Aug. 16, 1960 J. B. OTTESTAD ET AL 2,949,096

PNEUMATIC ACTUATOR

Filed Sept. 13, 1957 2 Sheets-Sheet 1

FIG. 1.

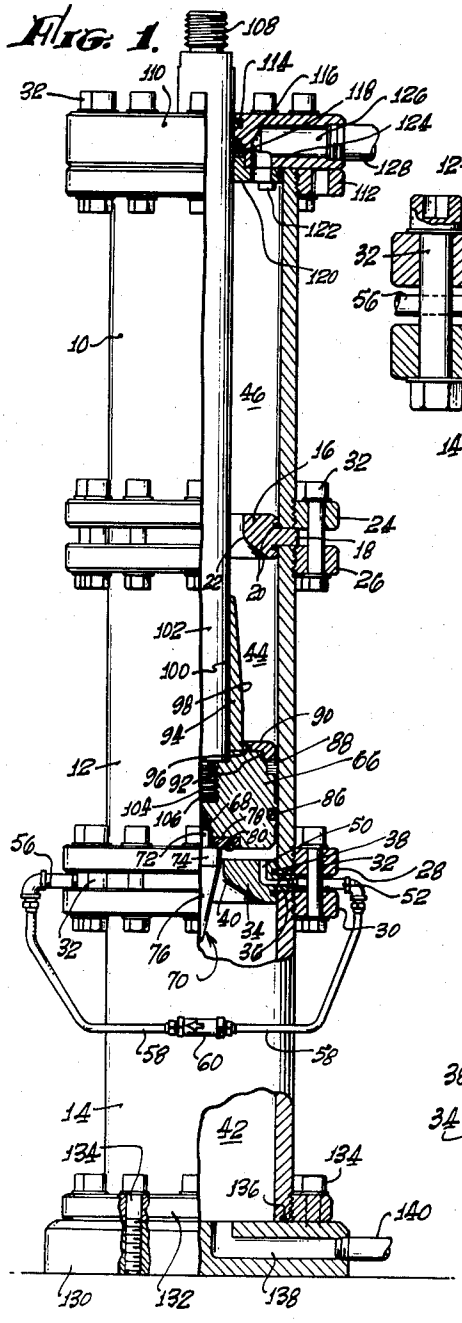


FIG. 2.

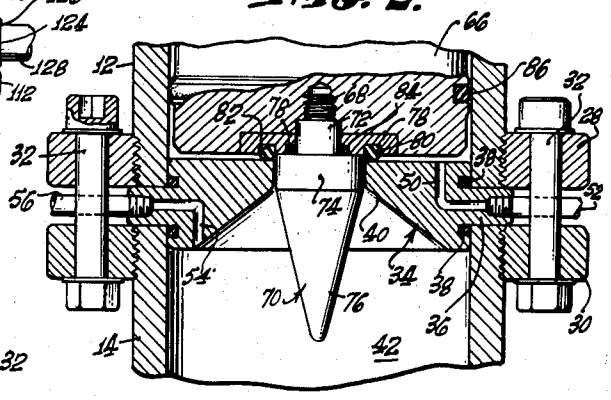
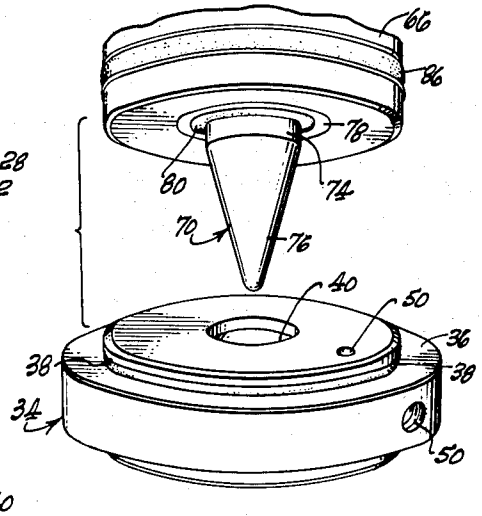


FIG. 3.



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Filed Sept. 13, 1957 2 Sheets-Sheet 2

FIG. 4.

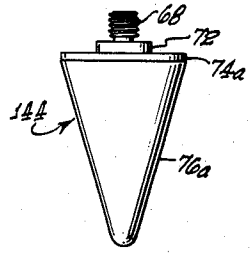


FIG. 5.

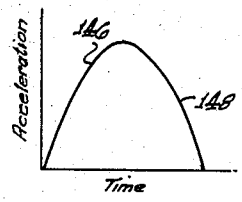


FIG. 6.

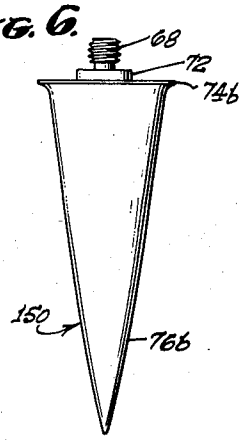


FIG. 7.

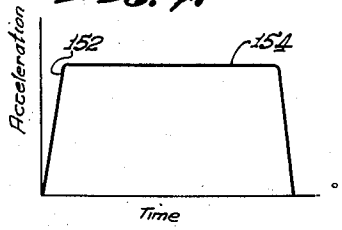


FIG. 8.

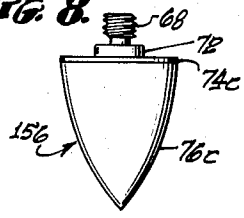


FIG. 9.

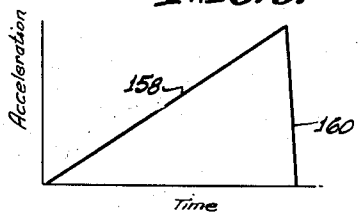
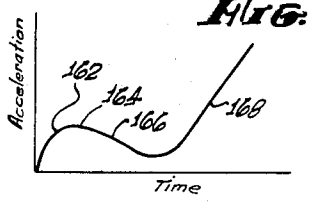


FIG. 10.



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Patented Aug. 16, 1960

2,949,096

PNEUMATIC ACTUATOR

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Filed Sept. 13, 1957, Ser. No. 683,855

16 Claims. (Cl. 121—38)

This invention relates generally to pneumatic actuators; more particularly, it relates to a pneumatic actuator wherein pressurized gas is metered to control a complete thrust-time pattern.

The present invention represents improvements upon the invention described and claimed in the copending application of Jack Benton Ottestad, Serial No. 617,014, filed October 19, 1956. Certain embodiments of the invention of the copending application effect control of a thrust-time output pattern through the coaction of a metering member and an orifice to regulate flow of hydraulic control fluid. The improved actuator of this invention obviates the use of hydraulic control fluid by utilizing only pneumatic energy for control. It therefore does not require certain structural elements associated with the use of hydraulic fluid. It eliminates problems associated with hydraulic control fluid and has distinct advantages over actuators utilizing such fluid.

It is, therefore, an object of the present invention to provide a pneumatic actuator wherein the pneumatic energy utilized in triggering the actuator is thereafter metered to produce a predetermined thrust-time output pattern.

It is an object of this invention to provide a pneumatic actuator wherein a complete acceleration-time pattern is produced by utilizing a contoured metering member to control the release of the pneumatic energy which initially triggers the actuator.

An object of the present invention is the provision of an actuator which eliminates component elements and problems associated with the utilization of hydraulic control fluid.

It is an object of this invention to provide a pneumatic actuator requiring substantially less energy for metering pressurized gas through a control orifice, than is required for similar metering in an hydraulic actuator, because of the higher orifice losses and tare mass of hydraulic fluid.

Another object of the present invention is the provision of a pneumatic actuator wherein pressurized control gas provides higher output energy potential for a given supply volume than is provided by hydraulic actuators.

It is a further object of this invention to provide a pneumatic actuator capable of providing predetermined high initial thrust output through the utilization of pneumatic energy for rapidly disengaging a sealing element disposed about an orifice to release the pneumatic energy upon the surface of an actuating piston.

Other objects and features of the present invention, as well as many advantages thereof, will become apparent to those skilled in the art from a consideration of the following description, the appended claims, and the accompanying drawings, in which:

Figure 1 is an elevational view, partially in section, showing a preferred embodiment of the pneumatic actuator of the present invention;

Figure 2 is a fragmentary view, partially in section, showing a portion of the pneumatic actuator of Figure 1 on an enlarged scale;

Figure 3 is a perspective view showing certain of the elements of Figures 1 and 2;

Figure 4 shows a metering member utilized with the present invention for producing a substantially sine-wave acceleration-time pattern;

Figure 5 is a graphical representation of the acceleration-time pattern produced by utilizing the metering member shown in Figure 4 with a pneumatic actuator according to this invention;

Figure 6 shows a metering member utilized with the present invention for producing the thrust-time pattern shown in Figure 7;

Figure 7 is a graphical representation of the thrust-time pattern produced by utilizing the metering member shown in Figure 6 with an actuator of the present invention;

Figure 8 shows a metering member for use with the pneumatic actuator of the present invention to produce a linear thrust-time pattern;

Figure 9 is a graphical representation of the thrust-time pattern produced by utilizing the metering member shown in Figure 8 in an actuator of the present invention; and

Figure 10 is a graphical representation of an undesirable premature acceleration-time waveform, the production of which is prevented by utilizing a metering pin of this invention.

Referring to the drawings, and particularly to Figures 1, 2 and 3, there is shown a preferred embodiment of the present invention. This embodiment is a pneumatic actuator capable of producing rapidly applied predetermined acceleration-time patterns. The actuator includes three cylindrical sections, **10**, **12** and **14**, which together constitute an elongated cylindrical housing. An apertured wall member **16** has a flange portion **18** interposed between adjacent ends of sections **10** and **12**, as shown. Resilient annular seals **20** are disposed in appropriate annular grooves in the wall member **16** at each side of a flange portion **18** to provide pressure sealing between the member and cylindrical sections **10** and **12**. An aperture **22** is provided in wall member **16** for a purpose discussed hereinbelow. A pair of internally threaded annular members **24** and **26** are provided for engagement with threaded end portions of cylindrical sections **10** and **12**, as shown. Bolts **32** extend through spaced openings in the annular members and engage appropriate nuts to secure sections **10** and **12** in alignment and to clamp flange portion **18**.

Cylindrical sections **12** and **14** are secured together and maintained in alignment by internally threaded annular members **28** and **30**, and by bolts **32**, in the same manner as sections **10** and **12** are secured. An orifice plate **34** is secured by its flange portion **36** in the same manner as wall member **16** is secured, and has annular grooves for resilient seals **38**, which provide pressure sealing between the orifice plate and cylindrical sections **12** and **14**. A contoured orifice **40** is provided for a purpose which is explained hereinbelow.

From the foregoing description, it will be understood that the cylindrical housing formed by cylindrical sections **10**, **12** and **14** may be considered as divided into pressure chambers **42**, **44** and **46** by orifice plate **34** and wall member **16**.

A fluid passage **50** in orifice plate **34** provides communication between chamber **44** and a coupling **52**, which is adapted for threaded engagement with the passage, as shown. A similar passage **54** is provided in the plate for communication between chamber **42** and a coupling **56**. Couplings **52** and **56** are interconnected by suitable couplings and by a tubular member **58**, into which is connected a unidirectional check valve **60** to

permit flow only in the direction indicated by the arrow. It will be understood that means are thereby provided for unidirectional flow of gas from chamber 44 to chamber 42, for a purpose which will become clear from further description herein.

A piston 66 is slidably positioned in chamber 44 and is provided with a threaded opening for engagement with a reduced threaded end portion 68 of a metering member 70, to secure the member to the piston. The metering member has a shank portion 72, an enlarged cylindrical section 74 fitting closely within orifice 40, and a contoured potrion 76. The purpose and construction of metering member 70 are described hereinbelow.

Secured to piston 66 by metering member 70 and seated in an appropriate recess, as shown, is an annular seal base 78. A circular resilient seal 80 encircles the member and is secured to the seal base, as by bonding in an appropriate groove 82. A resilient annular seal 84 is disposed in a recess of the seal base adjacent to shank 72 of the metering member to provide a pressure seal between the seal base and the member. An annular resilient sealing element 86 is positioned in a peripheral groove of piston 66 to provide pressure sealing between the piston and cylindrical section 12 of the housing.

Although metering member 70 may be formed as an integral part of piston 66, it is preferably fabricated as a separate part. As discussed hereinbelow, different metering member contours produce correspondingly different output thrust patterns. The construction shown permits interchanging of metering members, to provide a variety of output patterns through the use of a single actuator. This separate construction also provides for convenient removal and replacement of seal base 78.

A bearing ring 88 is spaced axially from sealing element 86 and is disposed in an appropriate recess in the piston for the purpose of reducing sliding friction and maintaining alignment between the piston and cylindrical section 12. A lock ring 90 threadedly engages a reduced threaded end portion 92 of the piston to secure the bearing ring and a deceleration metering pin 94 by means of mutually engaging flange portions, as shown at 96. The deceleration metering pin has a peripheral surface 98, which is contoured along its length, and has an internal bore 100 adapted to fit about a thrust column 102. The thrust column has a reduced threaded end portion 104 for engagement with threaded opening 106 of the piston. Thrust column 102 extends through aperture 22, chamber 46 and the end of the actuator. Exterior of the housing, the column has a reduced threaded end portion 108 for engagement with a workpiece or other member adapted for utilization of the thrust produced by the actuator.

Like metering member 70, the deceleration metering pin and the thrust column are preferably formed as separate parts. Different pin contours provide different deceleration patterns, and separate construtcion permits interchanging parts to produce a variety of patterns.

Chamber 46 is closed by an end member 110 which has an opening through which thrust column 102 extends. The end member is attached to cylindrical section 10 by an internally threaded annular ring 112, which threadedly engages the cylindrical section, as shown, and which is secured to end member 110, as by bolts 32. An annular wiper 114 is disposed in an appropriate groove within the opening of the end member and engages thrust column 102. A resilient annular sealing element 116 is disposed in an appropriate groove within the opening and provides pressure sealing between the end member and the thrust column. In an adjacent groove, there is disposed a bearing ring 118. Bearing 118 and sealing device 116 are secured in position as by a retaining plate 120 secured to member 110 by bolts 122. Pressure sealing is provided by an annular resilient seal 124 disposed in an appropriate recess in the retaining plate. A passage 126 and a fluid connection 128 interconnect chamber 46 with a source of pressure (not shown).

At the other end of the actuator housing, chamber 42 is closed by a base member 130, which is secured to cylindrical section 14 by an annular ring 132 and by bolts 134 in the same manner as end member 110 is secured to cylindrical section 10. A resilient sealing element 136 is disposed between the end of section 14 and the base member to provide pressure sealing. A passage 138 in the base member and a fluid coupling 140 interconnect a source of pressure (not shown) with chamber 42.

In operation, the actuator described herein is capable of an extremely rapid or substantially instantaneous output of very high acceleration. This very rapid triggering is effected by the coaction of the orifice plate, the seal 80 and the piston. Although the manner of effecting this sudden action is more fully described in the copending application of Jack Benton Ottestad (Serial No. 617,014) mentioned hereinbefore, it is described below for the purpose of relating it to the discussion of the present invention and to the particular embodiment herein shown and described.

A setting pressure is first introduced into chambers 46 and 44 through passage 126 and connection 128, which interconnects these chambers with a source of compressed gas (not shown). The setting pressure P_2 acts upon the area A_4 of piston 66 about thrust column 102, and urges the piston against the orifice plate. This effects compression of circular resilient seal 80 against the surface of orifice plate 34 to effect a positive pressure seal which isolates chamber 44 from chamber 42. A predetermined pressure P_1 is established in chamber 42, through passage 138 and coupling 140. This pressure P_1 acts upon the area A_2 of metering member 70 and piston 66 within seal 80, and is sufficient to balance the force of pressure P_2 acting upon the larger area A_4 at the opposite end of the piston. Piston 66 is thus held in a state of equilibrium.

The pressure in chamber 42 is then increased by a pressure differential sufficient to unbalance the forces upon the piston and to cause movement of the piston from the orifice plate. As more fully described in the copending application identified above, this movement disengages seal 80 and releases the high firing pressure substantially instantaneously to act upon the annular area of piston 66 outside circular seal 80. A great net force is thereby suddenly applied to the piston to impel it from the orifice plate with extremely high acceleration.

The force and acceleration developed upon the piston 66 and thrust column 102 are functions of the pressures P_2 and P_1 in chambers 44 and 42, the piston and thrust column masses, the area A_4 of the piston about the thrust column, and the area A_2 encompassed by circular seal 80. If pressure P_2 is 200 pounds per square inch, pressure P_1 is 2,000 pounds per square inch, area A_4 is 10 square inches, and area A_2 is one square inch, two equal 2,000 pound forces act to hold the piston in equilibrium. Assuming that a pressure differential of 100 pounds per square inch is sufficient to overbalance the equilibrium forces and disengage the seal, a net force of 19,000 pounds suddenly acts on the piston upon disengagement of the seal. This force is the difference between 21,000 pounds and 2,000 pounds acting oppositely on the piston. Assuming the mass being accelerated to be 10 pounds, acceleration imparted to the piston is 1900 g's, according to the equation

$$F=ma$$

where F=force, m=mass, and a=acceleration.

From the foregoing description and from the relevant description in the copending application, it will be understood that circular resilient seal 80 is a most essential element in making possible the extremely rapid output of very high acceleration or thrust. The seal is adapted

for sudden disengagement from the orifice plate under the action of the overbalancing pressure, and thereby releases high pressure substantially instantaneously upon a large piston area.

After the seal **80** is disengaged and piston **66** is in motion, the pressurized gas must flow through the net orifice area governed by metering member **70**, in order to act upon the surface of the piston. The net pressure on the piston and the accelerating force thereon therefore vary in accordance with the net flow area between the orifice and the metering member.

An important feature of the metering member of the present invention is that it is contoured along its length to control the complete acceleration-time pattern of the output. The cross-sectional area of contoured portion **76** of the metering member is different at different axial locations thereon. As the piston moves from the orifice plate, the net flow area is varied in accordance with piston position. The restriction of the orifice creates a pressure drop thereacross which is a function of the net orifice area. Therefore, regulation of this net area by the moving contoured portion **76** controls the variation in force and acceleration acting on the piston.

From the foregoing, it will be understood that a selected acceleration-time or thrust-time pattern may be produced by the provision of an appropriately contoured metering member.

Given the desired output acceleration-time pattern to be developed by the pneumatic actuator of this invention, there can be determined the contour of a metering member to produce this pattern upon a given mass M which includes the mass of the piston and thrust column. It will be understood that for any given instant of the acceleration-time pattern there can be readily determined the force required at that instant, the velocity of the mass M at that instant and displacement of the mass M at that instant. Thus, the force, velocity, and displacement of mass M may be established as functions of time. With these functions, the contour is determined by means of the equations developed hereinbelow.

The following symbols, relating to Figures 1, 2 and 3, are utilized herein in equations concerning the contour of the metering member:

A_{mp}=area of metering member **70** (in.^{2}) instantaneously regulating orifice flow.
A_0=area of orifice **40** (in.^{2})
A_1=internal cross-sectional area of chamber **42** (in.^{2})
A_3=area of piston **66** confronting the orifice plate (in.^{2})
A_4=area of piston **66** about thrust column **102** (in.^{2})
P_1=instantaneous pressure in chamber **42**
P_{1_0}=initial firing pressure in chamber **42** at which the unit is actuated (p.s.i.)
P_2=instantaneous pressure in chamber **44**
P_{2_0}=setting pressure in chamber **44** to establish piston **66** and orifice plate **34** in quiescent position (p.s.i.)
P_3=instantaneous pressure between orifice plate **34** and piston **66**
L_1=length of chamber **42** (in.)
L_4=combined lengths of chambers **44** and **46** on thrust column side of piston.
x=displacement of thrust column **102** relative to its quiescent position (in.)
$\dot{x}_3$=instantaneous velocity of thrust column **102** (in./sec.)
$\ddot{x}$=acceleration imparted to total mass

$$\left(\frac{\text{in.}}{\text{sec.}^2}\right)$$

g=acceleration due to gravity

$$\left(386\frac{\text{in.}}{\text{sec.}^2}\right)$$

w=density of the control gas (lb./in.^{3})
t=time (sec.)

The acceleration $\ddot{x}$ imparted to a given mass M by a force F is expressed as:

(1.1) $$\ddot{x}=\frac{F}{M}$$

(1.2) The force provided by the firing pressure is expressed as:

$$F=P_3(A_3-A_{mp})+P_1A_{mp}-P_2A_4$$

(1.3) Equating Equations 1.1 and 1.2:

$$F=M\ddot{x}=P_3(A_3-A_{mp})+P_1A_{mp}-P_2A_4$$

(1.4) Flow through the orifice=$G=AVw$, where A (net flow area)=$(A_0=A_{mp})$,

$$V=\sqrt{2gh},\ h=\frac{\Delta P}{w}\text{ ann }w=\frac{P^3}{RT}$$

Then:

$$G=\frac{P_3}{RT}(A_0-A_{mp})\sqrt{\frac{2g\Delta PRT}{P_3}}$$

(1.5) Actual physical flow through the orifice may be expressed as:

$$G=wx(A_3-A_{mp})$$

or:

$$G=\frac{P_3x}{RT}(A_3-A_{mp})$$

(1.6) Combining Equations 1.4 and 1.5:

$$G=G=\dot{x}(A_3-A_{mp})=(A_0-A_{mp})\sqrt{\frac{2g\Delta PRT}{P_3}}$$

(1.7) Transposing Equation 1.6:

$$A_{mp}=A_0-\frac{(A_3-A_{mp})\dot{x}}{\sqrt{2gRT}\sqrt{\frac{\Delta P}{P_3}}}$$

(1.8) P_1 is reduced in passing through the orifice, so that

$$P_3=P_1-\Delta P$$

(1.9) Further,

$$\Delta P=P_1-P_3$$

(2.0) From Equations 1.9 and 1.3

$$\Delta P\frac{P_1A_{mp}-P_2A_4-M\ddot{x}}{(A_3-A_{mp})}$$

(2.1) Substituting P and P_3 from above in Equations 1.7,

$$A_{mp}=A_0-\frac{(A_3-A_{mp})x}{\sqrt{2gRT}\sqrt{\frac{P_1A_3-P_2A_4-M\ddot{x}}{P_2A_4+M\ddot{x}-P_1A_{mp}}}}$$

which is the basic relation for determining the required metering pin cross-sectional area for a given piston displacement x.

(2.2) The general expression for P_1 at a particular displacement is determined as follows:

Because the time interval is extremely short, the gas in chamber **42** may be considered to expand adiabatically, so that

$$P_1V_1^{1.4}=C$$

where C is a constant and V_1 is the volume of chamber **42**.

$$V_1=A_1L_1$$

approximately.

Then, for the initial conditions:

$$P_{1_0}V_{1_0}^{1.4}=C_1=P_{1_0}(A_1L_1)^{1.4}$$

(2.3) $$C_1=P_{1_x}V_{1_x}^{1.4}=P_{1_x}(A_1L_1+A_1x)^{1.4}$$

(2.4) Equating 2.2 and 2.3:

$$P_{1_0}(A_1L_1)^{1.4}=P_{1_x}(A_1L_1+A_1x)^{1.4}$$

and

$$P_{1_x}=P_{1_0}\left(\frac{L_1}{L_1+x}\right)^{1.4}$$

(2.5) P_{2_x} is established in a similar manner:

$$P_2V_4^{1.4}=C_4$$

$$C_4=P_{2_0}(A_4L_4)^{1.4}$$

$$C^4=P_{2_x}(A^4(L^4-x))^{1.4}$$

$$P_{2_x}=P_{4_0}\left[\frac{A_4L_4}{A_4(L_4-x)}\right]^{1.4}$$

(2.6) Displacement x, velocity $\dot{x}$, and acceleration $\ddot{x}$ are related by the fundamental equations of motion:

$$\ddot{x}=f(t)$$

$$\dot{x}=f(t)\ dt$$

$$x=f(t)\ dt\ dt$$

(2.7) By substituting the relationships of Equations 2.4, 2.5 and 2.6 in Equation 2.1, the equation is obtained for determining A_{mp} for any displacement:

$$A_{mp}=A_0-\frac{\dot{x}(A_3-A_{mp})\sqrt{A_4P_{2_0}\left[\frac{A_4L_4}{A_4L_4-x}\right]^{1.4}+M\ddot{x}-P_{1_0}A_{mp}\left[\frac{L_1}{L_1}+x\right]^{1.4}}}{\sqrt{2gRT}\sqrt{A_3P_{1_0}\left[\frac{L_1}{L_1+x}\right]^{1.4}-A_4P_{2_0}\left[\frac{A_4L_4}{A_4(L_4-x)}\right]^{1.4}-M\ddot{x}}}$$

Referring to Figures 4 through 9, there are shown metering members **144**, **150** and **156**, which are contoured, in accordance with the formula derived above, to produce the acceleration-time patterns of Figures 5, 7 and 9, respectively. The patterns shown are exemplary, it being understood that substantially any acceleration-time relationship may be produced by an appropriate metering member. Contoured portion **76***a* of member **144** is designed to produce the portion of a sine wave indicated by the reference numeral **146** in Figure 5. The contoured portion **76***b* of member **150** produces the output waveform of Figure 7, wherein the acceleration increases rapidly in the region indicated by the numeral **152**, then remains substantially constant in the region indicated by reference numeral **154**. A substantially vertical acceleration-time wave form can be produced by a proper metering member, although an absolutely vertical waveform cannot, of course, be effected. Contoured portion **76***c* of metering pin **156** is adapted to provide the saw-tooth pattern of Figure 9, wherein the acceleration rises at a uniform linear slope at **158** before it suddenly begins a very rapid decline, as shown at **160**.

An important feature of the present invention is the utilization of the enlarged section **74** of the metering member for the prevention of premature undesired output thrust. Immediately following disengagement of seal **80** from the orifice plate, this section is in close engagement with orifice **40** to insure a large pressure drop across the orifice. This prevents the premature action on the piston of sufficient pressure to produce an undesirable acceleration therein, before the moving contoured portion **76** is in position to regulate the flow of gas and produce the desired acceleration-time pattern. Section **74** must be closely fitted to the orifice to insure a large gas pressure drop. It is preferred that the section be fabricated so that there is substantially no tolerance between the orifice and the section. Because the present invention utilizes only pneumatic control energy, such a close fit is preferred to insure against the premature passage of a sufficient percentage of the control pressure to affect the output waveform.

This is a problem peculiar to the use of gas. Hydraulic control fluid would not require so close a fit, because the fluid would not pass as readily.

In Figure 10 is shown a premature output pattern which might result from the use of an undersized section **74**. Immediately after the seal **80** is disengaged, the piston moves at relatively low velocity, and the pressure drop is not sufficiently high. For example, 15 percent of the control pressure may have leaked through the orifice. Therefore there is a rapid rise in acceleration as indicated by reference numeral **162**. As the piston moves more rapidly, the pressure drop increases, because the gas cannot leak through rapidly enough to compensate for the movement. The acceleration gradually declines, as shown by the regions of the wave-form indicated by numerals **164** and **166**, until the contoured portion **76** becomes operative to produce the desired pattern indicated by numeral **168**.

After the acceleration phase of the predetermined output cycle is completed, the deceleration metering pin **94** cooperates with aperture **22** in wall member **16** to effect a predetermined deceleration pattern. The piston **66** forces the gas in chamber **44** through the deceleration aperture. Pin **94** controls the flow of the gas by effecting predetermined regulation of the net aperture flow area. This net area is varied in accordance with piston position by the longitudinal contour of the deceleration pin, to produce a predetermined variation in back pressure. By using an approximately contoured pin, a desired deceleration-time pattern can be obtained. Thus such numerals **148** and **160** in Figures 5 and 7, respectively, are produced.

It is obvious that the pressures in chambers **42**, **44** and **46**, and the variations in pressures caused by volumetric changes during piston movement, have important effects upon the output acceleration pattern.

These factors are matters of design and are not essential features of the present invention.

In order to prepare the actuator for repeat operation, the piston **66** must be re-seated against the orifice plate to reestablish pressure sealing between the piston and the plate by means of resilient seal **80**. It is preferred to effect reseating by the simple method of reducing the pressure in chamber **42** to a value below the pressure in chamber **46**, thereby permitting the latter pressure to move the piston against the orifice plate. Using the exemplary pressures of 2,000 pounds per square inch and 200 pounds per square inch hereinbefore mentioned, the pressure in chamber **42** is reduced from 2,000 pounds per square inch to a pressure sufficiently below the 200 pounds per square inch in chamber **46**, that the latter pressure is operative to re-seat the piston. As seal **80** contacts the surface of the orifice plate, a gas pressure of approximately 200 pounds per square inch would be trapped by this seal and by seal **86** between the piston and the orifice plate if no outlet were provided. Even if the pressure in chamber **42** were dropped until it equalled atmospheric pressure, the approximately 200 pounds per square inch would remain trapped by seal **80**.

Fluid connections **52**, **56** and **58**, together with unidirectional check valve **60**, provide means for automatically relieving pressure, through the passage **50**, the connections, check valve **60** and passage **56** to chamber **42**. The pressure is relieved into chamber **42**, because if the release were to the exterior atmosphere, the firing pressure which passes through orifice **40** to actuate the piston would obviously be released to the atmosphere, thus making the actuator inoperative.

If pressure were trapped, the approximately 200 pounds per square inch pressure between the piston and the orifice plate would tend to balance the force exerted oppositely on the piston by the set pressure of 200 pounds per square inch in chamber **44**. The trapped pressure would act upon the piston area outside seal **80**.

Upon increasing the pressure in chamber 42 to fire the unit, the piston would be moved by a pressure in chamber 42 which need only be sufficient in acting upon the area within the seal 80 to overcome any net force exerted on the piston by the set pressure in excess of the force of the trapped pressure. Therefore, pressure which would otherwise be trapped by seal 80 must be relieved in order that the set pressure can produce a net force on the piston sufficient to maintain seal 80 against the orifice plate 34, until the actuating pressure in chamber 42 increases to 2,000 pounds per square inch and suddenly disengages the seal by overbalancing the force of the set pressure on the piston.

The above-described apparatus is the preferred means for relieving the entrapped pressure. However, it should be noted that it is possible to prevent the trapping of pressure without utilizing this means. This is accomplished by first bleeding off the set pressure in chamber 46, and by next bleeding off the pressure in chamber 42. The piston is therefore not re-seated by the pressure in chamber 46 and remains in an extended position relative to the orifice plate. The piston is next pushed against the orifice plate, as by hand pressure. The gas which is trapped between the piston and the orifice plate is thus under no pressure. There is some compression of the gas upon the compression of seal 80 by the setting pressure in chamber 46. However, this does not result in a substantial pressure. The set pressure is then introduced into chamber 46 and the firing pressure is increased in chamber 42 to actuate the device.

Although specific embodiments of the present invention have been described and illustrated in detail, it is to be clearly understood that the same are by way of illustration and example only; it is to be understood that the invention is not limited thereto, as many variations will be readily apparent to those versed in the art and the invention is to be given its broadest possible interpretation within the terms of the appended claims.

We claim:

1. In a pneumatic actuator having a piston movable in a cylinder by pressurized gas to produce useful output thrust, and having means defining an orifice within the cylinder adapted to be sealed by a setting pressure urging said piston toward said means to engage pressure sealing means positioned therebetween, a metering member carried by said piston for regulating flow of said pressurized gas through said orifice upon disengagement of said sealing means by said gas, said metering member comprising a contoured metering section for regulating flow of said pressurized gas through said orifice to produce a predetermined acceleration-time pattern on the piston, and a section closely fitting said orifice substantially to prevent passage of said gas therethrough upon said disengagement of the sealing means until said contoured section regulates flow, whereby premature output thrust is prevented.

2. In a pneumatic actuator having a piston movable within a cylinder by pressurized gas and confronting a wall defining an orifice within the cylinder, and having means for exerting setting pressure urging said piston toward said wall to effect a pressure seal by engaging a sealing member positioned therebetween, a metering member on said piston for regulating flow of said pressurized gas through said orifice upon movement of said piston by said pressurized gas to disengage said sealing member, said metering member comprising a contoured metering portion for regulating flow of said gas through said orifice to produce a predetermined complete thrust-time pattern on the piston, and an enlarged section for substantially closing said orifice substantially to prevent leakage of said gas therethrough upon disengagement of the sealing member until said contoured portion is operative to regulate flow, whereby premature output thrust is prevented.

3. In a pneumatic actuator having a piston movable within a cylinder by pressurized gas and confronting a wall defining an orifice within the cylinder, and having means for exerting setting pressure urging said piston toward said wall to effect a pressure seal by engaging a sealing member positioned therebetween, a metering member on said piston for regulating flow of said pressurized gas through said orifice upon movement of said piston by said pressurized gas to disengage said sealing member, said metering member comprising a metering portion having a predetermined contour for regulating flow of said pressurized gas through said orifice to produce a triangularly-shaped acceleration-time pattern on said piston, and an enlarged section for substantially closing said orifice substantially to prevent leakage of said gas therethrough upon disengagement of the sealing member until said contoured portion is operative to regulate flow, whereby premature output thrust is prevented.

4. In a pneumatic actuator having a piston movable within a cylinder by pressurized gas and confronting a wall defining an orifice within the cylinder, and having means for exerting setting pressure urging said piston toward said wall to eqect a pressure seal by engaging a sealing member positioned therebetween, a metering member on said piston for regulating flow of said pressurized gas through said orifice upon movement of said piston by said pressurized gas to disengage said sealing member, said metering member comprising a metering portion having a predetermined contour for regulating flow of said pressurized gas through said orifice to produce a linear force-time pattern on said piston, and an enlarged section for substantially closing said orifice substantially to prevent leakage of said gas therethrough upon disengagement of the sealing member until said contoured portion is operative to regulate flow, whereby premature output thrust is prevented.

5. In a pneumatic actuator having a piston movable within a cylinder by pressurized gas and confronting a wall defining an orifice within the cylinder, and having means for exerting setting pressure urging said piston toward said wall to effect a pressure seal by engaging a sealing member positioned therebetween, a metering member on said piston for regulating flow of said pressurized gas through said orifice upon movement of said piston by said pressurized gas to disengage said sealing member, said metering member comprising a metering portion having a predetermined contour for regulating flow of said pressurized gas through said orifice to produce on said piston a thrust-time pattern having linear portions of differing slopes, and an enlarged section for substantially closing said orifice substantially to prevent leakage of said gas therethrough upon disengagement of the sealing member until said contoured portion is operative to regulate flow, whereby premature output thrust is prevented.

6. In a pneumatic actuator having a piston movable in a cylinder by pressurized gas to produce useful output thrust, and having plate means defining an orifice within the cylinder adapted to be sealed by a setting pressure urging said piston toward said means to engage pressure sealing means positioned therebetween, a metering member carried by said piston for regulating flow of said pressurized gas through said orifice upon disengagement of said sealing means by said gas, to control the thrust-time pattern on said piston, the contour of said metering member being determined by the formula

$$A_{mp}=A_0-\frac{(A_3-A_{mp})\dot{x}}{\sqrt{2gRT}\sqrt{\frac{P_1A_3-P_2A_4-M\ddot{x}}{P_2A_4+M\ddot{x}-P_1A_{mp}}}}$$

where A_{mp} is the cross-sectional area of the metering member instantaneously governing the effective area of said orifice, A_0 the area of the orifice, A_3 the area of said piston confronting said plate means, $\dot{x}$ the instantaneous velocity of the piston, g the acceleration due to gravity, R a constant for the particular pressurized gas utilised,

T the absolute temperature, P_1 the instanataneous pressure of said pressurized gas, P_2 the instantaneous decelerating pressure acting upon the cross-sectional area of said piston, A_4 the cross-sectional area of the piston acted upon by pressure P_2, M the total mass being accelerated, and $\ddot{x}$ the instantaneous acceleration of mass M.

7. In an actuator for controlling a complete thrust-time pattern wherein a housing has a wall therein defining an orifice and wherein a piston is movable within the housing by pressurized gas for transmitting useful output thrust to a member connected therewith, a pneumatic thrust control apparatus comprising setting means for exerting a force on said piston urging said piston toward said wall to cover said orifice, resilient sealing means positioned between confronting surfaces of the piston and the wall for effecting a positive pressure seal therebetween about said orifice, pressurized gas established to act upon that portion of said piston covering said orifice to overbalance said force to move the piston from the wall surface to disengage the seal, thereby suddenly exposing an increased area of said piston to said pressurized gas, and a contoured metering member on said piston and positioned within said orifice for regulating flow of said gas through said orifice to produce a predetermined thrust-time pattern on said piston.

8. In an actuator for controlling a complete thrust-time pattern wherein a housing has a wall therein defining an orifice and wherein a piston is movable within the housing by pressurized gas for transmitting useful output thrust to a member connected therewith, a pneumatic thrust control apparatus comprising setting means for exerting a force on said piston urging said piston toward said wall to cover said orifice, sealing means positioned between said piston and said wall for effecting a pressure seal therebetween about said orifice, pressurized gas established to act upon that portion of said piston covering said orifice to over-balance said force and expose an increased area of said piston to said pressurized gas, and a contoured metering member on said piston and positioned within said orifice for regulating flow of said gas through said orifice to produce a predetermined thrust-time pattern on said piston, said metering member having a section adapted for close engagement with said orifice substantially to prevent passage of said pressurized gas therethrough upon disengagement of said sealing means until said metering member is in operative position to regulate said flow, whereby premature output thrust is prevented.

9. In an actuator for controlling a complete thrust-time pattern wherein a housing has a wall therein defining an orifice and wherein a piston is movable within the housing by pressurized gas for transmitting useful output thrust to a member connected therewith, a pneumatic thrust control apparatus comprising setting means for exerting a force on said piston urging said piston toward said wall to cover said orifice, sealing means positioned between said piston and said wall for effecting a pressure seal therebetween about said orifice, pressurized gas established to act upon a portion of said piston covering said orifice to overbalance said force and expose an increased area of said piston to said pressurized gas, a contoured metering member on said piston and positioned within said orifice for regulating flow of said gas through said orifice to produce a predetermined thrust-time pattern on said piston, means defining a restricted passage within said housing, and a contoured deceleration pin carried by said piston for movement into said restricted passage to regulate fluid flow therethrough to develop predetermined variation in decelerating pressure acting on said piston.

10. Control apparatus for use in a pneumatic actuator having a piston movable within a housing by pressurized gas for transmitting useful output thrust to a member connected therewith, said control apparatus comprising a wall with an orifice in said housing, resilient sealing means positioned between confronting surfaces of said piston and the wall for effecting a positive pressure seal therebetween about said orifice, setting means for exerting a force on said piston to effect said pressure seal, means for applying said pressurized gas to that portion of said piston covering said orifice to overbalance said force to disengage the seal and suddenly expose a greater portion of said piston to said pressurized gas, and a contoured metering member carried by said piston and positioned within said orifice for regulating flow of said pressurized gas through said orifice to produce a predetermined thrust-time pattern on said piston.

11. Control apparatus for use in a pneumatic actuator having a piston movable within a housing by pressurized gas for transmitting useful output thrust to a member connected therewith, said control apparatus comprising a wall with an orifice in said housing, sealing means positioned between said piston and said wall for effecting a pressure seal therebetween about said orifice, setting means for exerting a force on said piston to effect said pressure seal, means for applying said pressurized gas to that portion of said piston covering said orifice to overbalance said force to expose a greater portion of said piston to said pressurized gas, a contoured metering member carried by said piston and positioned within said orifice for regulating flow of said pressurized gas through said orifice to produce a predetermined thrust-time pattern on said piston, means defining a restricted passage within said housing, and a contoured deceleration pin carried by said piston for movement into said restricted passage to regulate fluid flow therethrough to develop predetermined variation in decelerating pressure acting on said piston.

12. Control apparatus for use in a pneumatic actuator having a piston movable within a housing by pressurized gas for transmitting useful output thrust to a member connected therewith, said control apparatus comprising a wall with an orifice in said housing, sealing means positioned between said piston and said wall for effecting a pressure seal therebetween about said orfice, setting means for exerting a force on said piston to effect said pressure seal, means for applying said pressurized gas to that portion of said piston covering said orifice to overbalance said force to expose a greater portion of said piston to said pressurized gas, and a contoured regulating member carried by said piston and positioned within said orifice to regulate flow of said pressurized gas through said orifice to produce a triangularly-shaped thrust-time pattern on said piston.

13. Control apparatus for use in a pneumatic actuator having a piston movable within a housing by pressurized gas for transmitting useful output thrust to a member connected therewith, said control apparatus comprising a wall with an orifice in said housing, sealing means positioned between said piston and said wall for effecting a pressure seal therebetween about said orifice, setting means for exerting a force on said piston to effect said pressure seal, means for applying said pressurized gas to that portion of said piston covering said orifice to overbalance said force to expose a greater portion of said piston to said pressurized gas, and a contoured regulating member carried by said piston and positioned within said orifice to regulate flow of said pressurized gas through said orifice to produce a linear force-time pattern on said piston.

14. Control apparatus for use in a pneumatic actuator having a piston movable within a housing by pressurized gas for transmitting useful output thrust to a member connected therewith, said control apparatus comprising a wall with an orifice in said housing, sealing means positioned between said piston and said wall for effecting a pressure seal therebetween about said orifice, setting means for exerting a force on said piston to effect said pressure seal, means for applying said pressurized gas to that portion of said piston covering said orifice to over-

balance said force to expose a greater portion of said piston to said pressurized gas, and a contoured regulating member carried by said piston and positioned within said orifice to regulate flow of said pressurized gas through said orifice to produce on said piston a force-time pattern having linear portions of differing slopes.

15. Control apparatus for use in a pneumatic actuator having a piston movable within a housing by pressurized gas for transmitting useful output thrust to a member connected therewith, said control apparatus comprising a wall with an orifice in said housing, sealing means positioned between said piston and said wall for effecting a pressure seal therebetween about said orifice, setting pressure for exerting a force on said piston to effect said pressure seal, means for applying said pressurized gas to a portion of said piston covering said orifice to overbalance said force to expose a greater portion of said piston to said pressurized gas, and a contoured metering member carried by said piston and positioned within said orifice for regulating flow of said pressurized gas through said orifice to produce a predetermined thrust-time pattern on said piston, the contour of said metering member being determined by the formula

$$A_{mp}=A_0-\frac{(A_3-A_{mp})\dot{x}}{\sqrt{2gRT}\sqrt{\frac{P_1A_3-P_2A_4-M\ddot{x}}{P_2A_4+M\ddot{x}-P_1A_{mp}}}}$$

where A_{mp} is the cross-sectional area of the metering member instantaneously governing the effective area of said orifice, A_0 the area of the orifice, A_3 the area of said piston confronting said wall, $\dot{x}$ the instantaneous velocity of the piston, g the acceleration due to gravity, R a constant for the particular pressurized gas utilized, T the absolute temperature, P_1 the instantaneous pressure

of said pressurized gas, P_2 the instantaneous decelerating pressure acting upon the cross-sectional area of said piston, A_4 the cross-sectional area of the piston acted upon by pressure P_2, M the total mass being accelerated, and $\ddot{x}$ the instantaneous acceleration of mass M.

16. A pneumatic actuator comprising a cylindrical housing, a wall in said housing, said wall having an orifice and defining first and second pressure chambers, a piston positioned within said first chamber and confronting said wall, means for establishing a setting pressure in said first chamber for exerting a force urging said piston against said wall to cover said orifice, a resilient pressure seal surrounding said orifice and disposed between said piston and said wall for effecting a pressure seal therebetween, pressurized gas established in said second chamber to act upon that portion of said piston within said seal to overbalance said force and disengage said seal, thereby exposing a greater area of said piston to said gas to accelerate said piston, a contoured metering member carried by said piston and positioned within said orifice for regulating flow of said pressurized gas through said orifice to produce a predetermined acceleration-time pattern on said piston, and means interconnecting said piston and a workpiece for applying said acceleration-time pattern to said workpiece.

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UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

Patent No. 2,949,096 August 16, 1960

Jack B. Ottestad et al.

It is hereby certified that error appears in the printed specification of the above numbered patent requiring correction and that the said Letters Patent should read as corrected below.

Column 6, line 15, for "$(A_o=A_{mp})$" read -- (A_o-A_{mp}) --; lines 17 and 18, the right-hand portion of the equation should appear as shown below instead of as in the patent:

$$\text{and } w=\frac{P_3}{RT}$$

same column 6, line 50, for the top line of the equation, for "$(A_3-A_{mp})x$" read -- $(A_3-A_{mp})\dot{x}$ --; column 7, line 10, the bottom line of the equation should appear as shown below instead of as in the patent:

$$C_4=P_{2_x}(A_4(L_4-x))^{1.4}$$

column 8, line 24, for "approximately" read -- appropriately --; line 30, after "such" insert -- deceleration patterns as those indicated by reference --.

Signed and sealed this 18th day of April 1961.

(SEAL)
Attest:

ERNEST W. SWIDER
Attesting Officer

DAVID L. LADD
Commissioner of Patents