CORIOLIS MASS FLOW CONTROLLER

CROSS-REFERENCE TO RELATED APPLICATIONS

This Application is a continuation-in-part of U.S. Patent Application Serial No. 09/430,881 filed November 1, 1999, which is a continuation-in-part of U.S. Patent Application Serial No. 09/326,949 filed June 7, 1999, which claims the benefit of U.S. Provisional Patent Application Serial No. 60/111,504, filed December 8, 1998.

BACKGROUND OF THE INVENTION

1. FIELD OF THE INVENTION

The invention relates generally to a mass flow measurement and control, and more particularly, to a mass flow measurement and control device based on the Coriolis force effect and having an integrated flow control valve with associated sense, control and communication electronics.

2. DESCRIPTION OF RELATED ART

Mass flow measurement based on the Coriolis force effect is achieved in the following manner. The Coriolis force results in the effect of a mass moving in an established direction and then being forced to change direction with a vector component normal to the established direction of flow. This can be expressed by the following equation:

$$\vec{F}_C = 2\vec{M} \times \vec{\omega}$$

Where $\vec{F}_C$ (the Coriolis force vector) is the result of the cross product of $\vec{M}$ (the momentum vector of the flowing mass) and $\vec{\omega}$ (the angular velocity vector of the rotating coordinate system).

In a rotating system, the angular velocity vector is aligned along the axis of rotation. Using the "Right Hand Rule", the fingers define the direction of rotation and the thumb, extended, defines the angular velocity vector direction. In the case of the typical Coriolis force flow sensor, a tube, through which fluid flow is to be established, is vibrated. Often the tube is in the shape of one or more loops. The loop shape is such that the mass flow vector is directed in opposite directions at different parts of the loop. The tube loops may, for example, be "U" shaped, rectangular, triangular or "delta" shaped or coiled. In the special case of a straight tube, there are two simultaneous angular velocity vectors that are coincident to the anchor points of the tube while the mass flow vector is in a single direction.

The angular velocity vector changes directions since, in a vibrating system, the direction of rotation changes. The result is that, at any given time, the Coriolis force is acting in opposite directions where the mass flow vectors or the angular velocity vectors are directed in opposite directions. Since the angular velocity vector is constantly changing due to the vibrating system, the Coriolis force is also constantly changing. The result is a dynamic twisting motion being imposed on top of the oscillating motion of the tube. The magnitude of twist is proportional to the mass flow for a given angular velocity.

Mass flow measurement is achieved by measuring the twist in the sensor tube due to the Coriolis force generated by a fluid moving through the sensor tube. Typical known devices use pick off sensors comprising magnet and coil pairs located on the flow tube where the Coriolis force's induced displacement is expected to be greatest. The coil and magnet are mounted on opposing structures, for example, the magnet is mounted on the tube and the coil is mounted on the stationary package wall. The coil will move through the magnet's field, inducing a current in the coil. This current is proportional to the velocity of the magnet relative to the coil. Since this is a velocity measurement, the velocity, and thus the signal, is at the maximum when the flow tube crosses its rest point (zero crossing). The Coriolis force induced twist causes a phase shift in the velocity signal that is detected by measuring the difference in the zero crossing times between the two velocity sensors. In practice this places a large accuracy burden on the time measurement circuitry. This may limit the ultimate sensitivity of mass flow measurement by this technique.

Further, the flow rate capabilities of known devices based on Coriolis technology often are limited to flow rates that are higher than desired for many applications. Moreover, existing Coriolis mass flow measuring devices only provide for mass flow sensing with no integral flow control capabilities. It has been left to the user to provide any means for controlling flow.

The present invention addresses shortcomings associated with the prior art.

SUMMARY OF THE INVENTION

In one aspect of the present invention, a Coriolis mass flow sensor includes a flow tube, a light source positioned adjacent a first side of the flow tube, a light detector positioned adjacent a second side of the flow tube, and a drive device operatively situated relative to the flow tube for vibrating the flow tube, such that the flow tube moves through a path defined between the light source and the light detector. In certain embodiments, the light source emits infrared light, such as an infrared LED used in conjunction with an infrared photo diode.

In accordance with other aspects of the invention, a flexible-tube Coriolis mass flow sensor includes a flexible flow tube having first and second ends. The flow tube defines a generally linear flow path, and a drive device is positioned to actuate the flow tube. First and second pick off sensors are positioned at the first and second ends of the flow tube, respectively. The first and second pick off sensors each output a signal in response to movement of the flow tube, wherein a Coriolis force established by a flow of material through the flow tube causes a phase shift between the signals output by the first and second pick off sensors.

In another aspect of the invention, a Coriolis mass flow sensor includes a flow tube, a frame having the flow tube mounted thereon, a drive device operatively situated relative to the frame for vibrating the frame, and at least one pick off sensor situated relative to the flow tube so as to measure the twist in the flow tube due to Coriolis force. The frame, for example, may comprise a silicon frame to which a stainless steel flow sensor tube is attached.

BRIEF DESCRIPTION OF THE DRAWINGS

Other objects and advantages of the invention will become apparent upon reading the following detailed description and upon reference to the drawings in which:

Figures 1A and 1B are block diagrams conceptually illustrating a Coriolis mass flow controller and sensor in accordance with aspects of the present invention;

Figures 2A and 2B illustrate a Coriolis mass flow sensor employing an electromagnetic drive in accordance with an embodiment if the present invention;

Figures 3A and 3B illustrate a Coriolis mass flow sensor employing an electrostatic drive in accordance with an embodiment if the present invention;

Figures 4A and 4B illustrate a Coriolis mass flow sensor employing an acoustic drive in accordance with an embodiment if the present invention;

Figures 5A, 5B and 5C illustrate a Coriolis mass flow sensor employing a piezoelectric drive in accordance with an embodiment if the present invention;

Figure 6 is a schematic of a lock-in amplifier for measuring the Coriolis force induced phase shift in accordance with the present invention;

Figure 7 is a schematic of a dual channel lock-in amplifier for measuring the Coriolis force induced phase shift in accordance with the present invention;

Figure 8 is a graph illustrating the relationship between the amplitudes of input signals from sensor tube position sensors using signal processing methods in accordance with the present application;

Figure 9 is a schematic of a dual lock-in amplifier for measuring the Coriolis force induced phase shift in accordance with the present invention;

Figure 10 is a schematic of a dual lock-in amplifier including reference frequency adjustment for measuring the Coriolis force induced phase shift in accordance with the present invention;

Figure 11 illustrates a first embodiment of a capacitive displacement probe in accordance with the present invention;

Figure 12 illustrates a second embodiment of a capacitive displacement probe in accordance with the present invention;

Figure 13 illustrates a third embodiment of a capacitive displacement probe in accordance with the present invention;

Figure 14 is a perspective view of a Coriolis mass flow controller in accordance with an embodiment of the present invention;

Figure 15 is a sectional view of the Coriolis mass flow controller shown in Figure 14;

Figure 16 is an exploded view of the Coriolis mass flow controller shown in Figure 15;

Figures 17A and 17B illustrate aspects of a prior art threaded valve connection and a sealed threaded valve connection in accordance with the present invention, respectively;

Figure 18 is a perspective view of an embodiment of a Coriolis mass flow controller in accordance further aspects of the present invention;

Figure 19 illustrates a Coriolis mass flow device employing an optical pick off sensor in accordance with embodiments of the present invention;

Figure 20 is a block diagram illustrating a Coriolis mass flow controller employing an optical pick off sensor as shown in Figure 19;

Figure 21 is a block diagram illustrating portions of a sensor pick off and drive circuit in accordance with aspects of the present invention;

Figure 22 is a block diagram illustrating portions of an application and control circuit in accordance with aspects of the present invention;

Figure 23 is a block diagram conceptually illustrating portions of a HART interface for a Coriolis mass flow controller in accordance with the present invention;

Figures 24A and 24B are front and side sectional views, respectively, of the flow sensing portion of a Coriolis mass flow controller in accordance with an embodiment of the present invention;

Figure 25 illustrates a hybrid Coriolis mass flow sensing tube in accordance with an embodiment of the present invention;

Figures 26A and 26B illustrate Wheatstone bridges functioning as piezoresistive sensors for the hybrid tube structure illustrated in Figure 25;

Figure 27 is a block diagram schematically illustrating a straight tube flow sensor in accordance with the present invention;

Figure 28 is a block diagram schematically illustrating an alternative straight tube flow sensor in accordance with the present invention; and

Figures 29A and 29B schematically illustrate exemplary piezoelectric tilt actuators in accordance with the present invention.

While the invention is susceptible to various modifications and alternative forms, specific embodiments thereof have been shown by way of example in the drawings and are herein described in detail. It should be understood, however, that the description herein of specific embodiments is not intended to limit the invention to the particular forms disclosed, but on the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the appended claims.

DETAILED DESCRIPTION OF THE INVENTION

Illustrative embodiments of the invention are described below. In the interest of clarity, not all features of an actual implementation are described in this specification. It

will of course be appreciated that in the development of any such actual embodiment, numerous implementation-specific decisions must be made to achieve the developers' specific goals, such as compliance with system-related and business-related constraints, which will vary from one implementation to another. Moreover, it will be appreciated that such a development effort might be complex and time-consuming, but would nevertheless be a routine undertaking for those of ordinary skill in the art having the benefit of this disclosure.

Figure 1A illustrates a Coriolis based mass flow sensor and controller in accordance with embodiments of the present invention. It is comprised of essentially two separate operational systems: a Coriolis sensor pickup and drive system A, and an application and control system B. The Coriolis sensor pickup and drive system interfaces with the Coriolis sensor 1. The application and control system B provides an interface for a user 5, and provides control signals to a flow control device such as a valve 6.

The purpose of the sensor pickup and drive system A is to control and sense the motion of the Coriolis sensor 1 for the purpose of determining relative mass flow as a function of Coriolis force, and relative density as a function of resonant frequency. The exemplary sensor pickup and drive system A provides three data values to the application and control system B:

1. *DeltaT* – the time difference that relates to the phase lag of one side of the sensor tube to the other indicating relative mass flow.

2. *Frequency* – the resonant frequency of the sensor tube that relates to the relative density of the measured material.

3. *Temperature* – an RTD is measured to determine the temperature of the sensor tube.

The application and control system B uses *DeltaT* in conjunction with calibration constants to present the desired mass flow units to the user 5. It also uses *Frequency* in conjunction with calibration constants to present the desired density and/or volumetric flow units to the user 5. *Temperature* is used for compensation of both mass flow and density calculations. The application and control system B uses the mass or volume flow unit output in comparison with the user's set point input to control the valve 6 that regulates flow to the desired setting.

Figure 1B is a block diagram conceptually illustrating a Coriolis mass flow sensor in accordance with aspects of the present invention. The Coriolis mass flow sensor 1 includes a flow sensor tube 2, with a drive device 3 situated relative thereto so as to vibrate the tube 2. Displacement gauges 4 are positioned relative to the tube 2 so as to measure the twist in the tube 2 due to Coriolis force.

A typical material for the sensor tube 2 is 316L stainless steel. Reasons for using 316L stainless steel include that it is resistant to chemical attack from many substances, it is resistant to rupture from normal process pressures, it is typically noncontaminating and can be readily formed to the desired shape of a Coriolis sensor tube. However, 316L stainless steel is not suitable for all applications. Therefore, it is necessary that other tube

materials be available to cover applications not suitable for 316L stainless steel. Known devices use silicon as an alternate material to 316L stainless steel. The advantage of silicon over 316L stainless steel is that sensor tubes can be made in a smaller form than can be realized by 316L stainless steel.

Another consideration for material selection for the sensor tube 2 is the resistance to stress induced or enhanced corrosion. Stress is generated at the base of the bending arm where the tubes are mounted. In polycrystalline materials stress will cause impurities in the material to diffuse and concentrate at grain boundaries between the microcrystalline granular regions. This will, in many cases, weaken the bonds between the microcrystalline grains making the material to be more susceptible to chemical attack. Single crystal materials like silicon or sapphire are less likely to be affected in this manner.

Metals, like 316L stainless steel are usually polycrystalline and therefore more susceptible to this type of chemical attack to varying degrees. Amorphous materials like silica glass and several plastics also are more resistant to stress induced chemical attack, since they do not have a grain structure like polycrystalline materials. Tube materials that are susceptible to chemical attack may have their surfaces modified or coated in such a way to minimize corrosion or attack at the surfaces if the use of the underlying material is otherwise attractive.

Surface modification may be accomplished by ion implantation, thermal diffusion, and chemical or electrochemical reaction. The intent, here, is to remove, redistribute, or introduce elemental or molecular species that leave a chemically resistant layer at the surface. Surface coating may be accomplished by thermally activated deposition from a

vapor, liquid or powder impinging on the surface at elevated temperatures. Lower temperatures may be used if the chemically reactive species is also excited or ionized by plasma or an intense photon flux as from a laser. Other materials resistant to chemical attack may be deposited by nonreactive, physical vapor deposition as accomplished by thermal or electron beam evaporation or by ion sputtering. If sputtering is accomplished using a highly energetic ion beam so that the sputtered species is chemically excited or ionized, then a chemical reaction with the surface is also accomplished, which may be desirable for certain deposited materials. Also, chemical reactions at the surface may be accomplished by accelerating the chemical species so that the kinetic energy can be used to activate or enhance the chemical reaction.

Tube materials used for the Coriolis flow sensing tube 2 in particular embodiments of the present invention are Austenitic and Martensitic stainless steels, high nickel alloys, Titanium and Zirconium and their alloys, particularly Titanium-Vanadium-Aluminum alloys and Zircalloy (for their high yield strength and low Young's modulus), silicon, sapphire, silicon carbide, silica glass and plastics. Tube coating materials employed in accordance with the present invention include silicon carbide, nickel, chrome, diamond, the refractory carbides, the refractory metal nitrides, and refractory metal oxides.

In other embodiments, the sensing tube comprises a hybrid of structures of different material compositions mechanically attached so as to utilize the best material properties of each part of the structure. The sensor structure is divided into a wetted portion and a non-wetted portion, for example. The wetted portion may be a tube of any material compatible with the application fluid, including metallic, ceramic and silica tubes.

This tube is attached to a vibratory structure, such as a frame, that conveys the tube in the proper vibrational mode to induce the Coriolis forces. The vibratory structure may itself be a tube in which the wetted tube fits, or it may be a frame to which the tube is attached. The vibratory structure may be made of a material that can be shaped into a beam of a form to support the wetted tube. An example would be silicon etched from a wafer in a shape that would support a wetted tube that could be stainless steel, plastic or other material that could be shaped into a tube to convey flow.

Figures 2A and 2B illustrate a Coriolis mass flow sensor 1 in accordance with particular embodiments of the present invention. The Coriolis mass flow sensor 1 employs an electromagnetic drive 10 that includes an electromagnet 12 driven by a signal source (not shown), which, in the embodiment illustrated, comprises a sinusoidal signal source. The electromagnet 12 is situated near a small permanent magnet 14 mounted on a sensor tube 16. The sensor tube 16 is connected to a base 18 that includes first and second ports 19, so as to define a flow path from one port 19 through the flow tube 16 to the other port 19. The exemplary sensor tube 16 shown in the embodiments disclosed herein is generally "U" shaped, though other shapes, such as delta shaped, rectangular, coiled, or straight tubes may also be used. Alternative tube shapes are discussed further herein below. Moreover, further embodiments are envisioned that employ multiple parallel sensing tubes, providing redundancy, rangeability (wherein selected tubes may be valved in or out), greater accuracy, etc.

Figures 3A and 3B illustrate an embodiment similar to that shown in Figure 2, using an electrostatic drive. The electrostatic drive 20 includes a charge plate 22

positioned near a small dielectric plate 24 mounted on the sensor tube 16. If the tube 16 is made of dielectric material, then the charge plate 22 is positioned near the tube 16 and the dielectric plate 24 may be eliminated. Again, the charge plate is driven by a signal source (not shown), such as a sinusoidal signal source. A voltage applied to the charge plate 22 will produce an electric field between it and the dielectric plate 24. This will produce a surface charge on the dielectric plate 24. As the voltage polarity is rapidly changed on the charge plate 22, the resultant electric field between it and the dielectric plate 24 will alternately be attractive or repulsive causing the flow tube 16 to vibrate.

Figures 4A and 4B illustrate another embodiment of the Coriolis mass flow sensor 1 that employs a novel acoustic drive 30. The acoustic drive 30 includes a small speaker 32 placed near the tube 16. The pressure waves generated by the speaker 32 cause the tube 16 to vibrate.

In Figures 5A, 5B and 5C, yet another embodiment of the Coriolis mass flow sensor 1 is illustrated. The Coriolis mass flow sensor 1 of Figures 5A, 5B and 5C uses a piezoelectric drive 40, wherein two piezoelectric stacks 42 are positioned on opposite sides each leg of the flow tube 16, in effect creating two bimorphs on each leg 16 as shown in Figure 5. The piezoelectric and reverse piezoelectric effects would be used to either drive and/or sense the deflection of the tube 16.

Mass flow measurement is achieved by measuring the twist in the sensor tube due to the Coriolis force generated by a fluid moving through the sensor tube. For example, in known Coriolis mass flow sensors, pick off sensors comprising magnet and coil pairs are typically located on the flow tube where the Coriolis forces induced displacement is

expected to be greatest. The coil and magnet are mounted on opposing structures, for example, the magnet is mounted on the tube and the coil is mounted on the stationary package wall. The coil will move in and out of the magnet's field, inducing a current in the coil. This current is proportional to the velocity of the magnet relative to the coil. Since this is a velocity measurement, the velocity, and thus the signal, is at the maximum when the flow tube crosses its rest point (zero crossing). The Coriolis force induced twist causes a phase shift in the velocity signal that is detected by measuring the difference in the zero crossing times between the two velocity sensors. In practice this places a large accuracy burden on the time measurement circuitry. This may limit the ultimate sensitivity of mass flow measurement by this technique.

U.S. Patent No. 5,555,190, assigned to the assignee of the present application, discloses digital signal processing methods and devices for determining frequency and phase relationships of a vibrating sensor tube such as the tubes disclosed in conjunction with the Coriolis mass flow sensing devices disclosed herein. The entire specification of U.S. Patent No. 5,555,190 is incorporated by reference herein.

Aspects of the present invention provide a flow measurement technique that provides for a lower flow capability, is more direct and requires less accuracy in the circuitry than typical time based signal conditioning techniques. Referring to the embodiments illustrated in Figures 2-4, displacement of the vibrating sensor tube is measured using capacitive pick off sensors. Two capacitance displacement gauges 50 are positioned near the tube 16 at positions symmetric to the shape of the tube 16 so as to measure the twist in the sensor tube 16 due to the Coriolis force generated by a fluid

moving through the sensor tube 16. In specific embodiments of the present invention, the capacitance displacement gauges 50 are miniaturized and surface mounted on the sensor package wall or on a sensor block inserted inside the loop of the flow sensor tube. The twist in the sensor tube 16 due to the Coriolis force results in a phase shift between the two signals from the capacitance displacement gauges 50. Since this is a displacement measurement, the signal is directly proportional to the displacement. The relative displacement of each side of the tube is measured as a phase shift. The gauge driver and signal conditioning electronics translate the relative displacement of the tube 16 into a high level signal which is a function of the phase shift that can be used to measure the Coriolis effect when flow is established through the tube 16.

A first signal processing technique uses a lock-in amplifier with a reference signal supplied by one of the displacement gauges 50, and an input signal supplied by the other displacement gauge 50. The lock-in amplifier may be implemented by hardware or software, or a combination of both. Either gauge 50 may supply the reference or the input signal. The phase output from the lock-in amplifier is proportional to flow. Figure 6 is a functional schematic of a lock-in amplifier 52, with which such a method for measuring the Coriolis force induced phase shift in accordance with the present invention may be implemented. The signals are moving left to right as illustrated in Figure 6. The Left input 100 and Right input 102 signals are from the Left and Right displacement gauges 50 respectively. For example, the Left input 100 may be used as the reference signal. The sine out 103 is the drive signal, phase locked to the Left input 100 signal. This will drive the flow sensor tube 16 at resonance. The Right Input 102 signal is mixed with the

Left/Reference Input 100 signal and its 90° phased-shifted signal 104 in the two Phase Sensitive Detectors (PSDs) 106. Functionally, the PSDs 106 multiply the two signals, producing a high frequency component and a DC component. The low pass filters 108 remove the high frequency component producing a DC voltage at the X and Y outputs 110, 112. The X output 110 is called the "in-phase" component and the Y output 112 is called the "quadrature" component of the vector signal relative to the reference signal. Each of these components is phase sensitive; however, the vector magnitude and phase components can be separated by the following relationships:

Eq. 1 $R = \sqrt{X^2 + Y^2}$, the magnitude

Eq. 2 $\theta = \tan^{-1}\left(Y/X\right)$, the phase angle.

The relationship between the outputs from the lock-in amplifier 52 and the inputs from the displacement gauges 50 is derived as follows:

Consider the two signals as sine waves with arbitrary amplitudes and arbitrary phase difference. Each signal can be represented as below:

$$V_{left} = V_{ref} = A \sin \omega t$$

$$V_{right} = B \sin(\omega t + \phi)$$

At the bottom PSD 106 the following operation occurs:

$$X' = V_{ref} * (V_{right}) = A \sin \omega t * [B \sin(\omega t + \phi)]$$

$$X' = \frac{1}{2}AB[\cos\phi - \cos(2\omega t + \phi)]$$

This signal has a DC voltage component and an AC component at twice the frequency. The Low Pass Filter (LPF) 108 removes the AC component leaving

$$X = \frac{1}{2}AB\cos\phi .$$

At the top PSD 106 the following operation occurs:

$$Y' = A\cos\omega t * [B\sin(\omega t + \phi)]$$

We have a cosine multiplier since $\cos\omega t = \sin(\omega t + 90°)$.

$$Y' = -\frac{1}{2}AB\sin\phi + \frac{1}{2}AB\sin(2\omega t + \phi)$$

Again, we have a signal with AC and DC components, which after passing through the LPF 108 , results in the following:

$$Y = -\frac{1}{2}AB\sin\phi .$$

Calculating the magnitude, R, and the phase angle, θ, from equations 1 and 2 we have:

$$R = \frac{1}{2}AB$$

and

$$\theta = \phi$$

These calculations may be executed by any suitable digital or analog processing device 120. The vector phase is proportional to mass flow.

Another method in accordance with embodiments of the invention requires a dual channel lock-in amplifier with the reference signal and one input signal supplied by one of the displacement gauges 50 and a second input signal supplied by the other displacement gauge 50. The lock-in amplifier may be implemented by hardware or software, or a combination of both. The difference between the two input signals is then measured against the reference signal. The resultant phase output from the lock-in amplifier is proportional to flow. Figure 7 is a functional schematic of a dual channel lock-in amplifier 54. The signals are moving in the same manner and have the same definitions as in Figure 6. The Left input 100 is also used as the reference signal. As before, the sine out 103 is the drive signal, phase locked to the Left input 100 signal. In this case, the Left Input 100 signal is subtracted from the Right Input 102 signal and mixed with the Left/Reference Input 100 signal and its 90° phased-shifted signal 104 in the two Phase Sensitive Detectors (PSDs) 106. The internal functions are the same as in the lock-in amplifier 52 of Figure 6.

The following derivation may be used to determine the relationship between the outputs from the lock-in amplifier 54 and the inputs from the displacement gauges 52. Any suitable digital or analog processing device 120 may be used to perform the calculations.

Consider the two signals as sine waves with arbitrary amplitudes and arbitrary phase difference. Each signal can be represented as below:

$$V_{left} = V_{ref} = A\sin\omega t$$

$$V_{right} = B\sin(\omega t + \phi)$$

The output of the Low Noise Differential Amplifier 114 in this case will be $V_{ref} - V_{right}$.

At the bottom PSD 106 the following operation occurs:

$$X' = V_{ref}(V_{ref} - V_{right}) = A\sin\omega t[A\sin\omega t - B\sin(\omega t + \phi)]$$

$$X' = \frac{1}{2}A^2[1 - \cos 2\omega t] - \frac{1}{2}AB[\cos\phi + \cos(2\omega t + \phi)]$$

This signal has a DC voltage component and an AC component at twice the frequency. The Low Pass Filter (LPF) 108 removes the AC component leaving

$$X = \frac{1}{2}A^2 - \frac{1}{2}AB\cos\phi$$

At the top PSD 106 the following operation occurs:

$$Y' = A\cos\omega t[A\sin\omega t - B\sin(\omega t + \phi)]$$

We have a cosine multiplier since $\cos\omega t = \sin(\omega t + 90°)$.

$$Y' = \frac{1}{2}A^2 \sin 2\omega t - \frac{1}{2}AB\sin\phi - \frac{1}{2}AB\sin(2\omega t + \phi)$$

Again, we have a signal with AC and DC components, which after passing through the LPF, results in the following:

$$Y = -\frac{1}{2}AB\sin\phi.$$

Calculating the magnitude, R, and the phase angle, θ, from equations 1 and 2 we have:

$$R = \frac{1}{2}A\sqrt{A^2 + B^2 - 2AB\cos\phi}$$

and

$$\theta = \tan^{-1}\left(\frac{B\sin\phi}{B\cos\phi - A}\right)$$

θ is no longer the phase angle, but is the arctangent, a function of the phase angle and the amplitudes of the Left and Right input signals. Analysis of this equation shows that θ is a strong function of ϕ. In fact, the relative amplitudes of the input signals can control the strength of this function. This can be illustrated in graph shown in Figure 8, in which A and B are the amplitudes of the Left and Right signals respectively. As the amplitudes are more closely matched, the sensitivity is higher for the lock-in amplifier output, θ. Even for amplitudes that are matched within 2%, the sensitivity of θ to ϕ is nearly 100 times that of the standard lock-in amplifier configuration.

Figure 9 is a functional schematic of a dual lock-in amplifier 56 with which another exemplary method for measuring the Coriolis force induced phase shift in accordance with the present invention is implemented. The lock-in amplifier may be implemented by hardware or software, or a combination of both. The signals are moving in the same manner and have the same definitions as disclosed above. The Left input 100 is also used as the reference signal. As before, the sine out 103 is the drive signal, phase locked to the Left input 100 signal. In this case, the Left Input 100 signal is mixed with itself and its 90° phased-shifted signal in the two Phase Sensitive Detectors (PSDs) 106 in the top lock-in amplifier 58. In the bottom lock-in amplifier 60, the Right Input 102 signal is mixed with the Left Input 100 signal and its 90° phased-shifted signal in the two Phase Sensitive Detectors (PSDs) 106. The paired outputs from the non-phase shifted PSDs 106 and phase shifted PSDs 106 are differentiated in the two Low Noise Differential Amplifiers 114. The DC components of the signals are passed by the Low Pass Filters 108 to give the usual lock-in amplifier outputs. The mathematics, which may be executed by any suitable digital or analog processing device 120, are the same as in the method outlined above in conjunction with Figure 7, though the order in which the operations occur is different. In the Dual Channel Lock-in technique of Figure 7, two high level signals, with very small differences are subtracted. The low-level signal is then multiplied with a high level signal, which can introduce noise in analog circuits or round off errors in digital circuits. In the Dual Lock-in technique of Figure 9, the high level signals are first multiplied and the resulting signals, which are close in amplitude, are then subtracted resulting in an output with lower noise.

A lock-in amplifier's use is most notable with respect to measuring a low-level signal that is buried in noise of a much higher amplitude. The lock-in amplifier accomplishes this by acting as an extremely narrow bandpass filter. The signal and noise is multiplied by a reference sine and cosine wave, and then passed through a low-pass filter to remove the reference frequency. The results of the multiply/filter operations are DC signals that represent a complex vector $(x + iy)$. The phase difference between the reference frequency and the signal of interest can be determined by $atan(y/x)$.

In terms of measuring Coriolis force, the phase difference between two signals of the same frequency is of interest. This can be accomplished using dual lock-in amplifiers, each driven with the same reference frequency as shown in Figure 10. In the functional schematic illustrated in Figure 10, Left and Right input signals 100, 102 are multiplied by reference sine and cosine waves provided by a reference frequency generator 144. The input signals 100, 102 are mixed with the sine and cosine signals in PSDs 106, then passed through fifth-order bessel IIR low pass filters 148 as described in conjunction with Figure 6, Figure 7 and Figure 9. The multiply/filter process described above is performed on the Left and Right input signals 100, 102 with a resulting phase difference output X, Y of each signal with respect to the reference frequency. The difference between the two output signals X, Y represents the phase difference between the two input signals 100, 102. In the case of Coriolis mass flow, this phase difference represents an indication of mass flow 152.

When using lock-in amplifiers to measure the extremely small phase differences associated with Coriolis mass flow, it is necessary to adjust the reference frequency to

match the signal of interest. If the reference signal is not very close to the signal of interest, a very low frequency AC signal will appear at the outputs of the low-pass filters 148. The frequency of the Coriolis sensor changes with mass flow, temperature, density and pressure, further complicating the measurement process.

The reference frequency can be adjusted accurately by processing the output vector from one of the input signals 100, 102. First, the derivative of the output vector is calculated. This may be accomplished by calculating the complex difference between two consecutive output vectors. Then, the original output vector is rotated 90 degrees and the dot product of this vector and the derivative is calculated, resulting in an error signal 150 that is provided to the reference frequency generator 144. The error signal 150 is negative, positive, or zero, if the reference frequency needs to be adjusted down, up or unchanged, respectively.

The amount of reference frequency adjustment is dependent on the accuracy of the phase measurement, but generally, the finer the adjustment, the better the accuracy as determined by calculating the standard deviation over a number of output samples. However, the finer adjustment (small step changes) of reference frequency will be detrimental if there are step changes in the signal frequency, as the reference frequency generator 144 will take too long reaching the intended frequency. If the signal frequency experiences frequent step changes, a PID or adaptive algorithm can be used to adjust the reference frequency in a more responsive manner.

In alternative embodiments, the capacitance displacement probes 50 may be mounted on piezoelectric actuators that would, first, align the capacitance displacement

probes 50 in three dimensions. Further, when used with the dual channel lock-in amplifier or dual lock-in amplifier methods disclosed herein, the piezoelectric actuators can dynamically adjust the sensitivity of the of the flow sensor, thereby providing an extended range of operation.

Such dynamic positioning provides compensation for manufacturing variability, particularly the positioning of the flow sensor tube relative to the capacitance displacement probe. Dynamic positioning also provides compensation for dimensional shifts due to relative thermal expansion of the various components. Used in combination with the dual channel lock-in amplifier or dual lock-in amplifier, dynamic positioning allows the two displacement signals to be closely matched to provide an adjustable sensitivity to flow. A low sensitivity would be used for high flow conditions while high sensitivity would be used for extended low flow conditions, thereby increasing the dynamic range of flow measurement.

Embodiments of the present invention additionally provide improved capacitance measurement techniques, specifically, a novel geometry of the capacitance displacement probe. Normally, the displacement of an object is measured as a distance normal to the capacitance displacement probe. The displacement may also be measured as a distance tangential to the capacitance displacement probe. Referring to Figure 11, this can be accomplished by placing two plates 130 side by side with a uniform gap 132 between the plates 130 and placed near a sensor tube 134 in the plane tangential to the motion (indicated by the arrow 136) as shown in Figure 11. In one embodiment, the plates 130 will be at the same potential and the sensor tube 134 will be at ground potential. The

sensor tube 134 is positioned directly over the gap 132 between the plates 130 with the expected motion 136 normal to the gap so that cyclic motion of the sensing tube 134 will position the tube 134 more closely to one plate 130 than the other 130. The relative capacitance is measured between each of the plates 130 and the sensor tube 134. As the sensor tube 134 moves over one plate 130 or the other, the amount of area contributing to the capacitance will change and thus the relative capacitance measured.

An alternative configuration has the gap 132 running diagonally across the sensor tube 134 as shown in Figure 12. This allows a less precise placement of the sensor tube 134 over the plane of the plates 130. Misalignment of the sensor tube 134 will cause a smaller mismatch in the signal as compared to the parallel gap 132.

A further embodiment has the gap 132 in a "saw tooth" pattern as shown in Figure 13. This is an improvement over the diagonal gap 132 in that an angular misalignment of the sensor tube 134 with respect to the gap 132, whether parallel or diagonal, will cause a difference in the rate of change of capacitance between the two plates 130. This will introduce an unwanted change in phase between the two signals. The "saw tooth" pattern will average out any angular misalignment of the sensor tube 134, providing more symmetrical signals.

Figure 14, Figure 15 and Figure 16 illustrate an exemplary low flow Coriolis mass flow controller 200 employing capacitive pick off sensors in accordance with an embodiment of the present invention. The Coriolis mass flow controller 200 includes a flow sensor portion 202 and a flow control portion 204. A processor either internal or external to the mass flow controller 200 receives an indication of a set point, or desired

mass flow. The set point value is compared to the actual mass flow as indicated by flow sensor portion 202 to generate an error value. The flow control portion 204 includes a valve that is manipulated to adjust the flow rate and minimize the error. The implementation of particular control schemes would be a routine undertaking for one skilled in the art having the benefit of this disclosure, and thus, the specifics of such an implementation are not addressed in detail herein.

The flow sensor portion 202, which is surrounded by an enclosure 205, includes a sensor tube 206 that is bent into a loop shape, a drive device 208 and two pick off sensors 210 positioned at opposite sides of the sensor tube 206 that measure the displacement of the sides of the sensor tube 206.

In existing Coriolis devices, the sensor is typically enclosed in a welded metal housing. The sensor tube within the housing also has attached to it displacement or velocity sensors with wires connecting through feedthroughs to electronics outside the housing. The sensor tube in such devices is relatively large and has a resonant frequency that is about 100 Hz. For smaller sensor tubes, as in embodiments of the present invention, the resonant frequency is somewhat higher, on the order of 200 Hz and greater. As the frequency increases, there will be an increased viscous damping effect due to the atmospheric conditions inside the sensor enclosure. By evacuating the enclosure and utilizing vacuum compatible materials inside the enclosure, the viscous damping can be reduced or even eliminated. Thus, in the exemplary embodiment illustrated, the sensor tube 206 is situated within a vacuum sensor housing 207.

The sensor tube 206 is designed to allow elastic bending orthogonal to a line connecting the legs of the tube's loop. The loop is wide enough to allow elastic twisting about the centerline of the loop. In order to measure the Coriolis force at low flows, the sensor tube 206 mass needs to be minimized. Tube sizing is critical since the tube needs to be small, yet still capable of retaining the fluids at extended pressures. It is also preferable for the pick off sensors 210 to be non-contact since any contact with the tube 206 or mass loading on the tube 206 may suppress the Coriolis force.

Pick off sensor technologies may include capacitive, magnetic, piezoresistive and optical. Piezoresistive, strain gauge displacement sensors do contact the tube but at the base of the loop where the displacement is minimum and the strain is the highest. This would have minimal effect on the tube's vibration. Optical technologies include various laser and white light interferometric displacement techniques, triangulation techniques, multiple internal reflection and beam occultation techniques. Magnetic displacement technologies include Hall effect, eddy current, variable reluctance and magnetoresistive techniques.

Capacitive pick off sensor technology is used in the embodiment illustrated in Figures 14-16, because it has the sensitivity required to measure the tube displacement, it is noncontact, and would not be affected by a magnetic drive device. The capacitive pick off sensors 210 each include at least one conductive plate 300, which is connected to a given voltage potential and situated adjacent the flow sensor tube 206 so as to define a gap therebetween. The flow sensor tube 206 is connected to a voltage potential different than the conductive plate 300. The capacitance between the conductive plate 300 and the

flow sensor tube 206 varies due to the relative motion of the conductive plate 300 and the flow sensor tube 206 when the flow sensor tube is vibrated 206.

In the embodiment shown in Figures 14-16, the conductive plates comprise first and second plates as disclosed above in conjunction with Figures 11-13. In the particular embodiment illustrated, saw-tooth shaped plates, as illustrated in Figure 13, are employed. The capacitive pick off sensors 210 are assembled into an integrated sensor block 301 sized to fit into the sensor enclosure 207, dimensionally referenced to the back wall of the enclosure 207 by press pins 302. The conductive plates 300 of the capacitive pick off sensors 210 are manufactured on a multilayer printed circuit board so as to provide a guard layer to minimize parasitic capacitance and a back contact layer for soldering to the sensor block 301. Since the capacitive pick off sensors 210 are required to operate in a vacuum, low outgassing materials are used in the illustrated embodiment. Standard fiberglass materials are not vacuum compatible. Desired material characteristics include that it be vacuum compatible, solderable, bondable into multilayers with a low outgassing bond and that it have a low dielectric constant for simple guard layer design. In a specific embodiment, commercially available DUROID is used.

The sensor block 301 containing the capacitive pick off sensors 208 can be adjusted to optimize the spacing to the sensor tube 206. This is accomplished using electron discharge machined hinge plates. Tapered setscrews spread gaps to effect linear and angular movement of the capacitive pick off sensors. Further, the conductive plates 300 of the capacitive pick off sensors include contact pads that allow wires to be soldered or wire bonded to a printed circuit board 303 on the front of the sensor block

interconnecting the capacitive pick off sensors 210 with a hermetically sealed electrical connector that interfaces with capacitance displacement electronics outside the sensor enclosure 207.

The drive device 208 drives the tube 206 into a bending mode vibration, causing it to vibrate. In the illustrated embodiment, the drive device 208 consists of a small magnet 304 soldered on the sensor tube 206 and a small electromagnetic coil 306 to alternately push and pull on the magnet 304. In the embodiment shown in Figure 16, a non-rare earth magnet, and more particularly, a nickel plated samarium cobalt magnet is used. The samarium cobalt magnet has a good magnetic strength to weight ratio. In this embodiment, the magnet weighs approximately 20 mg. The magnet 304 is positioned at the top, center of the sensor tube 206 so that the magnetic poles are directed parallel to the tube's preferred displacement direction.

The coil 306 is located outside the sensor enclosure 207, coupled to a circuit board 209. The sensor enclosure 207 is nonmagnetic and thus transparent to the magnetic fields. The coil 306 is an open coil type as opposed to a toroid design. In this embodiment the coil 306 is a commercially available power inductor rated at least 1 mH. The center axis of the coil 306 is aligned perpendicular to the face of the magnet 304. The sensor tube 206 is driven to resonance using the signal from one of the capacitive pick off sensors as feedback to the coil drive circuit through a phase locked loop (PLL) function. The function may be implemented as an electrical circuit or in software.

The sensor tube 206 is mounted to a base portion 212, which defines a flow inlet 214 and a flow outlet 216, such that a flow passage is provided from the inlet, through the

flow sensor tube 206, through the flow control portion 204, and through the sensor flow outlet 216. The flow control portion 202 includes a meter body 222 with a valve coil 228 and coil cover 230 situated therein. A valve stem 232 and plunger 234 are situated within the valve coil 228, and a valve body 236 is connected to the meter body 222 with a seal 238 therebetween. A valve seat 240, a spring 242 and an orifice 244 are positioned within the valve body 236. End blocks 224, 225 are situated on either end of the flow control portion 204 with seals 226 provided between the meter body 222 and end block 224, and between the valve body 236 and end block 225. In one embodiment, the seals 226 comprise electroformed nickel seals.

In an exemplary embodiment, the Coriolis mass flow controller 200 is assembled in the following manner. The meter body 222 and sensor enclosure 207, as well as a base plate 310, a center post 312 and the sensor tube 206 are assembled and held in place by a fixture that dimensionally references the sensor tube 206 to the walls of the sensor enclosure 207. The remaining parts are indexed by press pins 330. These parts are then brazed as a single unit. The magnet 304 is soldered onto the sensor tube 206. The sensor block 301 is assembled and installed into the sensor enclosure 207 using press pins 302. The press pins 302 extend through the back of the sensor enclosure 207 by approximately 0.5 mm. A hermetically sealed connector 320 is pressed into the back opening 322 of the sensor enclosure 207. The sensor block press pins 302 and hermetically sealed connector 320 are laser or e-beam welded to provide a leak tight seal. A cover 324 is placed over the front side of the sensor enclosure 207 in a vacuum environment and laser or e-beam welded into place, providing a vacuum tight environment.

The remaining valve components and end blocks 224, 225 are then assembled with the meter body 222. The electroformed nickel seals 226 may be used, or elastomeric o-rings may be used for calibration purposes, then replaced with the nickel seals. The electronics are assembled and installed on the completed assembly. An o-ring 332 is installed on the base plate 310 and the enclosure 205 is pressed down over the o-ring seal 332. Cam locks on the base plate 310 are rotated to lock down the enclosure 205. An o-ring 334 is installed on an electronics cover cap 336. The electronics cap 336 is positioned over a user interface connector 338. The electronics cap 336 is pressed into place on the enclosure 205 affecting the o-ring seal. The assembled mass flow controller 200 is then tested and calibrated.

The exemplary Coriolis mass flow controller 200 has a modular design that provides several benefits. As discussed above, the electronics packaging is designed to effect o-ring seals at the flow body (between the lower end of the enclosure 205 and base plate 310) and at the top to a user interface cap (between the upper end of the enclosure 205 and electronics cap 336). The electronics cap 336 is connected to a user interface board 340 internal to the Coriolis mass flow controller 200, which is also connected, to the sense and control electronics. The electronics cap 336 and user interface board 340 together define the interface to the user's electronics. This allows the flexibility to configure the interface according to the user's requirements without the need to design different sense and control electronics and enclosure for each user configuration.

A variant of the user interface cap, for example, will have seals and electrical conduit to provide a device that is IP-65/NEMA 4X compliant. An example of such a

device 400 is shown in Figure 18. In comparison, the embodiment illustrated in Figures 14-16 includes a connector 342 coupled to the user interface board 340. As shown in Figure 18, an electronics cap 337 is extended to provide space for the additional components required for a particular application.

Another feature of an o-ring sealed enclosure 205 is that it provides a tertiary fluid containment, the sensor tube 206 being the primary fluid containment and the sensor enclosure 207 providing the secondary containment.

In the event that there are bubbles in the fluid being controlled, the annular opening around the plunger in a conventional valve restricts the passage of bubbles to the outlet of the valve. Bubbles will collect at the entrance of the annular opening to the point that the liquid flow will be restricted and flow control will be lost. If the annular opening is enlarged, the increased spacing of the plunger from the valve coil will reduce the field strength in the magnetic circuit and thus reduce the effective force that can be achieved in order to open or close the valve against hydraulic forces created by the fluid. Thus, in the illustrated Coriolis mass flow controller 200, a circular hole 246 is provided through the plunger 234. The circular hole 246 is compatible with the shape and size of the bubbles, allowing bubbles to pass more freely through the valve. This minimizes the possibility of flow restriction caused by the bubbles. The hole 246 through the center of the plunger 234 minimizes any effects on the magnetic circuit so that the force to open and close the valve against hydraulic forces is maintained.

With typical existing valves, the valve plunger has a captive seat that is made from some deformable material that, when pressed against the land of the orifice, will form a

seal against flow. In the case of a normally closed, solenoid type valve, the force against the seat may be generated by a spring balanced so that the solenoid action lifts the seat from the orifice land. In the case of a normally open, solenoid type valve, the force against the set is generated by the solenoid action and is balanced so that the spring lifts the seat from the orifice when the magnetic field is removed. The seat material may be elastomeric, plastic, or a ductile metal.

It is usually preferable to have elastic deformation over plastic deformation so that the seal is repeatable. Alternatively, hard materials may be used for the seat and land, but fabricated to very tight tolerances including highly matched surfaces between the seat and land. This is a high cost approach. The spacing between the seat and land is critical to valve operation since the magnetic force on the plunger is not linear with displacement. In the case of a normally open valve, the normal position of the plunger and thus the seat relative to the land needs to be optimized in order to provide the maximum force when the seat is moved against the land, while allowing the maximum flow in the open position. In a normally closed valve, the force of the seat against the land is generated by the spring. The spring force needs to be sufficient to close against hydraulic forces, yet minimized to allow the magnetic force to lift the seat from the land sufficient distance to allow maximum flow.

Existing devices may use a variety of means to adjust the spacing between the seat and land, including placing shims under the land or seat, or having a threaded adjustment screw in the orifice component. As shown in Figure 17A, however, a typical threaded adjustment in the orifice does not seal between the orifice body 250 and the valve body

252, leaving a leak path 254 between threads 256. Such a threaded adjustment requires that the threads 256 be sealed against fluid leakage. A separate seal, such as an o-ring or gasket provides this seal.

In accordance with aspects of the present invention, the orifice 244 and/or land are made of a plastic material, such as VESPEL®, which is machinable into a threaded component with a precision orifice. As shown in the exemplary embodiment illustrated in Figure 17B, the threads 256 are machined oversized so that there is an interference fit 258 between the orifice body 250 and valve body 252, thus sealing, eliminating the need for a separate seal (o-ring or gasket). The orifice land now is the deformable member simplifying the design and manufacture of the valve seat 240 and plunger234 (referring to Figures 15 and 16).

The present invention, however, is not necessarily limited to any specific valve plunger configuration. In alternative embodiments, a pump is used in place of the valve. A metering pump, for example, may be used for fluid control purposes. In particular, a piezoelectric pump may be employed that includes a plurality of piezoelectric tube portions. The piezoelectric tube portions are controlled in a manner to cause different tube portions to constrict or expand, thus allowing the fluid flow to be controlled as desired.

Figure 19 illustrates another exemplary Coriolis mass flow sensing device in accordance with still further aspects of the invention. The illustrated Coriolis mass flow sensing device 500 includes, among other things, alternative structure for measuring the tube displacement to detect the Coriolis forces due to mass flow through the tube. Light

sources 510 are positioned on the sides near the top or on top of the flow tube 502 where the displacement is expected to be the greatest. Photo diodes or other photo detectors 512 can then be placed on the opposite side of the tube 502 facing the light source 510. The photo detectors 512 are connected to sensor electronics that process the signals received from the photo detectors 512. The sensor electronics may employ digital signal processing devices, such as the signal processing methods disclosed in U.S. Patent No. 5,555,190, or the lock in amplifier as disclosed herein in conjunction with the embodiments illustrated in Figures 6-11. Other embodiments are envisioned that use modal sensing or sinusoidal curve fit, wherein the received signal is compared to a reference using least squares phase determination, for example.

In one specific embodiment, the light sources 510 and photo detectors 512 are part of an optical sense circuit implemented on an optical sense printed circuit board (PCB). The light sources 510 and photo detectors 512 comprise infrared LEDs and photodiodes to sense the motion of the sensor tube 502. As shown in Figure 19, there are two sets of LEDs 510 and photodiodes 512, one set to sense each side of the sensor tube 502.

Figure 20 is a block diagram schematically illustrating portions of a Coriolis mass flow controller employing the optical Coriolis mass flow sensing device 500 shown in Figure 19. The optical Coriolis mass flow sensing device 500 makes up a portion of the optical sense PCB 520. The optical sense PCB 520 provides left and right output signals 521, 522 (corresponding to the left and right portions of the sensor tube 502) to a sensor pick off and drive circuit 524 residing on a motherboard PCB 526 via an optical drive PCB 540. An application and control circuit 528 is also implemented on the motherboard

PCB 526. A digital signal processing (DSP) PCB 530 includes a DSP processor 532, a flash EEPROM 534, a high-speed SRAM 536, and logic and supervisory circuits 538. A Texas Instrument TMS320C32 processor operating at 50MHz functions as the DSP processor 532 in one embodiment of the invention. An RTD 542 provides an output to the sensor pick off and drive circuit 524 via the optical drive PCB 540 to measure the sensor tube temperature. The sensor pick off and drive circuit 524 further provides an output signal to the drive coil 513 for controlling vibration of the sensor tube 502.

The tube is vibrated (in and out of the paper as illustrated in Figure 19) using a coil 513 driven with a sine wave at the resonant frequency of the tube 502. The magnetic force created by the coil 513 (for example, a 1mH inductor as in the embodiment described above in conjunction with Figures 14-16) pushes and pulls on a magnet 514 that is attached to the sensor tube 502, thus imparting motion. As the tube 502 vibrates, the amount of infrared light reaching the photodiodes 512 from the LEDs 510 is increased or decreased as the sensor tube 502 moves back and forth in the light path. The optical sense circuit translates the light variations into voltages that represent the position of the tube.

As the sensor tube 502 vibrates, the outputs of the optical sense circuit appear as two sine waves representing the motion of the left and right sides of the sensor tube 502. With no mass flow present through the sensor tube 502, the left and right sides of the tube 502 are in phase, and therefore the two sine waves are in phase indicating zero flow. As mass flow increases through the sensor tube 502, the phase difference between the motion of the left and right side of the sensor tube 502 increases (linearly with mass flow).

The sensor pick off and drive circuit 524 generates the sensor drive signal from the optical sense PCB outputs 521, 522. Therefore, the sensor tube 502, optical pick offs 510, 512 and drive coil/magnet system 513,514 make up a closed system that oscillates at a frequency determined by the mechanical properties of the sensor tube 502 itself. This concept is analogous to an electronic oscillator that uses a crystal instead of a mechanical object (the sensor tube 502).

The DSP PCB 430 and the associated electronics of the sensor pick off and drive circuit 524 translate the left and right sensor tube outputs 521, 522 to a numerical value representing the actual phase difference between the left and right side of the sensor tube 502. This phase difference represents mass flow.

As shown in Figure 21, the sensor pick off and drive circuit 524 includes a stereo A/D converter 550 that is used to sample the left and right outputs 521,522 from the optical sense PCB 520 for determining the phase difference between the left and right side of the sensor tube 502, for determining sensor tube 502 vibration frequency, and for determining the proper sensor tube 502 drive level. An RTD A/D converter 552 receives the output from the RTD 542 to measure the sensor tube 502 temperature via the RTD. A multiplying D/A converter 554 is used to adjust the sensor tube drive level. The DSP PCB 430 controls the stereo A/D converter 550, the RTD A/D converter 552 and the multiplying D/A converter 554.

Referring back to Figure 20, the optical drive PCB 540 functions to provide a 90 degree phase shift of the drive signal output, as well as providing attenuation and AC coupling of the optical sense PCB 520 left and right outputs 521,522. Further, the optical

drive PCB 540 provides an electrical connection of the RTD 542 to the sensor and pick off circuit 524 on the motherboard PCB 526.

A discussion of the signal flow further clarifies the purpose of the optical drive PCB 540 and illustrates how the sensor tube 502 is driven at its resonant frequency. The motion of the sensor tube 502 generates two sine waves (left and right output signals 521, 522) via the optical sense PCB 520. These signals pass through to the optical drive PCB 540 where they are AC coupled to remove any DC offset, and attenuated to reduce the amplitudes to that which are appropriate for the inputs of the stereo A/D converter 550 of the sensor pick off and drive circuit 524 on the motherboard PCB 526.

The sensor pick off and drive circuit 524 buffers these signals and samples them with the stereo A/D converter 550, and also feeds the left side signal 521 through the multiplying D/A converter 554 for adjusting drive gain. After the multiplying DAC 554, the signal is fed back to the optical drive PCB 540 where a 90-degree phase lag is induced before the signal is fed to the sensor drive coil 513. The 90-degree phase shift circuitry is necessary because a mechanical oscillator at resonance requires that the energy feeding back into the system (via the drive coil and magnet 513, 514) be 90 degrees out of phase with the motion of the tube 502.

As will be apparent to one skilled in the art, the attenuation, AC coupling and 90 degree phase shift could be incorporated on the optical sense PCB 520 or on the motherboard PCB 526. However, by implementing these functions on a separate PCB, the optical sense PCB 520 and optical drive PCB 540 may be removed from the system, allowing other mass flow sensors to be connected directly to the motherboard PCB 526.

The pick off inputs and the drive output on the motherboard PCB 526 must compatible with the corresponding outputs and drive system of the particular mass flow sensor to be implemented, or an appropriate interface must be provided.

Known Coriolis mass flow sensors do not require the 90 degree phase shift on the drive output, since typical prior art Coriolis sensor pick offs use magnets and coils that are velocity sensitive (pick off output amplitude is greatest at zero crossing), whereas the optical or capacitive pick offs disclosed herein are position sensitive (pick off output amplitude is greatest at the peaks). Since velocity is the derivative of position, and the derivative of a sine function is a cosine function, and the sine function is a 90-degree phase shifted cosine, the 90-degree phase shift in velocity-sensitive pick offs occurs naturally.

To initiate vibration of the sensor tube 502, the drive gain is increased much higher than normal. Ambient vibration that is always present vibrates the sensor tube 502 mostly at its resonant frequency. This small motion is detected by the optical pick offs 510, 512 and is used to drive the sensor tube 502 at greater amplitudes (via the high gain drive circuit). When the sensor tube 502 vibration reaches the desired amplitude, the drive circuit is switched to normal gain and the DSP PCB 530 takes over sensor tube amplitude control via the multiplying DAC 554. Without active control of the sensor tube drive amplitude, the sensor tube 502 would either stop vibrating, or vibrate out of control.

The phase difference, the sensor tube frequency and the sensor tube temperature calculated by the DSP PCB 530 is transmitted to the application and control system 528 via a 4800-baud serial link in the illustrated embodiment.

Figure 22 schematically illustrates aspects of the application and control circuit. The motherboard PCB 526 also contains the circuitry for the application and control circuit 528. A user interface (UI) PCB 560 may be plugged into the motherboard PCB 526. The motherboard PCB 526 includes a microcontroller 562, a flash EEPROM 564, a high-speed SRAM 566, and logic and supervisory circuits 568. One particular embodiment uses a Motorola 68LC302 microcontroller, running at 25Mhz. The microcontroller 562 controls

1. an A/D converter that is used to sense an analog set point input and analog valve override input 570;

2. a D/A converter used to output an analog flow signal 572; and

3. a D/A converter used to output a valve control signal 574.

The user interface PCB 560 shown in Figure 22 is an optional addition to the motherboard PCB 526 that provides for a variety of communication protocols. All of the electronics described to this point are not communication-specific. To obtain compatibility with various communication protocols, a unique user interface PCB 560 is provided for each desired protocol using a common user interface PCB form factor that will plug into the motherboard PCB 526.

For example, a common communication protocol is the HART protocol. The Analog/HART user interface PCB provides a 0(4)-20mA set point input and flow output in addition to the 0(1)-5V input and output already present on the motherboard PCB 526.

The HART physical layer is also present on this version, and an isolated power supply capable of 13VDC to 30VDC main power input is provided.

Figure 23 illustrates the HART interface 580. The flow output signal (0(4)-20mA) 582 is modulated with the appropriate carrier to allow the HART communication protocol to be transmitted and received on the output signal. The HART protocol provides a digital interface to the Coriolis mass flow controller for the purpose of monitoring data and for calibration and configuration of the device. The flow output signal 582 (0(4)-20mA) is also converted to a 0(1)-5V signal 584 for flow monitoring of a voltage in addition to current.

The set point input provides a jumper to select between a voltage 586 or a current 588 input. The set point input is converted to a voltage (if current input is selected) and passed through to the motherboard PCB 526 and is connected directly to the motherboard PCB set point input 570. The signal that is used for the flow output signal 572 on the motherboard PCB 526 only configuration is converted to a current output on the HART interface 580 and interpreted as a density output signal 590. The valve override input 570 is also passed through directly to the motherboard PCB 526 valve override input.

The motherboard PCB 526 only configuration shares a common ground between the power supply return and all signal returns. The power is supplied using +15VDC and ground. While separate ground connections exist on the motherboard PCB connector for input and output signals, they are electrically the same point.

The +15VDC input voltage 576 to the motherboard PCB 526 is used directly on all components requiring +15VDC. The +15VDC is also used to drive two DC-DC switching converters. One is used to convert +15VDC to +5VDC, the other to convert +15VDC to –9VDC. All of the electronic and electrical circuits (including the valve) are powered using these 3 voltage sources (+15VDC, -9VDC and +5VDC) in an exemplary Coriolis mass flow controller in accordance with the present invention. The only connection between chassis ground and power/signal ground is a 1M resistor and a 0.01uF capacitor in parallel.

The addition of the HART interface 580 provides isolation on the power supply input 576. The input voltage range of the HART interface is +13 to 30VDC and is completely isolated from the internal voltage sources and grounds. A DC-DC converter that converts 13 - 30VDC (reference number 592) to 15VDC, provides the isolation. The isolation is galvanic (main power transfer) and optical (feedback). The output of the DC-DC converter is electrically isolated +15VDC and ground.

Figures 24A and 24B illustrate the flow sensor portion 600 of a Coriolis mass flow controller in accordance with an embodiment of the invention employing optical pick off sensors. The flow sensing portion 600 shown in Figures 24A and 24B is suitable for use in a mass flow controller such as the controller 200 illustrated in Figures 14-16 hereof. Essentially, the flow sensor portion 600 of Figures 24A and 24B would be implemented in place of the flow sensor portion 202 of Figures 14-16. The flow sensing portion 600 includes the flow sensor tube 602, to which a magnet 604 is attached. Infrared LEDs 606 and photodiodes 608 are coupled to an optical sense PCB 610, positioned on either side of

the flow sensor tube 602. The flow sensor tube 602, magnet 604, LEDs 606, photodiodes 608 and PCB 610 are all situated within a housing 612, to which a cover 614 is attached. A 1mH inductor functions as a coil 616 to drive the tube. The coil 616 is positioned outside the housing 612.

Alternatively, the sensing tube, drive device and pick off sensors all may be contained within the enclosure, or selected components in addition to or in place of the coil may be positioned outside the enclosure. For example, certain embodiments may employ an enclosure having a window defined therein. This allows the light source and/or photo detector to be placed outside the enclosure. In still further embodiments, the sensor electronics are remoted from the enclosure, for example, using fiber optic cable. This may be desirable, for example, when the Coriolis mass flow sensing device is employed in a hazardous environment.

As disclosed above, the light source and detector may comprise an infrared LED light source matched to an infrared photo diode. The size of the photo diode active surface is close to but slightly larger than the tube diameter. As the tube vibrates, it moves through the path between the LED and photo diode, occulting the light from the LED. The tube may be positioned so that the light path between the LED and detector is partially broken when the tube is at rest. As the tube moves about this rest position in a vibratory fashion, the light reaching the detector will alternately be at a minimum or maximum providing a sinusoidal output from the detector. The relative outputs from each side of the tube can be measured for phase differences due to Coriolis induced flow effects.

As noted herein above, the flow sensing tube may be fabricated from any of a variety of materials. Further, the flow sensing tube may comprise a hybrid of materials. An example of such a hybrid structure is illustrated in Figure 25. A Coriolis mass flow sensor 700 is illustrated, including a silicon frame 702 and a stainless steel tube 704. The Coriolis mass flow sensor 700 further includes a clamp 706 and sensors 708, all of which are also implemented in silicon. Additional materials may be used; for example, the clamp 706 may be fabricated from metal, glass, plastic, ceramic, etc. Thin silicon arms 710 extend from the frame 702 and are attached to the sides of the sensor tube 704.

The sensors 708 are piezoresistors implemented in a Wheatstone bridge at the base of each of the silicon arms 710 attached to the sides of the sensor tube 704. These are, in effect, strain gauges, measuring the strain induced by the bending of the silicon arms 710. Figure 26A illustrates a first Wheatstone bridge 720. A Wheatstone bridge 720 is implemented at the base of each of the arms 710. The Wheatstone bridge 720 is typically also implemented in silicon, being deposited or implanted in the silicone frame 702. The Wheatstone bridge 720 includes four bridge resistors R1, R2, R3, R4, of which bridge resistors R1 and R4 are variable piezoresistors. The Wheatstone bridge 720 further includes an excitation supply connection Vs, a signal return GND, and sensor output signal connections –Vout and +Vout.

Figure 26B illustrates a second Wheatstone bridge 722 that is implemented between the two arms 710 to measure the differential stain between the two arms 710. In the Wheatstone bridge 722, resistors R1 and R2 are variable piezoresistors. Flow is

directly proportional to the differential strain. The phase does not have to be extracted from two separated signals.

Other aspects of the present invention involve Coriolis flow measurement devices employing straight sensor tubes – the flow tube defines a generally linear flow path. Figure 27 schematically illustrates a straight tube flow sensor 450 in accordance with embodiments of the invention. First, the tube 452 can be actuated in the usual vertically polarized mode by attaching piezoelectric drive devices 454 at each end of the tube 452. In certain embodiments, the piezoelectric drive devices comprise piezoelectric unimorphs, with the piezoelectric layer(s) attached to one side of the tube 452. Alternative embodiments are envisioned in which other piezoelectric drive devices are employed, such as piezoelectric bimorphs.

The opposite side may have either a piezoresistive layer attached or a piezoelectric layer attached to act as a sensor 456. The pair of unimorphs 454, actuated synchronously, drives the tube 452 at its resonant mode. As flow is established through the tube 452, the Coriolis forces will shift the relative strain on the piezo sensors 456, creating a phase shift in their output signal.

Another straight tube Coriolis sensor 451 is schematically illustrated in Figure 28. The straight tube 452 can be actuated in a circularly polarized mode, similar to that of a two-person jump rope. The component of the mass flow vector that induces the Coriolis force is perpendicular to the line of the tube 452. Each end of the tube 452 will experience a Coriolis force that will either be oriented in the direction of or in opposition to rotation. This will create a phase shift in at opposite ends of the tube 452. The tube

may be actuated, for example, by placing a magnet 460 at the center of the tube 452 and driving it in circular oscillation with 2 orthogonally positioned electromagnetic coils 462. The respective drive signals have a phase difference of 90 degrees. Sensors 456 are positioned at either end of the tube 452, alternatively, the sensors 452 could be placed in an orthogonal fashion similar to the drive coils 462 and magnet 460 at the 1/3 points on the tube 452. The sensors 456 could be optical, capacitive or electromagnetic in nature depending in part on the tube material.

As an alternative to the magnet 460 and coil 462 drive arrangement, a piezoelectric tilt actuator attached to each end of the tube acts as a driver for this mode in other embodiments of the invention. Known piezoelectric tilt actuators are typically used to dynamically align optical mirrors. The typical optical mirror configuration consists of threee piezoelectric stacks arranged in a tripod attached to a platform holding a mirror. To drive the tube in circular oscillation the piezoelectric stacks are driven with three sinusoidal signals, each with its phase 120 degrees advanced from the neighbor after it. This would be similar to a three-phase motor drive. Since piezoelectric tilt actuators are usually expensive and are large compared to a given mirror, the following alternative is employed in embodiments of the present invention.

Flat piezoelectric unimorphs are considerably less expensive than the three-stack actuator mentioned above. They typically require a lower voltage to achieve equivalent displacements and are much smaller that the stacked actuators. Exemplary tilt actuators 470, 471 are conceptually illustrated in Figures 29A and B. The tilt actuators 470, 471 employ, respectively, a three-arm and four-arm flat spiral springs 474, 475. Piezoelectric

devices are configured on each arm 476 of the flat spiral spring 474, 475. In the illustrated embodiment, the spring 474 has a piezoelectric unimorph 472 configured on each arm 476 near the outside ring structure 478 of the spring 474, 475. Piezoelectric or piezoresistive sensors are attached to the opposite side of the spring 474 from the piezoelectric actuators 472. The sensors sense the relative phase between the sensors on each end of the tube.

Application of a voltage to the unimorphs 472 thus results in displacement of the respective arm 476. With the three-arm spring 474, the unimorphs 472 are driven by a three-phase sinusoidal signal as with the three-stack tilt actuators described above, resulting in a generally circular drive motion. The four-arm spring 475 is more complicated in structure, but is simpler in actuation. Instead of a three-phase driver, a two- phase driver is required for the four-arm structure. Each drive signal is applied to 2 opposing arms 476. The motion is analogous to applying two sinusoidal signals to the x and y inputs to an analog oscilloscope and observing the Lissajous figures. If the two signals are 90 degrees out of phase and are of the same amplitude, result will be a circle.

The flat spiral spring 474,475 has the advantage over the sheet type unimorphs 454 disclosed in conjunction with Figure 27, in that the spring 474 will accommodate vertical displacement without the requirement that the diameter change as in the sheet type 454. Density can still be measured by an increase in the sensor signal amplitude driven by an increase in the centrifugal force on the tube. This mode of actuation allows for increased flexibility of tube material selection. The tube does not have to be a resonating structure.

The system does not even have to be in resonance since it can be driven to a continuum of frequencies just as with the example of the two person jump rope.

The particular embodiments disclosed above are illustrative only, as the invention may be modified and practiced in different but equivalent manners apparent to those skilled in the art having the benefit of the teachings herein. Furthermore, no limitations are intended to the details of construction or design herein shown, other than as described in the claims below. It is therefore evident that the particular embodiments disclosed above may be altered or modified and all such variations are considered within the scope and spirit of the invention. Accordingly, the protection sought herein is as set forth in the claims below.

CLAIMS

WHAT IS CLAIMED IS:

1. A Coriolis mass flow sensor, comprising:

a flow tube;

a light source positioned adjacent a first side of the flow tube;

a light detector positioned adjacent a second side of the flow tube; and

a drive device operatively situated relative to the flow tube for vibrating the flow tube, such that the flow tube moves through a path defined between the light source and the light detector.

2. The Coriolis mass flow sensor of claim 1, wherein the light source emits infrared light.

3. The Coriolis mass flow sensor of claim 2, wherein the light source comprises an infrared LED.

4. The Coriolis mass flow sensor of claim 3, wherein the light detector comprises an infrared photo diode.

5. The Coriolis mass flow sensor of claim 4, wherein the photo diode defines an active surface larger than the diameter of the flow tube.

6. The Coriolis mass flow sensor of claim 1, wherein the light source is positioned relative to the flow tube at a point wherein displacement of the vibrating flow tube is at a maximum.

7. The Coriolis mass flow sensor of claim 1, wherein the light source is positioned relative to the flow tube such that the flow tube is positioned partially within the path defined between the light source and the light detector when the flow tube is at rest.

8. A Coriolis mass flow sensor, comprising:

a flow tube;

a frame having the flow tube mounted thereon;

a drive device operatively situated relative to the frame for vibrating the frame; and

at least one pick off sensor situated relative to the flow tube so as to measure the twist in the flow tube due to Coriolis force.

9. The Coriolis mass flow sensor of claim 8, wherein the frame comprises a tube in which the flow tube is situated.

10. The Coriolis mass flow sensor of claim 8, wherein the flow tube and the frame are fabricated from different types of material.

11. The Coriolis mass flow sensor of claim 10, wherein the flow tube is fabricated of stainless steel.

12. The Coriolis mass flow sensor of claim 10, wherein the flow tube is fabricated of plastic.

13. The Coriolis mass flow sensor of claim 10, wherein the frame is fabricated of silicon.

14. A Coriolis mass flow sensor, comprising:

a flexible flow tube having first and second ends, the flow tube defining a generally linear flow path;

a drive device positioned to actuate the flow tube;

first and second pick off sensors positioned at the first and second ends of the flow tube, respectively, each of the first and second pick off sensors outputting a signal in response to movement of the flow tube, wherein a Coriolis force established by a flow of material through the flow tube causes a phase shift between the signals output by the first and second pick off sensors.

15. The Coriolis mass flow sensor of claim 14, wherein the drive device activates the flow tube in a vertically polarized mode.

16. The Coriolis mass flow sensor of claim 14, wherein the drive device activates the flow tube in a circularly polarized mode.

17. The Coriolis mass flow sensor of claim 14, wherein the drive device comprises first and second piezoelectric unimorphs operatively connected to the first and second ends of the flow tube, respectively.

18. The Coriolis mass flow sensor of claim 14, wherein the drive device comprises:

a flat spring defining a plurality of arms; and

a plurality of piezoelectric devices, each of the arms having one of the piezoelectric devices attached thereto.

19. The Coriolis mass flow sensor of claim 18, wherein the piezoelectric devices are each connected to a power source:

20. The Coriolis mass flow sensor of claim 18, wherein the piezoelectric device comprises a piezoelectric unimorph.