Jan. 28, 1969

C. I. CONNER ET AL

3,424,059

LINEAR HYDRAULIC MOTORS

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Fig. 1.

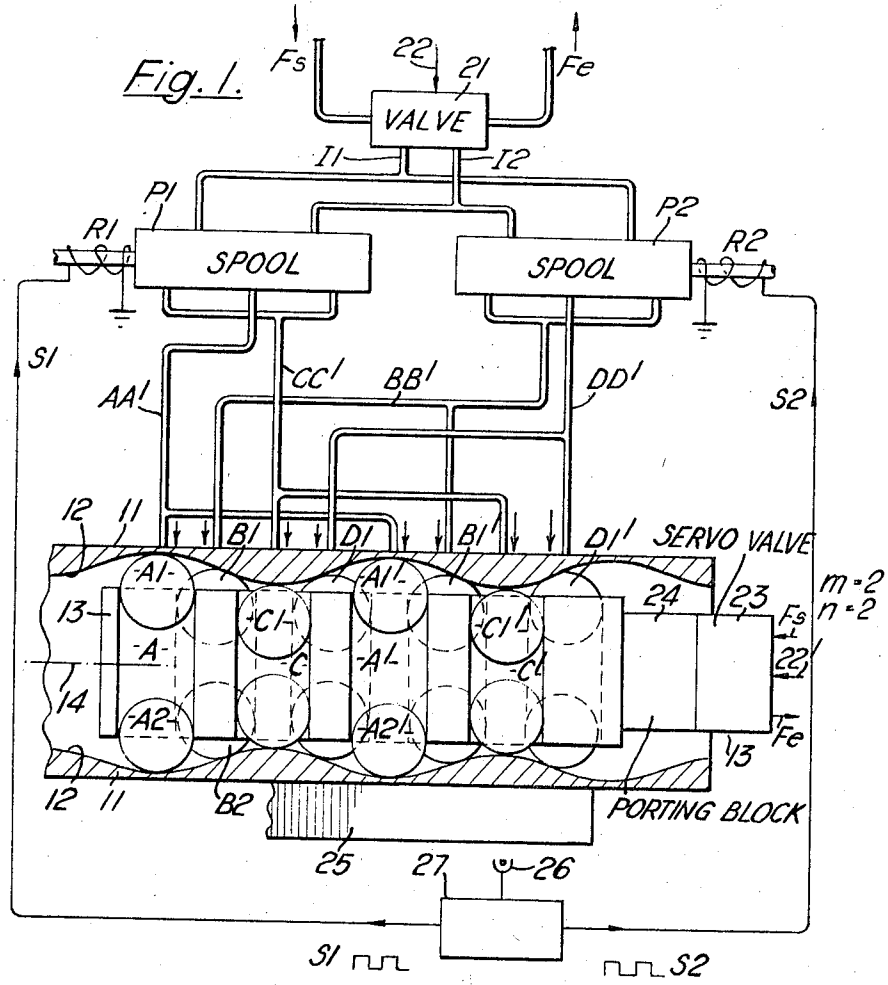
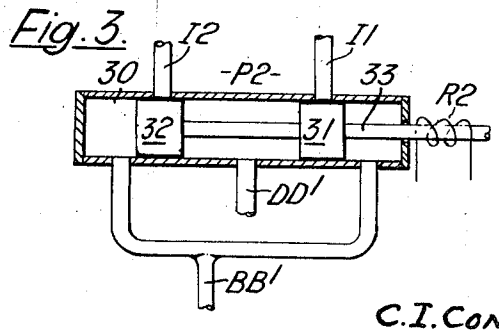



Fig. 3.




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Fig. 2.

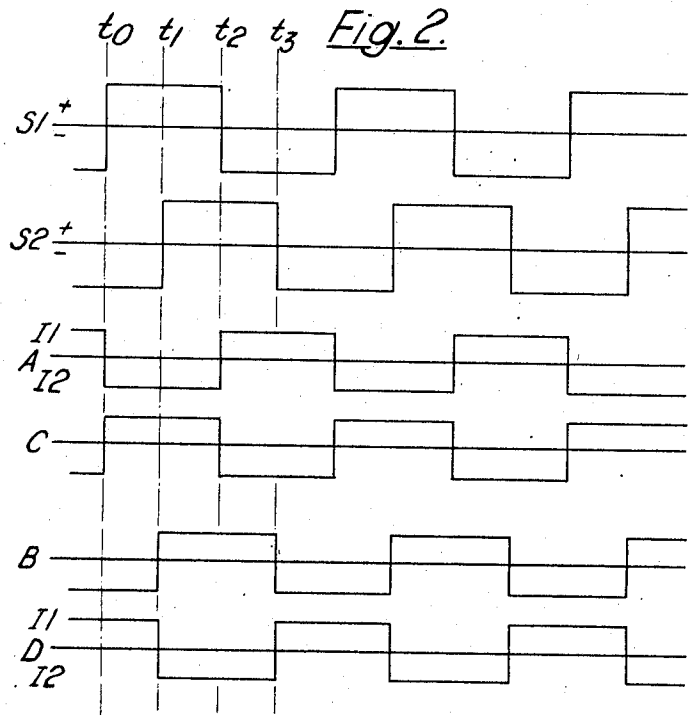
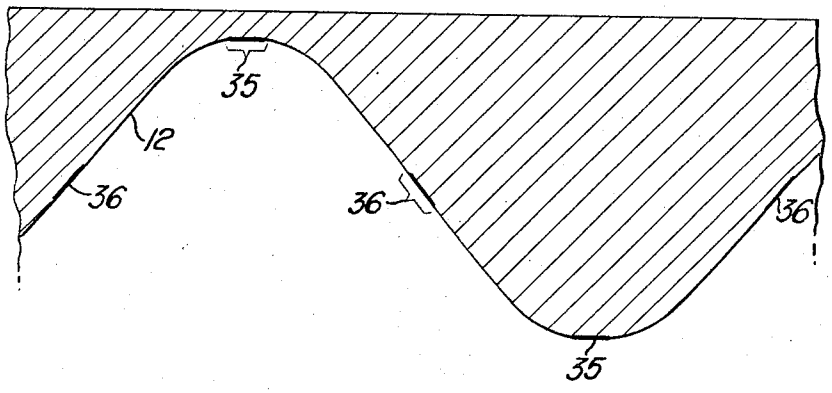



Fig. 4.




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Fig. 5.

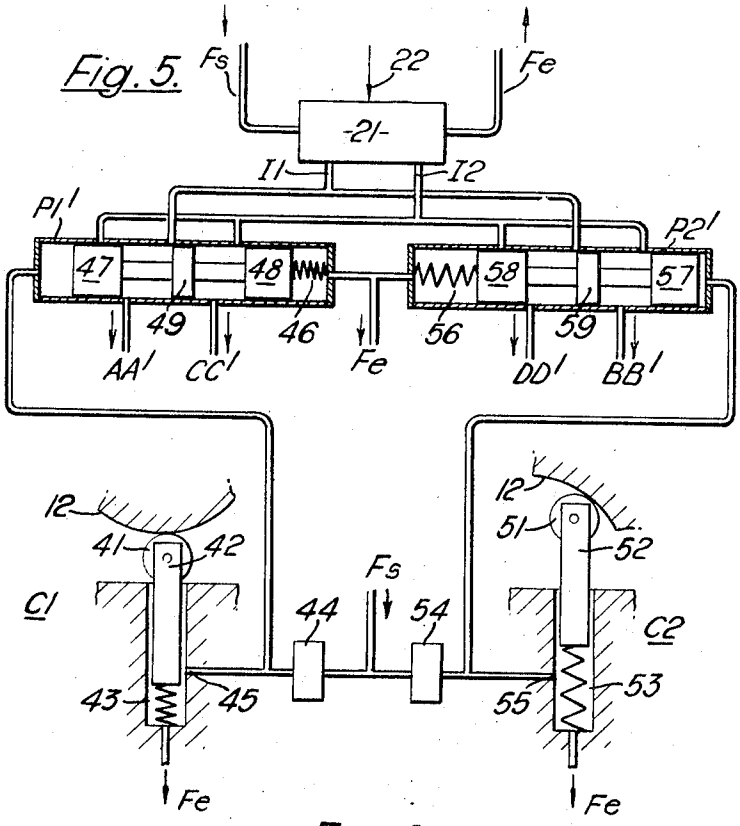
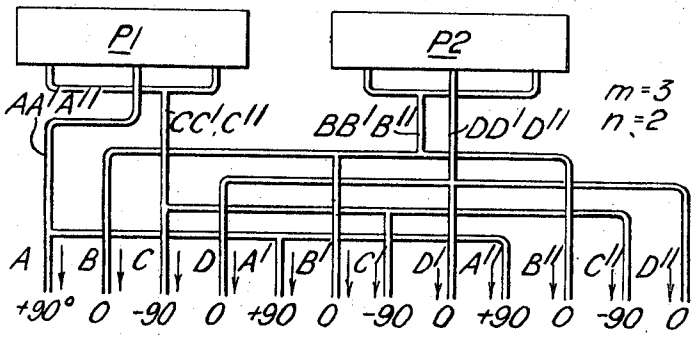



Fig. 6.




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Fig. 7.

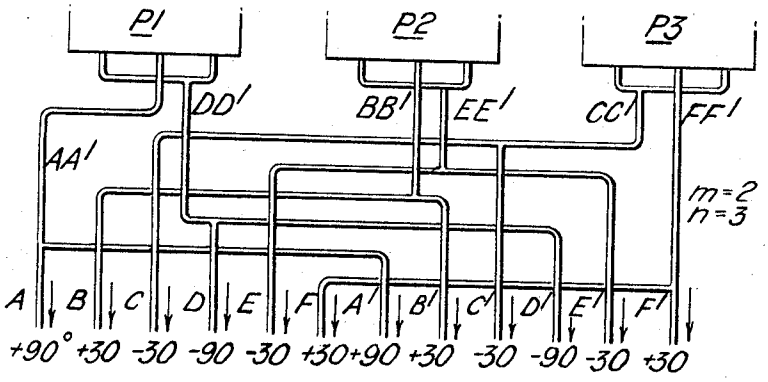
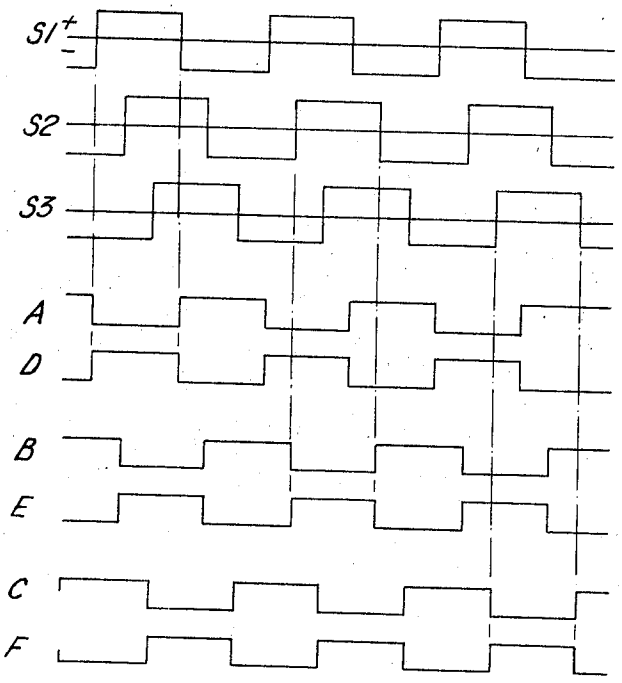



Fig. 8.




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3,424,059

# LINEAR HYDRAULIC MOTORS

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Claims priority, application Great Britain, Apr. 12, 1966, 15,838/66
U.S. Cl. 91—176 6 Claims
Int. Cl. F01b *15/00;* F01l *15/08*

## ABSTRACT OF THE DISCLOSURE

A linear hydraulic motor for motion along a straight axis including a stator having a cyclic edge profile which extends in the direction of the axis, and a translator having cylinders transverse to the axis. Each cylinder contains a steel ball which is urged by the actuating fluid in the cylinder into continuous engagement with the stator profile, the relative pressures of the fluid in the cylinders being controlled by porting spools (hydraulic valves) so as to maintain the translator in motion along the axis in a forward or backward sense as required by a command signal.

This invention relates to linear hydraulic motors of the type—hereinafter referred to as the type stated—which includes a stator and a translator mounted for straight-line movement relative to one another, the stator having a cyclic edge profile extending in the direction of movement and the translator having at least four cylinders disposed normal to that direction and containing hardened metal balls urged by the actuating fluid to engage the stator profile at fractional wave-length spacings along it, thereby causing the movement. In general, the stator may have for each of $m$ complete cycles of the profile $2n$ cylinders (where $n$ is greater than unity) spaced at $\frac{1}{2}n$-wavelength intervals over the cycle. The total number of cylinders is thus $2mn$.

Unless otherwise stated it will be assumed that the stator is the fixed and the translator the moving component of the motor, but the terms stator and translator should be understood as including an arrangement in which the fixed component is the translator, the stator moving along it.

It is usual in such motors for the fluid to be applied to the cylinders under both a servo and a cylinder-sequence form of control.

In obedience to some kind of signal, such as an error signal, the servo system controls by means of a two-way valve the connection between two channels from the source of fluid under pressure to two intermediate channels leading to the translator, the two from the source performing supply and exhaust functions respectively. The controlling signal is usually electrical but may be hydraulic.

The valve connects the supply channel to one or other of the intermediate channels in dependence on the sense of the movement required, or on the sense of the thrust where the servo valve is actuated to provide a thrust in the reverse direction to the actual movement in order to arrest it, the sense in each case being represented by the sense or other characteristic of the signal, and connects the other intermediate channel to the exhaust channel.

The connection of the intermediate channels to the cylinders of the translator is exercised by the cylinder-sequence control in dependence solely on the position of



the translator relative to the cycles of the stator profile. The apparatus for this purpose normally takes the form of a porting block which in every position of the translator couples the intermediate channels to the cylinders in such manner that a pressure difference between the fluids in those channels is effective in moving the translator.

The porting block thus acts as a kind of distributor and usually takes the form of a porting blade rotating in a cylinder having ports connected to the intermediate channels and to the cylinders of the translator. As the porting blade is controlled solely by the translator movement, independently of the servo signal, it is usually driven by a rack and pinion of which the pinion is coupled to the blade and the rack is disposed alongside the stator, to which the rack is secured, over the full linear range of movement of the translator.

An object of the present invention is to provide a new and useful motor of the type stated, a particular object being to provide such a motor in which the cylinder-sequence control is effected by means not including a rack and pinion arrangement as described.

In accordance with the present invention there is provided a linear hydraulic motor of the type which includes a stator and a translator mounted for straight-line movement relative to one another, the stator having having a cyclic edge profile extending in the direction of movement and the translator having for each of $m$ cycles of the stator profile $2n$ cylinders disposed normal to that direction and containing hardened metal balls urged by the actuating fluid to engage the stator profile at $\frac{1}{2}n$ wavelength spacings along the profile, where $n$ is greater than unity, the motor also including changeover means reversibly connecting a supply channel and an exhaust chanel of actuatig fluid to two intermediate channels in dependence on a control signal, $n$ porting devices each for reversibly connecting the two intermediate channels to two groups each of $m$ cylinders associated with only that device, the cylinders in each of the two groups associated with that device being at in-phase spacings of the profile and the cylinders of one of those two groups being at counterphase spacings from those of the other group, and porting-control arrangements for abruptly actuating the porting devices sequentially at respective positions of the translator along the stator profile at $\frac{1}{2}n$ wavelength spacings of the profile so as to render a pressure difference between the fluids in the intermediate channels effective in moving the translator in a direction dependent on the sense of that differece.

In the accompanying drawings:

FIGURE 1 is a diagram partly in section and partly in schematic form of a linear hydraulic motor in accordance with one embodiment of the invention,

FIGURE 2 is a set of waveforms to illustrate the operation of the motor of FIGURE 1,

FIGURE 3 shows in detail a part shown generally in FIGURE 1,

FIGURES 4 and 5 show parts of the motor of FIGURE 1 modified in accordance with two further embodiments,

FIGURES 6 and 7 show modified forms of the motor of FIGURE 1 in accordance with two further embodiments, and

FIGURE 8 is a set of waveforms to illustrate the operation of the motor of FIGURE 7.

An embodiment of the invention will be described by way of example where the motor has four cylinders for each of two cycles of the profile. Thus $n=2$ and $m=2$.

In carrying out the invention in accordance with this form, a linear hydraulic motor includes a fixed stator **11**—see FIG. 1—having a cyclic edge profile **12** and arranged to be traversed by a translator **13** along the straight line of axis **14**. Profile **12** is in two complementary parts,

an upper and a lower as seen in the drawing, which face one another across axis **14**. Each profile is of ribbon-like form as if generated by a movement of the curved line **12** of the diagram normal to the plane of the paper for a short distance.

The translator has eight cylinders A to D and A′ to D′ disposed with their axes normal to axis **14** at quadrature—that is, quarter-wavelength—spacings along the profile **12**. The cylinders are arranged alternately in two rows displaced from one another in a directional normal to the plane of the paper. Thus cylinders A, C, A′, C′, form one set at counterphase spacings with their axes coplanar in the plane of the paper, and B, D, B′, D′, a second counterphase set behind them (as seen in the diagram). This second set is therefore concealed to some extent by the first set. The staggering of the cylinders in this way allows them to have a larger diameter than if they were all in line with their axes all coplanar.

Each cylinder contains two hard metal balls A1, A2, B1, B2 and so on. They are urged apart to engage the respective parts of the stator profile by the actuating fluid, which is admitted to the cylinders by way of ports which are not shown.

For controlling the admission of the actuating fluid to the cylinders, the motor includes a servo control in the form of changeover means **21** for reversibly connecting a fluid supply channel *Fs* and an exhaust channel *Fe* to two intermediate channels I1 and I2 in dependence on an electrical control signal applied over a lead **22**. Channels *Fs* and *Fe* are in the form of high pressure pipes running respectively from the source (not shown) of the actuating fluid and to a convenient exhaust point. Changeover means **21** takes the form of an electrically-operated hydraulic valve, of which various known kinds are available.

The cylinder-sequence control is exercised by two porting devices P1 and P2 in the form of hydraulic spools. Spool P1 is associated with cylinder set A, C, A′, C′, and is arranged to connect channels I1 and I2 reversibly to the constituent groups AA′ and CC′. The cylinders in each group are thus at in-phase spacings, whilst the cylinders of one group are at counterphase spacings from those of the other group of the set.

To provide this reversal control, the connections from the spool to the cylinders are by way of high-pressure pipes or channels AA′ and CC′ to the corresponding groups of cylinders. The spool has two operative positions. In one of them it connects channel I1 to group AA′ and channel I2 to group CC′. In the other, these connections are reversed, so that channel I1 and I2 are connected to groups CC′ and AA′ respectively. Details of a suitable spool are described below with reference to FIG. 3.

Spool P2 is similarly arranged to connect channels I1 and I2 reversibly to cylinder pairs BB′ and DD′.

Valve **21** is actually carried by a part **23** of the translator, and the spools in another part **24** termed the porting block. The pipe channels between the valve and the spools and between them and the cylinders are also carried by the translator. For convenience, however, the valve, the spools, and the pipes are depicted to an enlarged scale as if detached from the translator.

The actuation of each spool from the one to the other of its operative positions is effected by porting control arrangements. These may take various forms in accordance with the invention. In the embodiment of FIG. 1 it is assumed that the movement of the worktable (or other object controlled by the motor of the invention) is measured by an optical fringe-counting method that includes an illuminated optical grating **25** long enough to extend over the full range of the translator movement. For deriving that measurement, there is provided photoelectric equipment which includes a bank of photocells and associated electrical circuits. As the present invention is not concerned with this equipment, apart from grating **25**, it is omitted from the drawing.

To provide the porting control, the translator carries a photocell **26** which traverses grating **25** as the translator traverses the stator. As the grating is so ruled as to form a pattern of alternate light and dark bands normal to the direction of movement, the signal derived by the cell has a square waveform. In a stage **27** (which, like photocell **26**, may be carried by the translator) this signal is frequency-divided to produce two switching square wave signals S1 and S2 in quadrature with one another at the frequency at which the stator profile is traversed. Stage **27** includes the usual array of binary counter circuits such that the count-down ratio is equal to the ratio of the wavelength of the stator edge profile to that of the grating pattern. To actuate the spools, signals S1 and S2 are applied to solenoid relays R1 and R2 which control the piston members of the respective spools, moving the spools in one direction or the other in dependence on the positive or negative sense of the signals.

The movement of the translator is effected by the pressure exerted by the cylinder balls on the sloping parts of the stator profile. With the translator in the position depicted, for example, it is clear that cylinders of set A, C, A′ and C′ are inoperative, whatever the pressure of the fluid in them, because the balls in them engage the troughs or crests of the profile—that is, the parts of the profile that are parallel to axis **14**.

On the other hand, as the cylinders of set B, D, B′, and D′ are in alignment with sloping parts of the profile the pressure in them tends to cause movement of the translator along its axis. Whether this movement is to the right or to the left (as viewed on the drawing) depends on whether the pressure in cylinders of group BB′ is greater or less than that in group DD′, the movement being to the left or to the right, as the case may be.

For a continuous movement in one direction, it is necessary to reverse these pressure differentials each time the cylinders concerned cross the troughs or crests of the profile. Thus after a movement of the translator to the right for a quarter wavelength of the profile from the position depicted, due to the pressure in the cylinders of group DD′ being greater than that in cylinders of group BB′, the pressure in cylinders BB′ must become the greater if the rightwards movement is to be continued. As the respective sets of cylinders are at quarter-wavelength spacings from one another, these reverses of pressure differentials must take place at a similar spacing—that is, in quadrature.

This control of the pressure differentials is exercised by the spools P1 and P2, each of which is itself controlled by signal S1 or S2, as the case may be, to change over the connections from intermediate channels I1 and I2 to the set of cylinders associated with the spool every half-wavelength of the translator movement.

Thus, assuming that the pressure in channel I1 is greater than that in channel I2, a movement of the translator to the right from the position depicted in FIG. 1 may be as illustrated by the waveforms of FIG. 2.

S1 and S2 are the waveforms of the controlling signal from stage **27**, each as a voltage alternately positive and negative plotted against time.

Waveforms A to D illustrate the relative pressures of the fluid in the respective cylinders; above the central horizontal line represents the higher pressure of the fluid in the channel I1 and below it the lower pressure of the fluid in channel I2.

At the time $t_0$, signal S1 is changing over from negative to positive and so actuating spool P1 to switch channel I1 from cylinders $AA^1$ to cylinders $CC^1$. The pressures in these cylinders is therefore changing from high to low, and low to high, respectively.

Also at time $t_0$, signal S2 is maintaining channel I1 connected to cylinders $DD^1$ and channel I2 to $BB^1$.

Hence at the time $t_0$, the drive is being provided by cylinders $DD^1$, which are about to be assisted by cylinders $CC^1$.

By the time $t_1$, the translator has moved a quarter wavelength of the pattern to the right from the position shown in FIG. 2. At this moment, whilst the drive is being effected by cylinders CC¹ alone, spool P2 is changing the higher pressure from cylinders DD¹ to BB¹, which at this moment are engaging troughs and crests of the profile. Similarly with the rest of the movement.

As signals S1 and S2 are in quadrature, they ensure the required quadrature relationship between these changeovers of the spools.

The direction of movement is not controlled by the porting system but by the servo system, through the actuation of valve **21** by the signal applied over lead **22**. The position of the valve decides which of the intermediate channels is connected to the supply channel Fs and which to the exhaust channel Fe, and in consequence which of the intermediate channels has the fluid at the greater pressure.

Each porting spool is the hydraulic equivalent of an electrical double-pole changeover switch. A suitable arrangement, taking spool P2 as an example, is shown in FIG. 3.

A cylinder **30** contains two piston valves **31** and **32** carried on a common piston rod **33** actuated by solenoid R2 under the control of signal S2. The entry ports for channels I1 and I2 are aligned with the centres of valves **31** and **32** (respectively) when rod **33** is in its mid position, which it in fact never occupies except momentarily when changing from one of its operative positions to the other. An exit port for the common channel BB′ leading to that group of cylinders is provided at each end of the cylinder. A single exit port for the common channel leading to cylinders D and D′ occupies a central position in the cylinder.

When the piston is in its operative position at the left-hand end of its stroke, as viewed in the drawing, channel I2 is connected to channel DD′ and channel I1 to channel BB′ (by way of the right hand exit port); with the piston at the right-hand end of its stroke those connections are reversed. The changeover switching action is rendered abrupt by the steep-edged waveform of the signal controlling the solenoid.

This comparatively abrupt action of the spools in a porting system in accordance with the invention has the advantage of allowing the pressure-difference changeover to take place when the translator cylinders are closely in alignment with troughs or crests of the profile and hence when there is very little fluid flow into or out of them. The effect of this is to reduce the risk of undesired pressure transients due to the changeover action. This advantage can be enhanced by providing the profile with "dwell" portions—that is, by providing in the region of each trough and crest a short linear (straight) portion parallel to the axis of translation.

Where such dwell portions are provided, it is desirable to provide corresponding straight portions in alignment with the other cylinders—that is, the cylinders not aligned with a trough or crest—so as to maintain constancy of thrust.

The positions of such straight portions or "flats" may be as shown in FIG. 4, which reproduces a cycle of the profile to an enlarged scale and with the amplitude much exaggerated. The flats **35** at trough and crest must merge smoothly into the curves, to which the flats should in effect be tangents. The other flats are shown at **36**. The length of each as projected on axis **14**—that is, in the direction of movement—is equal to the length of a flat **35**. With the translator in the position shown in FIG. 1, cylinders A and C are engaging flats **35** (not shown in FIG. 1) whilst B and D are engaging flats **36** (also not shown). Thus the balance of the thrusts from B and D is constant whilst A and C are traversing flats **35** and not themselves exerting any thrust.

A porting system under the control of an optical grating, as just described, is only practicable where the pitch of the stator profile is an even multiple of the grating pitch. Where that condition does not obtain, and also where the tool or other object controlled by the motor is not provided with a fringe counter measuring system and it is not desired to provide a grating for the porting control alone, that control may alternatively be exercised from the stator profile by means of cam followers, as shown in FIG. 5.

The pistons of the porting spools P1¹ and P2¹ are here spring loaded to one of their operative positions and arranged to be displaced to the other by the fluid under pressure in channel Fs under the control of cam-follower units C1 and C2 respectively.

Taking spool P1¹ as an example, the associated cam-follower unit C1 includes a cam roller **41** carried at the free end of a hydraulic plunger **42** operating in a cylinder **43** and spring-biased to maintain the roller **41** in engagement with the stator profile **12**. The fluid under pressure from channel Fs is applied by way of a flow resistor **44** to a port **45** in cylinder **43** part way along the stroke of the plunger and to the end of spool P1¹ remote from the biasing spring **46**. The end of the cylinder **43** remote from the plunger **42** and the spring biased end of spool P1¹ are connected to the exhaust channel Fe.

In order to prevent the fluid which actuates the spool from reaching the channels between valve **21** and the translator, spool P1¹ is arranged somewhat differently from its counterpart P1 of FIG. 1. One of the two intermediate channels—I1 as depicted— is brought to an entry port at the centre of the stroke, whereas the other—I2—is brought to entry ports at each end. The moving part of the spool includes piston valves **47** (at the end of the spool remote from spring **46**) and **48**, with a third piston valve **49** between them on the same piston rod. Channels AA′ and CC′ are fed from only one exit port each. The position of valve **49** on one or other side of the entry port for channel I1 determines whether that channel is connected to channel AA′ or CC′, the remaining connection being by the other two valves. In all positions of valve **47** to **49**, valve **47** maintains the actuating fluid isolated from the rest of the spool.

In operation, so long as plunger **42** is not covering the port **45**, the fluid from restrictor **44** exhausts through cylinder **43** to channel Fe and insufficient pressure is built up to overcome the force of spring **46** and switch the spool to its other operative position. As soon as the stator profile has driven plunger **42** sufficiently into its cylinder to close port **45**, the pressure in the channel between restrictor **44** and the spool becomes sufficient to actuate the spool abruptly to its other operative position against the force of spring **46**. The spool is shown so actuated in the drawing, with valve **49** causing channel I1 to be connected to channels AA′ and valve **48** freeing the adjacent entry port of channel I2 to connect it to channels CC′. The spring **46** is fully compressed, and valve **47** keeps the actuating fluid isolated.

Plunger **42** and port **45** in cylinder **43** together with the channels from the supply and to the spool, may accordingly be described as switching means whereby the movement of the cam-follower effects the porting action.

Similar arrangements are provided for spool P2¹, the components corresponding to components **41** to **49** just described being given the references **51** to **59**. Here the spool is shown in its unactuated condition, with the centre valve **59** connecting channel I1 to channels DD′ and valve **57** freeing the adjacent entry port of channel I2 as well as serving to isolate the actuating fluid.

The required quadrature actuation of the spools is obtained by arranging for the cam rollers **41** and **51** to engage parts of the stator profile at a quarter wavelength spacing.

The switching means may alternatively take an electrical form (not shown) the movement of the cam followers causing the closure or opening of electrical

switches in the circuits of solenoids which operate the spools as in the arrangement of FIG. 1.

Where cylinders are provided for a third cycle of the profile, so that $m=3$, each of the groups of cylinders controlled by the porting devices is expanded to include a third cylinder. Thus, as shown in FIG. 6, group AA' becomes AA'A'', and so on, The apparatus and its operation are otherwise as before. Similarly where $m$ is more than 3.

Where $n$ is increased beyond 2, the number of porting devices is increased correspondingly, each spool being arranged to connect the two intermediate channels I1 and I2 reversibly to two groups of cylinders. Thus, as shown in FIG. 7, where $n=3$, so that there are 6 cylinders—A to F, say—per cycle, a third porting spool P3 is added. Assuming that $m=2$, one spool—P1, say—controls counterphase groups AA' and DD'; spool P2 controls groups BB' and EE' with a lag of 60° on the groups controlled by spool P1; and spool P3 controls groups CC' and FF'. It is now necessary to derive a third signal S3 to control the additional spool P3. As shown in FIG. 8, the three signals are now at 60° spacings from one another, as opposed to the quadrature spacings of the two signals of the previously described embodiments, and stage 27 is modified accordingly. Each spool remains as before the equivalent of an electrical double-pole changeover switch. Where the profile is provided with flats, only those at trough and crest are required, as each pair of cylinders between the pair at trough and crest will be exerting a constant thrust between them over the short distance concerned.

What we claim is:

1. A linear hydraulic motor of the type which includes a stator and a translator mounted for straight-line movement relative to one another, the stator having a cyclic edge profile extending in the direction of movement and the translator having for each of $m$ cycles of the stator profile $2n$ cylinders disposed normal to that direction and containing hardened metal balls urgable by the actuating fluid in the cylinders to engage the stator profile at $\frac{1}{2}n$ wavelength spacings of the profile, $n$ being greater than unity, the motor also including changeover means reversibly connecting a supply channel and an exhaust channel of actuating fluid to two intermediate channels in dependence on a control signal, $n$ porting devices each for reversibly connecting the two intermediate channels to two groups each of $m$ cylinders associated with only that device, the cylinders in each of the two groups associated with that device being at in-phase spacings of the profile with respect to one another and the cylinders of one of those two groups being at counterphase spacings from those of the other group, and porting-control arrangements for abruptly actuating the porting devices sequentially at respective positions of the translator along the stator profile at $1/n$ wavelength spacings of the profile so as to render a pressure difference between the fluids in the intermediate channels effective in moving the translator in a direction dependent on the sense of that difference.

2. A motor as claimed in claim 1 wherein the porting-control arrangements include an optical grating fixed with respect to the stator and ruled with lines normal to the direction of movement of the translator, a photo-electric transducer secured to the translator so as to traverse the grating as the translator traverses the stator, an electrical stage for deriving from the transducer output $n$ square-wave signals in $\frac{1}{2}n$ wavelength phase relationship with one another at the frequency with which the translator traverses the stator edge profile, and connections for applying those $n$ signals to actuate the $n$ porting devices respectively.

3. A motor as claimed in claim 1 wherein the porting-control arrangements include $n$ cam-follower units the cam followers of which are arranged to engage the stator edge profile at $\frac{1}{2}n$ wavelength spacings, and switching means whereby the movements of the cam followers effect the actuation of the respective porting devices.

4. A motor as claimed in claim 1 wherein the porting-control arrangements are such that each porting device reverses the connections from the intermediate channels to the two groups of cylinders associated with that device when those cylinders are in alignment with parts of the stator profile that are approximately parallel to said direction of movement.

5. A motor as claimed in claim 4 wherein the stator profile is provided with a short straight portion parallel to said direction of movement in the region of said parts of the profile, and with corresponding straight portions with which the other cylinders are then aligned, thereby maintaining constancy of thrust whilst the connections to the said two groups of cylinders are being reversed as aforesaid.

6. A linear hydraulic motor of the type which includes a stator and a translator mounted for straight-line movement relative to one another, the stator having a cyclic edge profile extending in the direction of movement and the translator having two sets of four cylinders per set disposed normal to that direction and containing hardened metal balls urgable by the actuating fluid in the cylinders to engage the stator profile at ¼ wavelength spacings along the profile, the motor also including changeover means reversibly connecting a supply channel and an exhaust channel of actuating fluid to two intermediate channels in dependence on a control signal, two porting devices each for reversibly connecting the two intermediate channels to two groups each of two cylinders associated with only that device, the two cylinders in each of the two groups associated with that device being at in-phase spacings of the profile with respect to one another and the two cylinders of one of those two groups being at counterphase spacings from those of the other group, and porting-control arrangements for abruptly actuating the porting devices sequentially at positions of the translator along the stator profile at ½ wavelength spacings of the profile so as to render a pressure difference between the fluids in the intermediate channels effective in moving the translator in a direction dependent on the sense of that difference.

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PAUL E. MASLOUSKY, *Primary Examiner.*

U.S. Cl. X.R.

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