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Kalotay

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[54] **NOISE REDUCTION FILTER SYSTEM FOR A CORIOLIS FLOWMETER**

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[51] **Int. Cl.**[6] **G01F 1/68**

[52] **U.S. Cl.** **73/861.38**; 324/601

[58] **Field of Search** 73/861.37, 861.38, 73/861; 324/601

[56] **References Cited**

U.S. PATENT DOCUMENTS

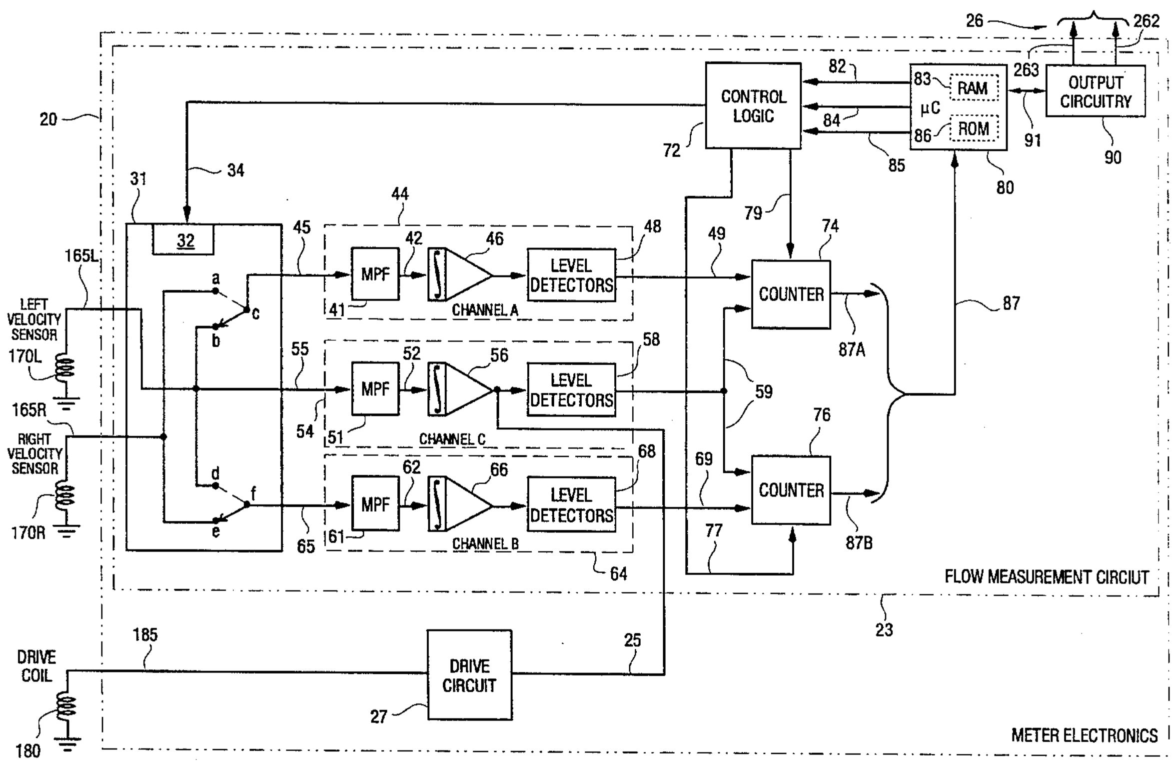
Re. 31,450	11/1983	Smith	73/861.38
4,109,524	8/1978	Smith	73/194 B
4,491,025	1/1985	Smith	73/861.38
4,879,911	11/1989	Zolock	73/861.38
5,228,327	7/1993	Bruck	73/3
5,231,884	8/1993	Zolock	73/861.38
5,331,859	7/1994	Zolock	73/861.38
5,343,761	9/1994	Myers	73/861

Primary Examiner—Hezron E. Williams
Assistant Examiner—Harshad Patel
Attorney, Agent, or Firm—Duft, Graziano & Forest

[57] **ABSTRACT**

A noise reduction system and method for measuring the phase difference between output signals of a Coriolis flowmeter. The output signals are applied to signal processing circuitry having three measurement channels, each of which includes a multi-pole filter having a relatively large phase shift. A channel pair is alternately switched in successive time intervals between a calibration status and an active status. In the calibration status, the two channels are connected during one time intervals to the same input signal and the output signals of the two channels are measured to determine the inherent phase delay between the two calibration channels. The two channels are then switched during the next time interval to an active status in which they are connected separately to the two output signals from the flowmeter. The output signals of the channels are then measured and the resultant measured phase delay is algebraicly combined with the phase delay measured during the calibration status to determine the true phase delay between the two signals received from the Coriolis flowmeter.

11 Claims, 2 Drawing Sheets



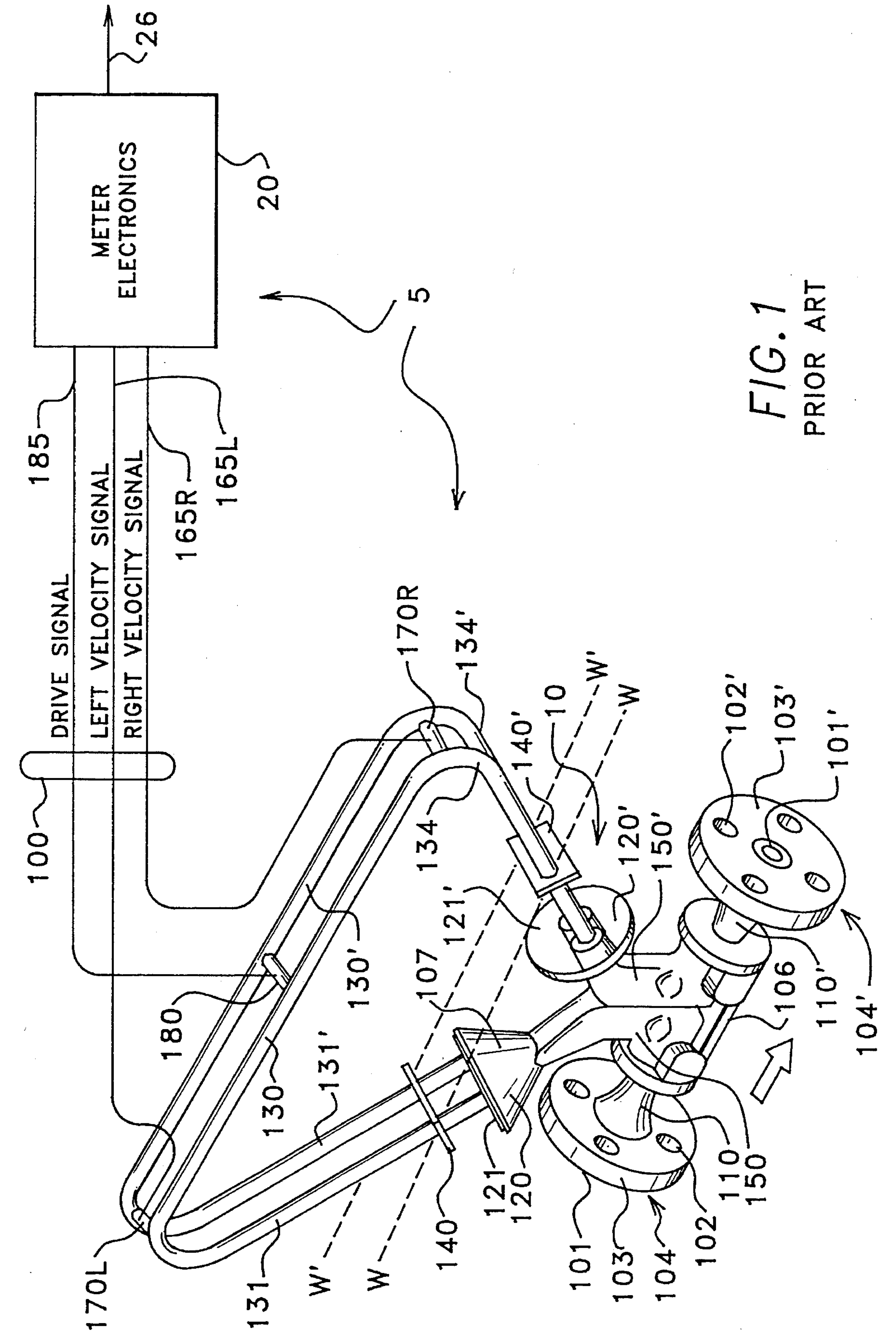
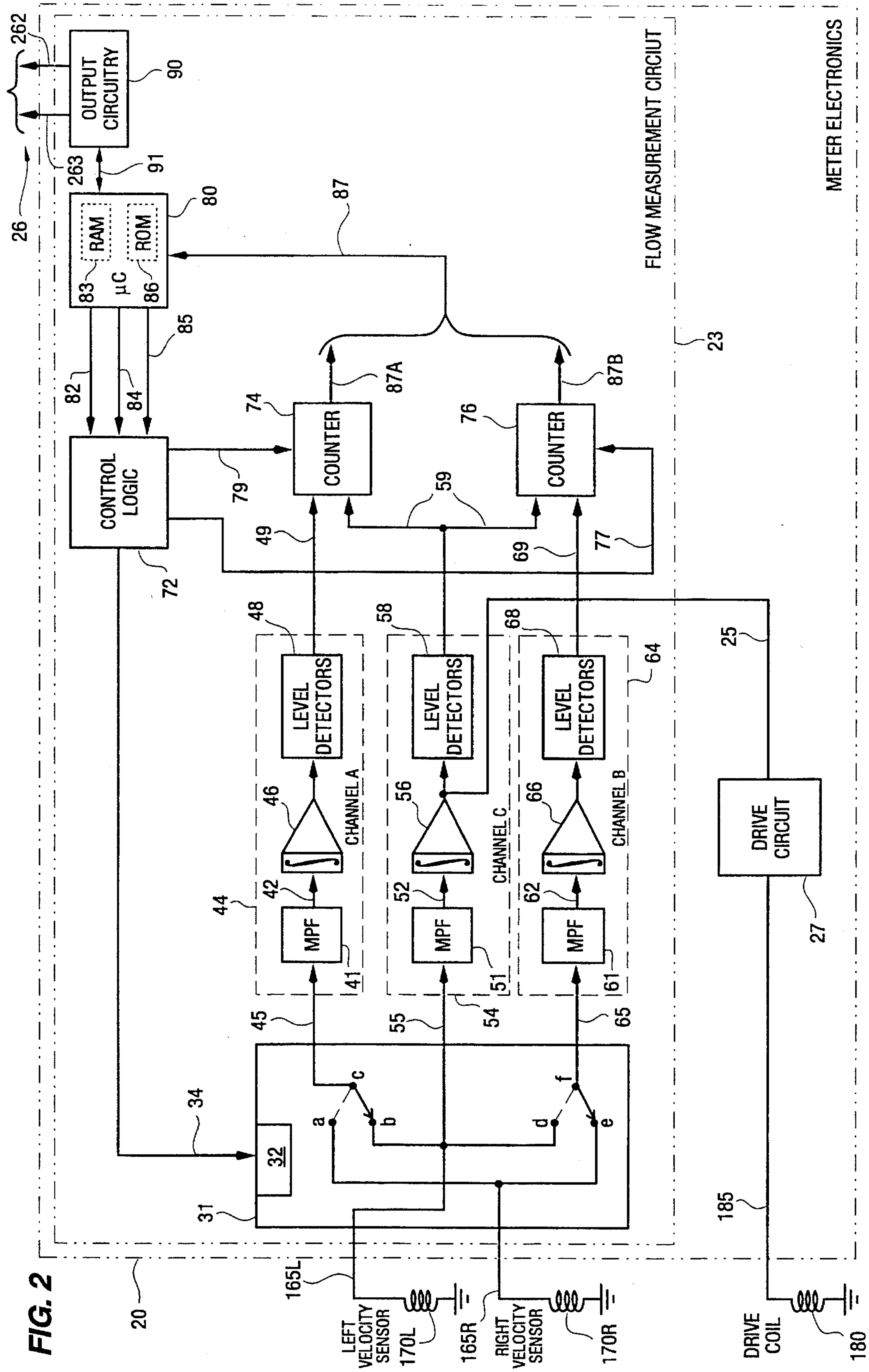


FIG. 1
PRIOR ART


OUTPUT CIRCUITRY
RAM
ROM
μC
CONTROL LOGIC
COUNTER
COUNTER
LEVEL DETECTORS
LEVEL DETECTORS
LEVEL DETECTORS
MPF
MPF
MPF
CHANNEL A
CHANNEL C
CHANNEL B
DRIVE CIRCUIT
FLOW MEASUREMENT CIRCUIT
METER ELECTRONICS
LEFT VELOCITY SENSOR
RIGHT VELOCITY SENSOR
DRIVE COIL
32
a
b
c
d
e
f
20
23
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31
34
41
42
44
45
46
48
49
51
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66
68
69
72
74
76
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79
80
82
83
84
85
86
87
87A
87B
90
91
165L
165R
170L
170R
180
185
262
263

FIG. 2

NOISE REDUCTION FILTER SYSTEM FOR A CORIOLIS FLOWMETER

FIELD OF THE INVENTION

This invention relates to a filter system and more particularly to a noise reduction filter system for a Coriolis flowmeter.

PROBLEM

It is known to use Coriolis effect mass flowmeters to measure mass flow and other information for materials flowing through a conduit. Such flowmeters are disclosed in U.S. Pat. Nos. 4,109,524 of Aug. 29, 1978, 4,491,025 of Jan. 1, 1985, and Re. 31,450 of Feb. 11, 1982, all to J. E. Smith et al. These flowmeters have one or more flow tubes of straight or curved configuration. Each flow tube configuration in a Coriolis mass flowmeter has a set of natural vibration modes, which may be of a simple bending, torsional or coupled type. Each flow tube is driven to oscillate at resonance in one of these natural modes. Material flows into the flowmeter from a connected conduit on the inlet side of the flowmeter, is directed through the flow tube or tubes, and exits the flowmeter through the outlet side. The natural vibration modes of the vibrating, fluid filled system are defined in part by the combined mass of the flow tubes and the material within the flow tubes.

When there is no flow through the flowmeter, all points along the flow tube oscillate with identical phase due to an applied driver force. As material begins to flow, Coriolis accelerations cause each point along the flow tube to have a different phase. The phase on the inlet side of the flow tube lags the driver, while the phase on the outlet side leads the driver. Sensors are placed on the flow tube to produce sinusoidal signals representative of the motion of the flow tube. The phase difference between two sensor signals is proportional to the mass flow rate of material through the flow tube.

A complicating factor in this measurement is that the density of typical process fluids varies. Changes in density cause the frequencies of the natural modes to vary. Since the flowmeter's control system maintains resonance, the oscillation frequency varies in response to changes in density. Mass flow rate in this situation is proportional to the ratio of phase difference and oscillation frequency.

The above-mentioned U.S. Pat. No. Re. 31,450 to Smith discloses a Coriolis flowmeter that avoids the need for measuring both phase difference and oscillation frequency. Phase difference is determined by measuring the time delay between level crossings of the two sinusoidal signals of the flowmeter. When this method is used, the variations in the oscillation frequency cancel, and mass flow rate is proportional to the measured time delay. This measurement method is hereinafter referred to as a time delay or Δt measurement.

Information regarding the characteristics of material flowing in a Coriolis mass flowmeter is typically derived by instrumentation which measures the phase or time delay between two output signals of the sensors of the flowmeter. These measurements must be made with great accuracy since this is often a requirement that the derived flow rate information have an accuracy of at least 0.15% of reading. These flowmeter output signals are sinusoidal and are displaced in time or phase by an amount determined by the Coriolis forces generated by the meter through which the material flows. The signal processing circuitry which receives these sensor output signals measures this phase

difference with precision and generates the desired characteristics of the flowing process material to the required accuracy of at least 0.15% of reading.

In order to achieve these accuracies, it is necessary that the signal processing circuitry operate with precision in measuring the phase shift of the two signals it receives from the flowmeter. Since the phase shift between the two output signals of the meter is the information used by the processing circuitry to derive the material characteristics, it is necessary that the processing circuitry not introduce any phase shift which would mask the phase shift information provided by the meter output signals. In practice, it is necessary that this processing circuitry have an extremely low inherent phase shift so that the phase of each input signal is shifted by less than 0.001° and, in some cases, less than a few parts per million. Phase accuracy of this magnitude is required if the derived information regarding the process material is to have an accuracy of less than 0.15%.

The frequencies of the Coriolis flowmeter output signals fall in the frequency range of many industrially generated noises. Also, the amplitude of the meter output signals is often small and, in many cases, is not significantly above the amplitude of the noise signals. This limits the sensitivity of the flowmeter and makes the extraction of the useful information quite difficult.

There is not much a designer can do either to move the meter output signal frequency out of the noise band or to increase the amplitude of the output signal. Practical Coriolis sensor and flowmeter design requires compromises that result in the generation of an output signal having a less than optimum signal to noise ratio and dynamic range. This limitation determines the flowmeter characteristics and specifications including the minimum and maximum flow rates which may be reliably derived from the flowmeter's output signals.

The magnitude of the minimum time delay that can be measured between the two Coriolis flowmeter output signals at a given drive frequency is limited by various factors including the signal to noise ratio, the complexity of associated circuitry and hardware, and economic considerations that limit the cost and complexity of the associated circuitry and hardware. Also, in order to achieve a flowmeter that is economically attractive, the low limit of time delay measurement must be as low as possible. The processing circuitry that receives the two output signals must be able to reliably measure the time delay between the two signals in order to provide a meter having the high sensitivity needed to measure the flowing characteristics of materials having a low density and mass such as, for example, gases.

There are limitations regarding the extent to which conventional circuit design can, by itself, permit accurate time delay measurements under all possible operating conditions of a Coriolis flowmeter. These limitations are due to the inherent noise present in any electronic equipment including the imperfections of semi-conductor devices and noise generated by other circuit elements. These limitations are also due to ambient noise which similarly limits the measurement can be reduced to some extent by techniques such as shielding, guarding, grounding, etc. Another limitation is the signal to noise ratio of the sensor output signals themselves.

Good circuit design can overcome some of the problems regarding noise in the electronic equipment as well as the ambient noise in the environment. However, an improvement in the signal to noise ratio of the output signals cannot be achieved without the use of filters. But filters alter the amplitude and phase of the signals to be processed. This is undesirable, since the time delay between the two signals is the base information used to derive characteristics of the process fluid. The use of filters having unknown or varying amplitude and/or phase characteristics can unacceptably alter the phase difference between the two sensor output signals and preclude the derivation of accurate information of the flowing material.

The flowmeter's drive signal is typically derived from one of the pick-off output signals after it is conditioned, phase shifted and used to produce the sinusoidal drive voltage for the drive coil of the meter. This has the disadvantage that harmonics and noise components present in the pick-off signal are amplified and applied to the drive coil to vibrate the flow tubes at their resonant frequency. However, an undesirable drive signal can be generated by unwanted mechanical vibrations and electrical interferences that are fed back to the meter drive circuit and reinforced in a closed loop so that they create relatively high amplitude self-perpetuating disturbing signals which further degrade the precision and accuracy of the time delay measurement.

A successful technique to reduce some of the above problems is described in U.S. Pat. No. 5,231,884 to M. Zolock and U.S. Pat. No. 5,228,327 to Bruck. These patents describe Coriolis flowmeter signal processing circuitry that uses three identical channels having precision integrators as filters. A first one of these channels is permanently connected to one pick-off signal, say, for example, the left. The other two channels (second and third) are alternately connected in successive time intervals, one at a time, to the right pick-off signal. When one of these, say the second channel, is connected to the right pick-off signal, the third channel is connected, along with the first channel, to the left pick-off signal. The inherent phase delay between the first and third channel is measured during a first time interval by comparing the time difference between the outputs of the two channels now both connected to the left signal. Once this characteristic delay is determined, the role of this third channel and the second channel connected to the right pick-off signal is switched during a second time interval. In this new configuration, the second channel undergoes a calibration of its delay characteristics while the third calibrated channel is connected to the right pick-off signal. The roles of second and third channels are alternately switched by a control circuit approximately once every minute. During this one-minute interval (about 30 to 60 seconds), aging, temperature, and other effects have no meaningful influence on the phase-shift of the filters and therefore their phase relationship is known and considered defined.

The precisely calibrated integrators used by Zolock provide a signal to noise ratio improvement amounting to about 6 db/octave roll-off in the amplitude transfer function of the integrator. Unfortunately, this 6 db/octave improvement is not enough under many circumstances in which Coriolis flowmeters are operated. The reason for this is that a single-pole filter, such as the Zolock integrator, has a relatively wide band width. As a result, noise signals generated by unwanted flow tube vibration modes, noisy environment, material flow noise, electromagnetic or radio frequency interference and disturbances are not removed to the extent necessary for high meter sensitivity required for precision. Depending on their frequency, their amplitude is reduced somewhat, but they can still interfere with the precision time delay measurement between the two pick-off output signals when measuring low mass materials such as gases.

There is another source for errors in the Zolock and Bruck system. The integrator time delay measurements are made at three (3) certain well defined points of the sinusoidal pick-

off signals. The two pick-off signals are ideal only when their shape is the same and is symmetrical around their peak values. However, when the two magnetic circuits (sensors) that generate the pick-off signals are not identical, the resulting non-ideal wave forms contain different amounts of harmonics with possibly undefined phase conditions which can alter their shape and potentially change their symmetrical character. The result of such variations is such that when, during normal operations, a Zolock integrator is calibrated with one wave form and is subsequently used to measure another wave form, the difference in wave forms may produce an undefined and unknown amount of error due to its harmonic content and its undefined and varying phase of its harmonics.

There are techniques currently available, such as digital signal processing and filtering, to overcome the above-discussed problems and simultaneously improve the signal to noise ratio of the signals being processed. However, these alternatives are complicated, expensive, and in most cases require design compromises that render their use less than ideal. It can therefore be seen that it is a problem to process the output signals of Coriolis flowmeters by circuitry that maintains the original phase shift between the two output signals and that by itself does not generate any unknown and unwanted phase shifts or other signal alterations which could degrade the accuracy of the output information generated by the processing circuitry regarding the characteristics of the material flowing through the flowmeter.

SOLUTION

The above problems are solved and an advance in the art is achieved by the present invention which provides additional and improved filtering apparatus and methods for Coriolis flowmeter output signal processing circuitry that uses the techniques of Zolock and Bruck. The integrating amplifiers of Zolock are relatively broad band 6 db/octave type filters that are primarily effective to filter out frequencies substantially higher than that of the meter output signals while maintaining a precise amount of phase shift influenced only by minor component variations. Since they are not of the sharp cut-off type, they are not effective in reducing and eliminating noise signals having a frequency close to that of the meter output signals. Thus, even though the Zolock self-calibrating feature eliminates errors due to long-term phase shift, the undesirable noise signals immediately adjacent the frequency of the process signals remain in the output of the Zolock circuit.

In accordance with my invention, I provide a multi-pole filter, such as a filter having eight or more poles, ahead of the precision integrators of the Zolock type. Since my filters are of the multi-pole type, they have a sharp roll-off characteristic and provide a narrow pass band that effectively eliminates all noise signals having a frequency near that of the processed flowmeter pick-off signals. The use of my multi-pole filters with the Zolock circuitry permits better filtering of undesirable signals so that the processed Coriolis pick-off signals have significantly reduced undesirable noise components. These signals can therefore be processed to generate information of improved precision regarding various characteristics of the process material.

Even with the use of my multi-pole filter, it is still necessary to meet the requirement of less than 0.001° of phase shift stability so that the time delay between the two pick-off signals can be measured with required precision. My multi-pole filters may have an undefined and unknown

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