Feb. 2, 1960 E. C. GROGAN 2,923,307

MEANS COMPENSATING FOR THE TIME DELAY OF A TRANSMISSION LINE

Filed Dec. 29, 1955 2 Sheets-Sheet 1

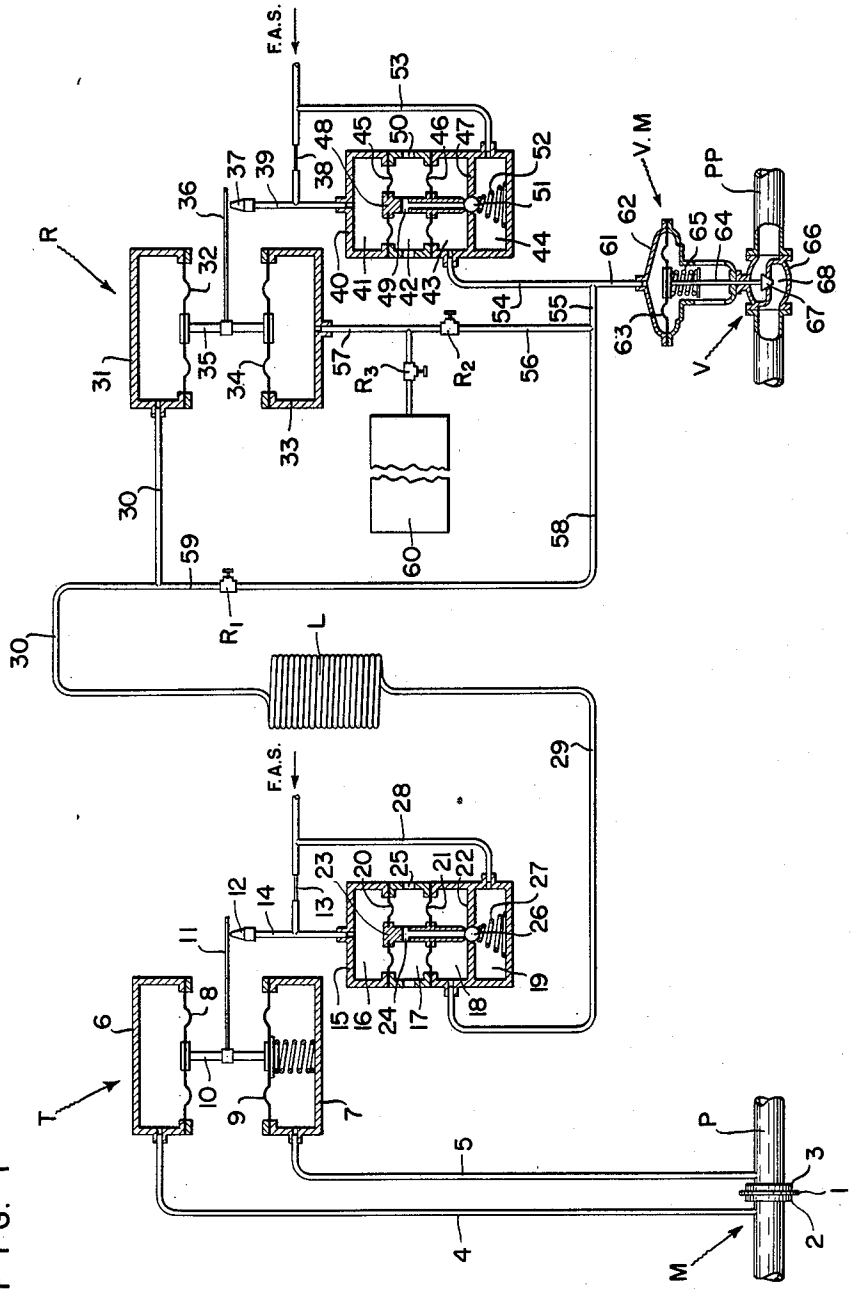


FIG. 1

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FIG. 2

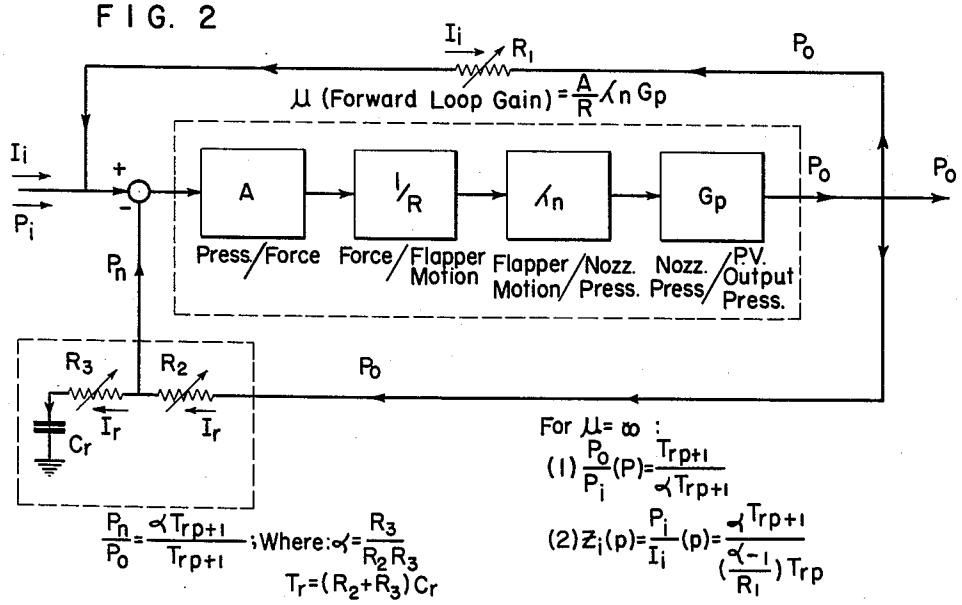


FIG. 4

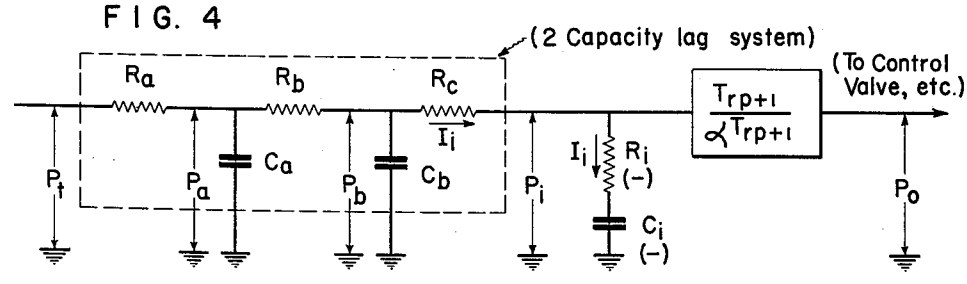
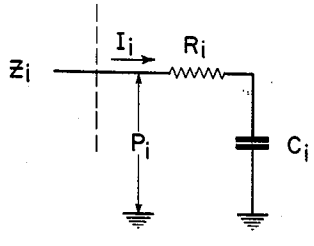


FIG. 3



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2,923,307

MEANS COMPENSATING FOR THE TIME DELAY OF A TRANSMISSION LINE

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Application December 29, 1955, Serial No. 556,319

10 Claims. (Cl. 137—86)

This invention relates to apparatus operated by an elastic fluid, such as air, which apparatus comprises: a measuring element, responsive to variations in a measured variable; a transmitter, which converts the variations sensed by the measuring element into variations in an air pressure; an elongated transmission line having a small cross section and adapted to conduct the variations in air pressure; a receiver connected to the transmission line so as to receive the variations in pressure therefrom; a motor operated by variations in pressure; and a final control element operated by said motor.

It is an object of this invention to provide means for compensating for the time delays in said transmission line due to distributed resistance and distributed capacitance in the transmission line.

More specifically, it is an object of this invention to provide a receiver which will feed power back into the transmission line and to thereby compensate for the time delays caused by the transmission line.

A further object of this invention is to provide an elastic-fluid-pressure operated circuit in which there is a receiver which has bi-lateral action. Bi-lateral action may be defined as an action having two effects. One of these is the effect obtained by feeding back a portion of the output of the receiver to its input in such a way as to compensate for the time delays due to the transmission line leading to the receiver. The other of these effects is the effect obtained by feeding the remaining portion of the output of the receiver forward to a motor for a final control valve or the like. This forward feeding is advanced in phase as compared to the phase of the input, and serves to compensate for any time lags due to the transmission and not already compensated for by the feedback to the input to the receiver.

It is yet a further object of this invention to provide a circuit in which a single pneumatic unit acts as a receiver and performs as two unilateral, ideal, proportional plus rate units, acting in tandem. This arrangement therefore serves to minimize considerably the "noise" problem and to simplify present-day unilateral circuit configurations designed to offer compensation for multi-capacity pneumatic circuits such as tubing connected as a transmission line.

The various features of novelty which characterize this invention are pointed out with particularity in the claims annexed to and forming a part of this specification. For a better understanding of the invention, however, its advantages and specific objects obtained with its use, reference should be had to the accompanying drawings and descriptive matter in which is illustrated and described a preferred embodiment of the invention.

In the drawings:

Fig. 1 is a diagram showing the circuit connections and the schematic outlines of the apparatus forming the device;

Fig. 2 is a block diagram forming part of a mathematical analysis;

Fig. 3 is a circuit diagram forming part of this mathematical analysis; and

Fig. 4 is a circuit diagram forming part of this mathematical analysis.

In that embodiment of my invention elected from among others for illustration and in the drawings and description in the specification, my device is shown as follows.

The measuring element M is shown as a flow meter although it may be a measuring element of many various kinds adapted to sense a variation in a variable quantity or condition. The measuring element M is adapted to measure the flow of a fluid through a pipe P. Measuring element M comprises an orifice plate 1 having a central opening therethrough coaxial with the pipe P. Perforated discs 2 and 3 are located on opposite sides of the measuring or orifice plate 1 and serve to conduct the pressure on the opposite sides of the orifice in plate 1 through pipes 4 and 5 to the transmitter T.

The transmitter T converts the variations in the measured variable into variations in the pressure of a supply of air. Transmitter T comprises a measurement-responsive element formed by two rigid, cup-shaped casings 6 and 7 each of which has a wall thereof formed by a flexible diaphragm 8 or 9. The centers of diaphragms 8 and 9 are connected together by a shaft or pin 10 to which a flapper 11 is connected so as to move therewith.

A nozzle 12 cooperates with flapper 11 and is supplied with an elastic fluid, such as compressed air, under pressure from a filtered air supply F.A.S. through a restriction 13 and a pipe 14. A rigid casing 15 is divided into four chambers 16, 17, 18, and 19 by two diaphragms 20, 21, and by a rigid, perforated wall 22. Diaphragms 20 and 21 are connected together by a hollow tube 23 having a closed, upper end and an open, lower end and an opening 24 through the wall thereof. Air is supplied to inlet chamber 19 by a pipe 28. Ball 26 constitutes an inlet valve in cooperation with the rim of a circular opening in wall 22. Spring 27 presses inlet valve ball 26 into engagement with the seat formed by the rim of the opening through wall 22. Exhaust pipe 23 forms an exhaust valve by means of the cooperation of the open, lower end of pipe 23 with ball 26 so that fluid may pass up through the interior of pipe 23, through hole 24 into chamber 17 whence the air escapes to atmosphere through hole 25.

The part just described forms a non-bleed high capacity pilot valve or relay which operates in the following way. When the relay is in its normal, steady state, the pressure in chamber 16 is equal to the pressure in chamber 18 (or at some other, preselected ratio thereto), and the inlet valve 26—22 and the exhaust valve 23—26 are both closed.

Now, if the pressure in chamber 16 increases with respect to the pressure in chamber 18, the pressure on diaphragm 20 causes pipe 23 to move down (as viewed in the drawing) and moves ball 26 away from its cooperating valve seat formed by the rim of the opening through wall 22. This opens the inlet valve and admits air under pressure from chamber 19 into chamber 18. At the same time, the exhaust valve 23—26 remains closed because of the engagement with the lower end of the exhaust pipe 23 with the ball 26.

The inlet valve 26—22 remains open until the pressure in the chamber 18 is equal to (or at some preselected ratio to) the pressure in chamber 16. When this occurs, the pipe 23 again moves upward (as seen in the drawing) and the inlet valve 26—22 closes.

If, on the contrary, the pressure in chamber 16 decreases with relation to the pressure in chamber 18, the inlet valve 26—22 remains closed. The decrease in pressure in chamber 16, however, allows pipe 23 to move upward (as seen in the drawing). This opens the exhaust

valve 23—26 because the lower end of the pipe 23 moves out of contact with the ball 26. Opening the exhaust valve 23—26 connects the chamber 18 to the chamber 17 through the opening 24 so that fluid in chamber 18 can escape to the atmosphere. When the desired ratio between the pressure in the chamber 16 and the pressure in the chamber 18 is again restored, the pipe 23 moves downward thereby closing the exhaust valve 23—26 and again restoring the normal, steady state of the relay.

The output of this relay and of transmitter T is connected by pipe 29 to the input to the transmission line L. Transmission line L comprises a tube of approximately 3/16 inch internal diameter and may be as much as 1,000 feet in length.

The output end of transmission line L is connected to the input of the receiver R. Receiver R comprises an input motor formed of a rigid, cup-shaped casing 31 having one wall thereof formed by a flexible diaphragm 32. A negative feedback motor is formed of a rigid, cup-shaped casing 33 having a flexible diaphragm 34 as a wall thereof. Flexible diaphragms 32 and 34 are connected by a shaft 35 which supports the flapper 36.

Flapper 36 cooperates with a nozzle 37 to which air under pressure is supplied from a filtered air supply F.A.S. through a restriction 38 and a pipe 39. A rigid casing 40 is divided into four chambers 41, 42, 43, and 44 by two flexible diaphgrams 45 and 46 and a rigid wall 47. Air is supplied to input chamber 44 by pipe 53. Ball 51 is biased by spring 52 into engagement with the rim of a circular opening in the center of rigid wall 47. An exhaust valve is formed by pipe 48, which is closed at its upper end and open at its lower end and connects diaphragms 45 and 46. Exhaust pipe 48 has a hole 49 in its side wall communicating with exhaust chamber 42 which communicates with the atmosphere through hole 50 in casing 40.

The foregoing elements comprise a second, non-bleed, high capacity pilot valve or relay which operates in the same way as relay 15—27, described above.

The output of this pilot valve or relay is conducted through pipe 54, 55, and 56, which form part of a negative feedback circuit including a series restriction R2 and a pipe 57, which communicates with the negative feedback motor 33, 34. A bypass connection is formed by a bypass restriction R_3 which communicates, at its inlet, with pipe 57 and, at its outlet, with a bypass chamber 60, which has a large capacity as compared with the capacity of input motor 31, 32 or with the capacity of negative feedback motor 33, 34.

A positive feedback circuit is formed of pipe 58, which communicates with pipes 56 and 55 and with the inlet to a positive feedback restriction R_1. Positive feedback restriction R_1 is connected, at its output side, to pipe 30 intermediate the end of transmission line L and the input to input motor 31, 32.

The output from receiver R is conducted from output chamber 43 by means of pipes 54 and 61 to the motor V.M., which actuates the final control element. Motor V.M. comprises a rigid casing 62 having a flexible diaphragm 63 forming a wall thereof. A valve stem 64 is connected to the center of diaphragm 63. A spring 65 bears at one end against diaphragm 63 and, at its opposite end, against a portion of the rigid casing 66.

The final control element V is shown as a valve controlling the flow of liquid through a pipe PP which, however, may be the same as pipe P or a different one. The final control element V comprises a rigid casing 66 divided into two chambers by a perforated partition 68. A valve plug 67, mounted on the end of valve stem 64 cooperates with the hole in partition 68 so as to open, partially open, or close this hole and to thereby permit or to shut off the flow of fluid through the pipe P.

The operation of the apparatus of this invention is as follows. Assuming the transmitter pilot valve or relay and the receiver pilot valve or relay to be in their steady state or balanced condition, if a variation in the flow through pipe P is sensed by the measuring element M, a difference in pressure exists between the discs 2 and 3. This difference in pressure is conducted, by means of pipes 4 and 5, to the chambers formed by the elements 6, 8 and the elements 7, 9, respectively. Any difference between the pressures in each of these chambers causes shaft 10 to move flapper 11 relative to nozzle 12 in one sense or the other. This movement of flapper 11 varys the flow of fluid through nozzle 12 and causes a corresponding variation of the pressure in the nozzle chamber 16. Since the pressure in nozzle chamber 16 is balanced against the pressure in outlet chamber 18, a change in pressure in nozzle chamber 16 causes either inlet valve 26 or exhaust valve 23 to open and to admit or exhaust air from the output chamber 18. This changes the air pressure in chamber 18, which change continues until the pressure in chamber 18 again balances the pressure in nozzle chamber 16. When this balance takes place, the inlet or exhaust valve closes and the pressure ceases to change.

This change in air pressure is transmitted, by means of pipe 29, to the inlet to transmission line L and passes through the transmission line L with more or less of a time delay depending upon the resistance and capacitance of the transmission line L. At the output of the transmission line L, the pipe 30 connects this change in air pressure to the inlet to positive feedback restriction R1 and to the input motor 31, 32. This change in air pressure flows through the restriction R_1 very slowly because of the resistance of the restriction R_1. This change in air pressure is applied directly to the input motor 31, 32 and causes immediate action of the motor to the full extent of the change in pressure. When the device is in balanced condition, the pressure in input motor 31, 32 is balanced by the pressure in the negative feedback motor 33, 34. If a difference exists between the pressure in input motor 31, 32 and in the negative feedback motor 33, 34, shaft 35 is moved. This moves flapper 36 relative to nozzle 37 in one sense or the other. Flapper 36 and nozzle 37 constitute first valve of the receiver R. This first valve 36, 37 controls the pressure in nozzle chamber 41. The pressure in nozzle chamber 41 is normally balanced by the pressure in output chamber 43. If the pressure in nozzle chamber 41 changes, either inlet valve 51, or exhaust valve 48 is opened and air is admitted to or exhausted from the output chamber 43. This admission or exhaust of air from the output chamber 43 continues until the pressure in nozzle chamber 41 again balances the pressure in output chamber 43. Inlet valve 51 and exhaust valve 48 thus constitute the second valve of the receiver R.

The output air pressure from the pilot valve or relay of receiver R is conducted from output chamber 43 through pipes 54 and 61 to the motor 62, 63 of the final control element. A change in the pressure in the motor VM causes valve stem 54 to move valve plug 67 relative to the orifice in partition 68 and to thereby vary the flow of fluid through pipe PP.

Any change in pressure of the output of receiver R is also fed from output chamber 43 through pipes 54, 55, and 56 to series restriction R_2 through which it passes and thence by means of pipe 57 to the negative feedback motor 33, 34. Any change in the pressure in negative feedback motor 33, 34 moves shaft 35 until the pressures in the input motor 31, 32 and in negative feedback motor 33, 34 are equal. When this occurs, flapper 36 is held at one position relative to nozzle 37 and the device is in stable or balanced condition.

The negative fedback circuit formed of pipes 54, 55, and 56, series restriction R_2 and pipe 57, also includes a bypass restriction R_3 which controls the supply of fluid to a bypass chamber 60, whose capacity is great as compared with the capacity of input motor 31, 32 and the capacity of negative feedback motor 33, 34.

Receiver R also includes a positive feedback circuit formed of pipe **58** which connects, at its input, with pipes **55** and **56** and, at its output, with the positive feedback restriction R_1. The output of positive feedback restriction R_1 communicates by means of pipe **59** with pipe **30**, intermediate the end of transmission line L and the input to input motor **31**, **32**.

The operation of the pneumatic circuit described above depends on using single derivative action for effective compensation on distributed lags through pneumatic transmitting elements which behave as multi-capacity systems (tubing, etc.). This is based upon bi-lateral action across a compensated rate unit (the receiver), which avoids the need for second derivative response that would ordinarily be required in unilateral arrangements.

The simple pneumatic circuit arrangement shown permits adjustments on rate amplitude and rate time. Bi-lateral action is obtained by resistance coupling between the input and the output of the receiver, which permits the receiver to feed air back into the line in which it is terminated. Since the pressure developed at the output of the receiver leads the transmitted input signal, a regenerative feedback effect will occur on the pressure signal which is propagated in a line feeding into the receiver. This action will minimize the effects of line capacitance and hence speed up signal transmission to the receiver.

The pressure developed at the output **54** of the receiver R can be said to lead in phase the input signal transmitted through the pipe **30** to the input chamber of the relay R for the following reasons. Any change of the pressure in the input chamber of the relay R causes a corresponding change in the output pressure of the relay R in the chamber **43** and consequently in the pipe **54**. This change in pressure is immediately transmitted through the pipe **61** to the diaphragm **63** of the valve motor VM.

This change in pressure is also transmitted through the positive feedback restriction R_1 to the input chamber of the relay R. The change in pressure is felt in the input chamber of the relay R after a time delay which depends upon the resistance of the restriction R_1.

The change in pressure is also fed through pipe **57** to the negative feedback chamber **33** of the relay R after a time delay which depends upon the resistance of the restrictions R_2 and R_3 and upon the capacitance **60**. The resistance of restrictions R_1, R_2, and R_3 and the capacitance of chamber **60** can be so adjusted that the positive feedback restriction R_1 causes a variation in flow to be conducted to the transmission line **30** and to the input motor **31—32**. This variation in flow is large enough to compensate for the time delay in the transmission of the variations in the pressure passing through the supply line L and caused by the resistance and capacitance of the transmission line L.

The interaction described in the above suggests that the receiver serves as an impedance matching device on a line in which it is terminated. Later herein, it will be shown that the input impedance of the receiver appears as a negative resistance in series with a negative capacitor to ground, which act as current sources. In feeding back into a multi-capacity system, the receiver will of course be limited in its ability to nullify, completely, the effects of distributed lags on the propagation of a signal transmitted to its input chamber. However, in acting "forward," the receiver transmits a pressure signal (to a valve actuator, etc.), which leads the signal transmitted to its input motor chamber, and hence will offer additional compensation for distributed resistance-capacitance effects in a transmission line.

In theory, the bi-lateral action of the device described in the above will thereby permit a single compensated proportional plus rate receiver to perform as two unilateral uncompensated proportional plus rate receivers acting in tandem.

The operation of the pneumatic circuit of this invention may be analyzed mathematically as follows. Referring to Fig. 2,

A=Effective area of diaphragms (assumed equal) on which the input (P_i) and feedback (P_n) pressures react.
k=Gradient (low) of spring loading on the "stack."
λ_n=Slope of flapper-nozzle curve (p.s.i./inch, etc.).
G_p=Pressure gain through the pilot valve relay.

The equations of response across the unit may be developed as follows:

R_1, R_2, and R_3=pneumatic resistances of the adjustable restrictions (needle valves, etc.), used in the scheme.
P_i=transmitted input pressure to the unit.
P_o=pressure developed at the output of the unit.
C_r=pneumatic capacitance of the volume chamber in which the pressure divider circuit in the negative feedback line of the unit is terminated.

Referring to Figure 1:

$$P_o=\frac{A}{k}\lambda_n G_p(P_i-P_n) \tag{1}$$

where A, k, λ_n, and G_p are defined above.

For the case where

$$\left(\frac{A}{k}\lambda_n G_p\right)\to\infty$$

$$P_n\approx P_i \tag{2}$$

Referring again to Figure 2:

$$Ir=\frac{P_o-P_n}{R_2}=\frac{P_n-P_r}{R_3} \tag{3}$$

assuming:

(*a*) Ohm's law for fluid flow through a pneumatic restriction.

(*b*) Negligible volume at the junction between R_2 and R_3.

From the law for a perfect gas:

$$C_r\frac{dP_r}{dt}=Ir \tag{4}$$

where C_r=the volumetric capacitance of the volume chamber **60** in which R_3 is terminated.

Substituting Equation 4 into Equation 3:

$$C_r\frac{dP_r}{dt}=\frac{P_o-P_n}{R_2}=\frac{P_n-P_r}{R_3} \tag{5}$$

Thus, from the equality,

$$\frac{P_o-P_n}{R_2}=\frac{P_n-P_r}{R_3};\ P_r=\left(\frac{R_3+R_2}{R_2}\right)P_n-\frac{R_3}{R_2}P_o$$

$$\frac{dP_r}{dt}=\left(\frac{R_3+R_2}{R_2}\right)\frac{dP_r}{dt}-\frac{R_3}{R_2}\frac{dP_o}{dt} \tag{6}$$

Substituting (6) into the equality (given in (5)),

$$C_r\frac{dP_r}{dt}=\frac{P_o-P_n}{R_2};\ C_r\left(\frac{R_3+R_2}{R_2}\right)\frac{dP_n}{dt}-\frac{C_rR_3}{R_2}\frac{dP_o}{dt}=\frac{P_o-P_n}{R_2}$$

Substituting P for the

$$\frac{d}{dt}$$

operator and rearranging terms:

$$C_r\left(\frac{R_3+R_2}{R_2}\right)PP_n+\frac{P_n}{R_2}=\frac{C_rR_3}{R_2}PP_o+\frac{P_o}{R_2}$$

$$P_n(C_r(R_3+R_2)P+1)=P_o(C_rR_3P+1) \tag{7}$$

From Equation 2:

$$P_n\approx P_i$$

Thus, substituting Equation 2 into Equation 7:

$$P_i(C_r(R_3+R_2)P+1)=P_o(C_rR_3P+1)$$

$$\frac{P_o}{P_i}\ \frac{C_r(R_3+R_2)P+1}{R_3C_rP+1}$$

Substituting:

$$T_r=(R_2+R_3)C_r$$

$$\alpha=\frac{R_3}{R_2+R_3}$$

$$\alpha T_r=R_3C_r$$

(1) $$\boxed{\frac{P_o}{P_i}(P)=\frac{T_rP+1}{\alpha T_rP+1}}$$

which is the transfer function across a compensated proportional plus rate unit; where α=rate amplitude ratio, and T_r=rate time. (Note that adjustments may be made on both α and T_r.) Referring again to Figures 1 and 2 and noting that air flow (I_i) into the unit is assumed positive:

$$I_i=\frac{P_i-P_o}{R_1};\ \frac{I_i}{P_i}=\frac{1}{R_1}\left(1-\frac{P_o}{P_i}\right)$$

Starting with the equation:

$$\frac{I_i}{P_i}=\frac{1}{R_1}\left(-\frac{P_o}{P_i}\right)$$

and substituting Equation 1 from column 7, into the above;

$$\frac{I_i}{P_i}(P)=\frac{1}{R_1}\left(1-\frac{T_rP+1}{\alpha T_rP+1}\right)$$

$$=\frac{1}{R_1}\left(\frac{\alpha T_rP+1-T_rP-1}{\alpha T_rP+1}\right)$$

$$=\frac{1}{R_1}\left(\frac{T_rP(\alpha-1)}{\alpha T_rP+1}\right)$$

For $Z_i(P)=\frac{P_i}{I_i}(P)$=input impedance of the unit:

(2) $$\boxed{Z_i(P)=\frac{\alpha T_rP+1}{\frac{(\alpha-1)}{R_1}T_rP}}$$

Note that since $\alpha<1$, the input impedance of the unit has a negative sign associated with it. A circuit with an analogous input impedance as illustrated in Fig. 3. Referring to Figure 3,

$$Z_i(P)=\frac{P_i}{I_i}(P)=R_1+\frac{1}{C_iP}$$

(3) $$\therefore Z_i(P)=\frac{R_iC_iP+1}{C_iP}$$

Comparing Equations 2 and 3:

(4) $$C_i=-\left(\frac{1-\alpha}{R_1}\right)T_r$$

(5) $$R_i=-R_1\left(\frac{\alpha}{1-\alpha}\right)$$

$$\Big\}R_iC_i=\alpha T_r$$

The input impedance of the unit will therefore appear as a negative resistance (R_1) in series with a negative capacitance (C_1) to ground, to a line in which it is terminated. Bi-lateral action will therefore permit the unit to serve two functions, as illustrated in Figure 4. In Figure 4, the unit terminates a transmission line approximated by an interacting two-capacity lag system. The pressure signal being transmitted to the receiver is designated as P*t*. Schematically, the receiver is shown to act simultaneously as a line terminating matching impedance as well as a unilateral lag compensating device.

Referring to Figure 4:

$$\frac{P_b-P_i}{R_c}=\frac{P_i}{Z_i}=I_i;\ Z_i=\frac{R_iC_iP+1}{C_iP};\ R_iC_i=\alpha T_r$$

(Re: Equations 4 and 5.

$$\therefore\frac{P_i}{P_b}=\frac{Z_i}{R_c+Z_i}=\frac{1}{C_iP}\left(\frac{R_iC_iP+1}{R_c+R_i+\frac{1}{C_iP}}\right)$$

$$=\frac{1}{C_iP}\left(\frac{1}{R_c+R_i+\frac{1}{C_iP}}\right)$$

$$(\alpha T_rP+1)\frac{P_o}{P_i}=\frac{T_rP+1}{\alpha T_rP+1}$$

With R_1, R_2, and R_3 adjusted so that:

$$R_i=-R_c;\ C_i=-C_b;\ T_r=R_aC_a:\ P_b=P_a=\frac{P_t}{R_aC_aP+1};$$

(R_b appears to be 'dead ended').

$$\frac{P_i}{P_b}=\alpha R_aC_aP+1$$

$$\frac{P_o}{P_i}=\frac{R_aC_aP+1}{\alpha R_aC_aP+1}$$

Combining the foregoing equations:

$$\frac{P_i}{P_t}=1;\ P_i=P_t\ @\ \text{every instant of time}$$

In theory, the bi-lateral action of the receiver would therefore offer total compensation on the effects of lag through a two-capacity system.

Substituting

$$\left(\frac{R_3}{R_2+R_3}\right)\text{ for }\alpha\text{ and }(R_2+R_3)C_r\text{ for }T_r$$

and rearranging terms in Equations 4 and 5---the settings on R_1, R_2, and R_3 required for desired values of R_1, C_1, and T_r may be determined from the following equations:

$$R_3=\frac{R_iC_i}{C_r}\qquad R_1=-R_i\left(\frac{R_2}{R_3}\right)$$

$$R_2=\frac{R_iC_i}{C_r}\left(\frac{T_r}{R_iC_i}-1\right)$$

Note that required values of R_1 and C_1, when substituted in the above, will be negative in sign.

Note, also, that adjustments in R_1, R_2, and R_3 will satisfy a complete range in values for R_1, C_1, and T_r in cases where optimum performance requires the rate time (T_r) of the receiver to exceed the time constant (R_1C_1) of its input matching impedance. Otherwise compromises will have to be made in the bi-lateral compensating nature of the receiver.

From a theoretical analysis made on the characteristics of tubing when loaded, the following have been determined as optimum settings for R_1, R_2, and R_3 in terms of the length of standard 3/16 in. I.D. tubing terminated by the receiver, when compensating the effects of distributed transmission lag:

$$R_3\cong.04n^2\text{ p.s.i./in. 3/sec.}$$

$$R_2\cong.13n^2\text{ p.s.i./in.3/sec. }n=\frac{\text{tubing length (ft.)}}{100\text{ feet}}$$

$$R_1\cong.05n\text{ p.s.i/in. 3/sec.}$$

The above is based on an operating pressure level of 9 p.s.i.g. and a 5-in.^{3} volume, terminating the pressure divider circuit in the negative feedback circuit of the receiver (i.e., C_r=.21 in.^{3}/p.s.i.).

While, in accordance with the provisions of the statutes, I have illustrated and described the best forms of the invention now known to me, it will be apparent to those skilled in the art that changes may be made in the form of the apparatus disclosed without departing from

the spirit of the invention as set forth in the appended claims, and that in some cases certain features of the invention may sometimes be used to advantage without a corresponding use of other features.

Having now described my invention what I claim as new and desire to secure by Letters Patent is as follows:

1. A circuit operated by the pressure of an elastic fluid, including, a transmitter responsive to a measuring element which senses variations in a variable, said transmitter controlling the pressure of a first supply of elastic fluid, an elongated transmission line having a small cross section and connected to said first supply and causing time delays in the transmission of the variations in the pressure of said first supply because of the resistance and capacitance of said transmission line, and a receiver connected to said transmission line and controlling the operation of a final control element operated in response to the variations in the variable, said receiver comprising, an input motor connected to said transmission line and having a small capacitance compared to the capacitance of said transmission line and responsive to the variations in the pressure of said first supply, a first valve actuated by said input motor in one sense and controlling the pressure of a second supply of elastic fluid, a second valve operated by the pressure of said second supply of fluid and controlling the pressure of a third supply of fluid adapted for connection to the final control element, a negative feedback motor connected to said third supply and actuating said first valve in a sense opposite to that in which said first valve is actuated by said input motor, a manually variable series restriction connected between said third supply and said negative feedback motor, a manually variable bypass restriction connected at its input to the output of said series restriction and to said negative feedback motor, a bypass chamber having a large capacitance compared to the capacitance of said negative feedback motor and connected to the output of said bypass restriction, and a manually variable positive feedback restriction connected at its input to said third supply and to the input of said series restriction and connected at its output to the input to said input motor, the resistance of each of said restrictions and the capacitance of said bypass chamber being so adjusted that said positive feedback restriction causes a variation in flow to be conducted to said transmission line and to said input motor, said variation in flow being large enough to compensate for the time delay in the transmission of the variations in the pressure of said first supply because of the resistance and capacitance of said transmission line.

2. In a connecting circuit conducting an elastic fluid under pressure and connecting a measuring instrument to a final control element spaced from said measuring instrument, means for compensating for the time delay due to the resistance and capacitance of said circuit and including, an input motor actuated by the pressure of an elastic fluid, a valve actuated in one sense by said motor and controlling the pressure of a supply of fluid from a source of fluid under pressure, a negative feed-back motor actuated by the pressure of said supply of fluid and actuating said valve in the opposite sense to that in which it is actuated by said input motor, a negative feed-back conduit conducting an elastic fluid under pressure and connecting said supply of fluid to said negative feed-back motor and including resistance and capacitance, and a positive feed-back circuit conducting elastic fluid under pressure and connecting said supply of fluid to said input motor and having resistance and capacitance, said circuits cooperating to compensate for the time delay due to the resistance and capacitance of said connecting circuits.

3. In a connecting circuit, means for compensating for the time delay due to the resistance and capacitance of said circuit and located adjacent a final control element and including, an input motor actuated by the pressure of an elastic fluid, a first valve actuated in one sense by said input motor and controlling the pressure of a first supply of fluid from a source of fluid under pressure, a second valve actuated by the pressure of said first supply of fluid and controlling the pressure of a second supply of fluid from a source of fluid under pressure, a negative feed-back motor actuated by the pressure of an elastic fluid and connected to said first valve to actuate it in the opposite sense to that in which it is actuated by said input motor, a negative feed-back conduit conducting an elastic fluid under pressure and connecting said second supply of fluid and said negative feed-back motor and having a capacitance and resistance, and a positive feed-back conduit conducting an elastic fluid under pressure and connecting said second supply of fluid and said input motor and having a resistance and capacitance, said circuits cooperating to compensate for the time delay due to the capacitance and resistance of said connecting circuits.

4. In a connecting circuit, means for compensating for the time delay due to the resistance and capacitance of said circuit and located adjacent to a final control element and including, an input motor actuated by the pressure of an elastic fluid, a valve actuated by said input motor in one sense and controlling the pressure of a supply of fluid from a source of fluid under pressure, a negative feed-back motor actuated by the pressure of an elastic fluid and actuating said valve in the sense opposite to that in which said valve is actuated by said input motor, a negative feed-back circuit conducting elastic fluid under pressure and connecting said supply of fluid and said negative feed-back motor and having resistance and capacitance, a restriction to the flow of elastic fluid in said negative feed-back circuit connected in series between said supply of fluid and said negative feed-back motor, and a positive feed-back circuit conducting an elastic fluid under pressure and connecting said supply of fluid and said input motor and having resistance and capacitance, said circuits cooperating to compensate for the time delay due to the resistance and capacitance of said connecting circuits.

5. In a connecting circuit connecting a measuring element and a final control element spaced from said measuring element, means for compensating for the time delay caused by the resistance and capacitance of said circuit and including, an input motor actuated by the pressure of an elastic fluid, a valve actuated by said input motor in one sense to control the pressure of a supply of fluid from a source of fluid under pressure, a negative feed-back motor actuated by an elastic fluid under pressure and connected to said valve to actuate it in a sense opposite to that in which said valve is actuated by said input motor, a negative feed-back circuit conducting an elastic fluid under pressure and connecting said supply of fluid to said negative feed-back motor and having a resistance and capacitance, a positive feed-back circuit conducting an elastic fluid under pressure and connecting said supply of fluid and said input motor, and a restriction to the flow of fluid connected in said positive feed-back motor between said supply of fluid and said input motor, said circuits cooperating to compensate for time delay due to the resistance and capacitance of said connecting circuit.

6. In a connecting circuit conducting an elastic fluid under pressure, means for compensating for the time delays due to the resistance and capacitance of said circuit and located adjacent a final control element and including, an input motor actuated by an elastic fluid under pressure, a valve actuated in one sense by said input motor to control the pressure of a supply of fluid from a source of fluid under pressure, a negative feed-back motor actuated by an elastic fluid under pressure and connected to said valve so as to actuate it in a sense opposite to that in which said valve is actuated by said input motor, a negative feed-back circuit conducting an elastic fluid un-

der pressure and connecting said supply of fluid and said negative feed-back motor, a restriction to the flow of fluid connected in series between the said supply of fluid and said negative feed-back motor, a restriction to the flow of fluid connected in said negative feed-back circuit in parallel with said negative feed-back motor, a closed chamber having a greater capacity for fluid than said negative feed-back motor and connected to the output side of said bypass restriction, and a positive feed-back conduit conducting an elastic fluid under pressure and connecting said supply of fluid to said input motor and having a resistance and capacitance, said conduits cooperating to compensate for time delay due to the resistance and capacitance of said connecting circuit.

7. In a connecting circuit, means for compensating for the time delay due to the resistance and capacitance of said circuit and located adjacent a final control element and including, an input motor actuated by the pressure of an elastic fluid, a valve actuated in one sense by said input motor to control the pressure of a supply of fluid from a source of fluid under pressure, a negative feed-back motor actuated by the pressure of an elastic fluid and connected to said valve so as to actuate it in a sense opposite to that in which said valve is actuated by said input motor, a negative feed-back circuit conducting an elastic fluid under pressure and connecting said supply of fluid and said negative feed-back motor, a restriction to the flow of fluid connected in series between said supply of fluid and said negative feed-back motor, a restriction to the flow of fluid connected in said negative feed-back circuit in parallel to said negative feed-back motor, a closed chamber having a greater capacity for fluid than said negative feed-back motor and connected to the output side of said by-pass restriction, a positive feed-back circuit conducting an elastic fluid under pressure and connecting said supply of fluid and said input motor and having a resistance and capacitance, and a restriction to the flow of fluid connected in said positive feed-back circuit between the input to said input motor and the input to said negative feed-back circuit, said conduits cooperating to compensate for the time delay due to the resistance and capacitance of said connecting circuit.

8. In a connecting circuit connecting a measuring element to a final control element, an elongated transmission line conducting elastic fluid under pressure, means for compensating for the time delay is due to the resistance and capacitance of said transmission line and including, an input motor actuated by the pressure of an elastic fluid and connected to that end of said transmission line adjacent to final control element, a valve connected to said input motor so as to be actuated thereby in one sense to control the pressure of a supply of fluid from a source of fluid under pressure, a negative feed-back motor actuated by the pressure of an elastic fluid and connected to said valve to actuate said valve in a sense opposite to that in which said valve is actuated by said input motor, a negative feed-back circuit conducting an elastic fluid under pressure and connected to said supply of fluid and to said negative feed-back motor and having a resistance and capacitance, and a positive feed-back conduit conducting elastic fluid under pressure and connecting said supply of fluid and said input motor and having a resistance and capacitance, said circuits cooperating to compensate for the time delay due to the resistance and capacitance of said connecting circuit.

9. A connecting circuit conducting an elastic fluid under pressure and connecting a measuring element to a final control element and including, a measurement-responsive element, a transmitter valve actuated by said measurement-responsive element and varying the pressure of a first supply of fluid from a source of fluid under pressure, an elongated transmission line connected to said first supply of fluid, an input motor actuated by the pressure of an elastic fluid and connected to the other end of said transmission line and located adjacent to said final control element, a receiver valve actuated in one sense by said input motor and controlling the pressure of a second supply of fluid from a source of fluid under pressure, a negative feed-back motor actuated by the pressure of an elastic fluid and connected to said receiver valve and actuating it in the sense opposite to the sense in which said receiver valve is actuated by said input motor, a negative feed-back circuit conducting elastic fluid under pressure and connecting said second supply of fluid to said negative feed-back motor and having a resistance and capacitance, and a positive feed-back circuit conducting elastic fluid under pressure and connecting said second supply of fluid to said input motor and having a resistance and capacitance, said circuits cooperating to compensate for the time delay due to the resistance and capacitance of said connecting circuit.

10. In a connecting circuit conducting an elastic fluid under pressure and connecting a measuring element to a final control element, means for compensating for the time delay due to the resistance and capacitance of said circuit and including, an elongated transmission line conducting an elastic fluid at a pressure which is variable in response to a deviation in a measured variable, an input motor connected to one end of said transmission line and adjacent to said final control element and responsive to variations in said measured variable pressure, a valve mechanically connected to said input motor and operable thereby to change the pressure of an elastic fluid, a negative feed-back motor responsive to the variations in the pressure of said fluid and mechanically connected to said valve to operate it in the opposite sense to that in which it is moved in response to said deviation, a series restriction connected between said first fluid under pressure and said negative feed-back motor, a bypass restriction connected at one end to the output of said series restriction and to said negative feed-back motor, a bypass chamber connected to the opposite side of said bypass restriction and containing an elastic fluid under pressure, and a third restriction connected at its input to said elastic fluid under pressure and to the output of said series restriction and connected at output to said input motor and manually adjustable and connected so as to conduct a variation in the pressure of the elastic fluid to said input motor, which variation is of a suitable size to compensate for the time delay in the transmission of said measured variable to said input motor.

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