

Nov. 24, 1970

R. M. COX ET AL

3,543,204

DIGITAL ACTUATOR WITH FLUID DAMPING

Filed Oct. 9, 1968

2 Sheets-Sheet 1

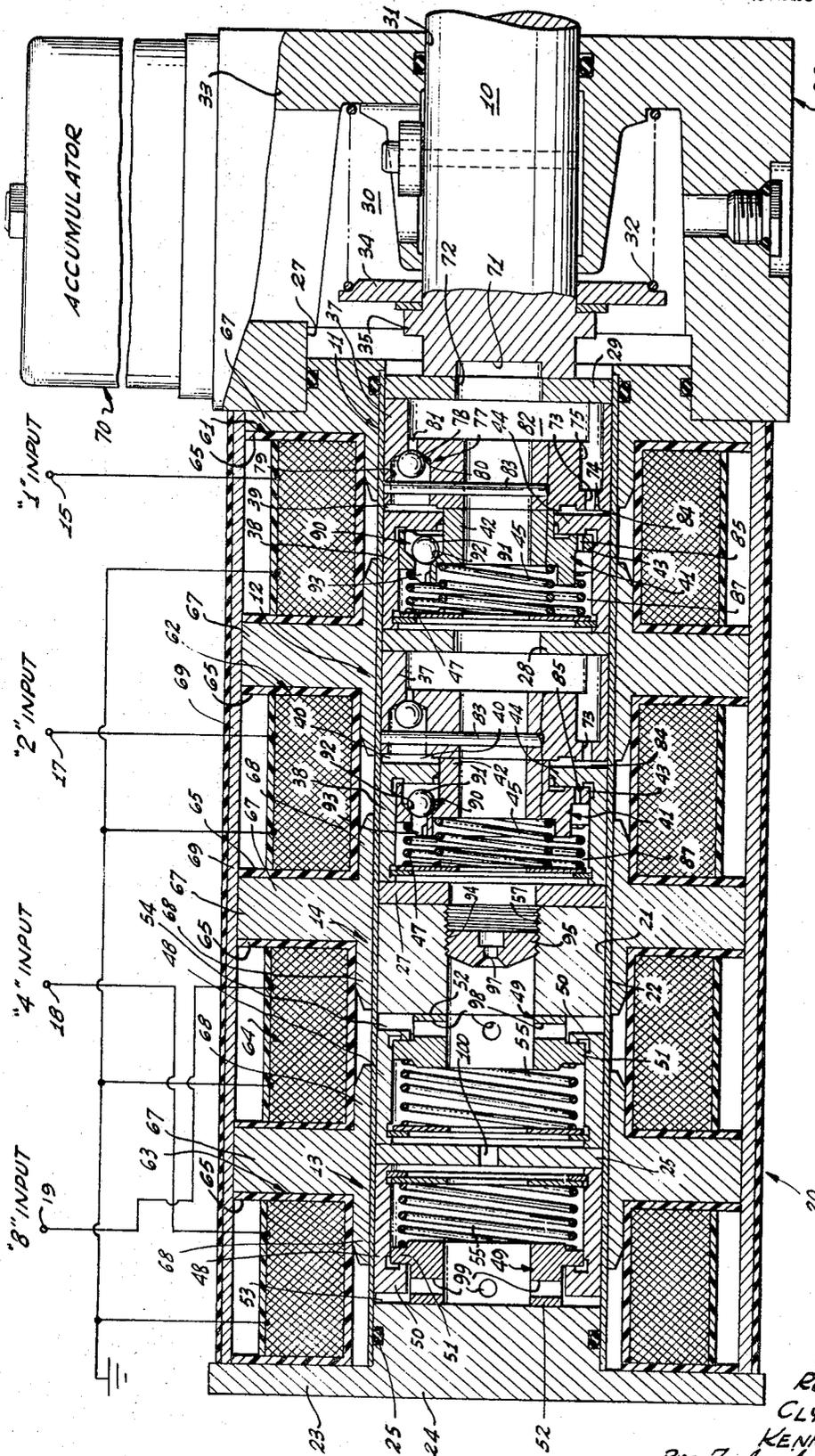


Fig. 1

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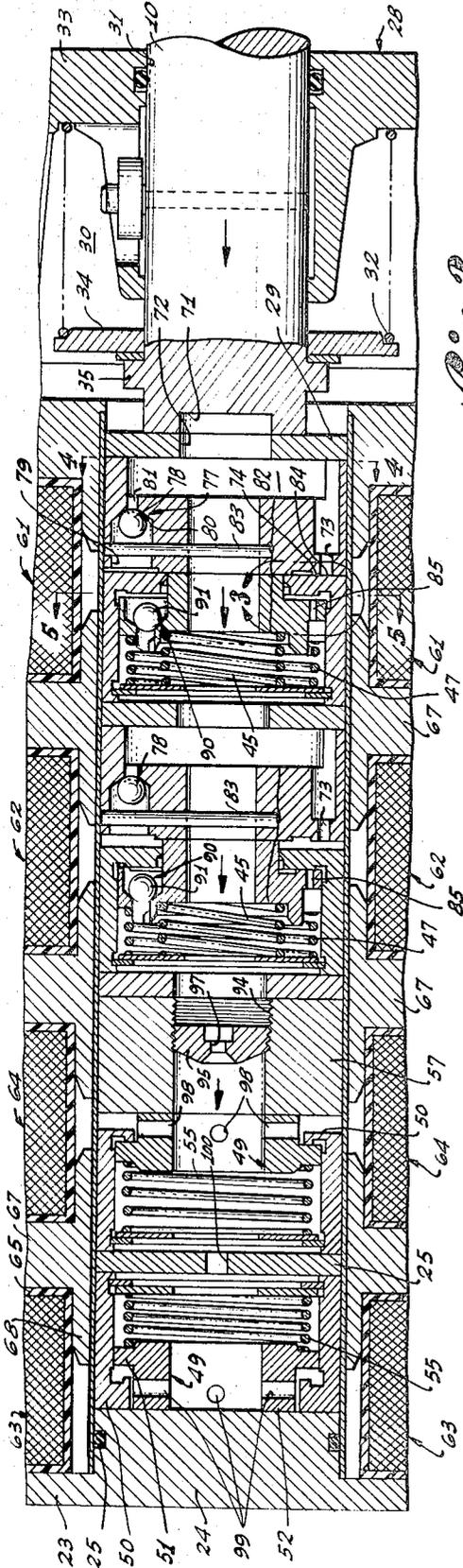


Fig. 2

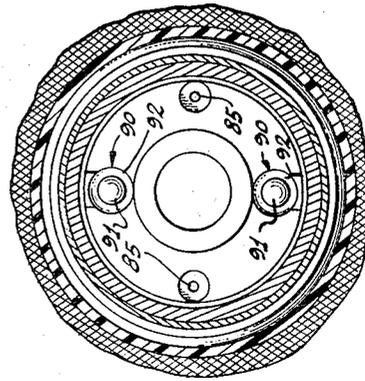


Fig. 5

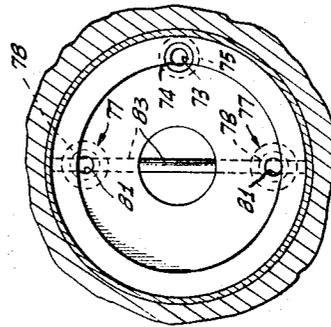


Fig. 4

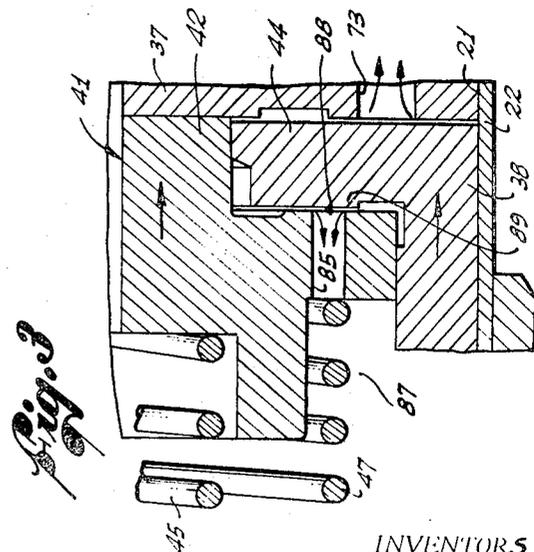


Fig. 3

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11 Claims

ABSTRACT OF THE DISCLOSURE

A digital actuator having an output shaft displaced longitudinally by a stack of four individually expandible and contractible piston adder assemblies in a fluid-filled bore, the assemblies comprising two relatively movable magnetic elements spring-urged apart and selectively contracted different preselected distances by solenoid coils encircling the assemblies. A follow-up spring urges the output shaft against the stack to contract the latter in response to contraction of individual assemblies, and two of the assemblies have speed-control passages controlling the rate of fluid escape from two chambers formed between the magnetic elements to control the maximum velocity in both directions, and also have blocking surfaces progressively restricting the speed-control passages near the ends of the strokes to decelerate the elements and cushion impacts. The other two assemblies have modified velocity control in the form of speed-control passages alone.

BACKGROUND OF THE INVENTION

This invention relates to actuators of the type having two relatively movable elements for assuming definite expanded and contracted states relative to each other, and has particular reference to digital actuators wherein a digital input signal is converted to a physical output displacement proportional to the real value of the digital input. More particularly, the invention relates to a new and improved actuator of the digital adder type disclosed in our copending application Ser. No. 664,013, filed Aug. 29, 1967, and entitled Digital Actuator.

As explained in more detail in the foregoing application, there has been a recent increase in the need for high precision digital actuators capable of producing an output displacement proportional to a digital input without excessive cost, complexity or size, and yet capable of satisfying the precision and durability requirements of modern control systems. For this purpose, the prior actuator uses a plurality of coaxial and abutting piston adder assemblies arranged as sections of a columnar stack and each comprising two relatively movable and low-mass elements spring-urged apart into a preselected spaced relationship but contractible electromagnetically a controlled distance in response to a digital command.

Upon contraction of one or more of the sections, a follow-up spring correspondingly contracts the columnar stack and thus moves the controlled load mass in one direction a distance constituting the sum of the increments represented by the contracted sections, and upon subsequent expansion, the follow-up spring yields to the spring expansion force of the expanded assemblies to accommodate the increased length of the stack, thereby displacing the load in the opposite direction. While the movement of the load mass was damped to avoid excessive acceleration and deceleration rates, the individual sections of the stack have been expanded and contracted at high and virtually uncontrolled rates within the limits

2

imposed by opposed surfaces abutting against each other at the opposite ends of the expanding and contracting strokes.

SUMMARY OF THE INVENTION

The primary object of the present invention is to improve the operation of actuators of the foregoing general character by internally controlling the maximum rate of expansion and contraction of one or more of the adder sections, and particularly controlling the deceleration of the elements at the ends of the expanding and contracting strokes, to avoid excessive impacts and possible overshooting of the proper positions in both the expanded and contracted states of the section. In accordance with a primary aspect of the invention, the spaced elements of each controlled section define a gap chamber for containing pressure fluid, and a speed-control passage or orifice is formed in one element to meter fluid through the passage at a controlled maximum rate under a given force, thereby regulating the maximum velocity that can be obtained. For controlled deceleration of the elements, a surface movable with the other element forms a curtain progressively restricting the area of the passage as the elements approach the end of a stroke, thus gradually decelerating the elements as an incident of their increasing proximity.

Moreover, a preferred form of the invention has two control chambers each having at least one speed-control passage and curtain surface operating in each direction of movement, and thus is controlled during both the expansion stroke and the contraction stroke. Combined with the speed-control passages are valve means for admitting fluid into the control chambers for rapid response of the section when the existing state is to be changed, despite the tight closure of the speed-control passages by the curtain surfaces.

Other objects and advantages of the invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a longitudinal view, primarily in cross-section, of an exemplary digital actuator embodying the novel features of the present invention, the view being taken partially in two perpendicular planes;

FIG. 2 is a fragmentary view similar to part of FIG. 1 with parts in moved positions;

FIG. 3 is a greatly enlarged fragmentary view taken within the arc 3 of FIG. 2 as one adder section is moving into the contracted state;

FIG. 4 is a fragmentary cross-sectional view taken substantially along the line 4-4 of FIG. 2; and

FIG. 5 is a fragmentary cross-sectional view taken substantially along the line 5-5 of FIG. 2.

DETAILED DESCRIPTION

As shown in the drawings for purposes of illustration, the invention is embodied in an electromagnetic digital actuator having an output shaft 10 capable of being displaced longitudinally by a columnar, series stack of piston adder assemblies 11, 12, 13 and 14 in the actuator through a plurality of different, definite positions, the adder assemblies herein representing the digital quantities "1," "2," "4" and "8," respectively, as indicated on the schematic representations of the digital command input terminals 15, 17, 18 and 19 in FIG. 1. Each individual assembly is capable of selective axial contraction and expansion to produce an incremental physical displacement of the opposite ends of the assembly which is proportional to the real value of the digital input quantity represented by the assembly, so that the stack is capable

3

of incrementally extending and retracting the output shaft 10 through a series of different positions representing different combinations of the digital quantities "1," "2," "4" and "8."

In this instance, the actuator comprises a cylindrical block 20 defining an elongated cylindrical bore 21 in a liner sleeve 22 closed at one end, the left end in FIGS. 1 and 2, by a cap 23 having a cylindrical stub 24 sealed at 25 in the sleeve, the other end of the sleeve being telescoped into and sealed in a circular opening 27 in one side of a hollow cap 28, forming the right end of the block. The adder assemblies 11-14 are fitted in the expanded state, and in end-to-end relation, in the bore 21, and preferably fill the latter from the cap 24 at the left end to the output shaft 10 at the right end of the bore, and are separated from each other by spacer washers 25, 27, 28 and 29, the latter being disposed between the right adder assembly 11 and the left end of the output shaft.

The output shaft 10 extends across a chamber 30 defined in the hollow cap 28, and exits from the cap through a sealed opening 31, being urged yieldably to the left by a coiled, follow-up spring 32 compressed between the end wall 33 of the cap and a ring 34 telescoped onto the shaft and abutting against an annular shoulder 35 thereon. Thus, the follow-up spring tends to collapse the stack of adder assemblies 11-14 to displace the shaft to the left in response to selective contraction of one or more of the adder assemblies, and is yieldable to the right upon re-expansion of any of the assemblies producing an increase in the total axial length of the stack.

In general, each adder assembly 11-14 comprises two cylindrical elements composed of magnetic material and disposed within the bore 21 in end-to-end relation with spring means acting to urge the elements apart and to hold the elements in axially separated condition with a preselected gap between them, the gap constituting the incremental output displacement proportional to the digital input of the particular assembly. While all of the assemblies may have the same basic construction, herein only the "1" and "2" assemblies 11 and 12 are substantially identical, each comprising two cylindrical piston sleeves 37 and 38 composed of magnetic material and having adjacent ends spaced apart by a gap 39, 40, and also including a piston or plunger 41 that is mounted in the left piston sleeve 38 and formed with hollow cylindrical portion 42 of reduced diameter projecting to the right across the gap and abutting against the left end of the other sleeve 37. An outwardly extending flange 43 on the plunger, which is composed of non-magnetic material, abuts against an internal flange 44 on the sleeve 38 to limit movement of the plunger to the right. The spring means of these two assemblies comprise two coiled springs 45 and 47 compressed between the left end of the plunger 41 and a pair of retaining washers held in the left end of the sleeve. Thus, the springs normally hold the plunger in the extended position with the reduced diameter portion 42 holding the sleeves in axially spaced relation to maintain the assembly 11, 12 in the expanded state, but are yieldable to permit yielding of the plunger relative to the sleeve 38 during contraction of the assembly.

The "4" and "8" assemblies 13 and 14, respectively, are generally similar, each having a piston sleeve 48 with a coaxial, non-magnetic plunger 49 movable therein, opposed flanges 50 and 51 on the sleeve and plunger limiting extension of a reduced diameter portion 52 of the piston across the associated gap 53, 54, and a spring 55 compressed between the plunger and retaining washers on the sleeve to hold the plunger yieldably in an extended position determining the width of the gap. The second magnetic element of the "8" assembly 13 is the stub 24 on the cap 23, which thus is fixed in the bore 21 on the left side of the sleeve 48. The second element of the "4"

4

assembly 14 is a cylinder 57 slidably mounted in the bore on the right side of the sleeve 48, the two plungers 49 of these two assemblies thus extending in opposite directions relative to the two sleeves.

Surrounding each adder assembly 11-14 is a solenoid coil 61, 62, 63 and 64, respectively, for generating an essentially axial, concentrated magnetic field extending through the separated magnetic elements of the associated adder assembly so as to overcome the separating force of the springs and draw the magnetic elements together. All of the coils are substantially the same, except for details of design related to the different sizes of gaps existing in the different assemblies. The coils are telescoped loosely around the liner sleeve 22 and are mounted coaxially therewith in annular slots defined by coil rings 65 supported by axially spaced magnetic spacers 67 having flanges 68 which fit snugly around the sleeve and form annular gaps between the inner sides of the coils and the outer side of the liner sleeve. A suitable cover 69 is disposed around the coils between the two caps 23 and 28.

When all of the coils 61-64 are deenergized, all of the piston adder assemblies 11-14 are maintained in the axially expanded state by the springs therein, which hold the plungers 41 and 49 extended across the gaps 39, 40, 53 and 54 to hold the magnetic elements in properly spaced relation. Thus, the follow-up spring 32 holds the output shaft 10 against the spacer 29 at the right end of the expanded stack, in the position shown in FIG. 1. When one or more of the solenoid coils is energized, the magnetic elements of the associated assembly (or assemblies) are drawn together to close the selected gap (or gaps) and thereby reduce the sum of the axial lengths of the adder assemblies by the amount of the closed gaps. Since the magnetic elements of each assembly have relatively low masses, as compared to the combined mass of the stack, the output shaft and the load, the individual assemblies may be contracted very rapidly in response to the digital input signals, with the change in the length of the stack being accomplished by the follow-up spring 32. Upon deenergization of a coil, the magnetic elements are released to the action of the spring means within the associated assembly, which thus is expanded against the lesser collapsing force exerted by the follow-up spring.

It will be seen, therefore, that the solenoid coils 61-64 are called upon only to contract the associated individual assemblies 11-14, and that the springs perform the heavier work of moving the load mass and the bulk of the stack. Thus, the rate of movement of the magnetic elements of each adder assembly is limited only by the relationship of the limited masses being moved and the strength of the magnetic field applied, and both maximum velocity and deceleration of the elements at the ends of the expanding and contracting strokes have been virtually uncontrolled. Of course, the strokes of the assemblies may be very rapid, ranging, for example, from twenty-five milliseconds for the "1" and "2" assemblies to eighty milliseconds for the "8" assembly.

In accordance with a primary aspect of the present invention, the maximum relative velocity of the magnetic elements of one or more of the assemblies 11-14, and also the rate of deceleration of the elements as they approach the ends of the strokes, are controlled internally in a novel and very effective manner to avoid adverse effects that would be produced by excessive impact, one such adverse effect being the possibility of momentary overshooting of the elements in one direction. Moreover, the same velocity and deceleration control may be obtained during both expansion and contraction of the assemblies, for smooth and controlled movement of the elements in both directions.

To the foregoing ends, the two movable elements of each adder assembly 11-14 cooperate with the bore 21

in defining a gap chamber between the elements for holding pressure fluid such as the usual hydraulic oil, and at least one speed-control orifice is formed in one of the elements to admit oil out of the gap chamber at a controlled maximum rate, thereby regulating the maximum closing velocity that the elements can attain during contraction of the assembly. On the other element is a blocking surface that is movable toward the speed-control orifice as the elements approach each other, this surface forming a curtain which progressively restricts the flow area of the orifice as the blocking surface moves toward the passage from within a preselected distance away. This progressive reduction in flow area progressively reduces the rate of escape of oil from the gap chamber to accelerate the elements automatically as an incident to their increasing proximity.

A second chamber is formed in each of the controlled deceleration assemblies 11, 12 to be contracted as the assemblies expand, and is similarly provided with a speed-control orifice and a blocking surface for gradually restricting the flow area of the orifice as the elements approach the expanded condition, thereby providing the desired deceleration in both directions of operation. In addition, means are provided for by-passing the control orifices when the latter are closed, and admitting fluid into the control chambers as the latter expand, thereby avoiding delays in the responsiveness of the adder assemblies resulting from snubbing of the control orifices.

In this instance, the bore 21 and the chamber 30 in the cap 28 are filled with oil which is maintained under light pressure by a spring accumulator 70 mounted on top of the cap. This oil enters the bore through a groove 71 in the shaft 10 and a center hole 72 in the spacer washer 29, and flows along the full length of the bore through the centers of the adder assemblies 11-14.

Deceleration control herein is applied only to the "1" and "2" assemblies 11 and 12, while velocity control is applied to all four of the assemblies. With specific reference to the "1" assembly, which is substantially the same as the "2" assembly, it will be seen that a single speed-control passage 73 (see FIG. 4) is formed in the outer peripheral portion of the right magnetic sleeve 37 to open through a raised circular pad 74 on the left end of the sleeve into the gap chamber 39 between the two sleeves 37 and 38 when the assembly 11 is expanded. The enlarged right end portion 75 of this passage opens into the central portion of the sleeve to the right of the assembly, and the left end of the passage constitutes the control orifice having a flow area which determines the maximum flow rate out of the gap chamber 39 during contraction of the assembly 11 under the net force exerted by the field of the solenoid coil 61 to overcome the force exerted by the expanding springs 45 and 47.

It will be seen that the reduced diameter portion 42 of the plunger 41 abuts against the adjacent end face of the right piston sleeve 37, inwardly from the speed-control passage 73, and is fitted closely within the internal flange 44 of the sleeve 38 to cooperate with the bore 21 and the magnetic sleeves in defining the gap chamber 39 as an annulus encircling the plunger portion 42, the chamber being substantially sealed except for the speed-control passage 73. Leakage around the various parts is negligible and can be ignored, from the standpoint of operation of the assembly during expansion and contraction.

Also formed in the right magnetic sleeve 37 of the assembly 11 are two one-way valves indicated generally at 77 (see FIG. 4) only one of these valves being shown in FIGS. 1 and 2 because of the angular nature of these views. Herein, the valves comprise balls 78, composed of non-magnetic material such as nylon, disposed in axially extending recesses 79 having conical seats 80 tapering to the right into flow passages 81 extending through the sleeve 37 so as to communicate with the gap chamber 39

at the enlarged left ends of the ball recesses 79 and with the oil-filled space 82 within the right end portion of the sleeve. A pin 83 is pressed into the sleeve across the enlarged ends of the ball recesses to maintain the balls closely adjacent the seats. During contraction of the assembly 11, the higher fluid pressure within the contracting gap chamber 39 maintains the one-way valves 77 closed so that the only appreciable escape path for fluid is through the restricted speed-control passage 73.

When the solenoid coil 61 is energized to draw the magnetic sleeves 37 and 38 together, the magnetic field builds up sufficient force to overcome the springs 45 and 47 and then starts the sleeves toward each other, thereby beginning to squeeze fluid out of the chamber through the passage 73. Initially, there is little restriction of velocity as the magnetic elements are accelerated toward each other, but the increase in velocity increases the rate of flow through the control passage 73 until a pressure drop is produced across the passage. When this occurs, a force counteracting the magnetic field is produced, and the velocity reaches an equilibrium value which is sustained until the elements are close together. It should be remembered, however, that the total contracting operation may be completed in twenty-five milliseconds or less, so the foregoing occurs very quickly and only momentarily.

Directly opposite the orifice at the left end of the speed-control passage 73 is a blocking surface 84 for controlling deceleration of the magnetic elements. Herein, the blocking surface is simply a portion of the flat right end of the left piston sleeve 38 aligned with the pads 74 on the left end of the right piston sleeve 37, as shown most clearly in FIGS. 1-3. When the piston sleeves are separated by the preselected gap 39, the blocking surface 84 is spaced axially from the pad 74 a distance substantially greater than one-quarter of the diameter of the orifice, and thus has no restricting effect on the initial flow capacity of the passage. As the blocking surface moves closer to the pad than one-quarter of the passage diameter, however, the flow area is reduced progressively—from the original orifice area when the blocking surface is spaced from the pad a distance equal to one-quarter of the diameter, to zero flow area when the surface lies flat against the pad. This, then, is the automatic curtain action for controlling deceleration in accordance with the proximity of the two magnetic elements during contraction of the adder assembly 11.

As the effective flow area is reduced, as shown in FIG. 3, a higher pressure is produced within the gap chamber 39, thus causing a slowing down of the magnetic elements 37, 38 as the two elements approach each other. Finally, the blocking surface 84 moves into abutting engagement with the pad 74 as the last amount of oil is squeezed out of the gap chamber. At this point, the restriction is the greatest, for effective cushioning of the closing impact of the two sleeves.

The one-way valves 77 permit the two sleeves 37, 38 to separate rapidly during expansion of the adder assembly 11 by opening to admit fluid into the chamber 39 as soon as the springs 45 and 47 begin to separate the elements after deenergization of the solenoid coil 61. Otherwise, the blocking surface 84 would restrict entry of fluid into the chamber and prevent rapid separation of the sleeves from the contracted state in FIG. 2.

The second chamber for controlling the maximum velocity during expansion of the adder assembly 11 herein is defined between the plunger 41 and the left piston sleeve 38 by the outer flange 43 of the plunger, which has a close sliding fit inside the sleeve, and by the internal sleeve flange 44, which fits closely around the reduced diameter portion 42 of the plunger. A pair of restricted speed-control passages 85 (see FIG. 5), similar to the passage 73, communicate through the flange 43 with the chamber and with the oil-filled space 87 in the bore 21 on the left side of the assembly 11, and the blocking sur-

face 88 for this passage is the end of a pad 89 on the left side of the internal flange 44 of the piston sleeve. Also, two one-way valves 90 (FIG. 5) are formed in the plunger flange 43 with nylon balls 91 in conical seats 92 tapering to the left to flow passages 93 opening through the flange, the balls being positioned loosely in the seats.

As the assembly 11 and the gap chamber 39 are contracted, as previously described, the second chamber expands freely as the balls 91 permit fluid to pass through the flange. When the coil 61 is deenergized and the springs 45 and 47 begin to expand the assembly, however, the second chamber begins to contract and the accompanying increase of pressure forces the balls into the seats 92 to close the one-way valves 90, leaving the speed-control passage 85 as the sole significant escape route for the fluid in the chamber. As before, the initial acceleration of the parts is not materially affected, but the increasing flow out if the chamber eventually produces a pressure drop across the control passage, and results in a counteracting force resisting the springs 45 and 47, thus controlling the maximum closing speed. Then, as before, the blocking surface 88 progressively restricts the speed-control orifice at the left end of the passage to decelerate the parts and cushion the final closing impact.

It should be noted that any number of speed-control passages may be used to make up a desired total flow area. The smaller the orifices are, however, the closer the two magnetic elements must come to each other before controlled deceleration begins. Thus, assuming the passage 85 has the same area as the two passages 81, the single-passage form will begin deceleration when the elements are a greater distance apart.

The same action could be provided in the "4" and "8" assemblies simply by duplicating the "1" and "2" assemblies, but the longer time interval used for actuating the "4" and "8" assemblies makes such control unnecessary, at least for some applications. Thus, these assemblies herein are provided only with modified speed control, and not with deceleration control.

For this purpose, the cylinder 57 of the "8" assembly 14 has a threaded center bore 94 in which an orifice plug 95 is threaded, as shown in FIGS. 1 and 2, the plug having a restricted speed-control passage 97 of preselected flow area for limiting the rate of flow from the gap chamber 54 between the magnetic elements 48 and 57, thus limiting the maximum speed of the cylinder to the left by producing a counteracting pressure drop after the desired maximum speed is attained. The reduced diameter portion 52 of the plunger 49 is formed with radial passages 98 for admitting the fluid into the center of the plunger, so the sleeve 48 initially closes to the right against the cylinder 57. Then as fluid flows out through the control passage 97, the assembly is shifted to the left by the follow-up spring 32. To change the speed characteristics, a different orifice plug may be inserted in the cylinder 57.

The flow out of the gap chamber 53 of the "4" assembly 13, between the stud 24 and the piston sleeve 48 of the assembly, is through radial passages 99 in the reduced diameter portion 52 of the plunger 49 to the center of the latter, and then through the retaining washers to the spacer 25 which separates the assembly from the "8" assembly. The center hole 100 of this spacer is of a preselected diameter small enough to constitute a restricting speed-control orifice for this assembly. Initially, as the sleeve 48 is shifted to the left against the stud 24, the oil in the gap chamber 53 is displaced through the passages 99, and the sleeve separates itself momentarily from the spacer 25. Then, the spacer is shifted to the left under the force exerted by the follow-up spring and at a rate determined by the rate of flow through the orifice 100.

From the foregoing, it will be seen that the digital actuator constituting the present invention has all of the operating capabilities of the prior actuator and, in addition, has internal velocity control for the assemblies 11 and 12, and also has modified velocity control in the re-

maining assemblies. In addition, the unique interacting elements of the assemblies 11 and 12 provide controlled deceleration of the two magnetic elements of each assembly to eliminate hard impacts between the elements during contraction, and also during expansion, for materially improved operating characteristics. Moreover, this internal control is achieved in a relatively uncomplicated manner with simple control elements that are operated automatically as an incident to the back and forth motion of the magnetic elements, and are directly responsive to the proximity of the opposed surfaces of the elements.

It also will be seen that, while a particular form of the invention has been illustrated and described, and a specific use has been suggested, various modifications and other uses can be made without departing from the spirit and scope of the invention.

We claim as our invention:

1. In a digital actuation system having a block formed with a bore, an actuator column in said bore comprising a plurality of coaxial actuator sections in end-to-end abutment, each of said sections being capable of selective expansion and contraction to assume expanded and contracted states, an output member coupled to one end of said actuator column, first means for normally maintaining each of said sections in said expanded state, and second means for each of said sections for selectively overriding the first means for the section and contracting the section to its contracted state, the improvement in at least one of said sections comprising:

means for holding a body of pressure fluid in said bore around said column;

first and second sleeves disposed in said bore for relative movement toward and away from each other to contract and expand said section, said sleeves having opposed sides defining a first chamber in said bore between the sleeves when the section is in the expanded state;

a plunger telescoped into said second sleeve and movably supported thereon with one end portion of the plunger extended across said chamber and abutting against said first sleeve;

said first means constituting a spring acting between said chamber and said bore on one side of said one section through said second sleeve to receive fluid therefrom as said one section and said first chamber are contracted, thereby controlling the rate of relative movement of said sleeves;

means on said second sleeve and said plunger defining a second chamber between the two, said second chamber increasing in volume as said plunger is retracted and decreasing as the plunger is extended;

a second speed-control passage communicating between said second chamber and said bore on the other side of said one section through said plunger thereby to receive fluid from said second chamber as said one section is expanded and said second chamber is contracted; and

blocking means on said sleeves movable into and out of positions overlying said passages as said sleeves move together and apart, said blocking means progressively restricting said first speed-control passage as said sleeves move together during contraction of said one section, and progressively restricting said second speed-control passage during contraction of said second chamber as said one section assumes said expanded state, thereby to control the maximum velocity and deceleration of said sleeves in each direction.

2. The improvement defined in claim 1 in which said blocking means comprise surfaces on said second sleeve movable into positions overlying said passages first to restrict the passages and then to close them, and further including one-way valves for admitting fluid into each of said chambers independently of the associated passage

during expansion of the chamber and movement of the associated blocking surface away from the passage.

3. In a digital actuation system having a piston adder assembly comprising first and second elements movable toward and away from each other between expanded and contracted states, first means for urging said elements away from each other and maintaining said assembly yieldably in its expanded state, and second means for overriding said first means to move said elements together and into said contracted state, the improvement comprising:

means defining a chamber for pressure fluid between said elements when the latter are in said expanded state;

at least one speed-control passage communicating through one of said elements with said chamber to pass fluid through said one element at a controlled rate during movement of the elements relative to each other into one of said states; and

a blocking member movable with the other of said elements and progressively restricting the effective flow area of said passage as said elements approach said one state, thereby progressively reducing the rate of relative movement of said elements to damp the approach of said elements to said one state.

4. The improvement as defined in claim 3 in which said speed-control passage is formed in said one element and communicates with said chamber to admit fluid out of the chamber as said elements approach each other, said blocking member being positioned on said other element first to restrict said passage and then to cover the latter as the elements move together.

5. The improvement as defined in claim 4 further including flow means in said one element for admitting fluid through the element to said chamber independently of said speed-control passage as the elements are moved apart.

6. The improvement as defined in claim 5 in which said flow means include at least one one-way valve in said one element permitting flow to said chamber through said valve but preventing flow from said chamber through said valve.

7. The improvement as defined in claim 4 further including means defining a second chamber when said elements are in said contracted state, flow means for admitting fluid into said second chamber as said elements are moved toward each other to said contracted state, a second speed-control passage through said first element for admitting fluid out of said second chamber as said elements are moved away from each other toward said expanded state, and a second blocking member movable with said second element and positioned first to restrict said second passage and then to cover the latter as the elements move to said expanded state.

8. The improvement as defined in claim 7 in which said flow means include at least one one-way valve in said first element permitting fluid flow to said second chamber through said valve but preventing flow from said second chamber through said valve.

9. In a digital actuation system having a piston adder assembly comprising first and second elements movable

toward and away from each other between expanded and contracted states and separated from each other by a gap of preselected size in said expanded state, first means for urging said elements away from each other and maintaining said assembly yieldably in its expanded state, and second means for overriding said first means to move said elements together across said gap and into said contracted state, the improvement comprising:

means defining a chamber for pressure fluid in said gap and between said elements when the latter are in said expanded state; and

means defining a speed-control passage communicating with said chamber through one of said elements, said chamber being substantially sealed except for said passage during relative movement of said elements toward each other and said passage having a preselected area for a flow of fluid out of said gap during movement of said elements to said contracted state thereby to control the maximum rate closing movement of said elements, said speed-control passage having an orifice of preselected area opening out of said one element toward the other element, and said other element having a blocking surface aligned with said orifice to move toward the latter during contraction of said assembly, first to restrict the effective flow area progressively as the elements close from within a preselected distance and then to cover said orifice, thereby to control deceleration of said elements during contraction of said assembly.

10. The improvement as defined in claim 9 further including means on said elements defining a second chamber that expands and then contracts as said elements are contracted and then expanded, a second speed-control passage on one of said elements having an orifice and communicating with said second chamber to admit fluid therefrom at a controlled rate, and a blocking surface movable toward said orifice to restrict and then cover the latter as said second passage is contracted, thereby to control deceleration of said elements during expansion of said assembly.

11. The improvement as defined in claim 10 further including one-way valves for admitting fluid into each of said chambers during expansion thereof but preventing fluid from flowing out of the chambers during contraction except through said passages.

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GEORGE HARRIS, Primary Examiner

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