Aug. 15, 1961 R. D. ATCHLEY 2,996,072

ACTUATOR

Filed May 23, 1960 2 Sheets-Sheet 1

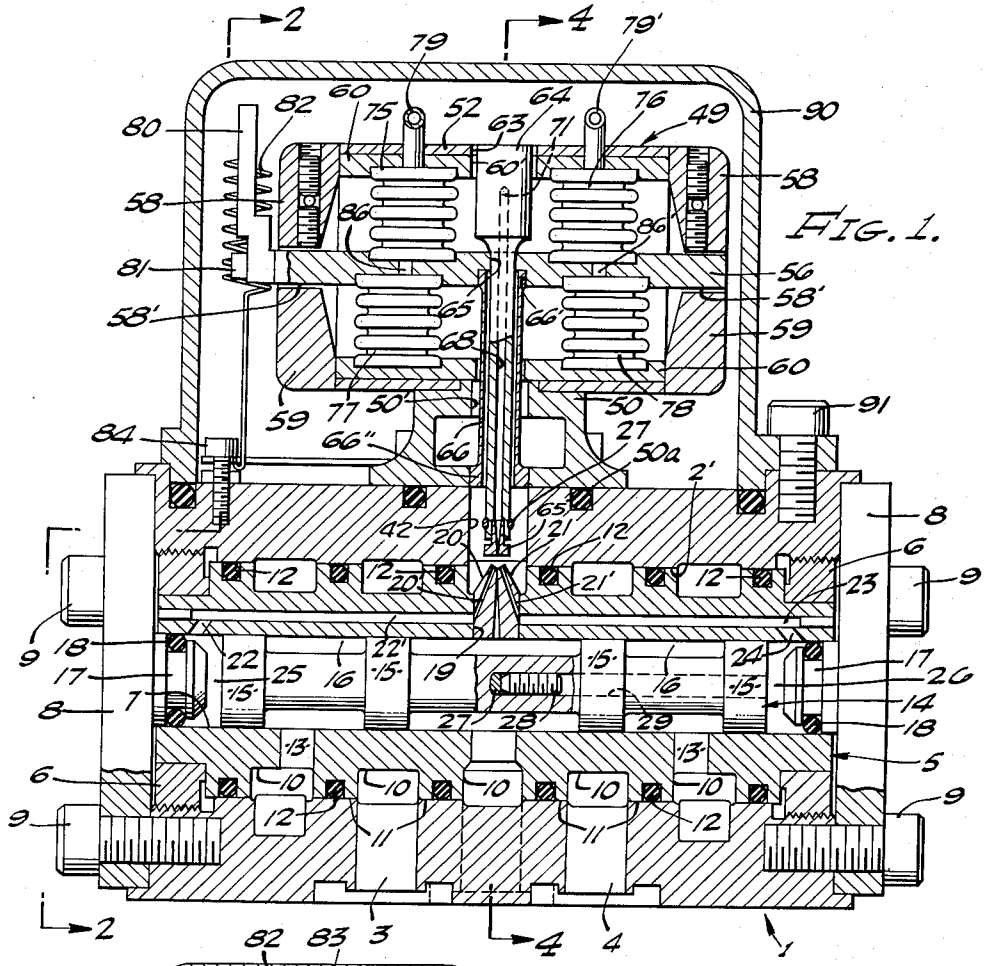


FIG. 1.

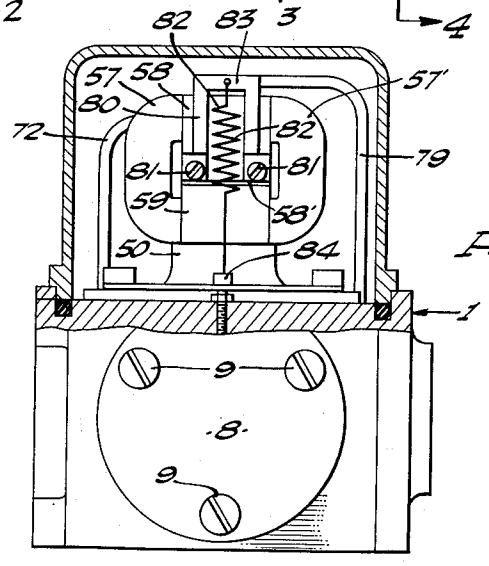


FIG. 2.

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ACTUATOR

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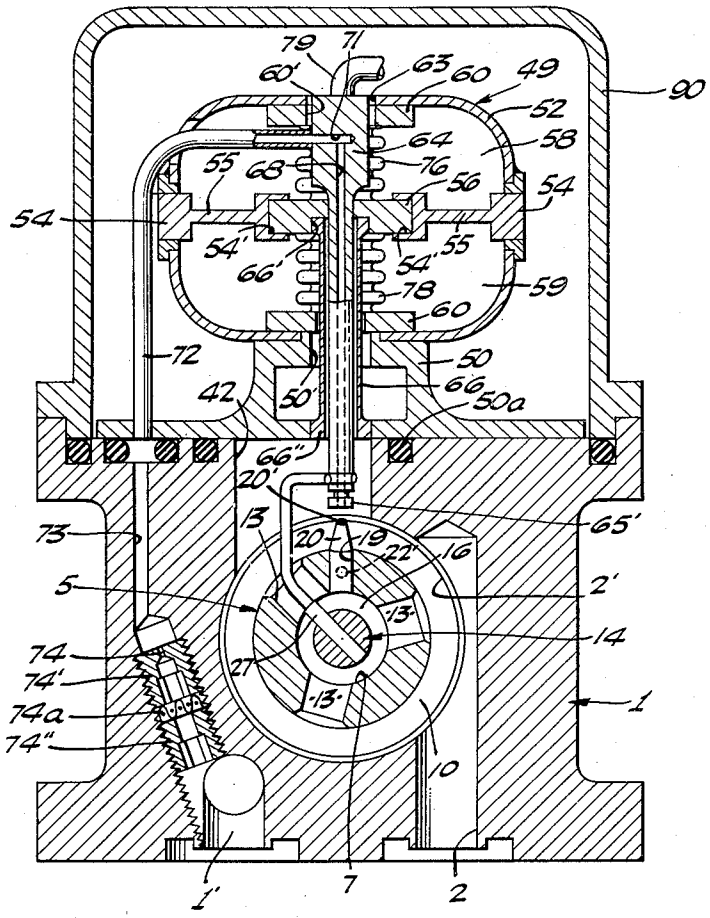


FIG. 4.

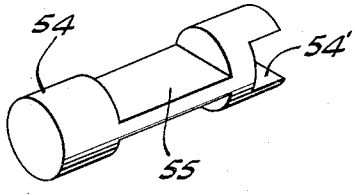


FIG. 3.

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United States Patent Office 2,996,072 Patented Aug. 15, 1961

2,996,072
ACTUATOR

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Filed May 23, 1960, Ser. No. 30,914
19 Claims. (Cl. 137—83)

This application is a continuation-in-part of application Serial No. 755,534, filed August 18, 1958, and Serial No. 755,775, filed August 18, 1958, now Patent Number 2,962,611, each of which is in turn a continuation-in-part of Serial No. 681,310, filed August 30, 1957, now Patent No. 2,884,907.

This invention relates to improvements in actuators.

It is an object of the present invention to provide a novel actuator design whereby a small change in signal input produces a large change in the unit controlled by the actuator.

Another object is the provision of an actuator comprising a movable beam or an armature and a motion transmitting device connected thereto, such armature and device being designed to be responsive to a small change in signal input.

A further object of the invention is the provision of an actuator in which the signal is mechanically applied to an armature in terms of an applied force or pressure tending to produce rotation of the armature.

A still further object is the provision of an actuator in which fluid pressure responsive devices are mechanically connected to the armature and wherein a small effective pressure causes actuation of the armature, or alternatively, a large displacement of the armature can be produced for any given effective pressure applied against the armature.

The actuator of my invention is designed to have a low stiffness coefficient and thus have a low natural frequency and to contain a movable member which is responsive to signals of low force and to have a relatively large displacement for low values of applied signal force.

The signal applied is in the preferred embodiment a mechanical force as distinguished from one applied by means of an electromagnetic transducer.

In my preferred embodiment the force is applied to the movable member either hydraulically or pneumatically.

The system for application of force to the movable member creates a balance of moments, each of large value but resulting in net moments of low value to cause the displacement of the movable member.

The actuator of the invention comprises basically a yieldably suspended armature mounted adjacent the pole pieces of permanent magnet means. In preferred practice the armature is suspended on a flexural constraint or flexure member. Means are provided for deflecting the armature by application of a force to said armature corresponding to the magnitude of a signal received by the force applying means. Unlike the actuator of my copending application, the force is a mechanical force and does not of itself modify the flux of the permanent magnets. A motion transmitting device, e.g. in the nature of a rod or jet pipe, as described more fully below, is connected to the armature for movement in response to displacement of the armature on the yieldable constraint or flexure. Such rod or jet pipe transmits the motion of said armature in response to said signal to a unit such as a hydraulic motor which is being controlled by the actuator.

The armature is constructed of a magnetically permeable material, and as the armature is displaced from its initial position toward a magnet pole piece, a greater attractive force exists between the armature and the

pole piece of the permanent magnet means toward which it is being displaced. This attractive force is in a direction opposite to the restoring force of the stressed yieldable constraint or flexure on which the armature is mounted. This effectively reduces the restoring force. The displacement obtained by the application of the signal force is thus greater than would be obtained in the absence of the magnets. The coefficient (spring constant) which relates force to displacement is thus reduced, that is the stiffness of the device is thus effectively less. The mechanical stiffness is considered a positive stiffness or spring constant and for like reason the effect of the magnetic force is considered to introduce a negative stiffness or spring constant. Ideally if the negative magnetic stiffness balances the mechanical stiffness there is ideally no restoring force exerted by the yieldable constraint to oppose the signal force causing displacement of the armature, and a minute signal force applied against the armature will produce a relatively large displacement thereof, and at zero stiffness an infinitely large response from the actuator control, that is, the, rod, jet pipe or other linkage connected to the armature, or a relatively large displacement of the armature is obtained for a given applied force. As a practical matter the stiffnesses are not exactly in balance and the net stiffness may be either positive or negative depending on the system into which the actuator is embodied.

The armature restoring force is large and ideally substantially produced by any means applying a force independent of the system stiffness and which opposes the signal force in magnitude and direction to restore and maintain the system in a null or balanced condition. Such restoring force can be produced, for example, by a feedback to the armature and may come either directly as a result of the motion of the armature or from some device actuated by the motion of the armature. This feedback connection introduces a degeneration of the signal force and acts as a restoring force to null out the motion of the armature. An example of such feedback is described in my above copending applications.

The attractive force between the armature and the pole piece towards which it moves varies as the square of the distance between the armature and such pole piece. The negative force or the mechanical stiffness of the yieldable constraint is substantially constant. Thus, the ratio between the mechanical stiffness of the yieldable constraint and the magnetic stiffness is variable. However, for small displacement of the armature, e.g. less than about one third the distance between the armature in its centered position and the adjacent pole piece, the magnetic stiffness provided by the pole pieces of the permanent magnet may be considered substantially constant because of the nature of the square law effect on the magnetic stiffness.

Because of the feedback provided, the system of the invention is designed to operate as a null balance unit so that the displacement of the armature is very minute, and under such operating conditions the ratio of the mechanical stiffness of the flexible constraint to the magnetic stiffness is substantially constant. Due to the great reduction in stiffness of the system, a greater response is obtained for a given frequency of movement of the armature as compared to prior art systems. In employing the actuator described here with the servo mechanism described in my copending applications and previous patent, a large gain from the hydraulic amplifier is obtained. By permitting displacement of the armature by a small force, a greater dynamic response is obtained.

The means for applying a force to the armature responsive to a signal received by such means, can be any mechanical force applying means, such as a rod, diaphragm, bellows or the like. As a feature of the invention, a plurality of such force applying means are employed in an

arrangement such that forces of large magnitude applied to the armature are resolved into a net differential force of small magnitude. Means may also be provided for setting the armature in its null position corresponding to a predetermined reference force applied to the armature.

According to one embodiment of the invention a plurality of fluid pressure diaphragms or bellows are attached mechanically to the armature which is mounted for angular motion about a pivot or hinges. One or more of such bellows may be actuating bellows to which the fluid pressure being sensed or measured is conducted, while one or more bellows may be subjected to a constant pressure. The various bellows are positioned with respect to the pivot point of the armature so that a minute differential pressure resulting from the signal applied to the actuating bellows produces a moment tending to displace the armature angularly.

Instead of employing a plurality of bellows a single bellows can be connected to the armature to function as the force applying means responsive to the input signal.

The invention will be more readily understood by reference to the description below of a predeferred embodiment, taken in connection with the accompanying drawing wherein:

FIG. 1 is a section in elevation, through the invention actuator;

FIG. 2 is a section taken on line 2—2 of FIG. 1;

FIG. 3 is a perspective view of the torsional flexure for the armature of FIG. 1; and

FIG. 4 is a section taken on line 4—4 of FIG. 1.

Referring to the drawing, the valve case **1** is provided with an axial bore **2'** therein. Case **1** also has a hole **2** (see FIG. 4) which intersects axial bore **2'**. Additional bores such as **3** and **4** are also provided in case **1**. Bores **3** and **4** may be connected to a reversible hydraulic or pneumatic motor (not shown) being controlled by the actuator herein described. Positioned in bore **2'** is a sleeve **5** which is retained in case **1** by retaining nuts **6**. The case **1** and bore **7** of sleeve **5** are sealed by two end caps **8** held in place by suitable bolts **9**. Sleeve **5** is grooved at a plurality of locations **10** to give a series of lands **11**, which are sealed by O-rings **12**, and the sleeve **5** is ported with bores **13**.

The sleeve **5** carries a spool **14** in the form of a piston which makes a sliding engagement with the interior of sleeve **5** by means of lands **15**, forming bores such as **16** intermediate the lands. Positioned at each end of bore **7** are stop members **17** sealed by O-rings **18**. The sleeve is further formed with bores at **19** into which the cone tip receptor jets **20** and **21** each provided with an inclined bore, **20'** and **21'**, are pressed. The bore of jet **20** communicates via cross bore **22'** with a port **22**, and the bore of jet **21** communicates via cross bore **23** with a port **24**, ports **22** and **24** connecting with chambers **25** and **26** in sleeve **5**, adjacent the opposite ends of spool **14**.

Positioned in the spool piston is a feedback spring held in the spool by means of a set screw **28** inserted through the threaded bore **29**.

The structure described above and its function are more fully described in my Patent No. 2,884,907, and such description in said patent is hereby incorporated into this specification by reference.

Carried on the upper face of the case **1** is an assembly, indicated generally by numeral **49**, which is mounted on a mounting base **50** and is composed of a frame **52** which carries the armature **56** mounted on torsion members **55** (see FIGS. 3 and 4) formed by milling the shaft member **54** to form a thin spring web member. One end of the shaft **54** is rigidly fixed to frame **52** by brazing, and the other end is formed as a fork **54'** into which the armature **56** is rigidly fixed by brazing. At each end of the frame **52** is positioned a pole and magnet assembly composed of a C-shaped magnet **57** and a C-shaped magnet **57'** oriented with their north poles and south poles opposite each other, each such assembly carrying a pole piece **58** at the north pole and a pole piece **59** at the south pole spaced from each other to produce a gap **58'**. The armature **56** is positioned symmetrically in each of said gaps to give four equal gaps, two at one end of the armature and two at the other end between the adjacent pole pieces. Interiorly of the frame **52** and abutting the pole pieces **58**, one at the north pole and one at the south pole, are the magnetically conductive members or pieces **60**.

The frame **52** is bored at **63** and the bars **60** are bored at **60'** and the armature is bored at **65** to receive the jet pipe **64** which is positioned within the bores **63**, **60'** and **65**, pipe **64** being rigidly affixed to the armature **56** in the bore **65**. The flexible pipe **66**, axially aligned with the pipe **64**, is rigidly connected to the armature **56** in a counterbore **66'**. The mounting **50** of the torque motor is bored at **50'** to permit the passage of the tube **66** and the pipe **64**. The tube **66** is rigidly connected at its end **66''** to the fitting **50**. The fitting **50** is connected to the top of the case **1** and sealed by means of O-rings **50***a* as shown.

The pipe **64** has an ejector jet **65'** brazed to it and extends into the slot **42** and is connected at its lower end to the feedback spring **27** at the slot **42**. The pipe **64** is bored with an axial bore **68**, which connects with a cross bore **71** and a sufficiently flexible pipe **72** (see FIG. 4). The pipe **72** registers and is in fluid communication with the bore **73** which communicates with the bore **1'** via restricted orifice **74** and the fittings **74'** and **74''** between which is positioned the screen **74***a*, as described more fully in Patent No. 2,884,907.

The receptor jets **20** and **21** are pressed into the sleeve **5** so that the angularly disposed bores **20'** and **21'** of the jets are so positioned that the center line of the bore **68** bisects the acute angle between the axis of the bores **20'** and **21'**. The ends of the nozzles **20** and **21** are symmetrically positioned with respect to the center line of bore **68**.

A first fluid pressure bellows **75** is connected between upper bar **60** on frame **52** and one side of the upper face of the armature **56**, and a second fluid pressure bellows **76** is connected betwen such bar **60** and the other side of the upper face of the armature **56**. The axis of each of these bellows is positioned equidistant from the axis of rotation of the armature **56**. A third fluid pressure bellows **77** is connected between the lower bar **60** on frame **52** and the lower face of one side of armature **56**, and a fourth fluid pressure bellows **78** is connected between the lower bar **60** and the lower face of the other side of the armature. The axis of each of the bellows **77** and **78** is positioned equidistant from the axis of rotation of the armature **56**. However, it will be noted that the axis of each of the lower bellows **77** and **78** are each displaced an equal distance from the axis of rotation of the armature, somewhat greater than the distance of the axis of each of the upper bellows **75** and **76** from such axis of rotation. Fluid pressure inlets **79** and **79'** are provided for fluid communication with the interior of bellows **75** and **76**, respectively. Fluid communication between bellows **75** and **77** and between bellows **76** and **78** is provided by the respective channels **86**. Thus, the pressure in bellows **77** is the same as that applied to **75**, and the pressure in bellows **78** is the same as the pressure applied to belows **76**.

One end of the armature **56** has mounted thereon by means of screws **81** a yoke **80**. A spring **82** has its upper end connected to the upper cross member **83** of the yoke, the other terminus of the spring being connected to an adjusting screw **84** threadably engaged in the upper face of case **1**. By adjusting screw **84** the initial position of the armature between the pole faces of magnets **57** and **57'** can be set as desired. Thus, for example, if the initial pressures applied to the bellows, as described more fully below, cause a clockwise rotation of armature **56**, viewing FIG. 1, screw **84** is turned down sufficiently to center the armature between the pole pieces, and if there is a

tendency toward counterclockwise rotation of the armature due to the initial forces applied by the bellows, the screw 84 is backed off sufficiently to raise the armature to a centered position. During adjustment of screw 84, the cover 90, which normally encloses the assembly 49, is removed and after adjustment of screw 84, the cover is replaced and attached to the case 1 by means of screws 91.

The interconnected bellows 76 and 78, and/or the interconnected bellows 75 and 77 may be subjected to a positive pressure, atmospheric pressure, or a vacuum. A reference pressure, which may be a positive absolute pressure or a substantially complete vacuum is applied to bellows 76 and 78. It will be noted as result of the slightly greater distance of bellows 78 than bellows 76 from the axis of rotation of the armature 56 at flexure 55, that a small counterclockwise moment will be exerted against the armature by bellows 78. A pressure, for example, a higher pressure corresponding to the base or zero level of the signal which is to be employed may be applied to bellows 75 and 77. At this base pressure corresponding to zero signal level the hydraulic or pneumatic motor being controlled by the actuator through flow of fluid via bores 3 and 4, is in the desired operating position. As result of the offset position of bellows 75 and 77, a clockwise moment will be exerted by bellows 77 against armature 56, as result of the base level pressure applied in bellows 75 and 77. Since such clockwise moment will be of greater magnitude than the opposing counterclockwise moment produced by the lower reference pressure in bellows 76 and 78, there will be a resulting net clockwise moment exerted against the armature. This will cause the jet pipe 64 to pivot to the left, viewing FIG. 1, causing a greater pressure in the receptor jet 20 than in the receptor jet 21, thus producing a greater pressure in chamber 25 than in chamber 26, and resulting in a displacement of the spool 14 to the right. This will result in a valving of the fluid by the spool to cause a flow of fluid through the valve to the fluid motor controlled by the spool valve.

In order to center the armature 56 to return the spool 14 to the null position shown in FIG. 1, the adjusting nut 84 is turned down to rotate armature 56 counterclockwise against the net clockwise moment applied by bellows 77 until the armature and the jet pipe are centered. Since now the moment on the armature produced by the signal force is balanced by the spring 82, the tension in the feedback spring moves the spool back to its central null position. This adjustment of screw 84 and counterclockwise rotation of armature 56 rotates the pipe 64 back to its centered position shown in FIG. 1, with respect to receptor jets 20 and 21. This equalizes the flow of fluid in bores 20' and 21' of the receptor jets and equalizes the pressure applied against the ends of spool 14. The centering of pipe 64 and the armature 56 and the balancing of the signal force by the spring 82 returns the spool 14 to its central position, as shown in FIG. 1. This will be indicated by a cessation of flow of fluid from ports 3 and 4 to the hydraulic motor. The armature 56 is now in a centered position with the oppositely applied moments of bellows 77 and 78 balanced, and the hydraulic motor being actuated is in the correct operating position desired for a net signal force at the design level of zero signal pressure.

Assume that no signal is impressed on the bellows 75 and 77, so that the armature 56 is in the null position and centered in the gaps between the pole pieces 58 and 59, as shown in FIG. 1. The jet pipe 64 is undeflected and the tube 66 is unbent and aligned symmetrically over receptor jets 20 and 21, as seen in FIG. 1. The spool 14 is in the centered position shown in FIG. 1. Fluid under pressure passes through pipes 73 and 72 and through the bore 68 and the ejector jet 65'. With the bores 20' and 21' symmetrically placed, each of such bores will receive an equal amount of fluid from the jet 65'. The fluid through 20 and 21 being thus under equal pressure exerts equal pressure against the opposite ends of spool 14, and the spool 14 is centered, as shown in FIG. 1. The spool 14 is thus hydraulically balanced, notwithstanding flow of fluid in jet pipe 64 and through receptor jets 20 and 21, and the hydraulic motor is not actuated.

If, now, the signal generated from the hydraulic or other motor being controlled by the actuator produces a pressure in bellows 75 and 77 greater than the initially set pressure therein, a relatively small differential clockwise moment is introduced against the armature 56 by bellows 77, tending to produce clockwise rotation of armature 56. The pipe 64 will rotate clockwise to the left as viewed in FIG. 1, producing a greater flow of fluid in bore 20' than 21' of the receptor jets and a displacement of the spool 14 to the right. This displacement of spool 14 causes a flow of fluid from the actuator via ports 3 and 4 to the hydraulic motor being controlled, to displace the hydraulic motor or to actuate it.

It will be observed that as the spool is displaced to the right, viewing FIG. 1, a spring force is imposed upon the pipe 64 by means of the spring 27, which spring force is proportional to the displacement of the piston spool so that the spring introduces a restoring force in an amount equal to balance the force causing movement of the armature in response to the signal, and to restore the pipe 64 to its neutral position, shown in FIG. 1, at which place the pressure in nozzles 20 and 21 and chambers 25 and 26 are again equal, and further displacement of the piston cannot occur. The spring 27 thus acts as a force feedback to null out and balance the force of the signal causing the initial displacement. It will be observed that in so doing the initial displacement of the piston occurring upon the reception of the signal is not altered so long as the signal force applied to the actuator is at the original strength and direction. In consequence thereof, upon the reception of a signal by the armature the ejector jet pipe 64 is displaced an amount proportional to the force of the signal in a direction determined by the direction of the signal, and the piston spool is displaced an amount proportional to the signal strength in a direction determined by the direction of the signal, and is maintained in such displaced condition so long as the signal remains unchanged in magnitude and direction. Should the signal fall in strength but not reverse in direction, the spring force at 27 will move the jet pipe 64 to the right, viewing FIG. 1, and now the bore 21' receives more fluid than does the bore 20', and the pressure in chamber 26 is greater than in chamber 25, and the spool 14 moves to the left. However, in so moving, the tension in the spring 27 will move the jet 65' to the left to relax the tension to a value proportional to the new spool position closer to the center position, and reducing the flow of fluid exiting through 3 to the hydraulic motor and returning through 4. This may continue until the signal strength falls to zero, in which case the spool is centered and no fluid flow occurs in the hydraulic motor.

The function of the force feedback spring is described in greater detail in my Patent 2,884,907, and such disclosure in incorporated herein by reference.

Substantially the same mode of operation except in reverse to that described above takes place when the signal from the hydraulic motor being controlled by the actuator is reversed in direction, producing a pressure in bellows 75 and 77 less than the pressure at the set zero signal level, but in this situation the small net moment produced as result of the longer moment arm of bellows 78 as compared to bellows 76 will produce a counterclockwise motion of armature 56 and jet pipe 64, and a displacement of spool 14 to the left. This will result in a reversal of flow of fluid to the hydraulic motor.

It will be noted particularly that very large pressures can be introduced into the bellows 75 and 77, but due

to the slightly offset relation of bellows 77 with respect to bellows 75, and of bellows 78 with respect to bellows 76, the net moment produced against armature 56 by the pressure in bellows 77 is very small, and hence the actuator of the invention can be made very small, yet is able to handle large signal pressures. Further, due to the balancing out of the mechanical stiffness of the flexure 55 by the magnetic attraction of the magnets 57 and 57' for the armature 56, so that there exists substantially no restoring force exerted by the flexure 55 to oppose the pressure, e.g. in bellows 77, causing a displacement of the armature, weak flexures can be used. In such case the natural frequency may be made low, and by suitable selection of magnets and thus the magnitude of the magnetic stiffness, this frequency may be adjusted up to the natural frequency of the system.

It is further to be noted that by means of the instant device, while the operation of the actuator has been described in terms of an actual rotation of the armature by the forces imposed thereon, there is actually practically no displacement of the armature, but rather only a tendency toward displacement, as result of changes in pressure in bellows 75 and 77 produced by changes in the input signal. The actuator hereof has as an additional advantage improved response at a given frequency.

Instead of employing a bellows system, any other mechanical means can be employed for impressing the signal on the armature from the device being controlled.

Instead of applying the invention actuator in conjunction with a servo mechanism of the type described in my above Patent 2,884,907, I may eliminate the jet pipe and spool valve structure described herein and connect the armature by suitable linking mechanism for control of any desired device. Thus, for example, I may employ my actuator, substituting, for example, a rod in place of the jet pipe 64, and eliminating the spool valve structure described herein, for controlling any other desired mechanism, by displacement of such rod, such as the system described in my application Serial No. 755,775, or by connecting a rod in the place of a jet pipe, the device may be used as a transducer to cause a displacement of a force summing means responsive to a pressure, e.g. as a pressure gage.

Although I have shown a force feedback connection between the spool and jet pipe, I can instead employ a position feedback in the nature of a rigid connection between the jet pipe and spool.

Also, it will be understood that I can substitute any other suitable permanent magnet device for the specific permanent magnet system described above.

While I have described particular embodiments of my invention for the purpose of illustration, it should be understood that various modifications and adaptations thereof may be made within the spirit of the invention as set forth in the appended claims.

I claim:

1. An actuator which comprises an armature composed of magnetically permeable material, a yieldable mounting for said armature, permanent magnet means positioned in operative relation adjacent said armature, means for mechanically applying a force to said armature in response to a signal, to move said armature from a null position, the force of magnetic attraction of said permanent magnet means substantially balancing the mechanical stiffness of said yieldable mounting, and a motion transmitting device connected to said armature and operative in response to motion of said armature, and means for applying to said armature a restoring force independent of said mechanical stiffness and opposed in magnitude and direction to said signal force, to restore said armature to its null position.

2. An actuator which comprises an armature composed of magnetically permeable material, a yieldable mounting for said armature, permanent magnet means positioned in operative relation adjacent said armature, means for mechanically applying a force to said armature in response to a signal, to move said armature from a null position, the force of magnetic attraction of said permanent magnet means substantially balancing the mechanical stiffness of said yieldable mounting, and a jet pipe connected to said armature and movable in response to displacement of said armature, and means for applying to said armature a restoring force independent of said mechanical stiffness and opposed in magnitude and direction to said signal force, to restore said armature to its null position.

3. An actuator which comprises an armature composed of magnetically permeable material, a yieldable mounting for said armature permanent magnet means positioned in operative relation adjacent said armature, means for mechanically applying a force to said armature, to move said armature from a null position, the force of magnetic attraction of said permanent magnet means substantially balancing the mechanical stiffness of said yieldable mounting, a motion transmitting device connected to said armature and operative in response to motion of said armature, means movable responsive to the motion of said motion transmitting device, and a feedback means connected to said motion transmitting device and said last named movable means for restoring said armature to its null position.

4. An actuator which comprises an armature composed of magnetically permeable material, a yieldable mounting for said armature permanent magnet means positioned in operative relation adjacent said armature, means for mechanically applying a force to said armature, the force of magnetic attraction of said permanent magnetic means substantially balancing the mechanical stiffness of said yieldable mounting, a jet pipe connected to said armature and movable from a null position in response to displacement of said armature, means movable responsive to the motion of said jet pipe and a feedback means connected to said jet pipe and said last named movable means for restoring said pipe to its null position.

5. An actuator which comprises an armature composed of magnetically permeable material, a yieldable mounting for said armature permanent magnet means positioned in operative relation adjacent said armature, means for mechanically applying a force to said armature, the force of magnetic attraction of said permanent magnet means substantially balancing the mechanical stiffness of said yieldable mounting, a jet pipe connected to said armature and movable from a null position in response to displacement of said armature, means movable responsive to the deflection of a fluid stream from said jet pipe on motion thereof, and a feedback means connected to said jet pipe and said last named movable means for restoring said pipe to its null position.

6. An actuator which comprises an armature composed of magnetically permeable material, a yieldable mounting for said armature, permanent magnet means positioned in operative relation adjacent said armature, means for mechanically applying a force to said armature, the force of magnetic attraction of said permanent magnet means substantially balancing the mechanical stiffness of said yieldable mounting, a jet pipe connected to said armature and movable from a null position in response to displacement of said armature, means movable responsive to the deflection of a fluid stream from said jet pipe on motion thereof, and a force feedback connected to said jet pipe and said last named movable means for restoring said pipe to its null position.

7. An actuator as defined in claim 1, including means for adjusting said armature in said null position corresponding to a base signal force applied to said armature.

8. An actuator which comprises an armature support frame, an armature in said frame, said armature composed of magnetically permeable material, a shaft fixedly con-

nected to said armature and to said frame, a torsional flexure in said shaft, permitting said armature to move angularly with respect to said shaft, a magnet assembly mounted one at each end of said armature frame, said assembly comprising a pair of permanent magnets and a pair of pole pieces, one of the pole pieces in each assembly being connected to a north magnetic pole of each of said magnets of said pair, and another of the pole pieces in each assembly being connected to a south magnetic pole of each said magnet of said pair, said pole pieces in each assembly being spaced to form a gap, one end of said armature being positioned in one of said gaps, and the other end of said armature being positioned in the other of said gaps, means for mechanically applying a force to said armature in response to a signal, to move said armature from a null position, the force of magnetic attraction of the pole pieces of said permanent magnets for said armature substantially balancing the mechanical stiffness of said flexure, and a motion transmitting device associated with said armature and operative in response to motion of said armature, and means for applying to said armature a restoring force independent of said mechanical stiffness and opposed in magnitude and direction to said signal force, to restore said armature to its null position.

9. An actuator which comprises a pair of spaced polarizing assemblies, each assembly composed of a pair of permanent magnets, said magnets being fastened at their north poles to a pole piece and at their south poles to a second pole piece, said pole pieces being spaced to form a gap completing a magnetic circuit through the pole pieces and each of said permanent magnets in each of said assemblies, an armature, said armature composed of magnetically permeable material and extending into the gap in each of said magnet assemblies, a mounting for said armature, said mounting comprising a support, a flexure fixedly connected to said armature and said support for angular motion of said armature in said gaps about an axis through said flexure, and mechanical means for applying a force to said armature in response to a signal, to move said armature from a null position, the force of magnetic attraction of the pole pieces of said permanent magnets for said armature substantially balancing the mechanical stiffness of said flexure, and a jet pipe connected to said armature substantially at said axis and extending perpendicular to said axis, and means for applying to said armature a restoring force independent of said mechanical stiffness and opposed in magnitude and direction to said signal force, to restore said armature to its null position.

10. An actuator which comprises a permanent magnet assembly, pole pieces connected to said assembly, said pole pieces being spaced to form a gap completing a magnetic circuit through the pole pieces and said permanent magnet assembly, an armature, said armature composed of magnetically permeable material and extending into the gaps between adjacent pole pieces of said magnetic assembly, a mounting for said armature, said mounting comprising a support, a flexure fixedly connected to said armature and said support for angular motion of said armature in said gaps about an axis through said flexure, a first mechanical force transmitting means connected to said armature on one side of said flexure, a second mechanical force transmitting means connected to said armature on said one side of said flexure and in opposing relation to said first force transmitting means, the distance between said flexure and said first means being somewhat greater than the distance between said flexure and said second means, at least one of said force transmitting means being operative in response to a signal, the force of magnetic attraction of the pole pieces of said permanent magnets for said armature substantially balancing the mechanical stiffness of said flexure, and a motion transmitting device associated with said armature and operative in response to motion of said armature.

11. An actuator which comprises a permanent magnet assembly, pole pieces connected to said assembly, said pole pieces being spaced to form a gap completing a magnetic circuit through the pole pieces and said permanent magnet assembly, an armature, said armature composed of magnetically permeable material and extending into the gaps between adjacent pole pieces of said magnet assembly, a mounting for said armature, said mounting comprising a support, a flexure fixedly connected to said armature and said support for angular motion of said armature in said gaps about an axis through said flexure, a first pressure responsive force transmitting member connected to said armature on one side of said flexure, a second pressure responsive force transmitting member connected to said armature on the other side of said flexure, said first and second members being mounted equidistant from said flexure and in force opposing relation on one face of said armature, a third pressure responsive force transmitting member connected to said armature on said one side of said flexure, and a fourth pressure responsive force transmitting member connected to said armature on said other side of said flexure, said third and fourth members being mounted equidistant from said flexure and in force opposing relation on the other face of said armature, the distance between said flexure and each of said first and second members being slightly greater than the distance between said flexure and each of said third and fourth members, means for applying equal pressures to said first and third members in response to a signal, means for applying equal pressures to said second and fourth members, the force of magnetic attraction of the pole pieces of said permanent magnets for said armature substantially balancing the mechanical stiffness of said flexure, and a motion transmitting device associated with said armature and operative in response to motion of said armature.

12. An actuator as defined in claim 11, wherein said motion transmitting device includes a jet pipe connected to said armature substantially at the axis of said flexure and extending perpendicular to said axis, means for passing fluid through said jet, and means responsive to the movement of fluid from said jet pipe.

13. An actuator which comprises a pair of spaced polarizing assemblies, each assembly composed of a pair of permanent magnets, said magnets being fastened at their north poles to a pole piece and at their south poles to a second pole piece, said pole pieces being spaced to form a gap completing a magnetic circuit through the pole pieces and each of said permanent magnets in each of said assemblies, an armature, said armature composed of magnetically permeable material and extending into the gap in each of said magnet assemblies, a mounting for said armature, said mounting comprising a support fastened to each of said assemblies, a flexure fixedly connected to said armature and said support for angular motion of said armature in said gaps about an axis through said flexure, a first pressure responsive force transmitting bellows connected to said armature on one side of said flexure, a second pressure responsive force transmitting bellows connected to said armature on said one side of said flexure in opposing relation to said first bellows, the distance between said flexure and said first bellows being slightly greater than the distance between said flexure and said second bellows, means for applying pressure to said first and second bellows, in response to a signal, the force of magnetic attraction of the pole pieces of said permanent magnets for said armature substantially balancing the mechanical stiffness of said flexure, and a motion transmitting device associated with said armature and operative in response to motion of said armature.

14. An actuator as defined in claim 13, wherein said motion transmitting device includes a jet pipe connected to said armature substantially at said axis of said flexure, and means responsive to the movement of fluid from said jet pipe for applying to said armature a restoring force independent of said mechanical stiffness and opposed in

magnitude and direction to said signal force, to restore said armature to its null position.

15. An actuator as defined in claim 13, including adjustable spring means connected to one end of said armature for adjusting the armature in a centered position between said pole pieces corresponding to a base signal force applied to said armature.

16. An actuator which comprises a permanent magnet assembly, pole pieces connected to said assembly, said pole pieces being spaced to form a gap completing a magnetic circuit through the pole pieces and said permanent magnet assembly, an armature, said armature composed of magnetically permeable material and extending into the gaps between adjacent pole pieces of said magnet assembly, a mounting for said armature, said mounting comprising a support, a flexure fixedly connected to said armature and said support for angular motion of said armature in said gaps about an axis through said flexure, mechanical means for applying a force to said armature in response to a signal, the force of magnetic attraction of the pole pieces of said permanent magnets for said armature substantially balancing the mechanical stiffness of said flexure, a jet pipe connected to said armature substantially at said axis and extending perpendicular to said axis and rotatable with said armature, an ejector jet at the end of said jet pipe, a pair of stationary receptor jets positioned adjacent said ejector jet and in fluid communication with said ejector jet, said ejector jet discharging a greater amount of fluid in one of said receptor jets than in the other on displacement of said ejector jet away from a centered position between said receptor jets, movable means responsive to the displacement of said ejector jet, and means connected to said movable means and said ejector jet for applying to said armature a restoring force independent of said mechanical stiffness and opposed in magnitude and direction to said signal force, to restore said armature to its null position.

17. An actuator which comprises a pair of spaced polarizing assemblies, each assembly composed of a pair of permanent magnets, said magnets being fastened at their north poles to a pole piece and at their south poles to a second pole piece, said pole pieces being spaced to form a gap completing a magnetic circuit through the pole pieces and each of said permanent magnets in each of said assemblies, an armature, said armature composed of magnetically permeable material and extending into the gap in each of said magnet assemblies, a mounting for said armature, said mounting comprising a support, a flexure fixedly connected to said armature and said support for angular motion of said armature in said gaps about an axis through said flexure, mechanical means for applying a force to said armature in response to a signal, the force of magnetic attraction of the pole pieces of said permanent magnets for said armature substantially balancing the mechanical stiffness of said flexure, a jet pipe connected to said armature substantially at said axis and extending perpendicular to said axis and rotatable with said armature, an ejector jet at the end of said jet pipe, a pair of stationary receptor jets positioned adjacent said ejector jet and in fluid communication with said ejector jet, said ejector jet discharging a greater amount of fluid in one of said receptor jets than in the other on rotation of said ejector jet away from a centered position between said receptor jets, a sleeve, a movable spool in said sleeve, closed first and second chambers in said sleeve at opposite ends of said spool, a first port in said sleeve communicating with said first chamber, a second port in said sleeve communicating with said second chamber, a first channel between one of said receptor jets and said first port, and a second channel between said other receptor jet and said second port, and feedback means connected between said spool and said jet pipe for restoring said pipe to its centered position.

18. An actuator which comprises a pair of spaced polarizing assemblies, each assembly composed of a pair of permanent magnets, said magnets being fastened at their north poles to a pole piece and at their south poles to a second pole piece, said pole pieces being spaced to form a gap completing a magnetic circuit through the pole pieces and each of said permanent magnets in each of said assemblies, an armature, said armature composed of magnetically permeable material and extending into the gap in each of said magnet assemblies, a mounting for said armature, said mounting comprising a support fastened to each of said assemblies, a flexure fixedly connected to said armature and said support for angular motion of said armature in said gaps about an axis through said flexure, a first pressure responsive force transmitting bellows connected to said armature on one side of said flexure, a second pressure responsive force transmitting bellows connected to said armature on the other side of said flexure, said first and second bellows being mounted equidistant from said flexure and in force opposing relation on one face of said armature, a third pressure responsive force transmitting bellows connected to said armature on said one side of said flexure, and a fourth pressure responsive force transmitting bellows connected to said armature on said other side of said flexure, said third and fourth bellows being mounted equidistant from said flexure and in force opposing relation on the other face of said armature, the distance between said flexure and the axis of each of said first and second bellows being slightly greater than the distance between said flexure and the axis of each of said third and fourth bellows, means for applying equal pressures to said first and third bellows, means for applying equal pressures to said second and fourth bellows, the force of magnetic attraction of the pole pieces of said permanent magnets for said armature substantially balancing the mechanical stiffness of said flexure, a jet pipe connected to said armature substantially at the axis of said flexure and extending perpendicular to said axis and rotatable with said armature, an ejector jet at the end of said jet pipe, a pair of stationary receptor jets positioned adjacent said ejector jet and in fluid communication with said ejector jet, said ejector jet discharging a greater amount of fluid in one of said receptor jets than in the other on rotation of said ejector jet away from a centered position between said receptor jets, a sleeve, a movable spool in said sleeve, closed first and second chambers in said sleeve at opposite ends of said spool, a first port in said sleeve communicating with said first chamber, a second port in said sleeve communicating with said second chamber, a first channel between one of said receptor jets and said first port, and a second channel between said other receptor jet and said second port, and a force feedback spring connected between said spool and said jet pipe.

19. An actuator which comprises a permanent magnet assembly having north and south poles located opposite each other, pole pieces mounted adjacent each other at said north and south poles, respectively, said pole pieces being spaced to form a gap completing a magnetic circuit through the pole pieces and said permanent magnet assembly, an armature, said armature composed of magnetically permeable material and extending into the gaps between said adjacent pole pieces of said magnet assembly, a mounting for said armature, said mounting comprising a support, a flexure connected to said armature and said support for angular motion of said armature in said gaps about an axis, said magnetic force substantially balancing the stiffness of said flexure, a mechanical force transmitting means connected to said armature operative in response to a signal, and a motion transmitting device associated with said armature and operative in response to motion of said armature.

No references cited.