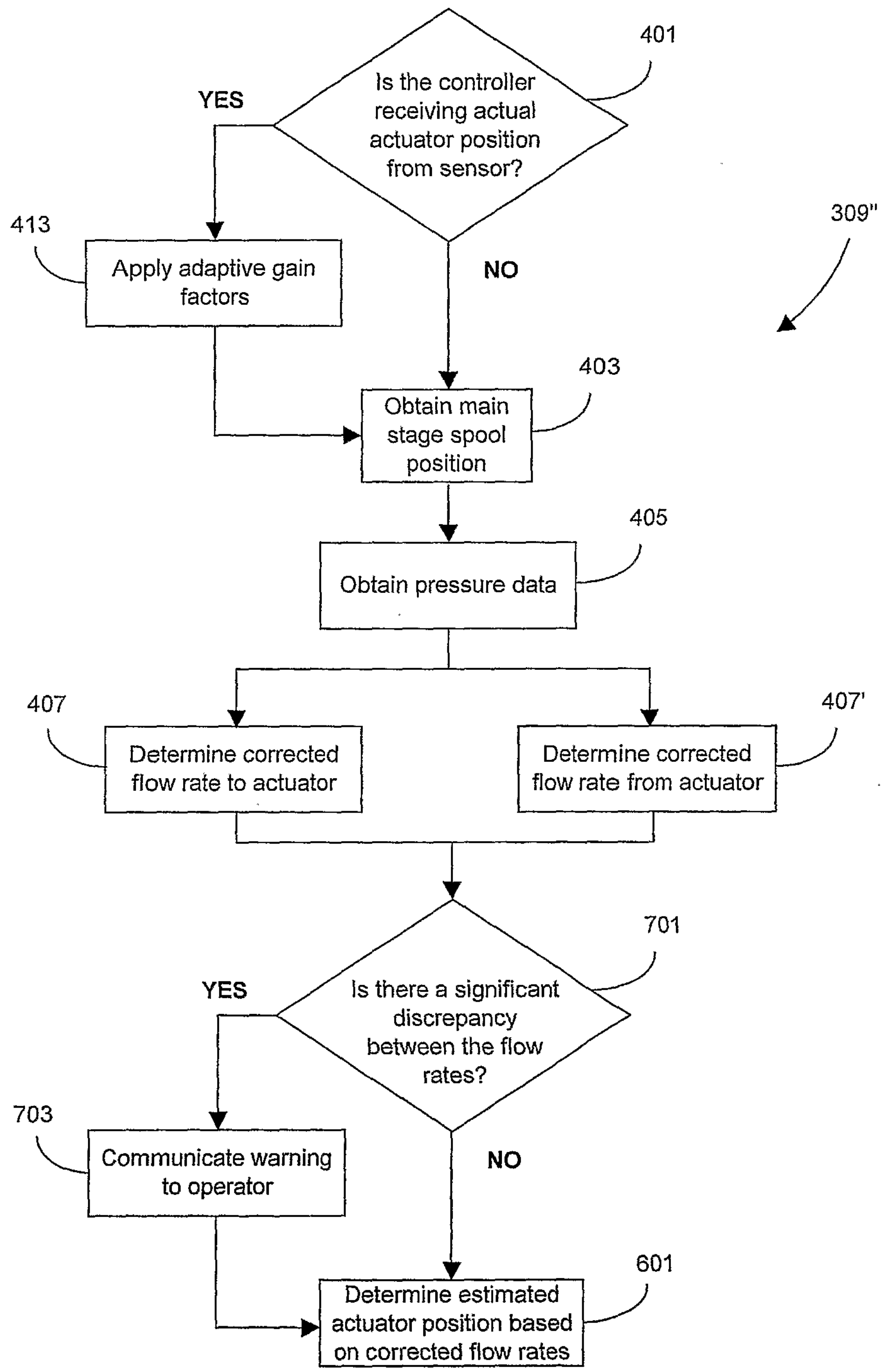
401
YES
Is the controller receiving actual actuator position from sensor?
413
Apply adaptive gain factors
309"
NO
403
Obtain main stage spool position
405
Obtain pressure data
407
407'
Determine corrected flow rate to actuator
Determine corrected flow rate from actuator
701
YES
Is there a significant discrepancy between the flow rates?
703
Communicate warning to operator
NO
601
Determine estimated actuator position based on corrected flow rates

FIG. 7