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[54] **FLUIDIC FREQUENCY-RESPONSIVE LAG
CIRCUIT COMPONENT**
18 Claims, 7 Drawing Figs.

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137/15, 137/271
[51] Int. Cl. F15c 1/06
[50] Field of Search 137/15,
81.5, 271

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ABSTRACT: A fluidic frequency-responsive circuit component for obtaining a moderate lag time constant in analog-type control systems utilizes a fluidic operational amplifier and a particular fluid flow impedance input network to obtain a high degree of stable operation over a wide range of fluid supply pressure and load. The input network comprises a fluid flow capacitor connected to the midpoint of the operational amplifier input resistor and the two functions of the input resistor achieve the frequency-responsive lag function without attenuation. The operational amplifier and resistors are comprised of a plurality of superposed laminae assembled in fluid-type relationship to provide a compact component having no moving mechanical parts.

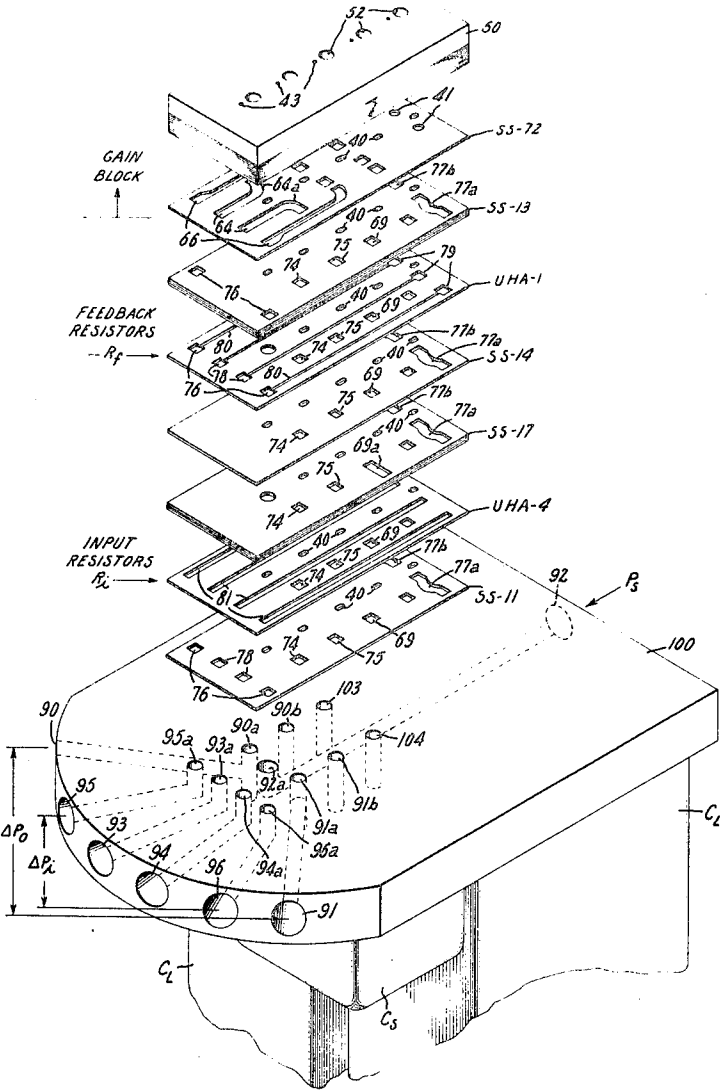
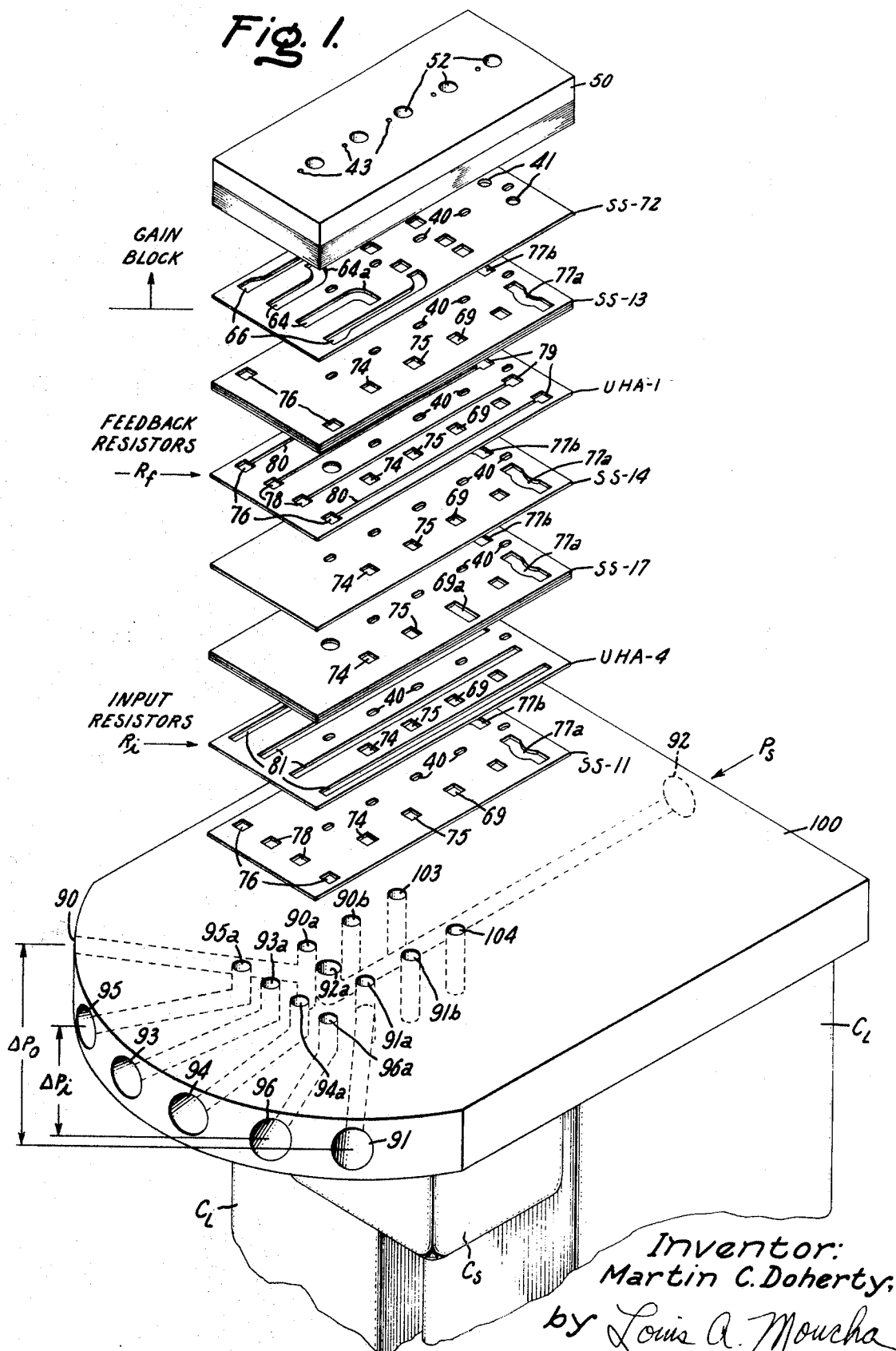


Fig. 1.



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Fig. 2.

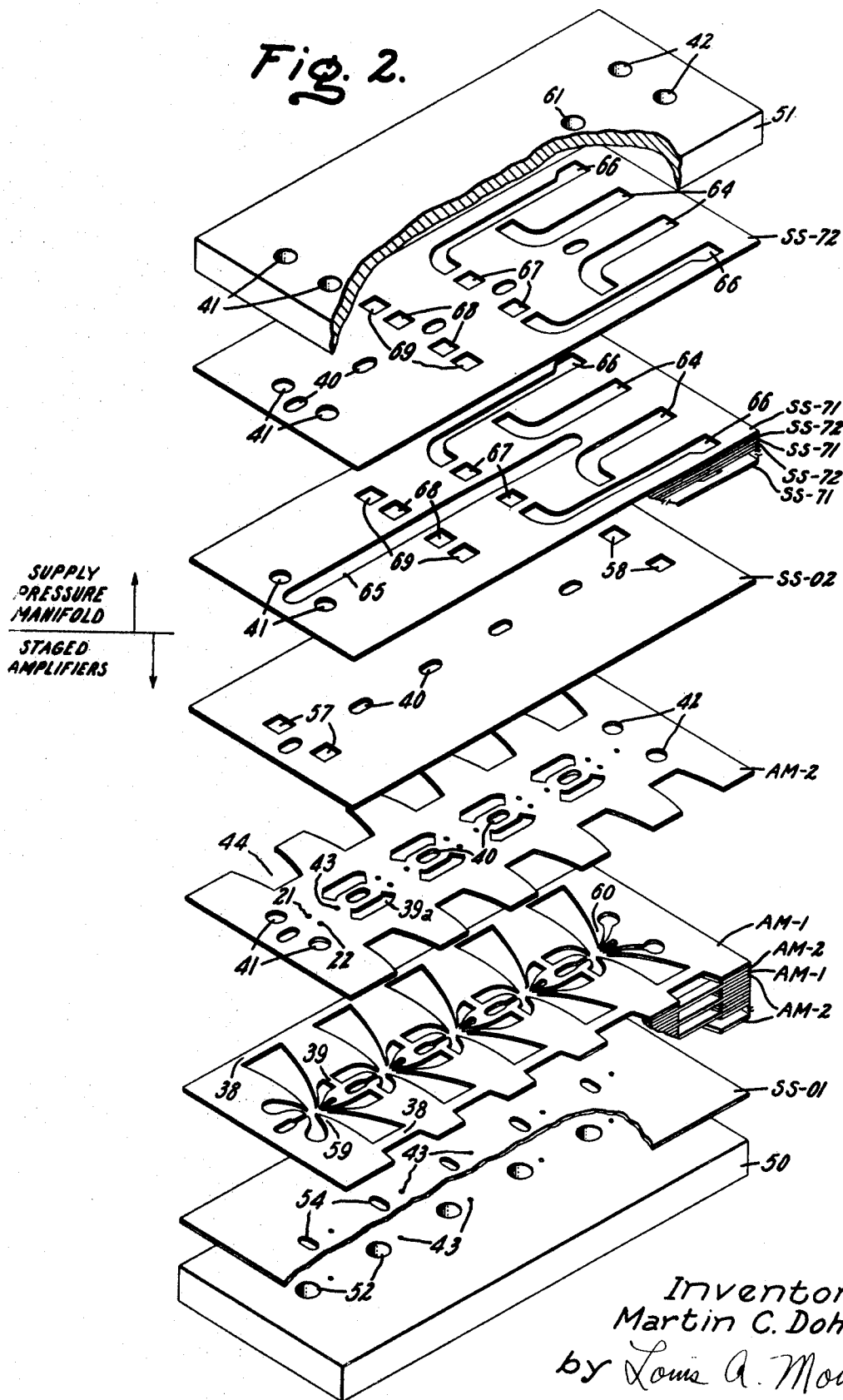


Fig. 3.

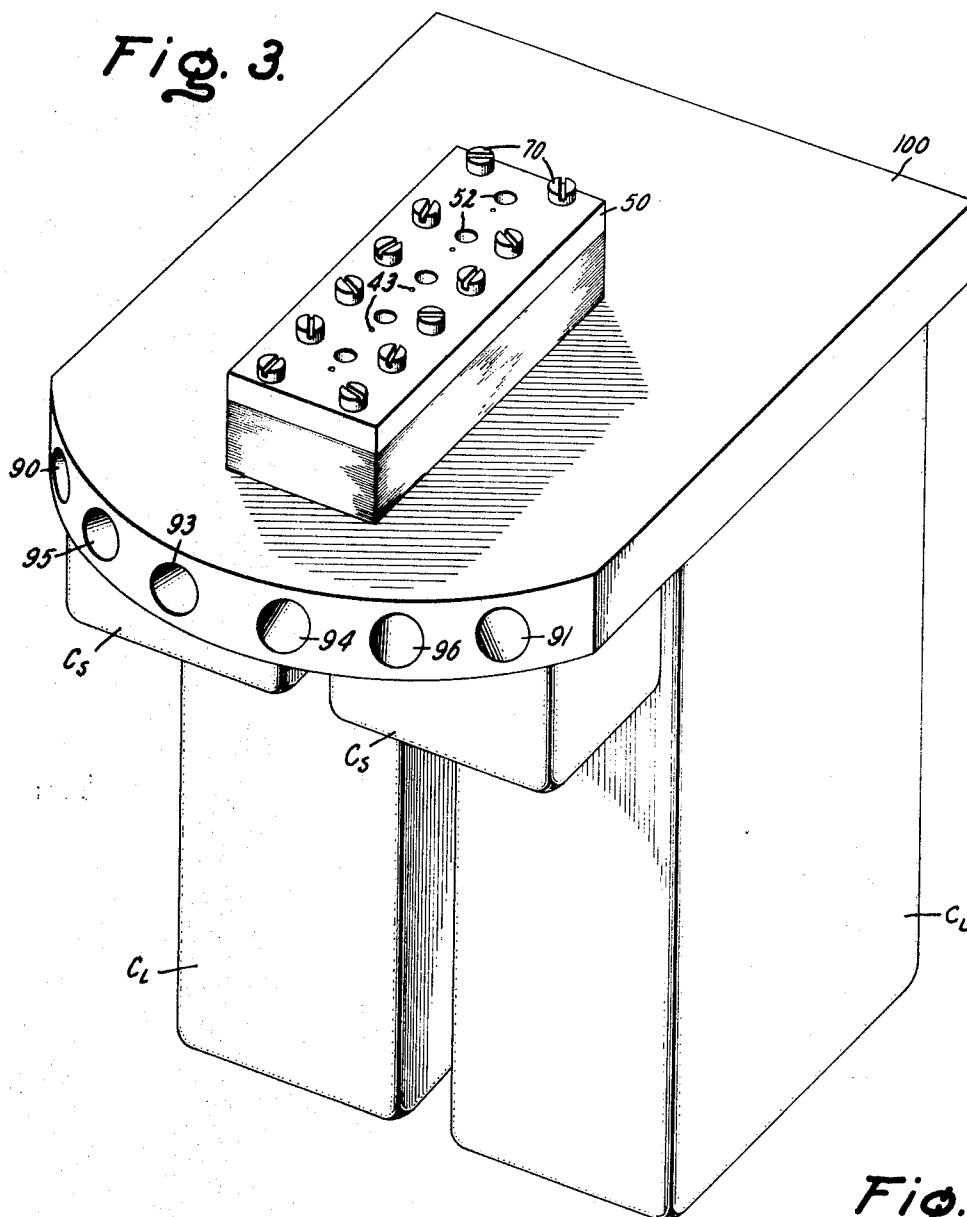


Fig. 5.

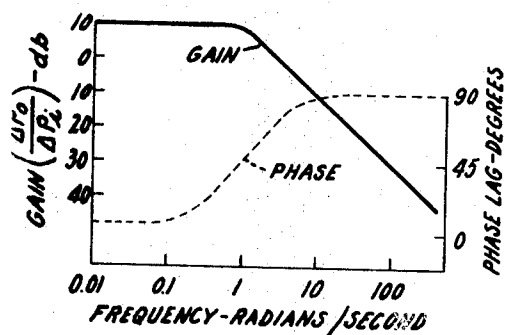
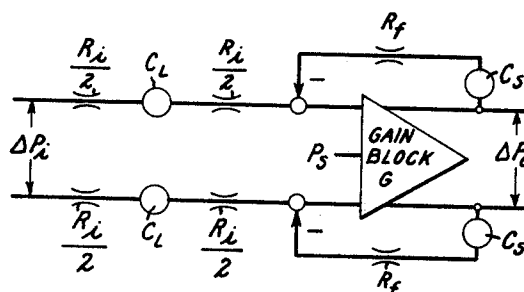


Fig. 4.



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Fig. 7.

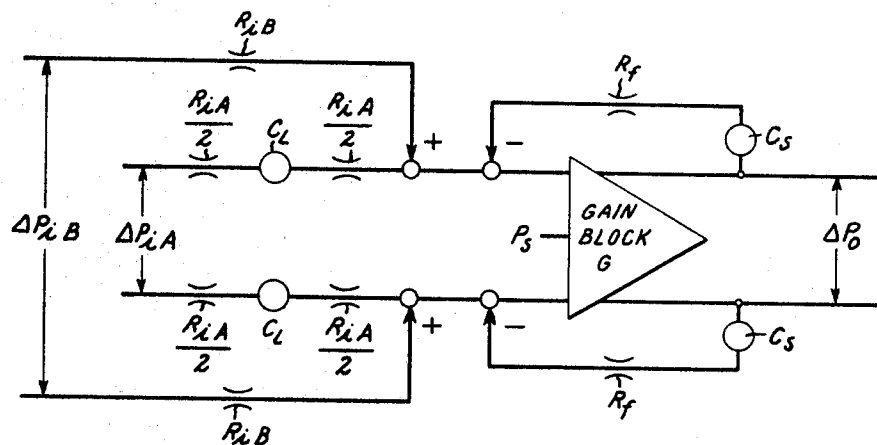
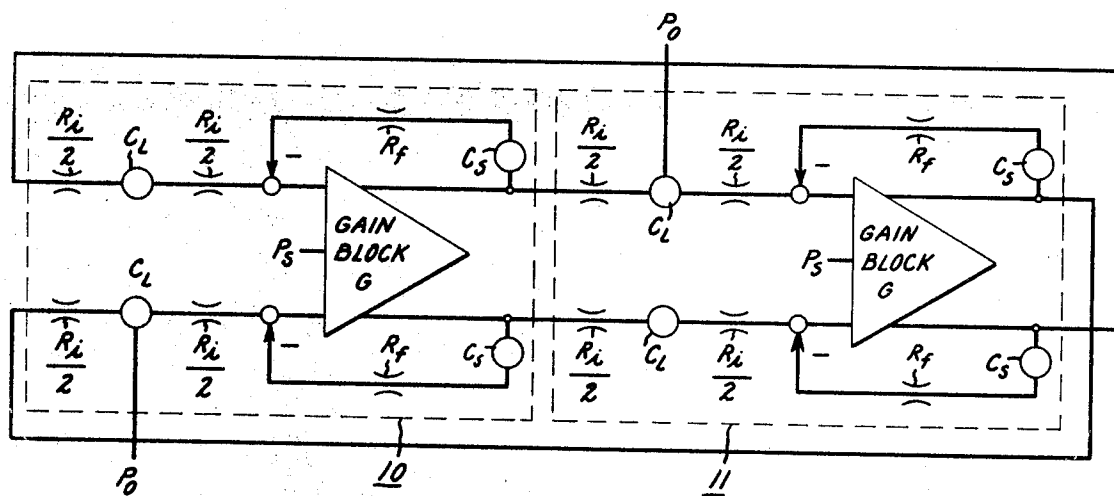


Fig. 6.



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FLUIDIC FREQUENCY-RESPONSIVE LAG CIRCUIT COMPONENT

My invention relates to fluidic circuits constructed of fluid control devices having no moving mechanical parts known as fluid amplifiers, and in particular, to a frequency-responsive fluidic circuit for providing a moderate lag time constant with a high degree of stable operation.

The recently developed fluid control devices having no moving mechanical parts and known as fluid amplifiers 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 temperature, and the no-moving parts feature permits 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 the analog-type fluid amplifier which is employed in my invention 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. In many analog circuits which require a high gain, and a desired frequency response, such as in the fluid control systems designed for high accuracy operation, the prior art analog fluid amplifiers and fluidic components employing such amplifiers have not been entirely satisfactory.

A particular frequency-responsive circuit, to which my invention is directed, is a lag circuit having a moderate lag time constant generally in the range of 0.1 to 1 second. As is well known in control system and servomechanism theory, predetermined frequency-responsive characteristics are often required to be added to a particular control system to obtain necessary conditions of gain or stability wherein the stability is determined by the accumulated phase lag in the open control system loop.

A fluidic lag circuit may be formed by several means. A lag circuit having a small (lag) time constant may be constructed from a simple fluid flow resistor and capacitor network whereas relatively complex fluidic (fluid amplifier) circuits employing operational amplifier techniques including positive feedback can achieve long lag time constants in the order of 5 to 60 seconds. Examples of the operational amplifier approach to achieve long time constants is exemplified in U.S. Pat. No. 3,155,825 to W.A. Boothe and in a concurrently filed U.S. Pat. application Ser. No. 752,098 of T.F. Urbanosky, entitled "High Signal-to-Noise Fluid Amplifier and Fluidic Components", both assigned to the assignee of the present invention. In the latter two examples, a fluidic operational amplifier utilizes both positive and negative feedback to obtain, in the general case, a lag-lead circuit wherein the lag break occurs at a relatively large time constant and the lead break occurs at a much smaller time constant (higher frequency). In the frequency range between the lag and lead breaks, integrator action is obtained.

Therefore, one of the principal objects of my invention is to provide a fluidic lag circuit which spans the time constant gap between a simple fluid flow resistor-capacitor network and the positive-negative feedback operational amplifier approach.

The simple fluid flow resistor-capacitor network attenuates the input signal over the entire frequency range due to the resistance component.

Another object of my invention is to provide a relatively simple lag circuit utilizing operational amplifier techniques which does not cause any attenuation of the input signal prior to the lag break.

A further object of my invention is to provide the lag circuit in a compact, laminated form wherein various laminae form the staged amplifier portion of an operational amplifier and

other laminae form a supply pressure manifold, input network resistors and feedback network resistors.

In carrying out the objects of my invention, I provide a fluidic operational amplifier wherein the input resistor network includes fluid flow capacitors connected to the midpoint of the resistors. The device is of laminated form wherein a first group of laminae form the staged amplifier portion of the operational amplifier and a second group form a supply pressure manifold for supplying the proper power fluid pressures to the staged amplifiers. Additional laminae have narrow channels providing precise, predetermined feedback and input fluid resistance values and the various laminae are stacked such that aligned apertures therein provide fluid flow passages for a negative feedback signal and a control input signal undergoing the lag circuit transformation. The laminae are superposed between a cover plate and a base plate and retained in fluid-tight relationship. The fluidic capacitors connected in the input network are connected to the bottom side of the base plate. The base plate is provided with ports for supplying the control input signal to the input network, for obtaining the output of the lag circuit and for providing the power fluid to the supply pressure manifold. Small stabilizing capacitors connected to the output of the lag circuit are also connected to the bottom side of the base plate.

The features of my invention which I 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 drawings wherein like parts in each of the several figures are identified by the same character reference and wherein:

FIGS. 1, 3, 4, and 5 illustrate unassembled, assembled, and schematic views, and frequency response characteristics, respectively, of my laminated fluidic lag circuit component;

FIG. 2 illustrates an unassembled view of the "gain block" component of my fluidic lag circuit component;

FIG. 6 illustrates a schematic diagram of a fluidic oscillator application of my lag circuit wherein two lag circuits are connected in a closed loop; and

FIG. 7 illustrates a schematic diagram of a further use of my lag circuit component wherein the component sums two signals, one undergoing a lag transformation and the other merely amplified by the component.

Referring now in particular to FIG. 1, there is shown, in unassembled view, a plurality of laminae and fluidic capacitors superposed in their aligned position prior to assembly thereof in fluid-tight relationship to form the fluidic frequency-responsive lag circuit component in accordance with my invention. My laminated fluidic lag circuit component is another extension of the fluidic operational amplifier component described in detail in the aforementioned concurrently filed U.S. Pat. application Ser. No. 752,098 and in accordance therewith a detailed explanation of such operational amplifier will not be described herein. However, the forward circuit portion of the operational amplifier which is common to my lag circuit and comprises a gain block component providing a high forward gain is illustrated in unassembled view in FIG. 2.

The gain block includes (1) a staged amplifier section which in the particular illustrated embodiment comprises a plurality of five staged analog-type fluid amplifiers, and (2) a supply pressure manifold section for supplying the power fluid to each of the stages at different predetermined values of pressure. As stated in the concurrently filed U.S. Pat. application Ser. No. 752,098, the fluid amplifiers employed in the staged amplifier section are of the miniature type, having power nozzle widths of approximately 0.010 inch width or smaller, and the various fluid flow passages are also accordingly of smaller length and cross-sectional area.

Reference to the staged amplifier portion of the gain block indicates that each of the staged amplifiers comprises a parallel interconnection of several separated, miniature amplifier

elements having the fluid flow capacity rating of an equivalent larger size single element which structure thereby obtains a high signal-to-noise ratio. The staged fluid amplifiers are comprised of a plurality of superposed two different laminae, a first (flow pattern) lamina identified as AM-1 having formed therethrough a major part of the various fluid flow passages and a second (spacer) lamina identified AM-2 including the remainder of the fluid flow passages in overlapping relationship with respect to the corresponding passages in the first lamina.

The primary purpose of using the spacer laminae is to produce separate miniature fluid amplifier elements which are connected in parallel relationship to obtain the desired flow capacity rating, but they also result in all the laminae having greater structural rigidity and thus permit ease of handling in the assembly process. Alternate layers of flow pattern laminae and spacer laminae are employed, each layer of flow pattern laminae comprising one or more individual lamina as determined by the desired aspect ratio (height to width) of the power nozzle. Each lamina is preferably of equal thickness dimension. Generally, only one spacer lamina is employed in each layer thereof, although more can be used, as required by the circumstances.

The flow pattern lamina AM-1 includes an incomplete fluid flow path 39 between each fluid receiver and the associated control fluid inlet of the next succeeding stage, and an incomplete flow path 38 for each of the side vent passages. The spacer lamina AM-2 includes overlapping passages 39a for completing the receiver-to-control fluid inlet path in adjacent flow pattern laminae, apertures 40 aligned with the input ends of the power fluid inlets for supplying the power fluid to each amplifier stage, apertures 41 aligned with the input ends of the control fluid inlets of the first stage for supplying the control fluid input signal thereto, and aligned apertures 42 for interconnecting the outputs of the receivers of the last stage. The spacer lamina further includes small entrainment vent holes 21, 22 immediately adjacent the power nozzle along the upstream side of the side vent passages, aligned apertures 43 for interconnecting the center vent passages within each particular stage, and overlapping cutouts 44 for completing the flow paths in the side vent passages of adjacent flow pattern laminae. The small entrainment vent holes 21, 22 eliminate a particular instability which may occur in the normal operating pressure range of analog amplifiers due to the natural flow entrainment of the power jet and also obtain reduced noise and increased gain in the fluid amplifier. The asymmetrical flow pattern laminae are preferably stacked, as illustrated, in an alternate face-to-back and back-to-face arrangement to prevent generation of bias pressures. The various flow passages and holes may be formed through the laminae by any conventional method such as stamping, etching, or molding. The assembled laminae may be held together in fluid-tight relationship by any conventional means such as an adhesive material, bonding or screws.

For purposes of simplification, screw means for retaining the assembled device in fluid-tight relationship are not illustrated in FIGS. 1 and 2 but are shown in the assembled view in FIG. 3.

The laminated structure of a plurality of parallel interconnected, separated miniature fluid amplifier elements provides an especially low noise level component since the noise of the separate amplifier elements is not additive but is rather an average, or more correctly, the root-mean-square of the various noise levels. The reduced noise level permits the attainment of high signal-to-noise ratios whereby it is feasible to design high gain fluid amplifier blocks for high accuracy control systems which were not previously practical with the larger size power nozzle width of 0.020 inch or larger single element amplifiers. The miniaturization of each amplifier also provides improved frequency response due to the smaller transmission time through the smaller amplifiers. The redundancy of the paralleling technique enhances operating reliability from one to three orders of magnitude. An aspect

ratio of less than unity is preferred for increasing the signal-to-noise ratio of the fluid amplifier due to its increasing the effect of the boundary layer flow which provides more stable flow conditions thereby decreasing the noise level and increasing the signal-to-noise ratio. Finally, another advantage of the laminated, paralleled structure of miniature amplifiers is the reduced size of the overall component.

The internal supply pressure manifold section of the gain block is employed for supplying the desired power fluid pressures to the various amplifier stages while utilizing only one external connection to a power fluid source. The pressure manifold receives the power fluid supply at the fifth (last) stage power fluid inlet and manifolds it through a fluid flow resistive path to the succeeding four stages. The power fluid pressure ratio between each of the stages is an important factor in determining the amplifier characteristics of gain, saturation, linearity, and signal-to-noise ratio.

The staged amplifier portion of the gain block is illustrated in the lower part of FIG. 2 and includes a base plate 50, a single lamina designated SS-01, a plurality of alternated spacer laminae AM-2 and flow pattern laminae AM-1 and a single lamina designated SS-02. The various laminae, base plate and cover plate 51 have identical length and width dimensions and vary only in the thickness dimension. Thus, in a particular embodiment to be described, base plate 50 and cover plate 51 each have a thickness of one-eighth inch, width of twenty-one thirty-seconds inch, length of 1-9/16 inch and are both fabricated of anodized aluminum. Obviously, these plates could also be formed of other metals or other suitable materials such as a plastic. Base plate 50 has formed therethrough along the centerline axis of the gain block five equally spaced large size circular aperture ports 52 and five equally spaced small size circular aperture ports 43. Apertures 52 completely overlap the entrainment vent holes 21, 22 in the spacer laminae, and apertures 43 are aligned with center vents 43 therein. As mentioned above, a plurality (12 in this particular embodiment) of screw holes (not shown) are also formed through the base and cover plates and each lamina for retaining the gain block in fluid-tight relationship.

Lamina SS-01 is stacked on base plate 50 and has formed therethrough along the centerline axis five equally spaced large size apertures 54 elongated in the lamina width direction, and five equally spaced small circular apertures 43, spaced from apertures 54 and of size identical to and aligned with apertures 43 in base plate 50. Apertures 54 and 52 (in base plate 50) are also aligned and apertures 52 completely overlap apertures 54. Lamina SS-01 and each of the other laminae in the staged amplifier portion of the gain block are 0.004 inch thick and fabricated of stainless steel ASTM No. 304. The laminae may obviously be fabricated from other suitable materials such as beryllium copper and the like, as desired. A convenient method of manufacturing all of the laminae is by chemical milling. The choice of 0.004 inch thick laminae has been found to be convenient as a particular embodiment, however, thicknesses greater and less than this value may readily be employed. The plurality of alternate spacer AM-2 and flow pattern AM-1 laminae are next stacked on lamina SS-01 having a spacer lamina AM-2 in contact with lamina SS-01. The particular plurality of laminae is determined by the desired fluid flow capacity rating of the gain block. Symmetrical laminae AM-2 are also alternately stacked face-to-back and back-to-face to average out geometry in etching imperfections which could influence the fluid flow field and thereby virtually eliminate the generation of unwanted bias pressures and other undesirable effects. In general, "n" flow pattern laminae AM-1 and "n + 1" spacer laminae AM-2 are employed, the particular illustrated embodiment employing nine spacer laminae AM-2 and eight flow pattern laminae AM-1 superposed as shown. The staged amplifier portion of the gain block is completed by a lamina SS-02 stacked on the topmost spacer laminae AM-2. Lamina SS-02 includes five equally spaced apertures 40 located on the centerline axis and aligned with and of equal size as aper-

tures 40 in the AM-2 laminae. Lamina SS-02 also includes a first pair of square apertures 57 aligned with apertures 41 in the AM-2 laminae, and a second pair of square apertures 58 (both pairs may also be circular) aligned with apertures 42 in the AM-2 laminae, each pair symmetrically disposed about the centerline axis.

The stacking of the elements in the staged amplifier portion of the gain block in the order recited as indicated above and illustrated in FIG. 2, that is, base plate 50, lamina SS-01, alternate " $n + 1$ " AM-2 and " n " AM-1 laminae, and lamina SS-02 provides the following communication between the laminae and base plate. The side entrainment vent holes 21, 22 in spacer laminae AM-2 are provided with passage to ambient through lamina SS-01 and base plate 50 by means of apertures 54 and 52, respectively. In like manner, the center vent apertures 43 in laminae AM-2 are provided with passage to ambient through lamina SS-01 and base plate 50 by means of apertures 43. All other fluid pressures (control input signal, amplified output, and power fluid supply) are dead ended from the base plate by lamina SS-01. However, it may be noted that base plate 50 and lamina SS-01 have similar, coincident apertures, and therefore lamina SS-01 is not a necessary element but is used as a convenience to separate the staged amplifiers from the base plate. Also, vent holes 21, 22, and 43 are dead ended from the supply pressure manifold by lamina SS-02. Lamina SS-02 also dead ends the control signals after the first stage from the supply pressure manifold. The control input signal to the first stage is supplied via the supply pressure manifold through apertures 57 in lamina SS-02, and the amplified output signal from the fifth stage is provided through apertures 58 in lamina SS-02 to the supply pressure manifold. The dimensions of aligned apertures are generally made identical, or nearly so, for reducing fluid flow resistance therethrough. Finally, apertures 40 in lamina SS-02 supply the predetermined different power fluid supply pressure to each staged amplifier.

The supply pressure manifold is constructed of a top cover plate 51 (in the case wherein the gain block is used as a separate component) and a plurality of alternately superposed laminae designated SS-72 and SS-71 of equal number. Cover plate 51 includes a pair of circular apertures (ports) 42, aligned with apertures 42 in laminae AM-2 and apertures 58 in laminae SS-02 and comprise the output terminals of the gain block, and a pair of circular apertures (ports) 41 aligned with apertures 41 in laminae SS-72, SS-71, AM-2 and apertures 57 in laminae SS-02 and comprise the input terminals. Thus, the control input signal is supplied to the first stage amplifier by means of ports 41 in cover plate 51 and the amplified output of the fifth stage is available at ports 42 in the cover plate. A fifth port 61 in cover plate 51 is positioned along the centerline axis for supplying the pressurized power fluid to the gain block last stage.

Laminae SS-72 each include five equally spaced apertures 40 along the centerline axis and of the same size and configuration (for uniformity in manufacture) as apertures 40 in lamina SS-02 and are aligned therewith. Laminae SS-72 also include a pair of circular apertures 41 of size equal to apertures 41 in cover plate 51 and aligned therewith for supplying the control input signal to the first stage amplifier. Laminae SS-72 also include a first pair of symmetrical wide channels 64 having first ends thereof aligned with the gain block output ports 42 in cover plate 51. Laminae SS-72 also include a second pair of symmetrical wide channels 66 and three pairs of symmetrically disposed square apertures 67, 68, and 69. It should be understood that for economy of manufacture, a minimum number of different type laminae are produced and thus various apertures and channels may not be used in the gain block (as in the case of apertures 67, 68, 69 and channels 64, 66 in laminae SS-72) but have use in other components such as the operational amplifier to be subsequently described. Laminae SS-71 have the same apertures and channels as laminae SS-72 except for a centerline axis channel 65 of length and width sufficient to overlap apertures 40 in

laminae SS-72. The effective height dimension of center channel 65 is varied by the alternate stacking of SS-71 laminae using the SS-72 laminae as separators. The effective height of channel 65 determines the fluid flow resistance to, or pressure drop of, the power fluid in passing from the fifth stage end aligned with power fluid inlet supply port 61 to the fourth, third, second, and finally the first stage which is at the lowest pressure level. The SS-71 laminae are fabricated in both 0.004 inch and 0.002 inch thicknesses to obtain a greater combination of fluid flow resistances whereas separator laminae SS-72 are each of 0.004 inch thickness only. A preferred stacking arrangement for the particular manifold embodiment herein described and illustrated in FIG. 2 utilizing a pressurized power fluid source of 10 p.s.i.g. includes in the order as illustrated in FIG. 2, four pairs of alternately superposed SS-72 and SS-71 laminae wherein each SS-71 lamina is of 0.002 inch thickness, and two additional pairs of alternately superposed SS-72 and SS-71 laminae wherein each SS-71 lamina is of 0.004 inch thickness. Thus, an SS-72 lamina is in contact with cover plate 51 and an SS-71 lamina is in contact with lamina SS-02 in the staged amplifier portion of the gain block.

Referring now to FIG. 3, there is shown my fluidic lag circuit component including the gain block component of FIG. 2 after assembly, and further shows 12 fillister head type machine screws 70 which in one particular embodiment are of size 00-80 for retaining the various laminae and cover plate 50 in fluid-tight communication with a base plate 100. The 12 holes through which screws 70 are fitted comprise five pairs equally spaced in the longitudinal direction and a sixth pair at the furthest end of the component as viewed in the illustration more greatly spaced from the fifth pair to prevent incorrect (backward) superposition of any lamina. The various laminae, and base and cover plates, may be assembled in any suitable manner such as by inserting dowels through two of the diagonal corner screw holes to align the various members during the stacking procedure, and then inserting and tightening the first 10 screws 70. The means for providing communication between the inlet and outlet ports in base plate 100 and external fluid conduits (tubing) may comprise any suitable fittings fastened or connected within the ports. The overall dimension of the gain block component illustrated in FIG. 2 including the cover and base plates and 31 laminae therebetween is 1 9/16 inch long, twenty-one thirty-seconds inch wide, and three-eighths inch thick (height dimension).

The operation of the gain block component may be summarized as follows. A differential pressurized control input signal $\Delta P_c = P_{c1} - P_{c2}$ is supplied through ports 41 in cover plate 51 in FIG. 2 to the first stage fluid amplifier 59 and the amplified differential pressurized output signal $\Delta P_o = P_{o1} - P_{o2}$ is available at ports 42 corresponding to the output of the fifth stage amplifier 60. The power fluid supply pressure P_s is supplied to port 61 and is distributed to the power fluid inlet of each amplifier stage at a particular pressure by means of the internal supply pressure manifold whereby a fluid flow resistance is generated across each section of channel 65 in combined laminae SS-71, 72. Each of the amplifiers has a power nozzle width of 0.010 inch and relatively high forward gains G of 2,000 are readily obtained with the five-stage amplifier.

The gain block component is an element of "integrated circuit" components, and in particular is a component of my fluidic lag circuit component to be described hereinafter. Such components have the following advantages, the containment of all the staged amplifiers and the supply pressure manifold in a single structure minimizes the plumbing and interconnection of elements which otherwise would be employed and would require time consuming labor as well as resulting in reduced reliability due to possible leakage at the points of interconnection. The integrated circuit approach results in a great saving of space requirements, increased reliability due to shortened paths between adjacent amplifiers, and improved frequency response.

The first logical extension of the fluidic gain block component is its utilization in a fluidic proportional operational amplifier component which is an element of my lag circuit component. The operational amplifier is essentially a gain block (comprising active staged fluid amplifiers) and the addition of passive fluidic feedback resistors for obtaining a closed loop circuit and an input circuit comprising fluidic input resistors. Due to the high gain which may be achieved with the operational amplifier, passive fluidic stabilizing capacitors are connected at the operational amplifier output to prevent unstable operation of the operational amplifier. It is well known in control system (servomechanism) theory that the closed loop gain for a negative feedback circuit exemplified by the operational amplifier reduces to a mathematical expression (transfer function) of the form:

$$\frac{\Delta P_o}{\Delta P_i} = \left[\frac{R_f}{R_i} \frac{1}{1 + \tau s / (1 + GH)} \right]$$

when the open loop gain GH is substantially greater than 1, which it is in typical operational amplifier cases. In the equation,

s is the Laplace operator $\frac{d(\)}{dt}$. This closed loop

expression indicates that the circuit gain is independent of the gain block forward gain G (except as a time constant consideration), and is dictated by the passive negative feedback and input resistive components R_f and R_i , respectively. Since these feedback and input fluidic resistors are stable and remain fixed, it is evident that the closed loop gain also remains constant regardless of changes in gain G of the gain block active component. The stabilizing capacitors C_s comprise a pair of small fixed volumes and the stabilizing volume requirement is determined by the open loop gain GH and varies directly therewith. It cannot be too strongly stressed that the frequency response (gain and phase lag vs. frequency) which is indicated mathematically in the above equation and graphically (for the lag circuit) in the Bode diagram of FIG. 5 is the most significant factor in indicating both steady state and transient (dynamic) performance of the operational amplifier circuit, and of frequency responsive circuits in general.

The frequency response of the operational amplifier portion of the lag circuit is excellent since the break frequency

$\left[\frac{1 + GH}{\tau} \right]$ therefore occurs, in general, beyond 1000 radians

per second. Thus, the operational amplifier provides its fixed

gain $\frac{R_f}{R_i}$ characteristic over a very wide frequency range

of control input signals.

Returning now to the description of FIG. 1, the laminae below the last lamina SS-72 of the gain block comprise, reading from top to bottom, separator laminae designated SS-13, negative feedback resistor lamina UHA-1, an additional separator lamina SS-14, resistor separating laminae SS-17, input resistor lamina UHA-4, separator lamina SS-11 and base plate 100. All of the laminae have the same length and width dimensions as the laminae in the gain block.

The laminae each have formed therethrough the same five equally spaced and aligned apertures 40 located on the centerline axis as provided on laminae SS-72, SS-02, and AM-2 in FIG. 2, although only one of these five (power fluid supply) apertures is utilized. These laminae also include four pairs of equally spaced and aligned square apertures symmetrical about the centerline axis, only three pairs 69, 74, 75 being utilized in the lag circuit. Separator laminae SS-13, SS-14, SS-11 and resistor separating laminae SS-17 each also include a pair of summing junction apertures 77a and 77b symmetrically disposed about the centerline axis. Finally, separator lamina SS-11 additionally includes two pairs of square apertures 76 and 78 symmetrically disposed about the centerline axis and laminae SS-13 include apertures 76.

Passages 64 in gain block lamina SS-72 channel the gain

block output ΔP_o from the last stage amplifier output to the input of the stabilizing capacitors and the output ports of the lag component. Thus, the gain block output is supplied to the outer ends of channels 64, passes through such channels to the inner ends 64a thereof and then downward through passages formed by aligned apertures 74 in the laminae superposed below lamina SS-72. Apertures 74 are aligned with channel ends 64a and with circular holes 90a, 91a formed through base plate 100 to thereby transmit the gain block output (which is also the lag circuit output ΔP_o) into the stabilizing capacitors C_s connected to the bottom surface of base plate 100. Stabilizing volumes C_s are connected to the bottom of base plate 100 by any suitable means such as by forming grooves in the bottom surface of the base plate 100 and soldering the open ends of volumes C_s within such grooves, or, by passing a screw through the bottom closed end of each volume upward into the bottom surface of the base plate. Suitable passages interconnect holes 90a and 90b with the ports 90 and 91, respectively, in base plate 100. The output of the stabilizing capacitors (the negative feedback signal) passes upward through holes 90b, 91b in base plate 100, aligned apertures 75 in laminae SS-11, UHA-4, SS-17, SS-14, UHA-1 and SS-13 and finally into the inner ends of channels 66 in supply pressure manifold lamina SS-72. In lamina SS-72, the feedback signal passes to the outer ends of channels 66 and then downward through aligned apertures 76 in laminae SS-13 and UHA-1. In lamina UHA-1, the negative feedback signal is dead ended by lamina SS-14 and thus passes through the negative feedback resistors ($-R_f$) defined by outer passages 80. At the second (output) ends of the feedback resistors (in apertures 79) the negative feedback signal is summed with the control input signal and passes upward through summing junction apertures 77a, 77b in laminae SS-13 and into the input of the gain block via apertures 41 in lamina SS-72. It should be understood that the output ΔP_o of my lag circuit may also be obtained at the outputs of the stabilizing capacitors C_s with virtually no change in operating characteristics.

Referring now to the resistor laminae, feedback resistor R_f lamina UHA-1 includes four matching fluidic resistors each comprised of a single very narrow capillary type passage extending for a length of 1.25 inches and having a width of 0.005 inch. The UHA-1 lamina may be of 0.002 or 0.004 inch thickness whereby each resistance passage provides 995 or 237 pound-seconds per inch⁵ resistance, respectively. All resistances herein cited are with air as the pressurized fluid medium at a temperature of 70°F. Due to the extreme narrowness of the resistance passages in lamina UHA-1, the resistance passages terminate in symmetrically disposed square apertures (76 and 78 at the input ends, and 79 at the output ends) for providing negligible fluid flow resistance in a vertical direction. Thus, apertures 79 provide a negligible resistance between the adjacent aligned summing junction apertures 77a and 77b in separator laminae SS-13 and SS-14. The input resistor R_i lamina UHA-4 has four equal resistance passage widths of 0.035 inch (and effective length of 1.25 inches) to provide an accordingly lower fluid flow resistance of 108 and 20.4 pound-seconds per inch⁵ for lamina thickness of 0.002 and 0.004 inch, respectively. Due to the substantially wider dimension of the resistance passages 81 in lamina UHA-4, no terminating apertures are required as in the case of the UHA-1 lamina. Resistance passages 81 have their input ends aligned with apertures 76, 78 in separator lamina SS-11 and their output ends aligned with summing junction apertures 77a, 77b in resistor separating lamina SS-17 (and SS-11). Thus, the pairs of passages 81 nearest and furthest from the viewer of FIG. 1 have their second (output) ends aligned with summing junction apertures 77a and 77b, respectively.

My laminated fluidic lag circuit component shown in unassembled view in FIG. 1 may be supplied with a single differential pressurized control input signal ΔP_i or may be supplied with two differential input signals ΔP_{iA} and ΔP_{iB} . In either event, the same number of laminae may be employed. The operation of the operational amplifier portion of my

fluidic lag circuit will now be described with reference to a single control input signal ΔP_i being supplied thereto.

All of the input and output signals and power fluid are supplied to the operational amplifier (and the lag component) through ports in the side of base plate 100. Thus, the power fluid is supplied through a port 92 connected by means of a drilled passage in base 100 to a hole 92a extending through the upper surface of base plate 100. Hole 92a is aligned with the centerline axis aperture 40 nearest the viewer in each of the superposed laminae from lamina SS-11 to SS-72 and thus provides the power fluid supply pressure directly to the fifth stage fluid amplifier in the gain block. In like manner, a first pair of control input signal ports 95 and 96 are formed on the side of base plate 100 opposite the power fluid supply port 92 and by means of drilled passages the differentially pressurized control input signal ΔP_i is supplied to holes 95a and 96a through the upper surface of the base plate in alignment with apertures 76 in lamina SS-11 and the input ends of the two outer input resistor passages 81 in lamina UHA-4. Thus, the control input signal ΔP_i passes from the input ports 95, 96 through apertures 76 in SS-11 and then through the outer passages 81 in the input resistor lamina UHA-4 due to the dead ending effect of laminae SS-17. At the output ends of the outer resistor passages 81, the signal then passes upward through the summing junction apertures 77a and 77b in laminae SS-17 and SS-14 and through resistance terminating apertures 79 in lamina UHA-4 (for summing with the negative feedback signal), the summing junction apertures in laminae SS-13, and finally through apertures 41 and in the supply pressure manifold laminae to be supplied to the first stage fluid amplifier. This completes the various paths traversed by the input, output, and feedback signals and power fluid supply in my fluidic lag circuit component which are also common to the proportional operational amplifier component.

As indicated in the schematic diagram of my lag circuit in FIG. 4, each input resistor R_i is separated into two equal resistance portions $\frac{R_i}{2}$ having the lag time constant determining volume (capacitor C_L) interposed therebetween. This

proportioning or separating of the input resistor is accomplished by utilizing resistor separating laminae SS-17 which have formed therein wide apertures 69a aligned with apertures 69 in the various laminae, apertures 69 being dead ended in an upward direction by lamina SS-02 in the gain block as illustrated in FIG. 2. Apertures 69a are of width sufficient to overlap the outer resistance passages, at the effective midpoint thereof, in the adjacent UHA-4 lamina. Thus, the control input signal in passing through the outer resistance passages 81 in the input resistor lamina UHA-4 (from left to right as seen by the viewer) is diverted by apertures 69a in laminae SS-17 downward through apertures 69 in lamina SS-11 through the base plate holes 103 and 104 into the lag time constant volumes C_L , and thence upward along the same paths to the output (right) ends of resistor passages 81, and thence upward through the summing junction apertures for summation with the negative feedback signal. It should be noted that volumes C_L are each provided with a common input-output passage as distinguished from the separate passages at stabilizing capacitors C_s .

In the case wherein a fluid signal passes horizontally in a separator lamina such as in the summing junction apertures 77a, 77b, the height of such apertures (which form an effective channel) should be sufficient to prevent the channel from becoming an effective orifice and contributing additional fluid flow resistance. Thus, the summing junction apertures are made negligibly resistive to fluid flow by stacking three of such laminae together, as illustrated. All of the laminae are of 0.004 inch thickness except that the resistor lamina are also available in 0.002 inch thickness to obtain a greater variety of resistance values. Various other types of passive resistance laminae of the UHA-X type as described in the concurrently filed application Ser. No. 752,098 may also be utilized in place

of the UHA-1 or UHA-4 laminae to obtain the desired fluid flow resistance for the feedback resistance R_f and input resistance R_i , respectively. It should be understood that all of the fluidic resistors in the UHA-X series of laminae are linear resistors, the laminar flow obtained through the resistor passages providing fluid flow resistance linearly proportional to the difference in pressure across each passage.

FIG. 3 illustrates a perspective view of my assembled lag circuit component indicating its compactness and ease of connection to external conduits or tubing for the control input signals, output and supply pressure. The lag circuit component described in FIG. 1 has the following dimensions after assembly, base plate 100 has a width of 2-5/16 inch and maximum length of 3 3/4 inch, and the overall height dimension from the bottom of the volumes C_L to the top of the gain block is approximately 3 1/4 inch. The dimension from the top of the gain block to the bottom of the base plate is approximately three-fourths inch. The bottom face of base plate 100 is provided with suitable means for connecting the stabilizing capacitors C_s and lag time constant capacitors C_L thereto. The stabilizing volumes are of size generally in the range 0.10 to 0.50 cubic inches and the lag time constant volumes are considerably larger and generally in the range 1.0 to 5.0 cubic inches. The capacitors comprise fixed volumes such as metallic cans of rectangular cross section, each having an open end which fits against the bottom face of the base plate. As another example of the means for connecting the capacitors to the base plate, depressions are formed within the bottom surface of the base plate over the entire area covered by the open end of the fixed volumes and the capacitor open ends are fitted within the depressions and the capacitors retained in fluid-tight communication therewith by means of a screw threaded into the base plate. The ports in base plate 100 may be internally threaded, if desired, for utilizing a screw type of external conduit connection.

FIG. 4 illustrates a schematic diagram of my lag circuit which, in the absence of the lag time constant capacitors C_L , would be the proportional operational amplifier described and claimed in the concurrently filed application Ser. No. 752,098. The lag circuit comprises (1) an input circuit including fluidic linear resistor R_i having lag time constant capacitor C_L interposed between the midpoints of resistor R_i , and (2) a closed loop circuit comprising (a) a forward gain circuit of the

gain block having a gain G and a time constant factor $\frac{1}{1+\tau s}$,

where τ is natural "RC" time constant of the circuit including the effect of the stabilizing capacitors C_s , the amplifier output resistance and load resistance of the lag circuit, and the feedback resistance R_f and (b) a negative feedback network which includes the effect of the feedback resistance as well as the control port resistance and to a lesser degree, the input resistance R_i . The closed loop gain for my lag circuit is expressed by the transfer function

$$\frac{\Delta P_o}{\Delta P_i} = \left[\frac{R_i}{R_i} \frac{GH}{1+GH} \right] \left[\frac{1}{1 + \frac{R_i C_L s}{4}} \right]$$

which can be approximated by the following expression when the open loop gain GH is substantially greater than 1, typical values of open loop gain being 20 to 50, although this no limiting range. The approximated equation becomes

$$\frac{\Delta P_o}{\Delta P_i} = \left[\frac{R_f}{R_i} \frac{1}{1 + \frac{R_i C_L s}{4}} \right]$$

where "S" is again the Laplace operator.

The latter equation indicates that the circuit gain is substantially independent of the forward gain G and is dictated by the passive resistive components R_f and R_i . Since these feedback and input fluidic resistors are stable and remain fixed, it is evident that the closed loop gain also remains constant regardless of changes in gain G of the gain block component.

The approximated equation can be represented in simplified form $\frac{\Delta P_o}{\Delta P_i} = \frac{K}{1+\tau s}$ where τ is the lag break time constant

$$\frac{R_i C_L}{4} \text{ and } K \text{ is the circuit gain constant } \frac{R_f}{R_i}.$$

The frequency response of my laminated fluidic lag circuit component is illustrated in the Bode diagram of FIG. 5 which is a plot of closed loop gain $\frac{\Delta P_o}{\Delta P_i}$ in decibels (db) and

phase lag in degrees versus control input signal frequency in radians per-second. The break frequency (frequency at which the gain is initially attenuated at 20 db per decade) is $\omega = \frac{1}{\tau}$.

The specific Bode diagram illustrated in FIG. 5 represents a lag circuit having the transfer function $\frac{\Delta P_o}{\Delta P_i} = \frac{3.1}{1+s}$,

that is, where $K=3.1$ (which equal 10 db) and $\tau=1.0$ second. The 1.0 second time constant can be obtained with capacitors C_L of five cubic inch volumes and input resistances each of 17 pound-seconds per inch⁵.

My fluidic lag circuit component is seen to be a combination of an active gain block element and passive elements comprising an input and feedback resistors and capacitors integrally packaged in a closed loop circuit. The Bode diagram indicates that the particular R_f-C_L network functions as the input circuit to the lag circuit component and also achieves a frequency-responsive lag function without attenuation, this latter feature being apparent from the Bode diagram wherein the initial attenuation begins only after the lag break. It is also apparent that my fluidic lag circuit spans the time constant gap between a simple fluid flow resistor-capacitor network which obtains relatively small time constant in the order of 0.01 seconds and the positive-negative feedback operational amplifier approach which achieves long lag time constants in the order of 5-60 seconds. The lag circuit time constants associated with my lag circuit are generally in the range of 0.1 to 1 second, it being recognized that the time constant may be varied by varying the input resistors or capacitors C_L , the time constant being increased by increasing the resistances and capacitances. Thus, my lag circuit performs the mathematical computation of integration over the frequency range of control input signals from the lag break determined by $1/\tau$ to the second lag break determined in part by the stabilizing capacitor which is generally in the order of 1,000 radians per second.

The characteristics of my lag circuit may be summarized as follows. The circuit provides a moderate time constant of up to 1.0 second which obviously can be increased most simply by the expedient of employing larger capacitors C_L . Further, the circuit provides a gain up to 5.0 with the circuit constants hereinabove described, such gain obviously also being able to be increased by the proper choice of feedback and input resistors. Finally, the circuit provides a linear output pressure range (output pressure ΔP_o varies linearly with the input signal pressure ΔP_i) of up to ± 15 p.s.i. for power fluid supply pressures of up to 30 p.s.i.g. The circuit also features very low drift and is virtually insensitive to power fluid supply pressure changes and independent of variations in lag circuit load due to the fixed gain of the operational amplifier portion of the lag circuit.

There are several applications and uses for my fluidic lag circuit. In addition to the integrator computation application hereinabove-described, the lag circuit finds considerable use in control systems for providing desired frequency-response shaping as is apparent from the Bode diagram to thereby obtain a particular dynamic response from the control system.

FIG. 6 illustrates another application of my lag circuit wherein two of these circuits are connected in a closed loop to form a fluidic oscillator. Thus, a first lag circuit depicted within the dashed lines and identified as a whole by numeral

10 has its two output terminals connected to the input terminals of a second, and identical, lag circuit 11. In like manner, the output terminals of the second lag circuit 11 are cross-connected to obtain polarity reversal to the input terminals of circuit 10 to thereby form a closed loop. As indicated in the Bode diagram of FIG. 5, each lag circuit contributes a 90° phase shift and has a gain greater than unity such that the particular interconnection of the two lag circuits into a closed loop accumulates the necessary 180° of phase shift to obtain a condition of instability for oscillation. The oscillatory

frequency of the closed loop is approximately $\frac{10}{\tau}$ where

$$\tau = \frac{R_i C_L}{4} \text{ and is more precisely defined at the}$$

frequency where 180° of phase shift are accumulated in the closed loop (i.e., 90° for each lag circuit). The output terminals of the oscillator, that is, the pickoff points, are at alternate capacitors C_L in the input circuits of the two lag circuits as indicated by the lead lines terminating in the output designation P_o . The oscillator frequency may be changed most simply by changing the values of the volumes of capacitors C_L .

Another application of my lag circuit component is illustrated schematically in FIG. 7 wherein the component sums two control input signals, one of which (ΔP_{iA}) undergoes the lag transformation and the other signal (ΔP_{iB}) is merely amplified by the component. The operational amplifier portion of my lag circuit has an inherent accurate summing ability as described in the concurrently filed application Ser. No. 752,098. A second control input signal ΔP_{iB} supplied to input ports 93 and 94 in base plate 100 passes through apertures 78 in lamina SS-11 and then through the inner resistance passages of lamina UHA-4 which are not overlapped by apertures 69a in laminae SS-17. Thus, the second input signal is not in communication with capacitors C_L and is summed with the first input signal in summing junction apertures 77a and 77b in laminae SS-17. In the most general case the input resistors R_{iA} and R_{iB} in the first and second control input signal networks need not be equal and the generalized transfer function for this circuit is

$$\Delta P_o = \Delta P_{iA} \frac{R_f}{R_{iA}} \left[\frac{1}{1 + \frac{R_{iA} C_L S}{4}} \right] + \Delta P_{iB} \frac{R_f}{R_{iB}}$$

thus, a single component as illustrated in FIG. 7 can be employed to amplify and sum two signals one of which is transformed with a lag and the other without such transformation.

In view of the foregoing description, it is believed that the objects of my invention have been clearly attained. In particular, I have provided a laminated fluidic lag circuit which spans the time constant gap between a simple fluid flow resistor-capacitor network and much larger time constants produced by the positive feedback operational amplifier approach. Further, I have provided a relatively simple lag circuit utilizing operational amplifier techniques which does not cause any attenuation of the control input signal prior to the lag break of the lag circuit. Finally, my lag circuit is a compact device having extremely small dimensions and is capable of withstanding extreme environmental conditions of shock, vibration, nuclear radiation and high temperature and since it has no moving mechanical parts, it has a substantially unlimited lifetime thereby achieving long periods of uninterrupted operation. The operating characteristics of my lag circuit are found to be far superior to any other existing fluidic lag circuit component, primarily due to the much lower noise level obtained with the parallel interconnected miniature amplifier elements in the gain block portion thereof. The compactness of the device permits very short internal fluid flow passages thereby minimizing undesirable time delays and obtaining improved frequency response.

I claim:

1. A laminated frequency-responsive fluidic component having no moving mechanical parts and characterized by com-

pactness, low noise level, high signal-to-noise ratio and excellent frequency response comprising:

- a cover plate;
- a base plate;
- a first plurality of laminae superposed between the cover and base plates and comprising a staged amplifier section and a supply pressure manifold section forming a fluidic gain block component; and
- a second plurality of laminae superposed between said cover and base plates and comprising:
 - first laminae means having narrow channels formed therethrough for providing predetermined passive linear resistances to fluid flow therethrough to form fluidic input resistors R_i and negative feedback resistors R_f ;
 - second laminae means for isolating the input and feedback resistors and the gain block and for forming a part of input and negative feedback circuits respectively including said input and feedback resistors to thereby form a fluidic operational amplifier component having

a substantially fixed gain $\frac{\Delta P_o}{\Delta P_i} = \frac{R_f}{R_i}$ deter-

mined by the passive resistors; and

- a third plurality of laminae superposed between said base and cover plates, and fixed volumes, for providing selected fluidic impedances in the input circuit of said operational amplifier to thereby convert the operational amplifier to a frequency responsive lag-type fluidic component, said first, second, and third plurality of laminae and said cover and base plates retained in fluid-tight relationship.

2. The laminated frequency-responsive fluidic component set forth in claim 1 and further comprising a second pair of fixed volumes for providing passive capacitances to fluid flow therethrough, said second pair of volumes in communication with the output of said lag component for preventing unstable operation thereof.

3. The laminated frequency-responsive fluidic component set forth in claim 1 wherein:

said third plurality of laminae are provided with aperture means for separating the resistances of said input resistors into two parts; and

said fixed volumes comprise a first pair of fixed volumes for providing passive capacitances to fluid flow therethrough, said first pair of fixed volumes in communication with said third plurality of laminae forming a pair of series circuit input impedances each comprising the two parts of the input resistor R_i and one of said first pair of volumes interposed therebetween to form the frequency-responsive lag type fluidic component.

4. The laminated frequency-responsive fluidic component set forth in claim 1 wherein said staged amplifier section comprises:

third laminae means having fluid flow passages formed therethrough defining parallel interconnected, separated, miniature size fluid amplifiers forming a high gain, high signal-to-noise ratio, multistage fluid amplifier component, said supply pressure manifold section comprising: fourth laminae means having formed therethrough a plurality of apertures equal in number to the number of staged amplifiers and overlapping channels for determining fluid flow resistance to power fluid flowing therethrough and thereby determining different predetermined pressures of the power fluid supplied to the stages of fluid amplifiers; and

said cover and base plates in combination provided with ports for supplying a control fluid input signal ΔP_i to the first stage fluid amplifier, for supplying power fluid to the last stage fluid amplifier, for supplying the fluidic lag component output ΔP_o externally thereof, and for venting the fluid amplifiers.

5. The laminated frequency-responsive fluidic component set forth in claim 4 and further comprising:

- a second pair of fixed volumes for providing passive capacitances to fluid flow therethrough, said second pair of volumes in communication with the output of the last stage amplifier for preventing unstable operation of the lag type fluidic component; and

said first, second, and third plurality of laminae each being of small dimension approximately $1 \frac{1}{2}$ inch long, two-third inch wide and of thickness in the range 0.001 to 0.010 inch for a five-stage amplifier fluidic gain block component, the power nozzle width of each amplifier approximately 0.010 inch or smaller, the small dimensions permitting very short internal fluid flow passages thereby minimizing undesirable time delays and obtaining improved frequency response compared to conventional larger size fluid amplifiers, the parallel interconnected, separated, miniature size fluid amplifier structure obtaining improved signal-to-noise ratio and reduced noise level compared to conventional size fluid amplifiers, the multistage amplifiers supplied with different predetermined power fluid pressures thereby obtaining a high forward gain G for the fluidic gain block component.

6. A laminated frequency-responsive lag type fluidic component having no moving mechanical parts and characterized by compactness, low noise level, high signal-to-noise ratio and excellent frequency response and comprising: a cover plate; a base plate; a first plurality of laminae superposed between said cover and base plates and comprising a staged amplifier section and a supply pressure manifold section forming a fluidic gain block component, said staged amplifier section comprising: a plurality of first different laminae each having formed therethrough a major part of the fluid flow passages defining a plurality of serially connected analog-type fluid amplifiers each including a power fluid nozzle, a pair of control fluid nozzles, a pair of fluid receivers, and vent passages; a plurality of second different laminae each having formed therethrough at least the remainder of said passages in overlapping relationship with respect to the corresponding passages in said first laminae, said second laminae functioning as spacer members between said first laminae to form parallel interconnected, separated, miniature size fluid amplifiers, said first and second laminae forming a high gain, high signal-to-noise ratio, multistage fluid amplifier component; and said first and second laminae superposed between said cover plate and a third different lamina functioning as an isolator between said staged amplifier section and said supply pressure manifold section; said supply pressure manifold section comprising: a plurality of alternately superposed fourth and fifth different laminae, said fourth laminae each provided with a plurality of apertures equal in number to the plurality of serially connected amplifiers and aligned with the inputs to the power fluid nozzles thereof; said fifth laminae each provided with a channel in overlapping relationship with said plurality of apertures, the effective height dimension of the channel formed by the plurality of superposed fourth and fifth laminae determining the fluid flow resistance to power fluid flowing therethrough and thereby determining a different particular pressure of the power fluid supplied to each stage fluid amplifier; said cover plate provided with ports aligned with said vent passages in said fluid amplifiers, said base plate provided with: an input port in communication with the input to the power fluid nozzle of the last stage fluid amplifier for supplying power fluid from an external source thereto; a pair of input ports in communication with the input to the control fluid nozzles of the first stage fluid amplifier for supplying a control fluid input signal ΔP_i thereto; and a pair of output ports in communication with the output of the receivers of the last stage fluid amplifier for supplying the fluidic lag component output ΔP_o externally thereof; a second plurality of laminae superposed between said base plate and said supply pressure manifold section and comprising: laminae each having formed therethrough at least one pair of equally dimensioned narrow

channels of predetermined length and width for providing predetermined passive linear resistances to fluid flow therethrough, at least one of the linear resistances laminae forming fluidic input resistors R_i , and at least another of the linear resistances laminae forming fluidic negative feedback resistors R_f ; and a plurality of sixth different laminae superposed between the negative feedback resistors lamina and said supply pressure manifold section for isolation thereof, and between the negative feedback resistors lamina and the input resistors lamina for isolation thereof, said plurality of sixth laminae forming a part of input and negative feedback networks in communication with said gain block component, and providing for the summation of the control fluid input signal and negative feedback signal after respective passage through the input and feedback resistors to thereby form a fluidic

operational amplifier component having a fixed $\frac{\Delta P_o}{\Delta P_i} = \frac{R_f}{R_i}$

gain determined solely by the passive resistors for high values of forward gain G of the gain block to thereby provide a fixed linear gain substantially independent of variations in the fluidic lag component load or in the power fluid supply pressure; a first pair of fixed volumes for providing passive capacitances to fluid flow therethrough, said volumes connected to said base plate and in communication with the output of the receivers of the last stage amplifier for preventing instability of the fluidic lag component; and additional laminae means superposed between said base plate and said supply pressure manifold section, and a second pair of fixed volumes, for providing selected fluidic impedances in the input circuit of said operational amplifier to thereby convert the operational amplifier to a frequency-responsive lag type fluidic component, said first and second plurality of laminae and said additional laminae means retained in fluid-tight relationship between said base and cover plates.

7. The laminated frequency-responsive lag type fluidic component set forth in claim 6 wherein:

said additional laminae means comprise laminae provided with overlapping apertures for separating the resistances of said input resistors into two parts; and said second pair of fixed volumes connected to said base plate and in communication with said input resistors for forming said selected input circuit fluidic impedances comprising a pair of series circuit impedances each comprising the two parts of the input resistor and one of said second pair of volumes interposed therebetween to form the frequency-responsive lag type fluidic component.

8. The laminated fluidic component set forth in claim 6 and further comprising: said base plate provided with a second pair of input ports in communication with the input to the control fluid nozzles of the first stage fluid amplifier for supplying a second control fluid input signal ΔP_{iB} thereto, said input resistors lamina having formed therethrough a second pair of equally dimensioned narrow channels of predetermined length and width for providing a second pair of passive linear input resistors R_{iB} , said second pair of resistors R_{iB} being operatively independent of said additional laminae means and thereby independent of the lag transformation whereby the first control input signal ΔP_i supplied to said input resistors R_i of said lag component undergoes the lag transformation and the second control input signal ΔP_{iB} supplied to said input resistors R_{iB} of the component is merely amplified thereby, said operational amplifier component providing an accurate summing function whereby said lag component provides an output

$$\Delta P_o = \Delta P_i \frac{R_f}{R_i} \frac{1}{1 + \frac{R_i C_L S}{4}} + \Delta P_{iB} \frac{R_f}{R_{iB}} \quad 70$$

where C_L is the fluidic capacitance of one of said second pair of volumes.

9. A laminated frequency-responsive lag type fluidic component comprising:

a cover plate;

a base plate;

a first plurality of laminae superposed between said cover and base plates forming a fluidic gain block component comprising a plurality of serially connected analog-type fluid amplifiers;

a second plurality of laminae superposed between said cover and base plates for providing predetermined passive linear resistances to fluid flow therethrough forming fluidic input resistors R_i and negative feedback resistors R_f , and for isolating the input and feedback resistors to thereby convert the gain block to a fluidic operational amplifier component having a substantially fixed gain

$\frac{\Delta P_o}{\Delta P_i} = \frac{R_f}{R_i}$ determined by the passive resistors for high

values of forward gain G of the gain block to thereby provide a fixed linear gain substantially independent of variations in load on the fluidic lag component or in the supply pressure of the power fluid supplied to the fluid amplifiers;

a first pair of fixed volumes for providing passive capacitances to fluid flow therethrough, said volumes connected to said base plate and in communication with the output of said gain block for preventing instability of the fluidic lag component;

laminae means for separating the resistances of said input resistors into two parts; and

a second pair of fixed volumes providing fluidic capacitors C_L connected to said base plate and in communication with the separating point of said input resistors for forming a pair of series circuit impedances each comprising the two parts of the input resistor R_i and one of said second pair of volumes interposed therebetween to form the frequency-responsive lag-type fluidic component.

10. The laminated frequency-responsive lag-type fluidic component set forth in claim 9 wherein said resistance separating laminae means comprise: at least one lamina superposed adjacent said input resistors lamina and provided with a pair of wide apertures in overlapping relationship with the midresistance point of the input resistors and for providing communication with said second pair of fixed volumes.

11. The laminated fluidic component set forth in claim 9 wherein: said second plurality of laminae providing predetermined passive linear resistances forming additional fluidic input resistors P_{iB} which may have a value of resistance different from the resistance of resistors R_i , said input resistors P_{iB} being operatively independent of said resistance separating laminae means and thereby independent of the lag transformation whereby a first control input signal ΔP_i supplied to said input resistors R_i undergoes the lag transformation and a second control input signal ΔP_{iB} supplied to said input resistors P_{iB} is merely amplified thereby to provide an output

$$\Delta P_o = \Delta P_i \frac{R_f}{R_i} \frac{1}{1 + \frac{R_i C_L S}{4}} + \Delta P_{iB} \frac{R_f}{R_{iB}} \quad 60$$

12. A first laminated lag type fluidic component as set forth in claim 9 and further comprising:

a second laminated lag-type fluidic component identical in structure to said first lag component;

the output of said first lag component connected to the input of said second lag component; and

the output of said second lag component cross-connected to the input of said first lag component to form a closed loop wherein each lag component contributes a 90° phase shift and has a gain greater than unity such that the particular interconnection of the two lag components into the closed loop accumulates the necessary 180° of phase shift

to obtain the necessary condition for oscillation, the oscillatory frequency of the closed loop being approximately

$$\frac{10}{\tau} \text{ where } \tau = \frac{R_i C_L}{4}$$

13. The laminated fluidic oscillator component set forth in claim 12 wherein the output terminals of said oscillator component disposed at alternate fluidic capacitors C_L in the input circuit of the two lag components.

14. A laminated frequency-responsive lag-type fluidic component having no moving mechanical parts comprising: a cover plate; a base plate; a first plurality of laminae superposed between said cover and base plates and comprising a staged amplifier section and a supply pressure manifold section forming a fluidic gain block component; said staged amplifier section positioned adjacent said cover plate and comprising: a plurality of first different laminae each having formed therethrough a major part of the fluid flow passages defining a plurality of serially connected analog-type fluid amplifiers, said passages including in each fluid amplifier a power fluid inlet passage terminating in a power nozzle, a pair of fluid receivers downstream of said power nozzle, a pair of control fluid inlet passages terminating in opposed control nozzles disposed intermediate said power nozzle and receivers, a pair of side vent passages disposed intermediate said control nozzles and receivers, and a center vent passage disposed intermediate said receivers; a plurality of aligned second different laminae each having formed therethrough at least the remainder of said passages in overlapping relationship with respect to the corresponding passages in said first laminae, said second laminae functioning as spacer members between said first laminae to form parallel interconnected, separated, miniature size fluid amplifiers, said first and second laminae superposed in a particular alternate arrangement of one second lamina and at least one first lamina, one of said second lamina positioned adjacent said cover plate, said first and second laminae forming a high gain, high signal-to-noise ratio multistage fluid amplifier component; and said first and second laminae superposed between said cover plate and a third different lamina functioning as an isolator between said staged amplifier section and said supply pressure manifold section, said supply pressure manifold section comprising: a plurality of alternately superposed aligned fourth and fifth different laminae; said fourth laminae each provided with a plurality of apertures equal in number to the number of stage amplifiers and aligned with the inputs to the power fluid nozzles thereof; said fifth laminae each provided with a channel in overlapping relationship with said plurality of apertures in said fourth laminae, the effective height dimension of the channel formed by the plurality of superposed fourth and fifth laminae determining the fluid flow resistance to power fluid flowing therethrough and thereby determining a different particular pressure of power fluid supplied to each stage fluid amplifier; said cover plate provided with ports aligned with said center vent passages in said fluid amplifiers; said base plate provided with: an input port in communication with the apertures in said fourth laminae aligned with the input to the power fluid nozzles of the last stage fluid amplifiers for supplying power fluid from an external source thereto; a pair of input ports in communication with the input to the control fluid nozzles of the first stage fluid amplifiers for supplying a control fluid input signal ΔP_i thereto; and a pair of output ports in communication with the output of the receivers of the last stage fluid amplifiers for supplying the fluidic lag component output ΔP_o externally thereof; a second plurality of aligned laminae superposed between said base plate and said supply pressure manifold section for providing fluidic input R_i and feedback R_f resistors and isolation between the resistors and base plate and supply pressure manifold section, said second plurality of laminae comprising: said resistor laminae each having formed therethrough at least one pair of equally dimensioned narrow channels of predetermined length and width for providing predetermined passive linear resistances to fluid flow

therethrough, at least one of the resistance laminae forming the fluidic input resistors R_i and at least another of the resistance lamina forming the fluidic negative feedback resistors R_f ; at least one sixth different lamina superposed between said supply pressure manifold section and said negative feedback resistor lamina for isolation therebetween; a seventh different lamina superposed adjacent said negative feedback resistance lamina on the side opposite from the said sixth lamina; at least one eighth different lamina superposed between said seventh lamina and said input resistor lamina for separating each of the input resistors into two parts, said seventh lamina providing isolation between said negative feedback resistor lamina and said eighth lamina; a ninth different lamina superposed between said input resistor lamina and said base plate for isolation therebetween; said second plurality of laminae providing the communication between the power fluid input port in said base plate and the apertures in said fourth laminae of said supply pressure manifold section associated with the last stage fluid amplifiers, said second plurality of laminae also providing the respective communication between said pairs of input and output ports in said base plate with the control fluid nozzles of the first stage amplifiers and the receivers of the last stage amplifiers, and for the summation of the control fluid input signal and negative feedback signal after respective passage through the input and feedback resistors; a first pair of fixed volumes for providing passive capacitances to fluid flow therethrough, said first volumes connected to said base plate and in communication with the output of the receivers of the last stage amplifier for preventing instability of the fluidic lag component; and a second pair of fixed volumes C_L connected to said base plate and in communication with said eighth laminae for forming a pair of series circuit input impedances each comprising the two parts of the input resistor and one of said second pair of volumes interposed therebetween to form the frequency-responsive lag-type fluidic component having a

$$\text{lag time constant of } \tau = \frac{R_i C_L}{4}$$

15. The laminated lag-type fluidic component set forth in claim 14 and further comprising:

a plurality of pairs of small vent holes disposed in each said second laminae of said staged amplifier section at regions corresponding to the upstream sides of the side vent passages formed in said first laminae, a pair of said small vent holes disposed immediately adjacent each power nozzle and on opposite sides thereof; and said cover plate further provided with ports each of size sufficient to overlap a pair of the small vent holes associated with a fluid amplifier.

16. The lag-type fluidic component set forth in claim 14 wherein:

said second laminae each provided with a pair of first apertures therethrough aligned with the output of the fluid receivers of the last stage fluid amplifiers, a pair of second apertures aligned with the input to the control fluid inlet passages of the first stage fluid amplifiers, and a plurality of third apertures aligned with the plurality of apertures in said fourth laminae;

said third lamina provided with said pair of first apertures, said pair of second apertures, and said plurality of third apertures respectively aligned with the corresponding apertures in said second laminae; and

said fourth and fifth laminae each provided with said pair of second apertures aligned with the corresponding apertures in said third lamina, said fourth and fifth laminae each also provided with a first pair of aligned wide channels having first ends thereof aligned with said pair of first apertures in said third lamina.

17. The lag-type fluidic component set forth in claim 16 wherein:

said sixth, seventh, eighth, ninth, and input and feedback resistor laminae are each provided with the particular of said plurality of third apertures associated with the last stage amplifiers and aligned therewith and further pro-

vided with aligned pairs of third and fourth apertures, said pairs of third apertures aligned with second ends of said first pairs of wide channels in said fourth laminae for providing the communication between the output of the receivers of the last stage fluid amplifiers and said output ports in said base plate and the input to said first pair of volumes, said pairs of fourth apertures aligned with the output of said first pair of volumes;
said fourth and fifth laminae each also provided with a second pair of aligned wide channels having first ends thereof aligned with said pairs of fourth apertures and second ends aligned with first ends of the feedback resistor channels;
said sixth laminae provided with a pair of fifth apertures aligned with the second ends of said second pair of wide channels for completing the communication passages between the output of said first pair of volumes and the input to the feedback resistors;
said sixth, seventh, and eighth laminae each provided with a pair of wide apertures aligned with said pairs of second

apertures, second ends of the input and feedback resistor channels aligned with said pairs of wide apertures for providing for the summation of the control fluid input signal and negative feedback signal and for providing the communication to the control fluid nozzles of the first stage amplifiers; and
said ninth lamina provided with said pair of first apertures aligned with first ends of the input resistor channels to provide passages for the control fluid input signal from said input ports in said base plate to the input of the input resistors.
18. The lag-type fluidic component set forth in claim 17 wherein: said eighth, ninth, and input resistor laminae are each provided with a sixth pair of apertures aligned with a common input-output to said second pair of fixed volumes, the pair of sixth apertures in said eighth laminae being each of sufficient width to overlap a corresponding sixth aperture and a resistor channel adjacent thereto in said input resistor lamina to thereby separate each of the input resistors into two parts.

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