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(54) **HYDRAULIC CYLINDER WITH POSITION ENCODER**

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(57) **ABSTRACT**

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An actuator has a position encoder provided by a helical groove formed in the piston rod. The groove is filled with a material of different magnetic characteristics to provide a smooth exterior surface and a varying discernible signal as the rod moves relative to the cylinder. An array of Hall effect sensors is provided around the rod to provide phase shifted signals as the rod moves so that the signal of one sensor may be correlated by the signals of other sensors.

Related U.S. Application Data

(63) Continuation of application No. 09/268,120, filed on Mar. 15, 1999, now Pat. No. 6,393,963, which is a continuation-in-part of application No. 08/965,246, filed on Nov. 6, 1997, now abandoned.

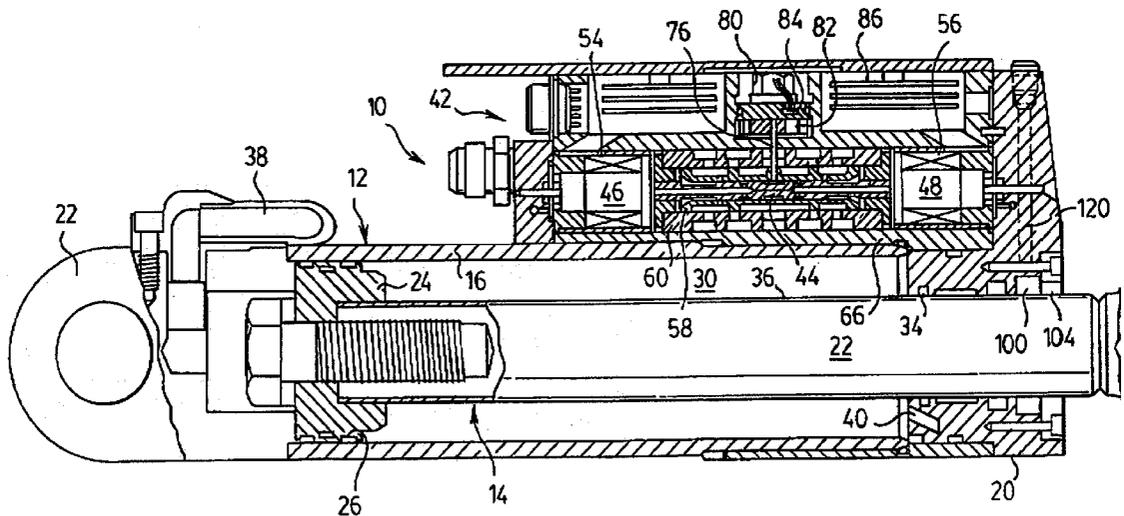
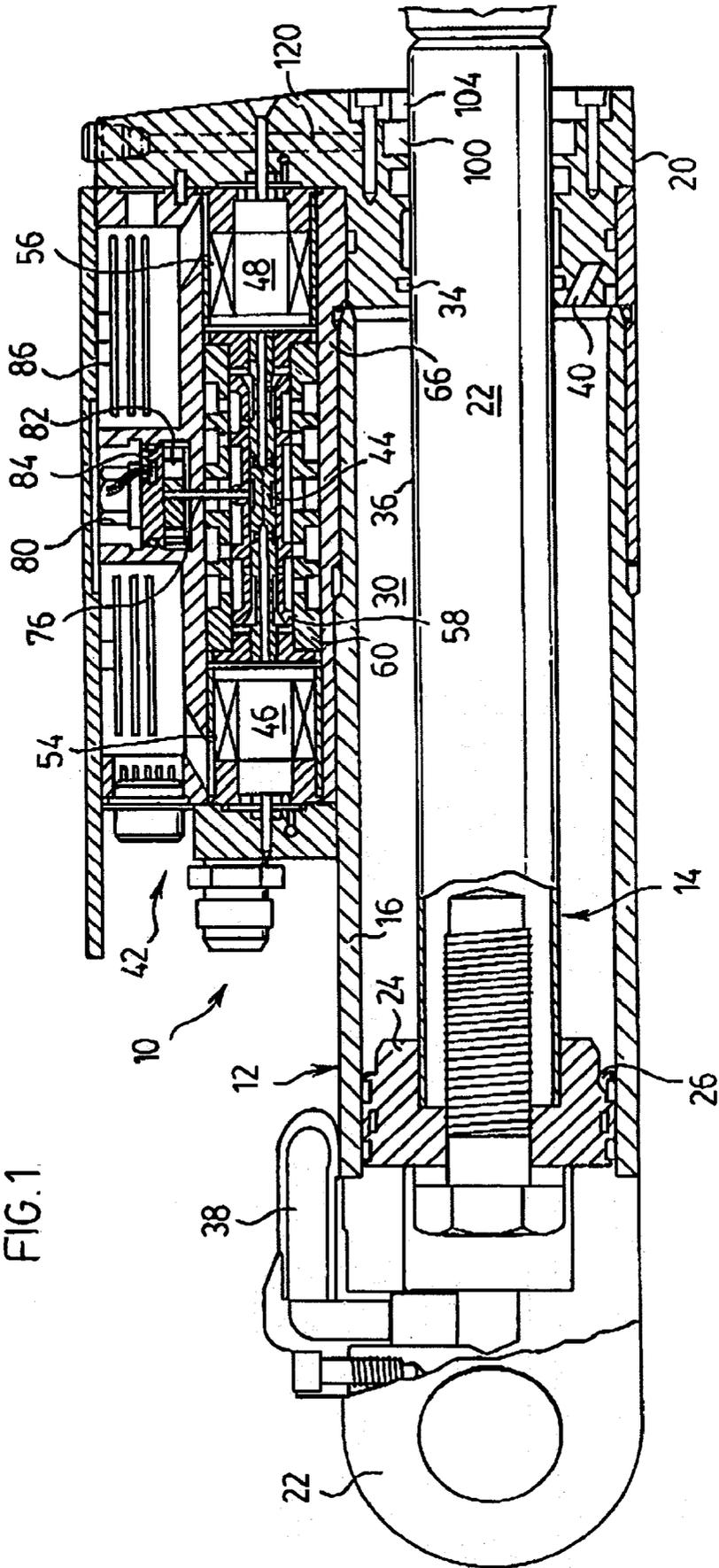


FIG. 1



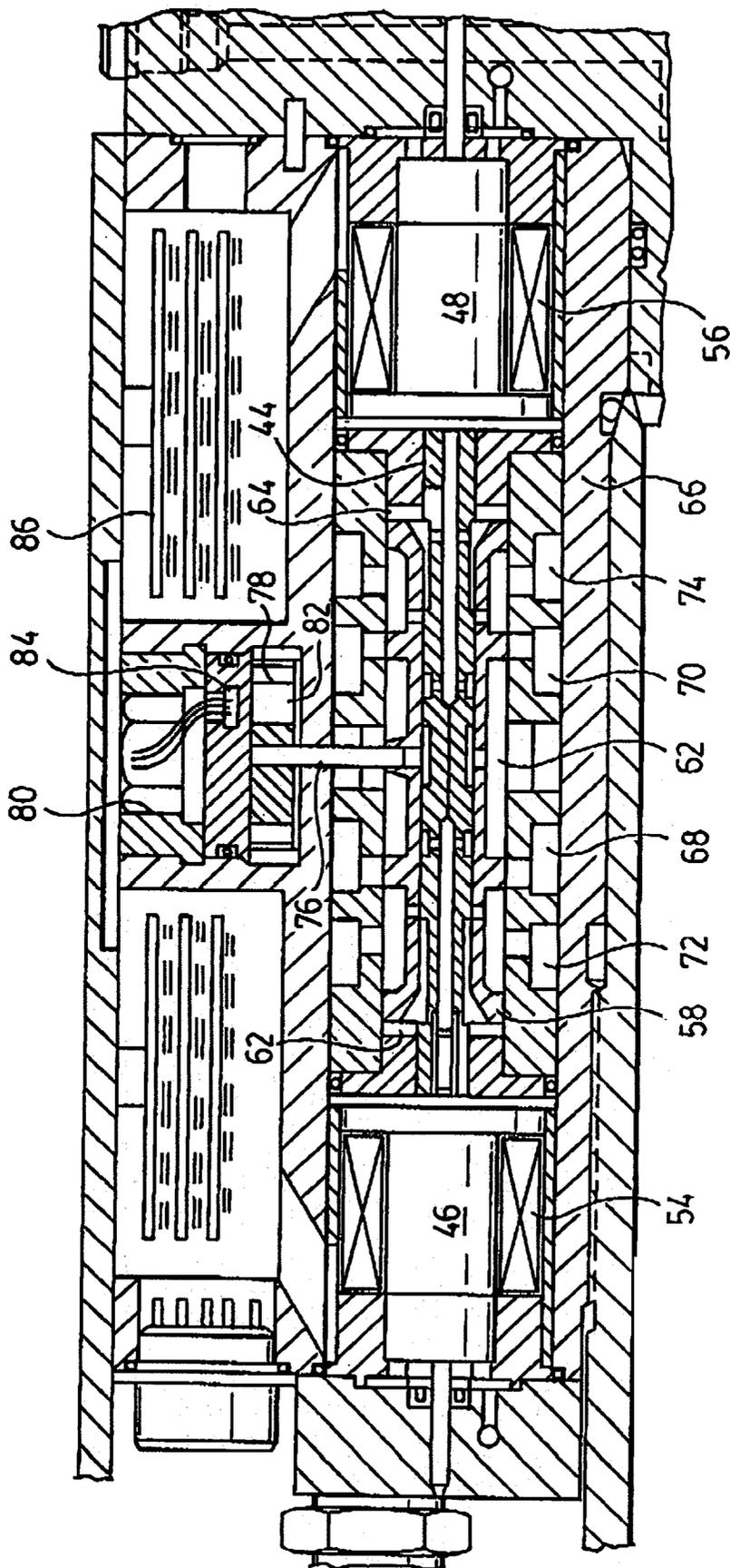


FIG. 2.

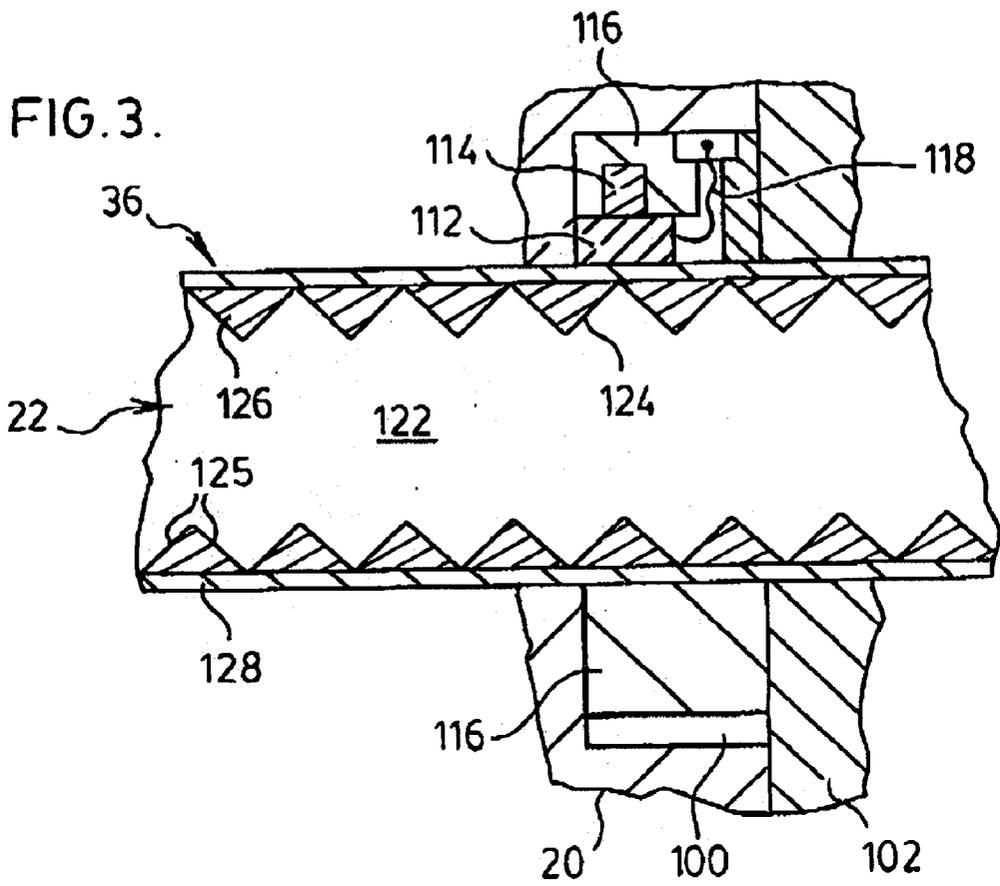


FIG. 4.

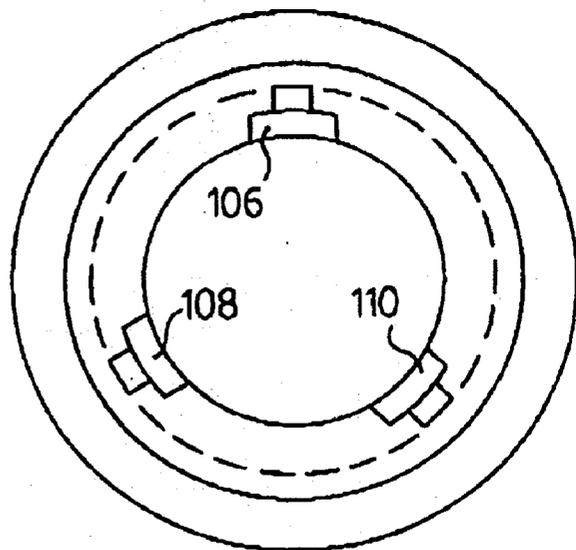


FIG. 5.

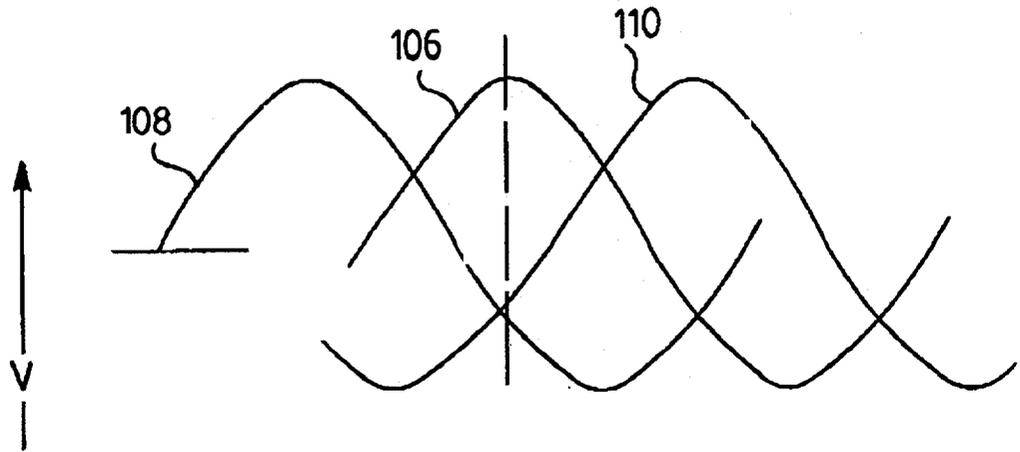


FIG. 6.

SENSOR	A	B	C
VOLTS	5	<u>3</u>	<u>3</u> ← PEAK 106
VOLTS	4	2	4
VOLTS	<u>3</u>	<u>1</u>	5 ← PEAK 110
VOLTS	2	2	4
VOLTS	1	3	3
VOLTS	2	4	2
VOLTS	<u>3</u>	5	<u>1</u> ← PEAK 108
VOLTS	4	4	2

140

FIG. 7.

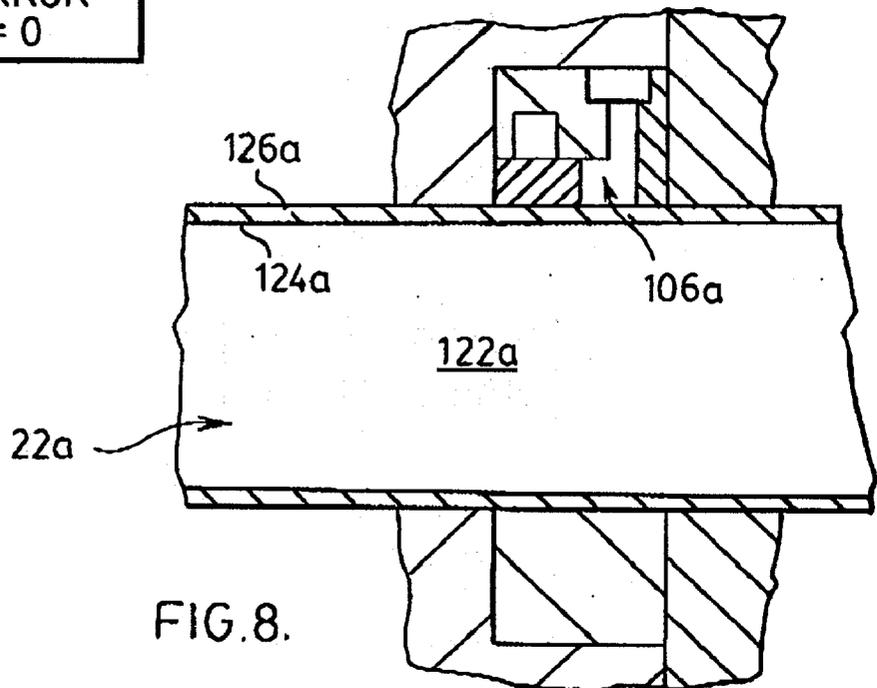
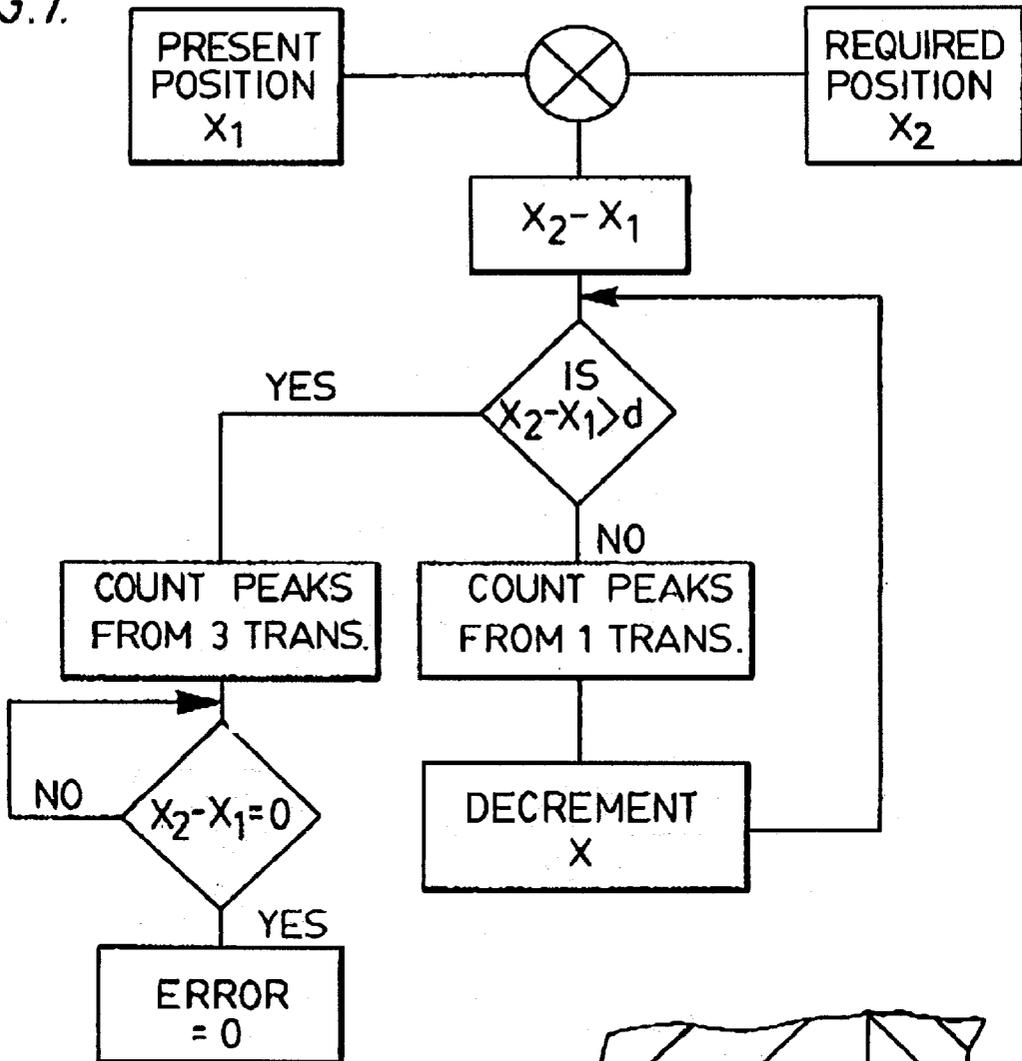


FIG. 8.

HYDRAULIC CYLINDER WITH POSITION ENCODER

[0001] This application is a continuation of U.S. application Ser. No. 09/268,120 filed on Mar. 15, 1999, which is a continuation-in-part of U.S. application Ser. No. 08/965,246 filed on Nov. 6, 1997 the contents of which are incorporated herein by reference, and which claims priority from United Kingdom Application No. 9623115.4 filed on Nov. 6, 1996.

[0002] The present invention relates to actuators and more particularly to apparatus and control systems for position controlling such actuators.

[0003] The use of hydraulic cylinders to control the movement and ultimate position of components is well known. Typically such cylinders are linear, utilizing a cylinder with a piston dividing the cylinder into a pair of chambers and a piston rod attached to the piston and extending out of one or both ends of the cylinder. A control valve will then control the admission of fluid into one or other of the chambers, causing the piston to move relative to the cylinder and adjust the length of the hydraulic actuator.

[0004] In its simplest form, the control of the hydraulic cylinder is performed manually through a simple control valve. More sophisticated controls may control the movement of the cylinder in response to fluctuations in the supply pressure, flow rate of fluid or a combination thereof. Attempts have also been made to control the movement of the cylinder by monitoring the position of the movable component and providing a feedback signal to a control valve that indicates the difference between the desired location and the actual location of the component. Such arrangements rely upon the accurate measurement of the position of the piston relative to the cylinder but the measuring device must be sufficiently robust to withstand the normal harsh environment in which the actuators may be used and at the same time must maintain the structural integrity of the actuator.

[0005] U.S. Pat. No. 3,956,973 shows a hydraulic cylinder in which a series of magnetic discontinuities are provided by a square thread form cut in the wall of a cylinder rod. The discontinuities are detected by a transducer that detects the change in magnetic intensity as the thread passes the transducer. The transducers create pulsed signals which are used to provide data relating to position, velocity, and acceleration of the piston rod. The signal produced by the square thread form only identifies whether the top or base of the thread is adjacent the transducer and therefore does not give a resolution greater than the pitch of the thread. To enhance the frequency of the signal, an array of transducers is used that are distributed about a portion of the circumference of the piston rod. Whilst the frequency of the signal is increased, each transducer is only able to detect edges of the thread form and therefore the resolution is dependent on the number of transducers. Moreover, because the signal is either "high" or "low" there is an ambiguity upon reversal of the direction of movement of the rod that leads to complexity in the signal processing.

[0006] It is therefore an object of the present invention to provide an actuator in which the above needs are addressed.

[0007] In general terms, the present invention provides an actuator having a cylinder and a piston assembly moveable within the cylinder. The piston assembly projects from the

cylinder and has a surface that presents to a predetermined location on the cylinder a periodically varying discernible characteristic as the surface moves relative to the cylinder. A sensor assembly monitors the discernible characteristic and measure changes therein to provide an indication of movement of the piston assembly relative to the cylinder. The varying discernible characteristic is provided by an interface on the piston assembly exhibiting a change in the discernible characteristic. The interface is inclined to the direction of travel of the rod whereby the distance between the interface and the transducer varies progressively and continuously as the piston assembly moves relative to said cylinder.

[0008] Preferably the surface of the cylinder is smooth to permit passage past a seal assembly.

[0009] In one embodiment it is preferred that the discernible characteristic is magnetic permeability and varying permeability is provided by a screw thread having convergent flanks formed in the outer surface and filled with a material of a different magnetic characteristic to present a continuous cylindrical surface to the piston assembly,

[0010] In a further embodiment, the magnetic to non-magnetic interface is provided by a tapered piston rod having a non-magnetic coating of varying thickness to provide a cylindrical outer surface.

[0011] As a further preference, a plurality of magnetic transducers are circumferentially spaced about the piston rod to enhance resolution of the movement of the piston assembly relative to the cylinder.

[0012] Embodiments of the invention will now be described by way of example only, with reference to the accompanying drawings, in which

[0013] FIG. 1 is a section through a linear actuator;

[0014] FIG. 2 is an enlarged portion of the valve shown in FIG. 1,

[0015] FIG. 3 is a detail view of a portion of FIG. 1;

[0016] FIG. 4 is a view on the line 4-4 of FIG. 3;

[0017] FIG. 5 is a graph showing the traces obtained from the sensing apparatus shown in FIGS. 3 and 4;

[0018] FIG. 6 is a schematic illustration of a lookup table used with the sensing apparatus of FIGS. 3 and 4;

[0019] FIG. 7 is a flow chart showing a control system utilizing the transducer shown in FIGS. 3 and 4; and

[0020] FIG. 8 is a sectional view similar to FIG. 3 of a further embodiment of cylinder.

[0021] Referring therefore to FIG. 1, a linear hydraulic actuator 10 includes a cylinder assembly 12 and a piston assembly 14. The cylinder assembly 12 includes a tubular body 16 and a pair of end caps 18,20.

[0022] The piston assembly 14 includes a piston rod 22 that is connected at one end to a piston that is slidably received within the tubular body 16 and includes piston seals 26 to seal against the tubular body in a conventional manner. The piston 24 thus divides the cylinder assembly 12 into a pair of chambers, namely a head end chamber 28 and a rod end chamber 30. The rod 22 projects through a bore 32 in the

end cap 20 and leakage from the chamber 30 is inhibited by seal assemblies 34 that engage with the outer surface 36 of the rod 22.

[0023] Each of the end caps 18,20 includes a duct 38,40 that permits the flow of hydraulic fluid into the chambers 28,30 respectively under the control of a valve assembly 42. As shown, the valve assembly 42 is mounted on the cylinder assembly 12 but it will be understood that the valve assembly 42 may be remote from the cylinder and may be of suitable convenient form. In the embodiment shown, the valve assembly includes a primary spool 44 whose position is controlled by a pair of direct acting solenoid assemblies including coils 54,56. The details of the direct acting solenoids are more fully described in our prior application PCT/CA95/00057 and as such need not be described further at this time.

[0024] As best seen in FIG. 2, the primary spool 44 controls movement of a secondary spool 58 that is slidable within a ported sleeve 60. The secondary spool has a pair of pilot chambers 62,64 formed between opposite ends of the secondary spool 48 and spacers 66 that support the control spool 44. The pressure differential in the pilot chamber 62,64 causes the secondary spool to move relative to the ported sleeve 60 and allows fluid to flow from the pressure port 66 into one of the supply ports 68,70. At the same time, the other of the ports 68, 70 is connected through the exhaust ports 72, 74 to the sump.

[0025] Accordingly, current may be adjusted in the coils 54,56 to cause the primary spool 44 to be displaced and thus allows pressurized fluid from the port 62 to flow through the secondary spool and through cross-drillings in the primary spool to one of the pilot chambers 62,64. The other of the pilot chambers 62,64 is connected through cross-drillings in the primary and secondary spools to the exhaust ports 74. A pressure differential is thus established in the pilot chamber 62,64 causing the secondary spool to move and allow pressurized fluid to flow from the port 62 into one of the supply ports 68,70 and allow fluid to flow past the secondary spool 58 and into the exhaust port 72,74 from the other of the supply ports 68,70. Supply ducts 68,70 are connected to respective ones of the supply ducts 38,40 and thus control the flow of fluid into the chambers 28,30 causing relative movement between the piston assembly 14 and the cylinder assembly 12.

[0026] The secondary spool 58 is connected through a pin 76 to a plug 78 that is slidably mounted within a sensor assembly 80 secured in the valve 42. The plug 48 carries a magnetic insert 82 and a Hall effect sensor 84 is positioned in the sensor assembly 80 adjacent the magnetic insert 82. Movement of the secondary spool 58 relative to the ported sleeve 60 thus adjusts the relative position between the magnetic insert 82 and the Hall effect sensor 84. A varying signal is provided to a control circuit assembly indicated by the circuit boards 86 which controls the supply of current to the coils 54,56.

[0027] As can best be seen in FIGS. 1 and 3, the end cap 20 has an annular recess 100 that is closed by a plate 102 secured to the end cap 20. The plate 102 supports a wiper seal 104 that engages the outer surface of the rod 22 in a conventional manner. The recess 100, as shown in FIGS. 3 and 4, includes three uniformly spaced transducer assemblies 106,108,110, each of which is similar in construction.

The transducer assembly 106 includes a Hall effect sensor 112 and a magnetic insert 114 supported on the transducer 112 in an annular collar 116. The annular ring 116 is non-magnetic, for example bronze, plastics or aluminum and is located within the annulus 100 to permit radial float relative to the end cap 20 but inhibit axial movement. The sensors 112 are connected through conductors 118 located within internal passageways 120 in the end cap 20 (FIG. 1) for connection to the circuit boards 86.

[0028] The Hall effect sensors 112 are positioned in close proximity to the surface 36 of the piston rod 22. As shown in FIG. 3, the piston rod 22 has a steel body 122 with a helical thread 124 formed on the outer surface. The thread 124 is a single start thread of relatively fine pitch and has oppositely inclined flanks 125. The thread is filled with a material 126 of different magnetic characteristics to the body 122—for example, a copper plasma-sprayed onto the body so that a magnetic to non-magnetic interface is provided that is inclined to the longitudinal axis of the rod. A smooth cylindrical surface is provided on the body and if necessary, the body may be ground cylindrical after the application of the filler material 126. The body is then plated as indicated at 128 with a wear-resistant surface such as chromium plating so that a hardwearing cylindrical outer surface 36 is provided.

[0029] The flanks of the thread 124 provides an undulating interface that progressively and continuously vary in distance from the transducer as the rod moves relative to the cylinder. The transducer in turn provides a periodically varying discernible signal indicative of the changes in the magnetic permeability in the direction of movement of the piston rod 122, so that as the piston rod moves past the transducer assembly 106,108,110, a varying signal is obtained in the respective conductor 118. At the same time, a relatively smooth outer surface 36 is retained to maintain the integrity of the seal assemblies 34.

[0030] The transducers 106,108,110 are displaced 120° from one another so that the voltage signal obtained from the Hall effect sensor 112 is phase shifted by 120° relative to the other transducers. The resultant signals are shown in FIG. 5 where it can be seen that three continuously varying voltages are obtained, each of similar form, with the peak voltage corresponding to the passage of the tip of the thread 124 past the respective transducer 106,108,110 with the minimum voltage corresponding to the root of the thread passing the transducer. Each of the transducers provides an analog signal whose instantaneous value is indicative of the position along the flank. The analog signal will vary from a maximum to a minimum value over the course of ½ pitch and so enable very high resolutions to be obtained. The voltages obtained may be digitized for use in a digital control circuit.

[0031] In its simplest form, the transducer 106,108,110 can be used to count the peaks and thereby provide an indication of the movement relative to the cylinder. Because the thread can be formed with an accurate pitch, the peak crossings can be counted and the total distance moved by the piston rod can be obtained. In this way, a very simple position transducer is obtained to provide a position signal to the control circuits 86 for control of the hydraulic valve 42.

[0032] The provision of the three transducers 106,108,110 does, however, allow an enhanced resolution as three trans-

ducers in combination with the inclined flanks **125** of the thread allows the peak crossings to be more accurately identified to enhance the accuracy of the transducer.

[0033] As maybe seen in **FIG. 5**, with the fixed spacing of the transducers, the peak of one transducer will coincide with the position of the other two on the flanks of the threads. The peak value is difficult to identify accurately as any discrepancy in manufacturing is likely to occur at the tip or root of the thread and the rate of change of the spacing between the tip and the transducer is minimal. However, the flanks of the thread are accurately machined and the rate of change of the spacing of the interface from the transducer to vary the signal of the Hall effect sensor is at a maximum. To avoid ambiguity, the peak value is correlated with the occurrence of signals from the other two transducers of predetermined magnitude so that a pair of values from transducers **106,108** indicates the passage of the tip of the thread past the transducer **112**. As shown in **FIG. 6**, the digitized output from each of the transducers **106,108,110** is monitored against a lookup table **140**. The occurrence of predetermined values in transducers **106,108** is correlated to the peak value of transducer **110**. Similarly, values at transducers **108, 110** respectively are correlated to the peak value at transducer **106** and likewise for transducer **108**. In this way accurate counting and resolution of the movement of the rod may be obtained. This technique may also be used to resolve the position of transducer along a flank as three unique signals will be provided which may be cross-correlated to provide confirmation of the position of the rod. It will be appreciated therefore that the combination of enhanced peak crossing detection and the resolution along the flank by virtue of the continuously varying signal provides a position encoder with high resolution.

[0034] The cylinder **10** and associated control valve **42** may be used to implement a number of different control strategies in which a position-controlled actuator is required. The provision of the multiple transducers does, however, facilitate the implementation of a control strategy that reduces the bandwidth of the transducer and at the same time provides the requisite accuracy of position control. The implementation of the strategy will be described with reference to the flow chart in **FIG. 7** and the cylinder shown in **FIG. 1**. Assuming that the piston assembly **14** is at rest in the desired position, the solenoids **46,48** provide equal and opposite forces so that the primary spool **44** is centered. In this position, the fluid is locked in the chambers **28,30** and movement of the piston assembly **14** relative to the cylinder assembly **12** is inhibited. Upon application of a control signal to the circuits **86** from an outside controller—for example, a manual controller—indicating a new position is to be attained, a control signal is provided by the control circuit **86** to the coils **54,56** to adjust the position of the primary spool **44**. Fluid is caused to flow from the pressure port **62** into the chamber **28** causing the piston **24** to move relative to the cylinder **16**. The movement of the piston induces movement of the piston rod **22** past the transducers **106,108,110** but provides a position feedback signal to the control circuit **86**. The control circuit **86** compares the present position with the desired position as shown by the input signal and if the difference is greater than a predetermined value d , then it continues to count the peaks provided by one of the transducers, e.g. transducer **106**. Each peak is thus interpreted as the distance corresponding to a full pitch.

[0035] Continued movement of the piston **24** reduces the error signal between the desired position and the actual position below the preset value d and causes the control circuit to monitor the peak crossings of each of the transducers **106,108**. A finer resolution is thus provided and the comparison continues until the error signal is reduced to zero. The error signal between the actual position and the required position is also used to modulate the current to the coils **54,56** so that the primary spool **44** progressively moves the secondary spool back toward a neutral position. The position feedback associated with the secondary spool provides a closed loop control for the spool valve to enhance its response time.

[0036] It will be seen, therefore, that a simple position transducer is provided for a linear actuator through the provision of the varying magnetic permeability in the surface of the piston rod and that the signals obtained can be processed so as to provide a high resolution at a relatively low band width during the majority of the movement. The inclined flanks provide a continuously varying signal that can be used to enhance the resolution of the position sensor and avoid ambiguity upon direction reversal. In this case the signal will show a reversal in the amplitude from each transducer at other than the peak value allowing the change in direction of movement to be detected. It will be understood that alternative forms of control valve may be used with the transducer and that only one transducer need be used if appropriate for the intended purpose.

[0037] A further embodiment is shown in **FIG. 8** in which like reference numerals will be used with like components with a suffix “a” added for clarity. Referring to **FIG. 8** therefore, the piston rod **22a** has a core **122a** formed with a tapered outer surface **124a**. The taper of the surface **124a** may be adjusted to suit particular applications but a taper of 0.10 in. in diameter on a 24 inch stroke has been found satisfactory. The core **122a** is formed from a magnetically reactive material and a non-magnetic coating **126a** applied to the surface **124a**. The coating is typically chrome plating to provide a hardwearing outer surface and is ground to a cylindrical finish after coating. The outer surface **124a** thus provides a magnetic to non-magnetic interface which varies in distance from the transducer along the length of the rod **22a**. The transducer assemblies **106a, 108a, 110a** are positioned to detect the varying magnetic signal as the rod moves relative to the cylinder assembly **12a** and thereby provide a signal proportional to the position of the rod **22a**. It will be noted that because of the tapered surface, a unique signal is provided for each position of the piston rod with a maximum at one end and a minimum at the other. This unique signal enables a single transducer to be utilised whilst giving the requisite resolution although multiple transducers may be used if preferred. The unique signal at each position of the rod permits the position of the rod to be determined even after an electrical power interruption which is particularly important in some applications.

[0038] To avoid ambiguity in the signal obtained from the transducer, a thermal compensation may be incorporated into the signal processing. Elongation of the rod due to elevated temperatures may lead to a different signal for a given position and this may then be compensated to maintain the desired accuracy. The unique value of the signal for each position permits the thermal compensation to be tailored to each position of the cylinder.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. An actuator having a cylinder and a piston assembly moveable within said cylinder, said piston assembly projecting from said cylinder and having a surface that presents to a predetermined location on said cylinder a periodically varying discernible characteristic as said surface moves relative to said cylinder, and a sensor assembly to monitor said discernible characteristic and measure changes therein to provide an indication of movement of said piston assembly relative to said cylinder, said varying discernible characteristic being provided by an interface on said piston assembly exhibiting a change in said discernible characteristic, said interface being inclined to the direction of travel of the rod whereby the distance between said interface and said transducer varies progressively and continuously as said piston assembly moves relative to said cylinder.

2. An actuator according to claim 1 wherein said discernible characteristic is magnetic permeability.

3. An actuator according to claim 1 wherein said predetermined location is positioned adjacent the exit of said piston assembly from said cylinder.

4. An actuator according to claim 1 wherein said discernible characteristic is provided by a continuous groove formed in and extending along and about said surface.

5. An actuator according to claim 4 wherein said surface is cylindrical and said groove is wound about said surface.

6. An actuator according to claim 5 wherein said sensor assembly includes a plurality of sensors circumferentially spaced about said surface to provide a plurality of similar but phase shifted signals as said surface moves past said location.

7. An actuator according to claim 6 wherein a signal from one of said transducers is correlated to predetermined signals from other of said transducers.

8. An actuator according to claim 1 wherein said piston assembly includes a piston rod projecting from said cylinder and having a cylindrical outer surface and said interface is provided by flanks of a helical groove formed in said outer surface.

9. An actuator according to claim 8 wherein said groove is filled with a material different to that of said piston to provide a smooth outer surface.

10. An actuator according to claim 9 wherein said rod is supported in a bearing in said cylinder and a seal assembly encompasses said rod, said sensor assembly being located adjacent said bearing assembly.

11. An actuator according to claim 10 wherein said sensor assembly includes a plurality of sensors circumferentially spaced about said rod.

12. An actuator according to claim 11 wherein each of said sensors produces a similar but phase shifted signal as said piston rod moves past said sensor assembly, said signals

being correlated to one another to provide verification of a signal obtained from one of said sensors by reference to other of said signals.

13. An actuator according to claim 12 wherein said helical groove is in the form of a screw thread having tips adjacent to said cylindrical outer surface, each of said sensors providing a peak signal upon a tip passing thereby.

14. An actuator according to claim 13 wherein the number of peak signals received from a sensor are monitored to provide an indication of movement of said rod relative to said cylinder.

15. An actuator according to claim 14 wherein identification of a peak signal is verified by correlation to signals from other of said sensors.

16. An actuator according to claim 14 wherein peak signals are monitored from one of said sensors when an error signal representing the difference between a desired position and an actual position is greater than a predetermined value and peak signals from a plurality of sensors are monitored when said error signal is less than said predetermined value.

17. An actuator according to claim 11 wherein said discernible characteristic is the magnetic permeability and said sensors are Hall effect sensors.

18. An actuator according to claim 1 wherein said interface is provided by a tapered surface on said piston assembly.

19. An actuator according to claim 18 wherein said tapered surface progressively and continuously decreases in diameter along said piston assembly in the direction of relative movement between said piston assembly and said cylinder assembly.

20. An actuator according to claim 19 wherein said tapered surface is coated to provide a cylindrical outer surface for said piston assembly.

21. An actuator according to claim 20 wherein said discernible characteristic is the magnetic permeability.

22. An actuator according to claim 21 wherein said interface is formed between a magnetically reactive body and a magnetically non-reactive coating.

23. An actuator according to claim 22 wherein said sensor assembly includes a Hall effect sensor mounted on said cylinder adjacent said piston assembly.

24. An actuator according to claim 23 wherein said sensor assembly further includes a magnet and said Hall effect sensor is interposed between said magnet and said piston assembly.

25. An actuator according to claim 22 wherein said sensor assembly is mounted on a support on said cylinder, said support being radially adjustable relative to said cylinder to accommodate radial movement between said piston assembly and said cylinder.

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