Jan. 30, 1968 C. G. RINGWALL ETAL 3,366,327

NEGATIVE FEEDBACK FLUIDIC INTEGRATOR CIRCUIT

Filed Oct. 28, 1966

Fig. 1.

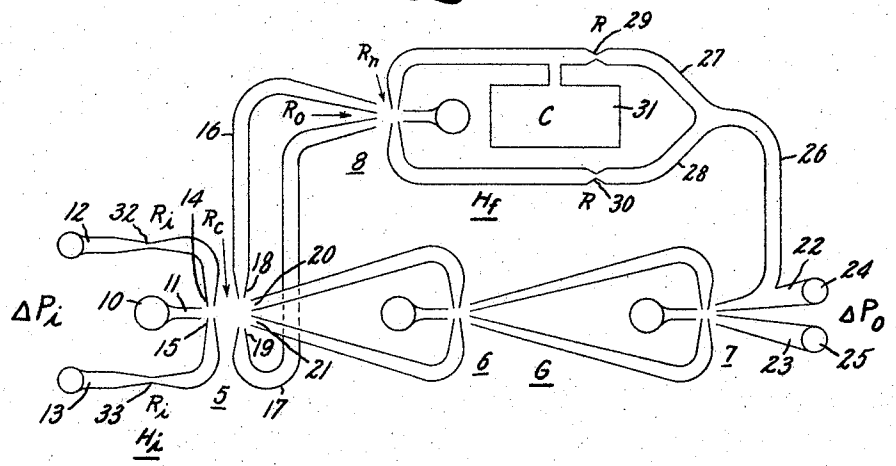


Fig. 2.

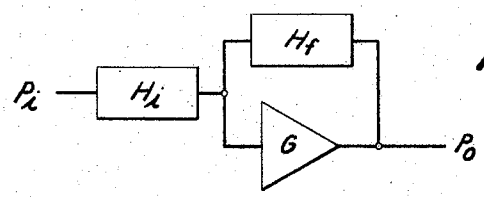


Fig. 3.

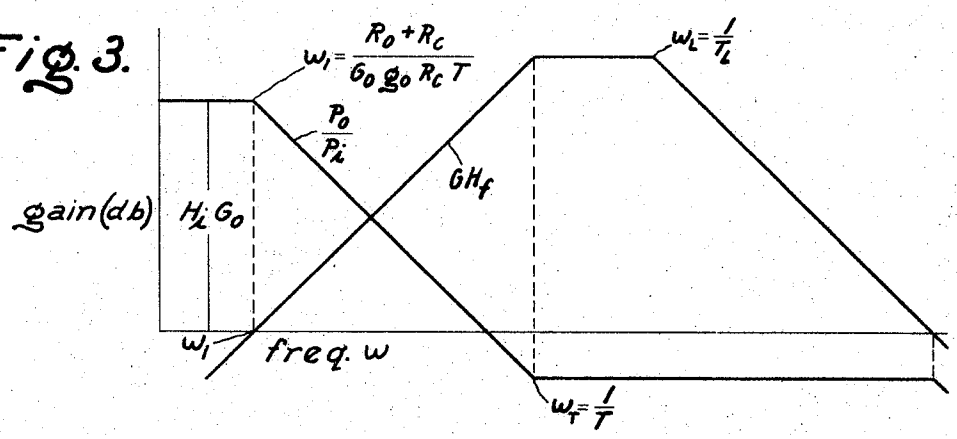
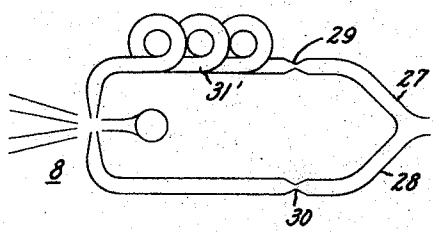


Fig. 4.



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NEGATIVE FEEDBACK FLUIDIC INTEGRATOR CIRCUIT

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9 Claims. (Cl. 235—200)

ABSTRACT OF THE DISCLOSURE

A fluidic circuit for developing a differential pressurized fluid signal representing the integral of an input signal. The circuit includes a fluidic operational amplifier comprising a forward network having a high gain and a feedback network connected from one of the outputs of the circuit to two inputs thereof. The feedback network includes a passage including a fluid resistive element and a passage including reactive-resistive elements for defining an impedance transfer function of a form for generating a pressurized fluid signal characterized as the output of a differentiator circuit with a lag. The high gain of the forward network increases the integration time constant over that produced in the absence of such operational amplifier. The addition of a fluid amplifier in the feedback circuit further increases the integration time constant multiplication factor.

Our invention relates to analog-type fluid amplifier circuits, and in particular, to fluidic integrator circuits having a large integration time constant.

Circuits employing the recently developed fluid control devices having no moving mechanical parts and known as fluid amplifiers or fluidic devices have many advantages over analogous electronic circuitry. In particular, the fluid amplifier is relatively simple in design, inexpensive in fabrication, capable of withstanding extreme environmental conditions such as shock, vibration, nuclear radiation and high temperatures, and the no-moving parts feature permits a substantially unlimited lifetime thereby achieving long periods of uninterrupted operation. These devices may be employed as analog and digital computing and control circuit elements, and also as power devices to operate valves and the like. The analog-type fluid amplifier is commonly referred to as the momentum exchange type wherein a main or power fluid jet is deflected by one or more control jets directed laterally at the power jet from opposite sides thereof. The power jet is normally directed midway between two fluid receivers and is deflected relative to the receivers by an amount proportional to the net sideways momentum of the control jets. This device is therefore commonly described as a proportional or analog device and may be operated by employing either incompressible fluids such as liquids or compressible fluids such as gases, including air. Our invention is directed to the analog-type fluid amplifier and particularly to the application of this amplifier in an integration computing circuit for performing system control functions. An example of a fluidic integrator circuit is illustrated in U. S. Patent No. 3,155,825 to W. A. Boothe and assigned to the same assignee as the present invention. In this prior art fluidic integrator, a true or pure integrating transfer impedance function

$$\frac{\Delta P_o}{\Delta P_i}=\frac{K}{S}$$

(where S is the Laplace transform and K is a constant) is obtained. In many applications a pure integrating transfer function is not essential and the frequency-gain characteristics in the frequency range of interest of a circuit conventionally described as a lag-lead circuit may provide a reasonable approximation of pure integration. One advantage of the fluidic lag-lead circuit over the pure integrator circuit is the reduced number of fluid flow impedance elements to thereby obtain a more simplified and inexpensive circuit.

Therefore, one of the principal objects of our invention is to provide a fluidic circuit having the characteristic of a lag-lead circuit over a frequency range of interest to thereby obtain a reasonable approximation of a pure integrator circuit.

A disadvantage of known fluidic lag-lead circuits is the relatively small integration time constant obtained (i.e. a relatively high frequency lag break on the frequency-gain Bode diagram representation of the closed loop circuit) resulting in the pure integration function being approximated for a frequency range centered at a high frequency (small computing time) and thus providing an integrator circuit inadequate for many applications.

Another object of our invention is to provide a fluidic circuit having the characteristics of a lag-lead circuit over a frequency range of interest and having a relatively low frequency lag break and corresponding large time constant to thereby obtain a reasonable approximation of a pure integrator.

In the electronics field, integration is normally accomplished by employing a high gain operational amplifier and series capacitor as a feedback element. The effective capacity of this combination is the capacitance of the series capacitor multiplied by the loop gain of the oeprational amplifier. Very large integration time constants can thereby be obtained with practical sized electrical components.

Passive capacities are obtained in fluidics circuitry employing compressible and incompressible fluids by utilizing fixed volumes and hydraulic accumulators, respectively. Unfortunately, the fluidic capacitor has the characteristics of a shunt capacity (capacity to ground) and thus cannot be used in conjunction with an operational amplifier to obtain an integrator in the same manner as its electronic series capacitor counterpart. Known methods of integration employing passive fluid flow reactive elements are (1) integration in a volume, but this requires very large volumes to obtain long integration times, (2) operational amplifier used in conjunction with a fluid inductor, not very practical for compressible fluids because of the small value of fluid inductances that can be obtained, and (3) operational amplifier used in conjunction with a volume and positive feedback, this obtains the desired long integration time (large time constant) but is rather sensitive to gain variations due to the positive feedback. Thus, there is a need for a fluidic integrator circuit having a relatively large integration time constant and a high degree of insensitivity to gain or other parameter variations but employing a passive fluid flow reactive element of reasonable size.

Therefore, another object of our invention is to provide a fluidic circuit which achieves a desired multiplication of a time constant formed by a passive fluid flow reactive element of reasonable size to obtain a fluidic integrator circuit having a large integration time constant and a high degree of insensitivity to gain or other parameter variations.

A more specific object of our invention is to provide a negative feedback fluidic circuit including a particular feedback network to obtain the multiplication of the time constant.

In carrying out the objects of our invention, we provide a fluidic integrator circuit comprising an operational amplifier having a feedback network for developing two

pressurized fluid signals. The two fluid signals are developed in two fluid passages wherein the first passage includes fluid flow resistive and reactive elements, and the second passage includes a resistive element. The difference between the two signals is characterized as the output of a differentiator circuit with a lag and is supplied as an input to the worward network of the operational amplifier in negative feedback relationship. The integration time constant, as determined by the elements in the first feedback passage, is increased by a factor proportional to the gain of the forward network to provide a reasonable approximation of a pure integrator over a wide frequency range. An analog fluid amplifier may be inserted in the feedback network between the two feedback passages and the input to the forward network whereby the integration time constant is further increased by a factor proportional to the gain of the latter amplifier.

The features of our invention which we desire to protect herein are pointed out with particularity in the appended claims. The invention itself, however, both as to its organization and method of operation, together with further objects and advantages thereof, may best be understood by reference to the following description taken in connection with the accompanying drawing wherein:

FIGURE 1 is a diagrammatic representation of a preferred embodiment of a fluidic integrator circuit constructed in accordance with our invention;

FIGURE 2 is a block diagram representation of the circuit illustrated in FIGURE 1;

FIGURE 3 is a Bode diagram (gain versus frequency) of our integrator circuit illustrated in FIGURE 1 and

FIGURE 4 is a diagrammatic representation of a second embodiment of the feedback network shown in FIGURE 1.

Referring now in particular to FIGURE 1, there is shown a plurality of analog-type fluid amplifiers and associated passive fluid flow impedance elements interconnected to form a fluidic operational amplifier employing a differentiator and lag circuit in a negative feedback network thereof. Each of the fluid amplifiers may be of the conventional type provided with at least two input control fluid passages, an input power fluid passage and two fluid receiving passages. The fluid amplifiers designated as a whole by numbers **5**, **6** and **7** are serially connected in the forward network G of the operational amplifier such that the fluid receiving passages of one stage are in communication with the input control fluid passages of the next succeeding stage. A fourth analog fluid amplifier **8** may be connected in the feedback network H_f, as illustrated. The fluid amplifiers and impedance elements are preferably all formed within a single structure but may be formed in separate, externally interconnected structures, if desired. As exemplary of the various amplifiers, the first stage amplifier **5** (which also functions as a summer) includes an input power fluid passage comprising power fluid inlet (passage) **10** terminating in a nozzle **11** for generating a continuous power jet of pressurized fluid when inlet **10** is supplied from a source (not shown) of relatively constant pressurized fluid. The supply pressures of the power fluid may be equal in each of the amplifier stages or may be of increasing magnitude in successive stages. A first pair of input control fluid passages comprise input signal control fluid inlets **12** and **13** terminating respectively in opposed nozzles **14** and **15** to provide control jets of pressurized fluid directed laterally at the power jet for causing a proportional deflection thereof by momentum exchange, the degree of deflection being determined by the differential pressure ΔP_i of the fluid supplied to inlets **12** and **13**. In the most general case, the fluid signal applied to control fluid inlets **12** and **13** is a push-pull pressurized signal supplied from a source (not shown) of variable pressure such as the output of another fluidic circuit and represents the signal to be integrated by our circuit. A second pair of input control fluid passages comprise feedback signal control fluid inlets **16** and **17** terminating respectively in opposed nozzles **18** and **19** to provide a second pair of control jets of pressurized fluid directed laterally at the power jet for causing a proportional deflection thereof by momentum exchange. The two fluid receiving passages **20** and **21**, commonly described as fluid receivers, are often separated by a center vent passage (not shown) and a pair of side vent passages (not shown) may be positioned intermediate the receivers and control fluid nozzles. Fluid receiving passages **20** and **21** are in communication with respective control fluid passages of the second stage amplifier **6**. In like manner, the receivers of the second stage amplifier **6** are in communication with the control fluid passages of the third stage amplifier **7**. Receivers **22** and **23** of the third stage amplifier **7** are respectively in communication with output fluid passages **24** and **25** which provide the differential pressurized output ΔP_o of the integrator.

The feedback network H_f comprises one (or two) fluid passages in communication with fluid receiving passage **22**. In the case of a single passage **26**, such passage branches into two separate passages **27** and **28**. Passages **27** and **28** each include a passive fluid flow resistor element **29** and **30** (herein designated R) in the form of fluid flow restrictors of equal predetermined size (to provide equal resistance to fluid flow). Passage **27** further includes a passive fluid flow capacitor element (herein designated C) in the form of a conventional hydraulic accumulator **31**, e.g., a pressure vessel with a moveable septum, such as a rubber diaphragm separating a liquid from a gas, or a fixed volume for providing a means for storing the energy of the fluid as potential energy. The fixed volume is employed when the fluid is a compressible gas and a hydraulic accumulator is used with an incompressible fluid such as a liquid. The electronic equivalent of an accumulator or volume is a capacitor connected to ground. Feedback network H_f may also include an analog fluid amplifier **8**, as shown, primarily for purposes of isolating and impedance matching the RC time constant network and the input impedance of summer amplifier **5**. In addition to the passive fluid flow resistors and capacitor in the feedback network H_f, fluid flow restrictors **32** and **33** (designated R_i) of equal predetermined size (and resistance) are employed in the input signal control fluid inlets **12** and **13** of a input network H_i of the integrator. Our integrator circuit is thus seen to comprise a relatively simple circuit comprising a plurality of analog-type fluid amplifiers and five passive fluid flow impedance elements.

FIGURE 2 is a simplified block diagram of the fluidic integrator hereinabove described wherein the conventional control system terms G, H_f and H_i represent the transfer impedance functions of the forward, feedback and input networks, respectively, and the differential symbols for the input and output signals have been omitted. The transfer function for a negative feedback operational amplifier is:

$$\frac{P_o}{P_i}=\frac{H_i}{H_f}\left(\frac{GH_f}{1+GH_f}\right) \tag{1}$$

It is assumed that the feedback and input networks H_f and H_i are fluidically isolated from each other and that the feedback network has the characteristics of a differentiator circuit with a lag whereby:

$$H_f=\frac{g_o TS}{1+TS}\left(\frac{R_c}{R_o+R_c}\right) \tag{2}$$

where

$$g_o=g\left(\frac{R_n}{R+R_n}\right)$$

and g is the blocked load gain of any fluid amplifier in the feedback circuit; T is a time constant $T=R_pC$ where

$$R_p=\frac{RR_n}{R+R_n}$$

and R_n is a control input resistance of the feedback amplifier. R_c is a control input resistance of the first stage amplifier **5** and R_o is an output resistance of the feedback amplifier, if employed.

The transfer function of the input network is:

$$H_i=\frac{R_c}{R_i+R_c} \tag{3}$$

where R_i is one of the equal resistors **32**, **33** added to the input signal control fluid passage **12** and **13** of the first stage amplifier.

The expression H_i/H_f in Equation 1 thus becomes:

$$\frac{H_i}{H_f}=\frac{(R_o+R_c)(1+TS)}{(R_i+R_c)g_oTS} \tag{4}$$

The open loop transfer function GH_f is given by the expression:

$$GH_f=\frac{G_og_oR_cT_LS}{(1+TS)(1+T_LS)(R_o+R_c)} \tag{5}$$

wherein the forward network transfer function G has the form

$$\frac{G_o}{1+T_LS}$$

and T_L is a time constant added to stabilize the closed loop. Referring to Equation 1, it is apparent that if GH_f is much less than ($<<$) 1,

$$\frac{P_o}{P_i}=H_iG$$

and if $GH_f>>1$

$$\frac{P_o}{P_i}=\frac{H_i}{H_f}$$

Referring to Equation 5, it is apparent that GH_f approaches zero when S approaches zero, and over a first range of frequencies the gain of GH_f is directly proportional to frequency (i.e., has the characteristics of a differentiator circuit). Thus, there is a first range of frequencies from zero to an upper limit determined primarily by

$$\frac{G_og_oR_cT}{R_o+R_c}$$

where the open loop gain $GH_f<1$, and a second range of frequencies determined by

$$\frac{G_og_oR_cT}{R_o+R_c}$$

and T and T_L where $GH_f>1$. The transition point between these two ranges of frequencies is the frequency at which:

$$GH_f=\frac{G_og_oR_cTS}{(1+TS)(1+T_LS)(R_o+R_c)}=1 \tag{6}$$

In a fluidic system employing current state of the art fluid amplifiers, the lower frequency where $GH_f=1$ is very much lower than $1/T$ or $1/T_L$, hence the lower cross-over frequency, ω_1, for GH_f is

$$\omega_1=\frac{R_o+R_c}{G_og_oR_cT}$$

It follows that for frequencies $\omega<\omega_1$, $GH_f<1$ and

$$\frac{P_o}{P_i}\approx H_iG_o$$

For frequencies $\omega_1<\omega<\omega_L$, $GH_f>1$ and

$$\frac{P_o}{P_i}\approx\frac{H_i}{H_f}=\frac{(R_o+R_c)(1+TS)}{(R_i+R_c)g_oTS}$$

Thus the cross-over frequency ω_1 also represents a first downbreak or lag in the closed loop transfer function P_o/P_i and $1/\omega_1$ is the integration time constant in our integrator circuit.

Knowing the expressions for the closed loop transfer function P_o/P_i on both sides of the lower cross-over frequency ω_1, the gain versus frequency plot for both the closed loop integrator circuit P_o/P_i and open loop circuit (GH_f) may be obtained as illustrated in the Bode diagram of FIGURE 3 wherein the second downbreak or lag in P_o/P_i is a secondary effect occurring at the higher cross-over frequency for GH_f and has been ignored in the above analysis.

The closed loop transfer function for the integrator circuit is thus:

$$\frac{P_o}{P_i}=\frac{H_iG_o(1+TS)}{\left(1+\frac{G_og_oR_cTS}{R_o+R_c}\right)} \tag{7}$$

wherein the only approximations are that the pairs of amplifier impedances R_n, R_o and R_c and external impedances R and R_i are each balanced and a second lag break in P_o/P_i occurs at a sufficiently high frequency that it may be neglected. As seen with reference to Equations 3 and 7, resistors R_i are a factor in determining the magnitude of the input network transfer function H_i, and their resistance is chosen as a vernier adjustment to set the desired final gain for the closed loop P_o/P_i.

If the same resistor R and capacitor C were used to perform integration without the use of an operational amplifier, the transfer function would be

$$\frac{1}{1+TS}$$

where $T=RC$. Therefore, the use of an operational amplifier and a differentiator circuit with a lag in the negative feedback portion thereof, in accordance with our invention, has the effect of increasing a time constant (formed primarily by passive fluid flow elements R and C of reasonable size) by a factor of

$$\frac{G_og_oR_c}{R_o+R_c}$$

to obtain a large (integration) time constant $1/\omega_1$ in the denominator of the lag-lead transfer function P_o/P_i of Equation 7 and thereby approach a pure integrator. In the case wherein feedack amplifier **8** is not used, the integration time constant multiplying factor is reduced to

$$\frac{G_oR_c}{R+R_c}$$

In this latter case, the output ends of passages **27** and **28** are connected to nozzles **19** and **18**, respectively.

Since Equation 7 is a negative feedback transfer function, it is apparent that the large integration time constant

$$\frac{1}{\omega_1}=\frac{G_og_oR_cT}{R_o+R_c}$$

is relatively insensitive to variation in gain or other parameters as compared to the known method for obtaining long integration times by employing an operational amplifier with a volume and positive feedback.

Our negative feedback integrator circuit, as derived by the mathematical expressions hereinabove, is implemented in its preferred embodiment by the fluidic circuit illustrated in FIGURE 1. It can be appreciated that the forward network gain G_o is the largest factor for increasing the integration time constant although the feedback network gain g_o is also significant. The integration time constant may be increased by a factor of up to 20 for operational amplifier comprising three current state of the art fluid amplifiers in the forward network. As one example, an integration time constant of approximately 2.0 seconds is obtained for the following reasonable size passive elements: C is a volume of 10 cubic inches and R, which is preferably a restrictor of the laminar flow type (such as a capillary tube), has a resistance of 10^5 second/inch^2. With our integrator circuit employing the same size passive elements and three fluid amplifiers in the forward network, an effective integration time constant of 40 seconds in achieved. Although some increase in the in-

tegration time constant is obtained by increasing the resistance of the fluid flow resistors R, a limit is soon reached with this approach since a high resistance requires a very small flow passage through the restrictor.

A second embodiment of the feedback network H_f in FIGURE 1 is illustrated in FIGURE 4. The mathematical analysis of this network is similar to that employed with respect to FIGURE 1 with the obvious difference being that the time constant T is now of the form L/R_p wherein L represents the inductance of series connected fluidic inductor **31'**. Inductor **31'** may comprise a long length of tubing, preferably arranged in a helix as illustrated for compaction of such device, to impart a greater inertia to the fluid flow therethrough and thereby obtain a delay response to changes in fluid flow. Since inductor **31'** also has some resistance to fluid flow, the resistors **29** and **30** are not balanced (equal) in this case, but the sum of the resistances of inductor **31'** and resistor **29** is made equal to that of resistor **30**. It can be appreciated that with both the FIGURES 1 and 4 embodiments of the feedback network, the difference signal obtained at nozzles **18** and **19** is characterized as the output of a differentiator circuit with a lag as indicated in Equation 2.

Having described two embodiments of our negative feedback fluidic integrator circuit, it is believed obvious that modification and variation of our invention is possible in light of the above teachings. Thus, the feedback network H_f may include any number (including zero) of fluid amplifiers but in the most general case would include only one amplifier. Further, the forward network G may include any number of fluid amplifiers as determined by the effective integration time constant desired. In most cases, it is preferred to increase the number of amplifiers in the forward network to achieve a larger increase in the integration time constant since this also provides a larger closed loop gain whereas increasing the gain in the feedback network merely increases the integration time constant without affecting the closed loop gain. Also, a two control input amplifier **5** may be used instead of the illustrated four input device by employing four appropriate fluid flow summing resistors and two summing junctions for summing the signal to be integrated and the feedback signal into the two control fluid passages adjacent their associated opposed control nozzles. Finally, a second feedback network, identical to the first, but connected from receiver **23**, may be employed in cases requiring extreme linearity and insensitiveness to power fluid supply pressure. It is, therefore, to be understood that changes may be made in the particular embodiments of our invention described which are within the full intended scope of the invention as defined by the following claims.

What we claim as new and desire to secure by Letters Patent of the United States is:

1. A negative feedback fluidic integrator circuit having a large integration time constant and comprising

a fluidic operational amplifier comprising a forward network having a gain G_o and a feedback network,

said forward network including at least one analog-type fluid amplifier having a first input adapted to be supplied with pressurized fluid signal to be integrated,

said feedback network comprising a first fluid flow passage including fluid flow reactive and resistive elements and a second fluid flow passage including only a fluid flow resistive element R, said first and second fluid flow passages each having a first end thereof in communication with a common output of said forward network for defining a feedback network impedance transfer function of a form

$$\frac{K_1TS}{1+TS}$$

for generating a pressurized fluid difference signal characterized as the output of a differentiator circuit with a lag, and

said forward network having a second input in negative feedback communication with the output of said feedback network for defining a closed loop impedance transfer function of a form

$$\frac{K_2(1+TS)}{1+G_oK_1TS}$$

to thereby produce an integrator circuit having an integration time constant which is greater than the integration time constant produced with the same reactive and resistive elements and without said forward network by a multiplication factor

$$G_oK_1=\frac{G_oR_c}{R+R_c}$$

where R_c is a control input resistance of said analog fluid amplifier.

2. The fluidic integrator circuit set forth in claim **1** wherein

said forward network comprises a plurality of serially connected analog-type fluid amplifiers to increase the forward network gain G_o and thereby further increase the integration time constant multiplication factor and also provide a larger closed loop gain of the integrator circuit.

3. The fluidic integrator circuit set forth in claim **1** wherein

said feedback network further comprises an analog-type fluid amplifier having the control fluid inlets thereof in communication with second ends of said first and second passages, and having the fluid receivers thereof in communication with said forward network second input to thereby further increase the integration time constant multiplication factor by a quantity directly proportional to the gain of said feedback network fluid amplifier.

4. The fluidic integrator circuit set forth in claim **1** and further comprising

a fluid flow resistive element input network in communication with said forward network first input and fluidically isolated from said feedback network for setting a desired gain for the integrator circuit.

5. The fluidic integrator circuit set forth in claim **1** wherein said fluid flow reactive element is a passive shunt capacitor comprising a hydraulic accumulator in the case of the fluid employed being an incompressible fluid and a fixed volume in the case of the fluid being a compressible gas, and the resistive elements in said first and second passages have equal resistance to fluid flow.

6. The fluidic integrator circuit set forth in claim **1** wherein said fluid flow reactive element is a passive series connected inductor comprising a long length of tubing, and the resistance of the resistive element in said second passage is equal to the sum of the resistances of the resistive element and inductor in said first passage.

7. A negative feedback fluidic integrator circuit having a large integration time constant and comprising

a fluidic operational amplifier comprising a forward network and negative feedback network,

said forward network comprising a plurality of serially connected analog-type fluid amplifiers,

each of said fluid amplifiers provided with means for generating a continuous power jet of fluid, a pair of fluid receiver means downstream from said power jet generating means for receiving fluid from the power jet, and a pair of opposed control means for controllably deflecting said power jet relative to said receiver means,

the pair of opposed control means associated with the first fluid amplifier in said forward

network adapted to be supplied with a differential pressurized fluid signal to be integrated,

said feedback network comprising first and second fluid flow passages each having their input end in communication with a first receiver means of the last fluid amplifier in said forward network,

said first passage including passive fliud flow reactive and resistive elements,

said second passage including only a passive fluid flow resistive element for defining a feedback network impedance transfer function of a form

$$\frac{KS}{1+TS}$$

said first fluid amplifier in said forward network further provided with means for further controllably deflecting the power jet relative to the receiver means in said first amplifier, and

said first and second fluid flow passages of said feedback network having their output ends in negative feedback communication with said further controllably deflecting means associated with said first amplifier for supplying a pressurized fluid signal generated in said feedback network to said further controllably deflecting means to thereby produce an integrator circuit wherein the integration time constant as determined by the reactive and resistive elements in said first passage is increased by a factor proportional to the gain of the said forward network, and the negative feedback relationship renders the resultant large integration time constant relatively insensitive to gain and other parameter variations.

8. The negative feedback fluidic integrator circuit set forth in claim 9 wherein the fluid flow resistances of said first and second of said passages of said feedback network are equal.

9. The negative feedback fluidic integrator circuit set forth in claim 9 wherein said further controllably deflecting means comprises a second pair of opposed control means for controllably deflecting the power jet relative to the receiver means in said first amplifier.

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