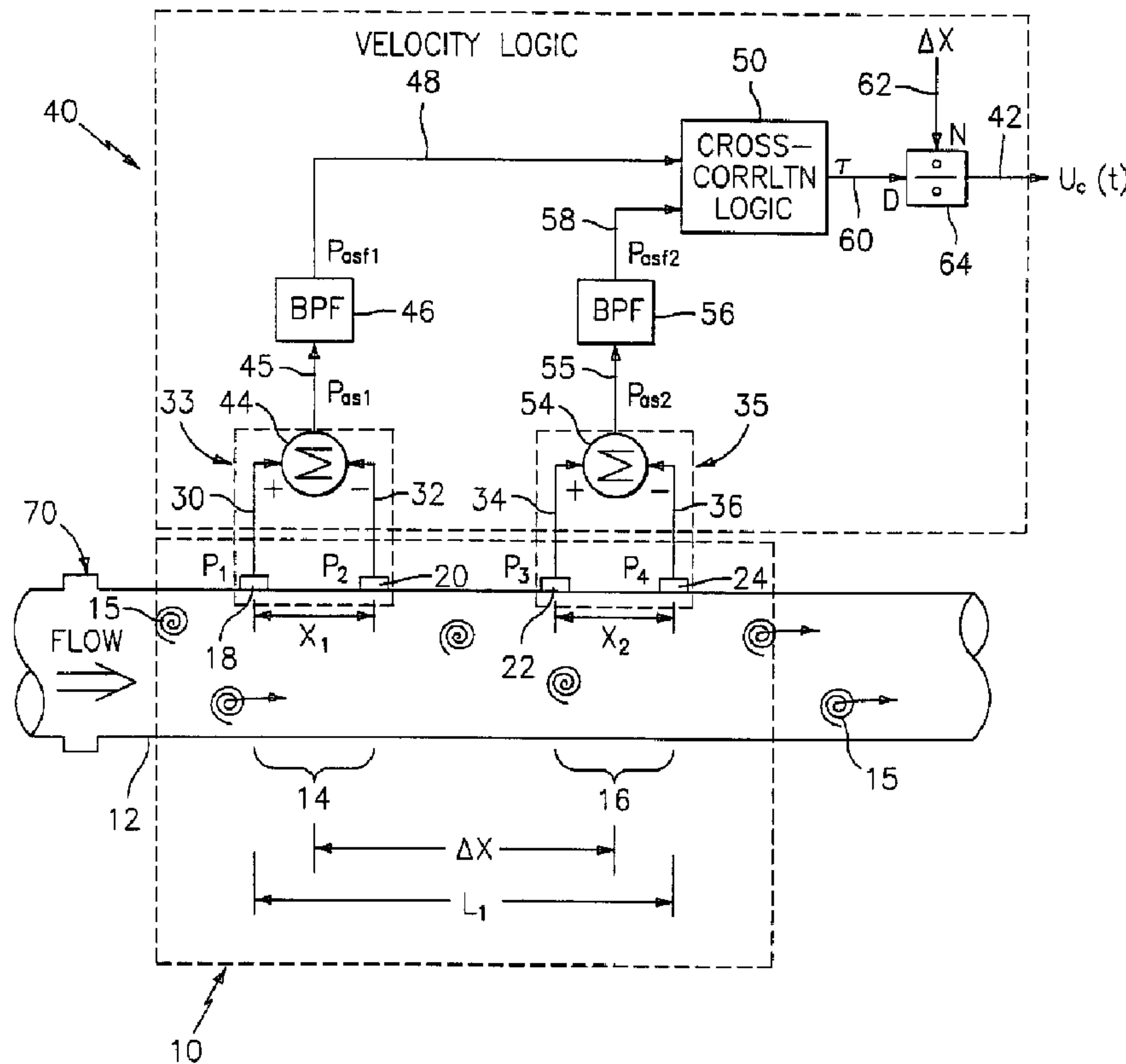




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 (54) Title: MULTIPLE FLOW RATE MEASUREMENT USING UNSTEADY PRESSURES



(57) Abrégé/Abstract:

A multiple flow rate measurement system includes an array of spatial filters (650-658) located a predetermined distance ΔX apart along the pipe (12), each filter comprised of unsteady pressure sensors capable of measuring the unsteady pressure in

(57) **Abrégé(suite)/Abstract(continued):**

the pipe (12). Each spatial filter (650-658) provides signals which indicative of a vortical pressure disturbance associated with a constituent within the flow mixture. The signals are cross-correlated by Cross-Correlation Logic (50) to determine a time delay τ between each of the filter locations which is divided into the distances ΔX between certain spatial filters to obtain a convection velocity $U_c(t)$ that is related to a velocity of a constituent within the fluid mixture.

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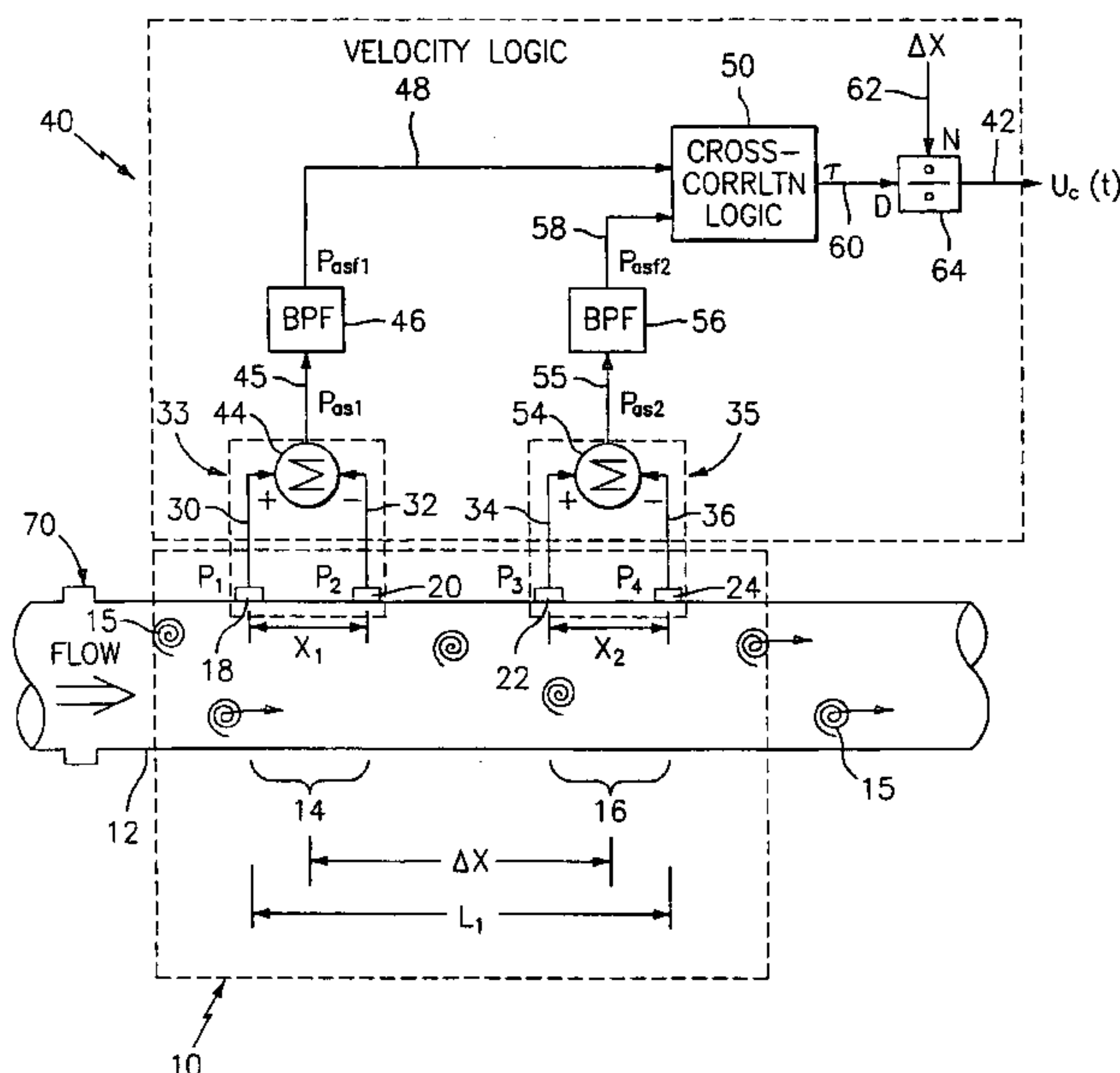
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(54) Title: MULTIPLE FLOW RATE MEASUREMENT USING UNSTEADY PRESSURES



(57) Abstract: A multiple flow rate measurement system includes an array of spatial filters (650-658) located a predetermined distance ΔX apart along the pipe (12), each filter comprised of unsteady pressure sensors capable of measuring the unsteady pressure in the pipe (12). Each spatial filter (650-658) provides signals which indicative of a vortical pressure disturbance associated with a constituent within the flow mixture. The signals are cross-correlated by Cross-Correlation Logic (50) to determine a time delay τ between each of the filter locations which is divided into the distances ΔX between certain spatial filters to obtain a convection velocity $U_c(t)$ that is related to a velocity of a constituent within the fluid mixture.

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Multiple Flow Rate Measurement Using Unsteady Pressures

Technical Field

This invention relates to the measurement of flow rate of a fluid and more particularly to measuring flow rate using unsteady pressure measurements.

Background Art

In many industries it is desirable to measure the flow rate of a multiphase fluid. In the oil and gas industry, or comparable industries, for example, it is desirable to measure the flow rate of multiphase fluids, especially fluids having three phases, such as oil, water and gas. It is known also to measure the flow rate of certain fluids (one or more liquids and/or gases) in a pipe using cross-correlation flow meters. Such meters measure an element of the flow that moves or convects with (or is related to) the fluid flow (or a group of fluid particles). The meter measures this element at two locations separated by a known distance along the flow path and then calculates the time for such element to move between the two locations. The time delay is determined by a cross-correlation of the two measured signals. A velocity is then determined by the distance between the measurements divided by the time delay. The flow velocity is then related to the flow rate by calibration.

One such cross-correlation meter that measures flow rate in a multiphase flow is described in US Patent No. 5,591,922, entitled „Method and Apparatus for Measuring Multiphase Flow“, to Segeral et al, issued Jan. 7, 1997. In that case, a pair of venturis are located a predetermined distance apart which induce a change in flow speed through the venturi and a resulting pressure difference (or delta-P) across each venturi, which are measured. The delta-P pressure signals measured at each venturi are cross-correlated to determine the time delay which is indicative of the total volume flow rate. However, such a technique requires a change in the flow properties

(e.g., flow velocity or density) at the two measurement points to make the measurement. Also, the delta-P is generated with an area contraction or constriction, and is not a naturally occurring observable characteristic of the fluid.

5 **Summary of the Invention**

Objects of the present invention include provision of a system for measuring the flow rate (or velocity) of multiple constituents within a fluid mixture flowing in pipes.

10 According to the present invention, an apparatus for measuring a velocity of a fluid mixture moving in a pipe, comprising a spatial array of unsteady pressure sensors disposed on the pipe, the sensors providing a corresponding array of unsteady pressure signals and a signal processor which is responsive to the array of unsteady pressure signals, and which provides a velocity signal indicative of a velocity of a vortical pressure field moving in the pipe.

15

According further to the present invention the signal processor combines certain ones of the unsteady pressure signals to provide a first filter which measures the vortical pressure field at a first location about the pipe and which provides a first vortical pressure signal indicative of the vortical pressure field and a second filter
20 which measures the vortical pressure field at a second location about the pipe and which provides a second vortical pressure signal indicative of the vortical pressure field. The signal processor comprises logic, which calculates a cross-correlation between the first and the second vortical pressure signals and provides a time delay signal indicative of the time it takes for the vortical pressure field to move from the
25 first location to the second location. The signal processor further comprises logic, which provides a vortical velocity signal indicative of the velocity of the vortical pressure field moving in the pipe that is related to the velocity of the fluid mixture moving in the pipe. According further, the present invention, the fluid mixture is comprised of a plurality of constituents and the velocity signal is related to the
30 velocity of one of the constituents moving in the pipe.

Still further in accordance with the present invention, an apparatus for measuring a velocity of a fluid mixture comprised of a plurality of constituents

moving in a pipe comprises a spatial array of unsteady pressure sensors disposed on the pipe, the sensors providing a corresponding array of unsteady pressure signals and a signal processor, responsive to the array of unsteady pressure signals, which provides a plurality of velocity signals, each velocity signal indicative of a velocity of a vortical pressure field moving in the pipe. Further in accordance with the present invention the signal processor combines certain ones of the unsteady pressure signals to provide a first filter which measures the vortical pressure field at a first location about the pipe and which provides a first vortical pressure signal indicative of each the vortical pressure field and a second filter which measures the vortical pressure field at a second location about the pipe and which provides a second vortical pressure signal indicative of the vortical pressure field. According still further to the present invention the velocity signals are related to the velocity of each of the constituents moving in the pipe.

The present invention determines a convection velocity by measuring unsteady (or dynamic or ac) pressures and extracting the pressure signal indicative of a vortical pressure (or flow) field (or perturbation) which convects at or near the average velocity of the fluid. The vortical pressure field is then used to determine the convection velocity by cross-correlation techniques, such convection velocity being proportional (or approximately equal to) the flow rate of a constituent of the fluid mixture. If needed, the flow rate of the constituent may then be determined by calibrating the convection velocity to the flow rate.

The invention may be used to measure the velocity of any inhomogeneous flow field, such as gas bubbles, gas slugs, particles, or chunks of material, and its associated pressure field that propagates within a flow provided the spatial filters have a separation within the acceptable coherence length of the flow field to be measured and the sensor spacing within each spatial filter is longer than a characteristic spatial length of the flow field.

Also, the invention may be used with any combinations of liquids and/or gases. The invention will also work in any other environment or applications or any other fluids (one or more liquids and/or gases) or mixtures. The invention will work with any pipe or tube or with any conduit that carries fluid. Also, the invention has no inherent flow range limitations, and, as such, can measure very low flow rates and has

no maximum flow rate limit. The invention will also work if the fluid is flowing in either direction in the pipe. Further, the invention may be used directly on a pipe or on a tube inserted into a flowing fluid.

The foregoing and other objects, features and advantages of the present invention will become more apparent in light of the following detailed description of exemplary embodiments thereof.

Brief Description of the Drawings

Fig. 1 is a schematic block diagram of a velocity measurement system, in accordance with the present invention.

Fig. 2 is a side view of a pipe having a plurality of spatial filters along an axial array with varying distances from a first filter, in accordance with the present invention.

Fig. 3 is a side view of a pipe having a plurality of spatial filters along an axial array with varying distances between filters and each filter having a different sensor spacing, in accordance with the present invention.

Fig. 4 is a schematic block diagram of a velocity measurement system having a plurality of spatial filters along an axial array along a pipe, in accordance with the present invention.

Fig. 5 is a schematic drawing of a flow meter in a well, in accordance with the present invention.

Best Mode for Carrying Out the Invention

Referring to Fig. 1, a velocity and flow measurement system includes a sensing section 10 along a pipe 12 and a velocity logic section 40. The pipe (or conduit) 12 has two measurement regions 14,16 located a distance ΔX apart along the pipe 12. At the first measurement region 14 are two unsteady (or dynamic or ac) pressure sensors 18,20, located a distance X_1 apart, capable of measuring the unsteady pressure in the pipe 12, and at the second measurement region 16, are two other unsteady pressure sensors 22,24, located a distance X_2 apart, capable of measuring the unsteady pressure in the pipe 12. Each pair of pressure sensors 18,20 and 22,24 act as spatial filters to remove certain acoustic signals from the unsteady pressure signals, and the distances

X_1, X_2 are determined by the desired filtering characteristic for each spatial filter, as discussed hereinafter.

The flow measurement system 10 of an embodiment of the present invention measures velocities associated with unsteady flow fields and/or pressure disturbances represented by 15 associated therewith relating to turbulent eddies (or vortical flow fields), inhomogeneities in the flow (such as bubbles, slugs, and the like), or any other properties of the flow, fluid, or pressure, having time varying or stochastic properties that are manifested at least in part in the form of unsteady pressures. The vortical flow fields 15 are, in general, comprised of pressure disturbances having a wide variation in length scales and which have a variety of coherence length scales such as that described in the reference „Sound and Sources of Sound“, A. P. Dowling et al, Halsted Press, 1983. Certain of these vortical flow fields convect at or near/or related to the mean velocity of at least one of the fluids within a mixture flowing in a pipe. More specifically, the vortices convect in a predictable manner with reference to the fluids. The vortical pressure disturbances 15 that contain information regarding convection velocity have temporal and spatial length scales as well as coherence length scales that differ from other disturbances in the flow. The present invention utilizes these properties to preferentially select disturbances of a desired axial length scale and coherence length scale as will be more fully described hereinafter. For illustrative purposes, the terms vortical flow field and vortical pressure field will be used to describe the above-described group of unsteady pressure fields having temporal and spatial length and coherence scales described herein.

The velocity and flow measurement system of Fig. 1 utilizes the output of pressure sensors 18-24 to provide a signal indicative of the velocity of at least one of the fluids in a fluid mixture flowing in the pipe as described WO-A- 01/02811 incorporated herein by reference in its entirety. The velocity and flow system will work over a wide range of mixtures of oil/water/gas comprising the fluid within the pipe.

The various constituents will have vortical pressure disturbances convecting therewith having particular axial and coherence lengths. The present invention

utilizes an array of spatial filters to detect and identify the various vortical pressure disturbances with respect to a particular constituent within the mixture. Once detected, the vortical pressure disturbances are combined with the spatial filtering to obtain a convection velocity at which a particular constituent within the vortical pressure disturbance is convecting. With reference to Figs. 1, 2 and 3 each of the spatial filters is combined with a velocity logic 40 as in a similar manner to that described in the referenced copending application. Various spacing signals ΔX on a line 62 indicative of the distances $\Delta X_1, \Delta X_2, \Delta X_3, \Delta X_4$ between the sensing regions are divided by the various time delay signals τ associated with each time lag between spatial filters on the line 60 by a divider 64. Each divider 64 provides various output signals on the line 42 indicative of convection velocities $U_c(t)_1, U_c(t)_2, U_c(t)_3$. The convection velocities $U_c(t)_1, U_c(t)_2, U_c(t)_3$ are, for example, each related to a particular constituent of a three constituent mixture of fluids flowing in the pipe 12. The various convection velocities are related to (or proportional to or approximately equal to) the average (or mean) flow velocity $U_f(t)_1, U_f(t)_2, U_f(t)_3$ of the various constituents of the fluid mixture. The velocities $U_c(t)_1, U_c(t)_2, U_c(t)_3$ and $U_f(t)_1, U_f(t)_2, U_f(t)_3$ may be converted to volumetric flow rate if there is sufficient knowledge of the phase concentrations and cross sectional area of the pipe. Such configurations as shown in the figures may also be used to determine a mean velocity for the fluid mixture.

Referring to Fig. 2, a single sensor system 10 is shown having more than one pair of unsteady pressure sensors having different spacings to measure multiple flow rates in the same mixture. The invention may have an array of pressure sensors configured as spatial filters 650-658 each having a predetermined spacing ΔX_1 - ΔX_4 between the first and each successive spatial filter. The spatial filters 650-658 may variously be combined with velocity logic 40 (Fig. 1) as described above. Such a configuration may be used to measure the various vortical pressure fields and the corresponding velocities for various constituents associated with a variety of unsteady and/or stochastic pressure fields within the mixture.

Referring to Fig. 3, alternatively, different pairs of spatial filters may have different internal spacing between sensors as well as different spacing between spatial filters. For example, a first pair of spatial filters 660,662 each has the same sensor spacing X_1, X_2 , and a filter spacing of ΔX_1 , and a second pair of spatial filters

664,666 each has the same sensor spacing X_3, X_4 (different from the first sensor spacing X_1, X_2) and a filter spacing of ΔX_2 (different from the first filter spacing ΔX_1). The spatial filters 660-666 may also be variously combined with velocity logic 40 (Fig. 1) as described above. Similarly, such a configuration may be used to measure the various vortical pressure fields and the corresponding velocities for various constituents within the mixture.

Referring to Fig. 4, in general, unsteady pressure signals P_1-P_m from a phased array of equally or unequally spaced ac pressure sensors 670-688 may be fed to spatial filter logic 690 which combines the sensor signals in various groupings to create multiple spatial filters and filter spacings which may be automatically reconfigured to select the desired spacing (e.g., X_1, X_2) between sensors within each spatial filter and the desired spacing (ΔX) between the spatial filters. In that case, the spatial filter logic 690 may provide a plurality of spatially filtered signals $P_{as1}-P_{asn}$ on lines 692 to the cross-correlation logic 50 which selects the desired two input signals to cross-correlate based on a spacing signal ΔX on a line 694 from the filter logic 690. Also, the signal ΔX is fed to the numerator N input of the divider 64 for the calculation of the velocity signal U_c on the line 42. Alternatively, the logic 690 may provide only the two signals selected to be cross-correlated. In that case, the input ΔX would not need to be fed to the cross-correlation logic 50.

Although sensor system 10 is shown in the figures as an array of axially spaced pressure sensors it is within the scope of the present invention that the pressure sensors are circumferentially and variously combined with axially spaced sensors as described in the above referenced co-pending application.

Referring to Fig. 5, there is shown an embodiment of the present invention in an oil or gas well application, the sensor array system 600 may be connected to or part of production tubing 502 within a well 500. An outer housing, sheath, or cover 512 may be located over the array 600 and attached to the pipe (not shown) at the axial ends to protect the array 600 (or fibers or components thereof) from damage during deployment, use, or retrieval, and/or to help isolate the sensors from external pressure effects that may exist outside the pipe 12, and/or to help isolate ac pressures in the pipe 12 from ac pressures outside the pipe 12. The array 600 is connected to a cable

506 which may comprise the optical fiber 300 (Fig. 1) and is connected to a transceiver/converter-510-located outside the well.

When optical sensors are used in the array 600, the transceiver/converter 510 may be used to receive and transmit optical signals to the array 600 and provides
5 output signals indicative of the pressures at the array 600. Also, the transceiver/
converter 510 may be part of the Velocity Logic 40. The transceiver/converter 510
may be any device that performs the corresponding functions described herein. In
particular, the transceiver/ converter 510 together with the optical sensors described
hereinbefore may use any type of optical grating-based measurement technique, e.g.,
10 scanning interferometric, scanning Fabry Perot, acousto-optic-tuned filter (AOTF),
optical filter, time-of-flight, etc., having sufficient sensitivity to measure the ac
pressures within the pipe, such as that described in one or more of the following
references: A. Kersey et al., „Multiplexed fiber Bragg grating strain-sensor system
with a Fabry-Perot wavelength filter“, Opt. Letters, Vol. 18, No. 16, Aug. 1993, US
15 Patent No. 5,493,390, issued Feb. 20, 1996 to Mauro Verasi, et al., US Patent No.
5,317,576, issued May 31, 1994, to Ball et al., US Patent No. 5,564,832, issued Oct.
15, 1996 to Ball et al., US Patent No. 5,513,913, issued May 7, 1996, to Ball et al., US
Patent No. 5,426,297, issued June 20, 1995, to Dunphy et al., US Patent No.
5,401,956, issued March 28, 1995 to Dunphy et al., US Patent No. 4,950,883, issued
20 Aug. 21, 1990 to Glenn, US Patent No. 4,996,419, issued Feb. 26, 1991 to Morey all
of which are incorporated by reference. Also, the pressure sensors described herein
may operate using one or more of the techniques described in the aforementioned
references.

It should be understood that any of the features, characteristics, alternatives or
25 modifications described regarding a particular embodiment herein may also be
applied, used, or incorporated with any other embodiment described herein.

Although the invention has been described and illustrated with respect to
exemplary embodiments thereof, the foregoing and various other additions and
omissions may be made therein and thereto without departing from the scope of the
30 present invention.

Claims

What is claimed is:

1. An apparatus for measuring a velocity of a fluid mixture moving in a pipe
5 (12), comprising:
a spatial array (600) of unsteady pressure sensors (18-24; 670-688) disposed on the pipe (12), said sensors (18-24; 670-688) providing a corresponding array of unsteady pressure signals (P1-P4; P1-P10; P1-PN); and
a signal processor (40), responsive to said array of unsteady pressure signals
10 (P1-P4; P1-P10; P1-PN), which provides a velocity Signal (Uc) indicative of a velocity of a vortical pressure field (15) moving in the pipe (12).
2. The apparatus of claim 1 wherein said signal processor (40) combines certain ones of said unsteady pressure signals (P1-P4; P1-P10; P1-PN) to provide:
15 a first filter (18, 20) which measures said vortical pressure field (15) at a first location (14) along the pipe (12) and which provides a first vortical pressure signal (Pas1) indicative of said vortical pressure field (15); and
a second filter (22, 24) which measures said vortical pressure field (15) at a second location (16) along the pipe (12) and which provides a second vortical pressure
20 signal (Pas2) indicative of said vortical pressure field (15).
3. The apparatus of claim 2 wherein said signal processor (40) comprises logic (48) which calculates a cross-correlation between said first and said second vortical pressure signals (Pas1, Pas2) and provides a time delay signal (τ) indicative of the
25 time it takes for said vortical pressure field (15) to move from said first location (14) to said second location (16).
4. The apparatus of claim 3 wherein said signal processor (40) comprises logic (48) responsive to said time delay signal (τ) which provides a vortical velocity signal (Uc) indicative of the velocity of said vortical pressure field (15) moving in said pipe
30 (12).

5. The apparatus of claim 4 wherein said velocity signal (U_c) is related to the velocity of said fluid mixture moving in said pipe (12).
- 5 6. The apparatus of claim 4 wherein said velocity signal (U_c) is indicative of the velocity of said fluid mixture moving in said pipe (12).
7. The apparatus of claim 1 wherein said array of pressure sensors comprises at least three unsteady pressure sensors (18-24; 670-688).
- 10
8. The apparatus of claim 1 wherein pressure sensors (18-24; 670-688) comprise at least one optical strain gage disposed on a surface of the pipe (12).
9. The apparatus of any of claims 1-8 for measuring a velocity of a fluid mixture moving in a pipe (12), said fluid mixture comprised of a plurality of constituents, wherein said signal processor (40) is adapted provide a plurality of velocity signals each velocity signal indicative of a velocity of a vortical pressure field (15) moving in the pipe (12).
- 15
10. Use of the apparatus of claim 9 for measuring a fluid mixture comprised of a plurality of constituents, wherein said velocity signal (U_c) is related to the velocity of one of said constituents moving in said pipe (12).
- 20
11. Use of the apparatus of claim 9 for measuring a fluid mixture comprised of a plurality of constituents, wherein said velocity signal (U_c) is indicative of the velocity of one of said constituents moving in said pipe (12).
- 25
12. Use of the apparatus of claim 9 for measuring a fluid mixture having a vortical pressure field (15) which comprises an inhomogeneous pressure field.
- 30

13. Use of the apparatus of claim 9 for measuring a fluid mixture the constituents of which are comprised of oil, gas and water.
14. A method for measuring a velocity of a constituent within a fluid mixture moving in a pipe (12), the method comprising:
- 5
- a) measuring a vortical pressure field (15) at a first location (14) along the pipe (12) and providing a first vortical pressure signal (P_{as1}) indicative of said vortical pressure field (15);
 - b) measuring said vortical pressure field (15) at a second location (16) along the pipe (12) and providing a second vortical pressure signal (P_{as2}) indicative of said vortical pressure field (15), said first and said second locations (14, 16) being a predetermined distance (Δx) apart; and
 - c) calculating the velocity of said vortical pressure field (15) using said first and said second vortical pressure signals (P_{as1} , P_{as2}).
- 10
- 15
15. The method of claim 14, wherein said calculating step (c) comprises:
- d) calculating a cross-correlation of said first and said second pressure signals (P_{as1} , P_{as2}) to obtain a time delay signal (τ) indicative of the time it takes for said vortical pressure field (15) to move from said first location (14) to said second location (16).
- 20
16. The method of claim 15, wherein said calculating step (d) comprises:
- e) calculating a velocity signal (U_c) from said time delay signal (τ).
- 25
17. The method of claim 16, wherein said calculating step (e) comprises:
- f) dividing said axial distance (Δx) between said measurement locations by said time delay signal (τ)
- 30
18. The method of claim 14 wherein:
said measuring step (a) comprises:

measuring a first unsteady pressure and a second unsteady pressure;
subtracting said second unsteady pressure from said first unsteady
pressure to form said first vertical pressure signal (Pas1); and
said measuring step (b) comprises:

5 measuring a third unsteady pressure and a fourth unsteady pressure;
and

 subtracting said fourth unsteady pressure from said third unsteady
pressure to form said second vortical pressure signal (Pas2).

10 **19.** The method of claim 14 wherein:

 said first vertical pressure signal (Pas1) is indicative of wavelengths
associated with a vortical pressure field (15) and not associated with an
acoustic pressure field at said first location (14); and

15 said second vortical pressure signal (Pas2) is indicative of wavelengths
associated with said vortical pressure field (15) and not associated with an
acoustic pressure field at said second location (16).

20. The method of claim 14 wherein said velocity is indicative of a velocity of a
constituent within the fluid mixture.

20

21. The method of claim 14 wherein said measuring steps (a) and (b) comprise
measuring a strain of the pipe (12).

22. The method of claim 18 wherein said step of measuring said first and said
25 second unsteady pressures comprises measuring a strain of the pipe (12).

23. The method of claim 18 wherein said step of measuring said third and said
fourth unsteady pressures comprises measuring a strain of the pipe (12).

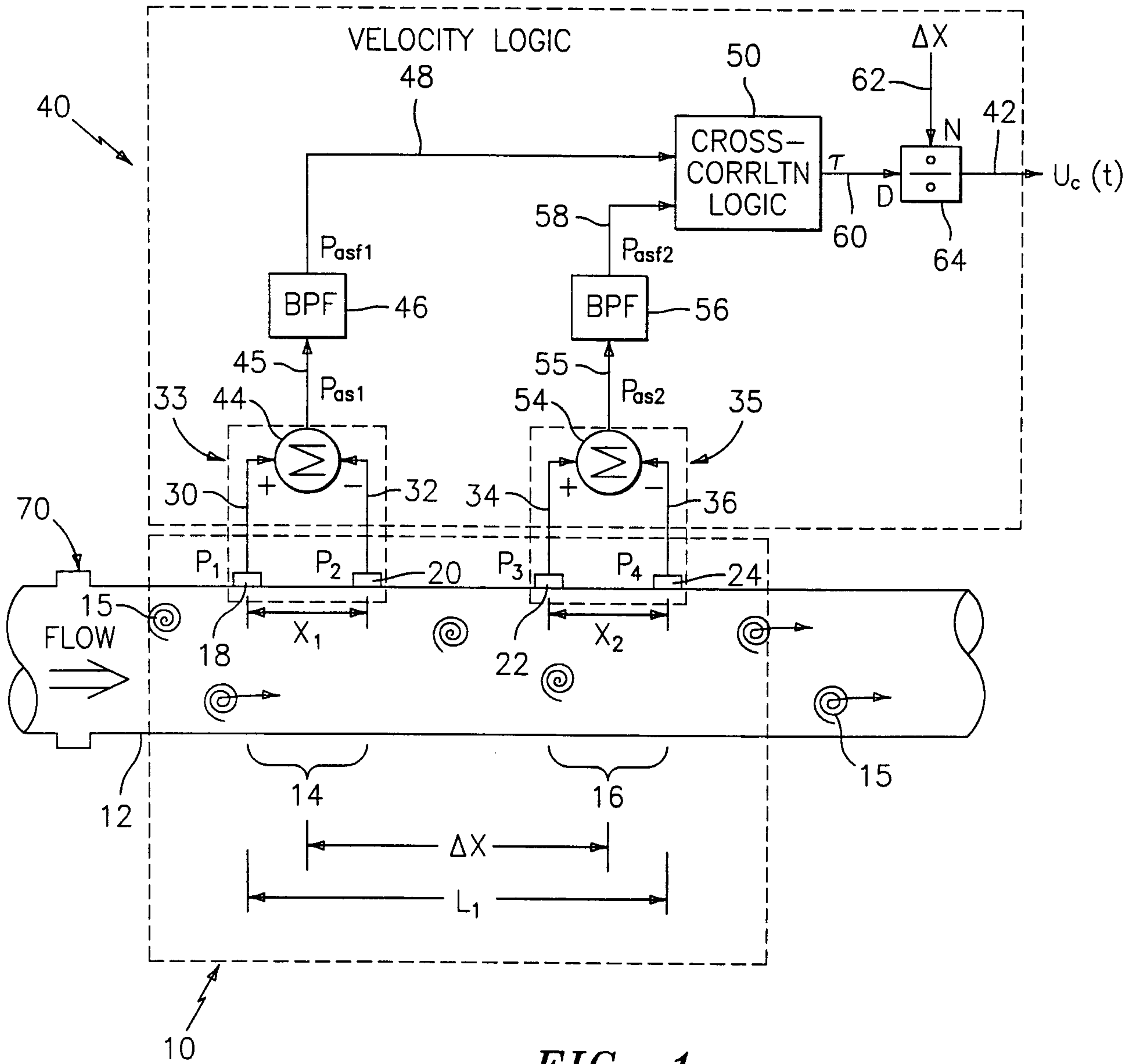


FIG. 1

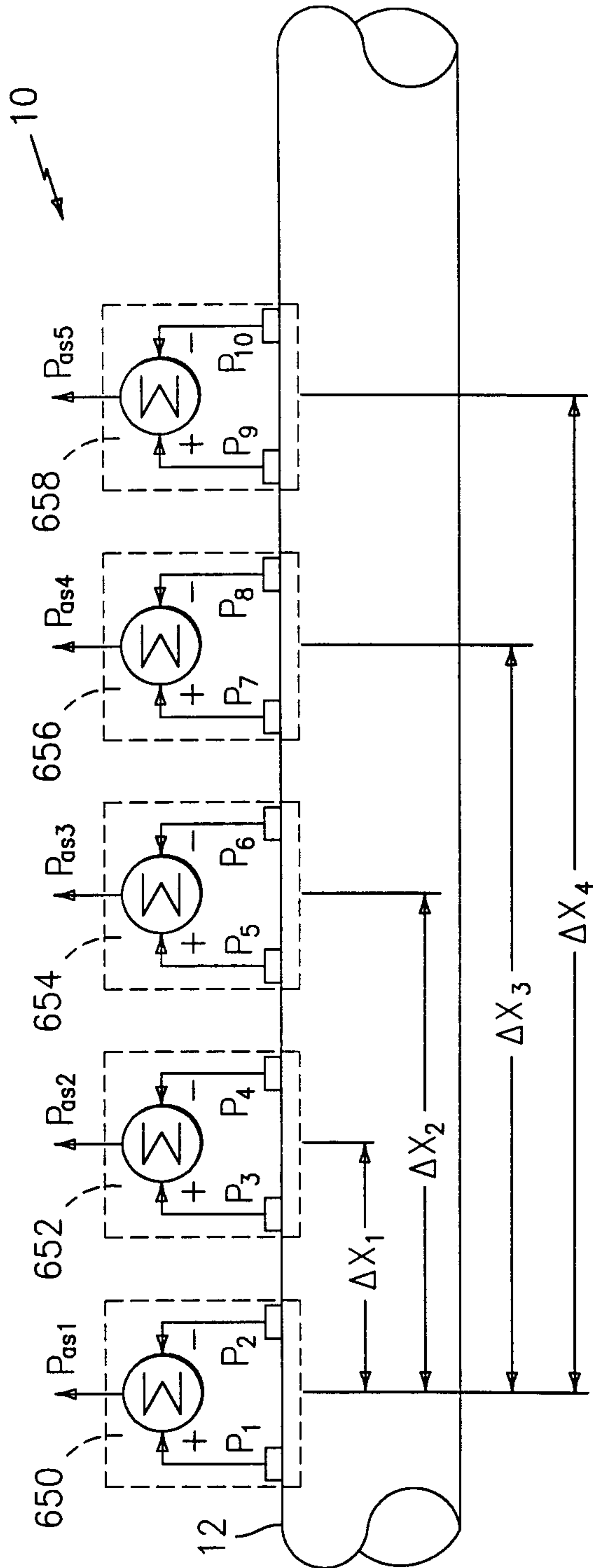


FIG. 2

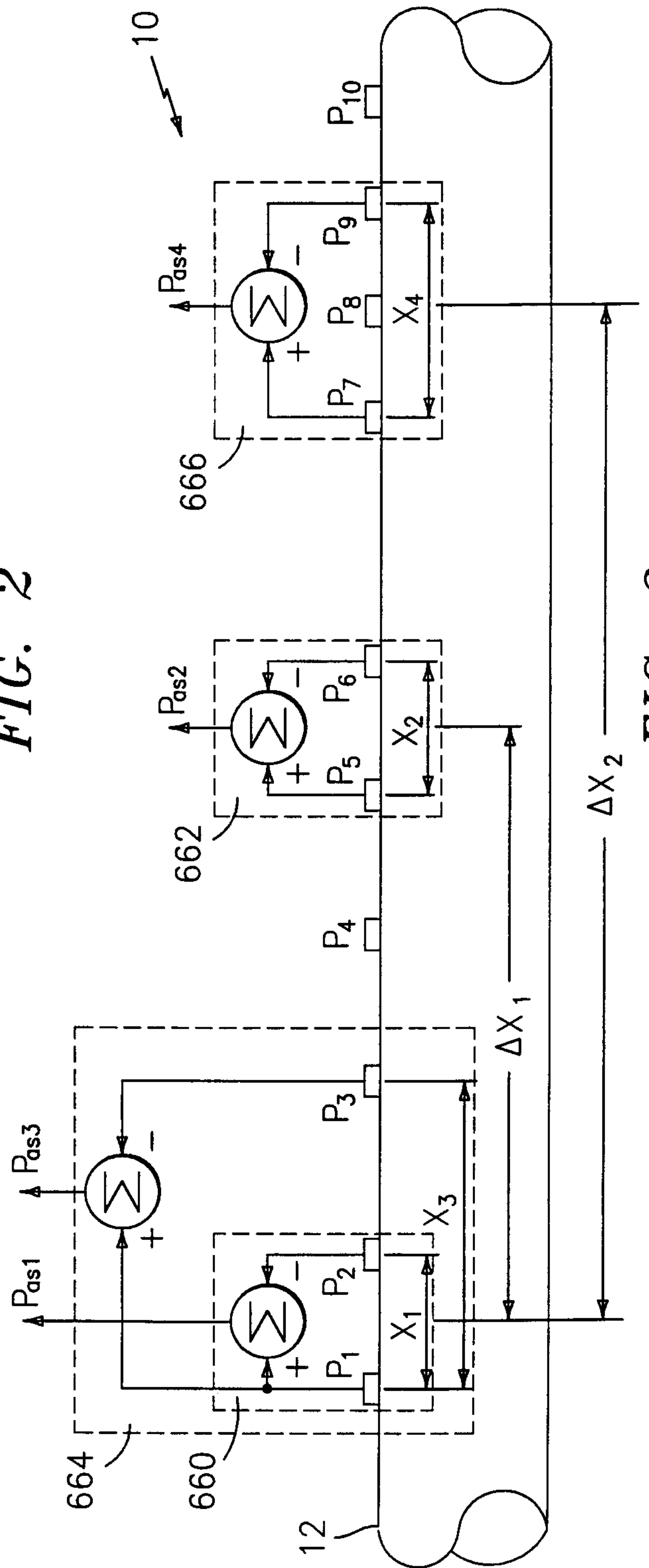
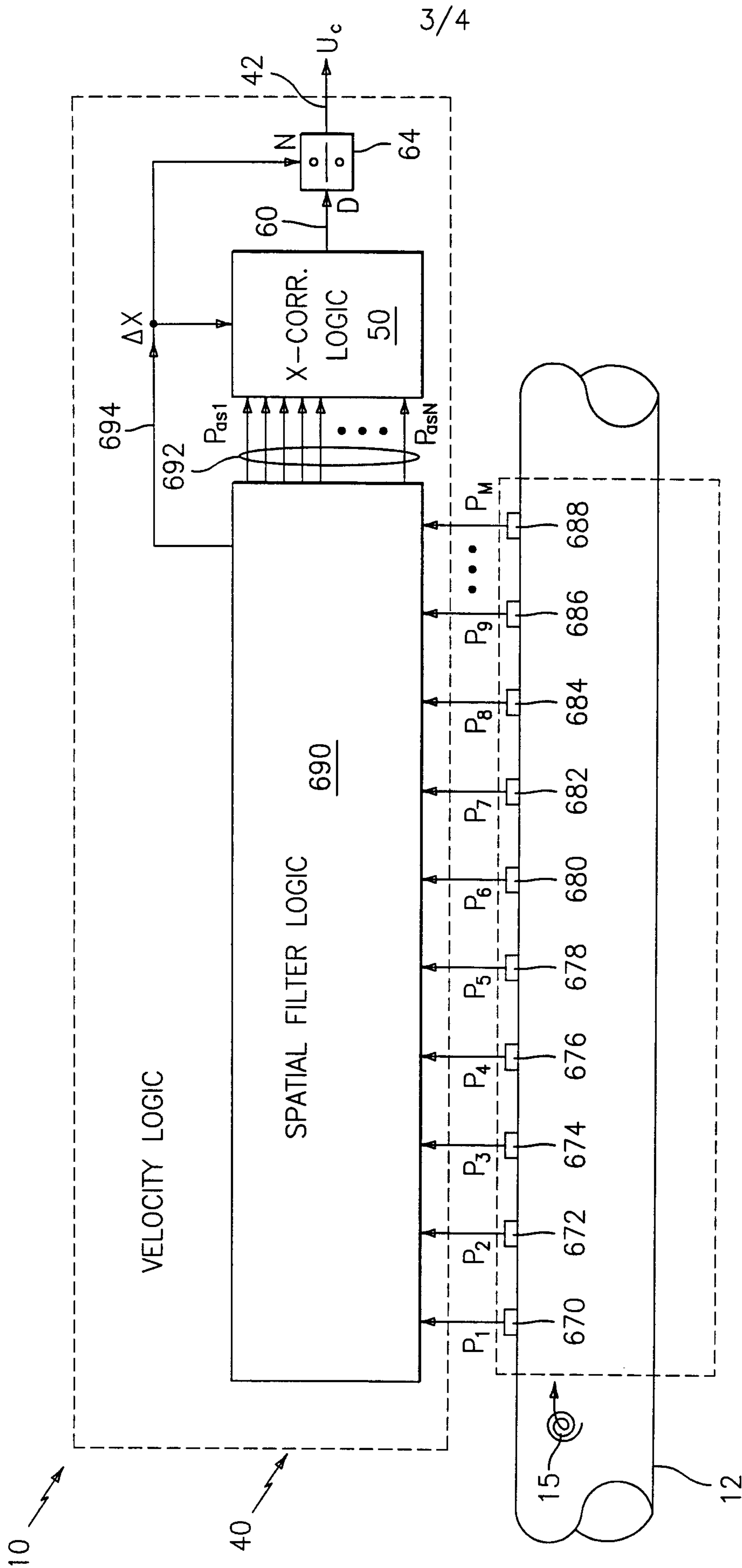


FIG. 3



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FIG. 4

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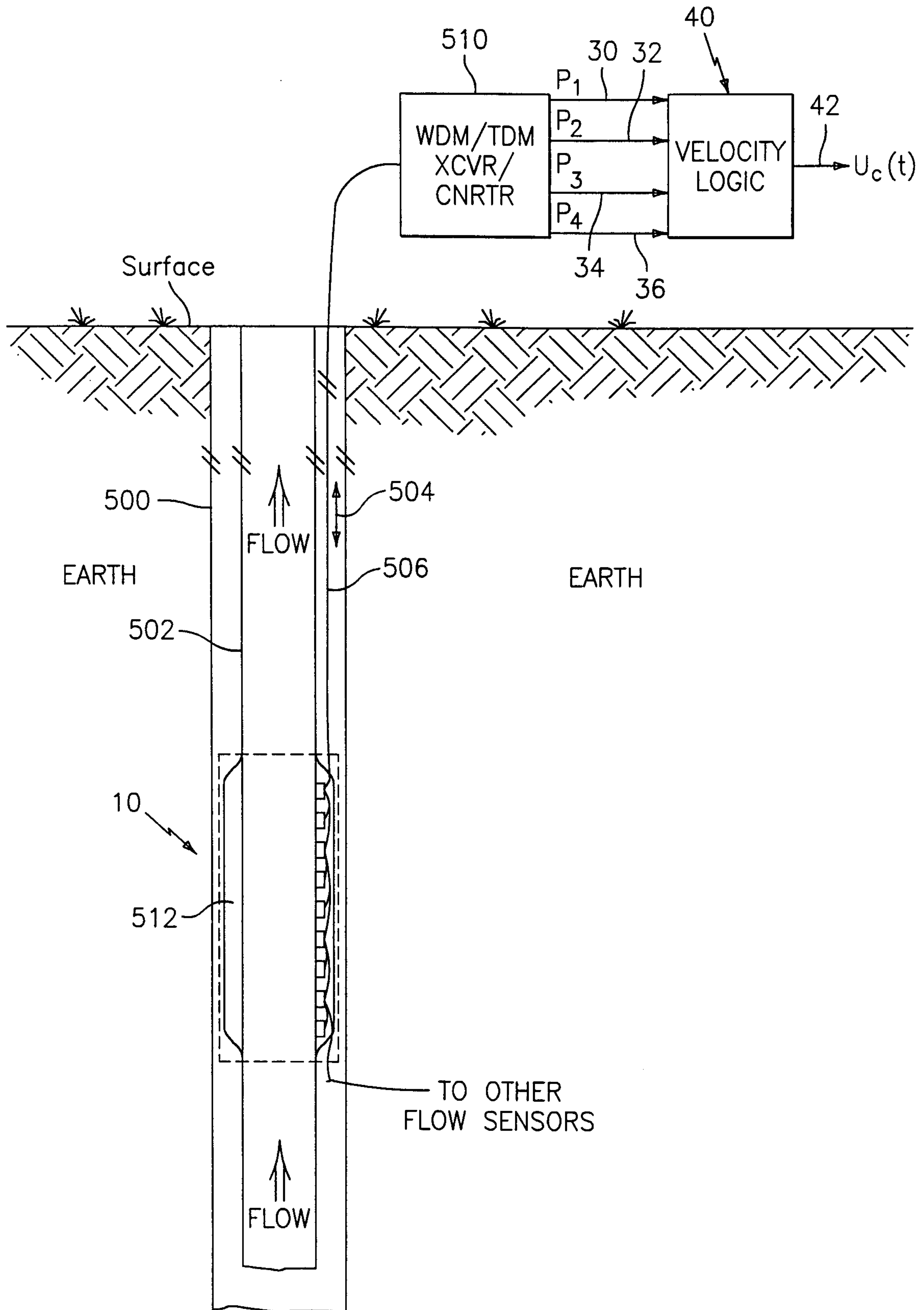


FIG. 5