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FLOW SENSOR, CONTROLLER, AND METHOD WITH CALIBRATION

Abstract

An illustrative sensor controller includes: a transmitter, a first receiver, a second receiver, a propagation speed circuit, and a level circuit. The transmitter provides a drive signal to an ultrasonic sending transducer to generate an acoustic burst. The first receiver receives a first response signal from a first ultrasonic receiving transducer. The second receiver receives a second response signal from a second ultrasonic receiving transducer at a predetermined distance from the ultrasonic sending transducer. The propagation speed circuit is configured to detect a direct arrival of the acoustic burst in the second response signal and to measure a corresponding propagation speed. The level circuit detects a reflected arrival of the acoustic burst in the first response signal, measures a corresponding time of flight, and derives a fluid level based on the time of flight and the propagation speed.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] This application is a continuation of U.S. application Ser. No. 19/042,615, filed 2025 Jan. 31, titled “ROBUST FLOW SENSOR, CONTROLLER, AND METHOD”, which in turn claims the benefit of U.S. Provisional Application No. 63/551,338, filed 2024 Feb. 8 and titled “Ultrasonic flow/level meter with high level of functional safety and online calibration function” by inventor Marek Hustava. Each of these applications is hereby incorporated herein by reference.

TECHNICAL FIELD
[0002] The present disclosure pertains to the field of ultrasonic sensing technology. More specifically, it relates to flow meters, flow sensor controllers, and associated methods that utilize ultrasonic transducers for determining fluid flow rates, levels, and conditions in various environments.
BACKGROUND
[0003] Flow meters are widely employed in industrial processes, environmental monitoring, and fluid management systems to ascertain fluid flow rates, levels, and conditions. Despite their prevalent use and established functionality, there have been ongoing challenges related to measurement precision, reliability, and functional safety. These factors can impact the overall accuracy of readings, necessitating the need for maintenance, redundancy, and frequent recalibration, thereby increasing operational costs and downtime.
[0004] Furthermore, integration of online calibration functions and redundant safety checks are increasingly critical in applications demanding high functional safety standards. Modern systems require not only precise measurement capabilities but also the ability to diagnose and alert operators to any operational faults, thereby contributing to improved safety and reduced risk of malfunctions.
SUMMARY
[0005] In light of these challenges, the present disclosure explores systems, methods, and sensors capable of addressing the imperfections associated with existing flow meter technology, offering enhanced reliability while reducing component, system, and maintenance costs.
[0006] One illustrative sensor controller includes: a transmitter, a receiver, a time-of-flight circuit, and a phase shift circuit. The transmitter is configured to provide a drive signal to an ultrasonic sending transducer to generate an acoustic burst. The receiver is configured to receive a response signal from an ultrasonic receiving transducer. The time-of-flight circuit is configured to detect an arrival of the acoustic burst in the response signal and to measure a first time of flight associated with that arrival. The phase shift circuit is configured to measure a phase shift of the acoustic burst in the response signal and to determine a second time of flight corresponding to the phase shift.
[0007] One illustrative sensing method includes: providing a drive signal to an ultrasonic sending transducer to generate an acoustic burst; receiving a response signal from an ultrasonic receiving transducer; using a time of flight circuit to detect an arrival of the acoustic burst in the response signal and to measure a first time of flight associated with that arrival; and using a phase shift

circuit to measure a phase shift of the acoustic burst in the response signal and to determine a second time of flight corresponding to the phase shift.

[0008] One illustrative flow sensor includes: a first ultrasonic transducer positionable to emit in a first propagation direction through a fluid flow; a second ultrasonic transducer positionable to emit in an opposite propagation direction through the fluid flow; and a sensor controller having a transmitter, a receiver, a time-of-flight circuit, a phase shift circuit, and control logic. The transmitter is configured to provide a drive signal to an ultrasonic sending transducer to generate an acoustic burst. The receiver is configured to receive a response signal from an ultrasonic receiving transducer, the ultrasonic receiving transducer being a selectable one of the first ultrasonic transducer and the second ultrasonic transducer and the ultrasonic sending transducer being an other one of the first ultrasonic transducer and the second ultrasonic transducer. The time-of-flight circuit is configured to detect an arrival of the acoustic burst in the response signal and to measure a first time of flight associated with that arrival. The phase shift circuit is configured to measure a phase shift of the acoustic burst in the response signal and to determine a second time of flight corresponding to the phase shift. The control logic is configured to swap the ultrasonic sending transducer and the ultrasonic receiving transducer to obtain a first time of flight and a second time of flight for each of the first propagation direction and the opposite propagation direction, and is configured to determine a first time of flight difference between directions and a second time of flight difference between directions.

[0009] Another illustrative sensor controller includes: a transmitter, a first receiver, a second receiver, a propagation speed circuit, and a level circuit. The transmitter is configured to provide a drive signal to an ultrasonic sending transducer to generate an acoustic burst. The first receiver is configured to receive a first response signal from a first ultrasonic receiving transducer. The second receiver is configured to receive a second response signal from a second ultrasonic receiving transducer at a predetermined distance from the ultrasonic sending transducer. The propagation speed circuit is configured to detect a direct arrival of the acoustic burst in the second response signal and to measure a corresponding propagation speed. The level circuit is configured to detect a reflected arrival of the acoustic burst in the first response signal, to measure a corresponding time of flight, and configured to derive a fluid level based on the time of flight and the propagation speed.

[0010] Another illustrative sensing method includes: providing a drive signal to an ultrasonic sending transducer to generate an acoustic burst; receiving a first response signal from a first ultrasonic receiving transducer; receiving a second response signal from a second ultrasonic receiving transducer at a predetermined distance from the ultrasonic sending transducer; measuring a propagation speed based on a direct arrival of the acoustic burst in the second response signal; measuring a time of flight for a reflected arrival of the acoustic burst in the first response signal; and deriving a fluid level based on the time of flight and the propagation speed.

[0011] Yet another illustrative sensor controller includes: a transmitter, a first receiver, a second receiver, and a signal processing circuit. The transmitter is configured to provide a drive signal to an ultrasonic sending transducer to generate an acoustic burst. The first receiver is configured to receive a first response signal from an ultrasonic receiving transducer. The second receiver is configured to receive a second response signal from a MEMS transducer. The signal processing circuit is coupled to the first receiver and configured to measure a first time of flight associated with an arrival of the acoustic burst in the first response signal, and is further coupled to the second receiver and further configured to measure at least one of: a leak noise intensity, an acoustic burst intensity, and a second time of flight associated with an arrival of the acoustic burst in the second response signal.

[0012] Yet another illustrative sensing method includes: providing a drive signal to an ultrasonic sending transducer to generate an acoustic burst; receiving a first response signal from an ultrasonic receiving transducer; receiving a second response signal from a MEMS transducer; and using a signal processing circuit to measure a first time of flight associated with an arrival of the acoustic burst in the first response signal and to measure at least one of: a leak noise intensity in the second response signal, an acoustic burst intensity in the second response signal, and a second time of flight associated with an arrival of the acoustic burst in the second response signal.

[0013] Still another illustrative sensor controller includes: a transmitter, a receiver, and a signal processing circuit. The transmitter is configured to provide a drive signal to an ultrasonic sending transducer to generate an acoustic burst. The receiver is configured to receive a response signal from an ultrasonic receiving transducer. The signal processing circuit is configured to measure a time of flight for the acoustic burst in the response signal. The transmitter is further configured to measure an impedance of the ultrasonic sending transducer.

[0014] Still another illustrative sensing method includes: providing a drive signal to an ultrasonic sending transducer to generate an acoustic burst; receiving a response signal from an ultrasonic receiving transducer; measuring a time of flight for the acoustic burst in the response signal; and monitoring an impedance of the ultrasonic sending transducer.

[0015] Still yet another illustrative sensor controller includes: a transmitter, a receiver, a signal processing circuit, and control logic. The transmitter is configured to provide a drive signal to an ultrasonic sending transducer to generate an acoustic burst. The receiver is configured to receive a response signal from an ultrasonic receiving transducer. The signal processing circuit is configured to measure a time of flight for the acoustic burst in the response signal. The control logic is configured to modulate the drive signal to generate a near range communication signal.

[0016] Still yet another illustrative sensing method includes: providing a drive signal to an ultrasonic sending transducer to generate an acoustic burst; receiving a response signal from an ultrasonic receiving transducer; measuring a time of flight for the acoustic burst in the response signal; and modulating the drive signal to generate a near range communication signal.

[0017] Each of the foregoing illustrative implementations can be embodied individually or conjointly, together with one or more of the following optional features in any suitable combination: 1. control logic configured to determine a flow rate based on both the first time of flight and on the second time of flight. 2. control logic configured to compare the first time of flight to the second time of flight. 3. control logic configured to compare a first flow rate derived from the first time of flight to a second flow rate derived from the second time of flight. 4. the controller is configured to assert a fault signal if the comparison indicates a persistent mismatch. 5. the ultrasonic receiving transducer is a different, separate transducer from the ultrasonic sending transducer. 6. control logic configured to swap the ultrasonic sending transducer and the ultrasonic receiving transducer to obtain a first time of flight and a second time of flight for each burst propagation direction. 7. the control logic determines a first time of flight difference between directions and a second time of flight difference between directions. 8. the control logic is configured to determine a flow rate based on both the first time of flight difference and on the second time of flight difference. 9. the control logic is configured to compare the first time of flight difference to the second time of flight difference. 10. the control logic is configured to compare a first flow rate derived from the first time of flight difference to a second flow rate derived from the second time of flight difference. 11. a second receiver configured to receive a reflection signal from the ultrasonic sending transducer. 12. a Doppler shift circuit configured to detect an echo of the acoustic burst in the reflection signal and to measure a velocity associated with that echo. 13. control logic configured to determine a flow rate based on the velocity when the echo has a magnitude above a threshold. 14. control logic that determines a flow rate based on the fluid level. 15. the first ultrasonic receiving transducer is also the ultrasonic sending transducer. 16. the second ultrasonic receiving transducer is a MEMS transducer. 17. control logic configured to assert a leak detection signal when the leak noise intensity exceeds a predetermined threshold. 18. control logic configured to assert a fault signal when the acoustic burst intensity falls below a given threshold. 19. control logic configured to initiate a cleaning cycle if the second response signal indicates loading of the ultrasonic sending receiver. 20. the signal processing circuit is configured to derive a propagation speed from the second time of flight. 21. control logic configured to assert a fault signal if the impedance is outside a predetermined range. 22. control logic configured to initiate a cleaning cycle if the impedance exceeds a predetermined threshold. 23. control logic configured to monitor the impedance as a function of frequency. 24. based on the impedance as a function of frequency, the control logic is configured to adjust a carrier frequency of the drive signal to match a resonance frequency of the ultrasonic sending transducer. 25. a built-in self-test (BIST) circuit, and control logic configured to assert a fault signal if the BIST circuit indicates a fault in the transmitter, the receiver, the signal processing circuit, or the control logic. 26. the control logic is configured to operate the BIST circuit prior to generating each acoustic burst. 27. comprising control logic configured to compare the acoustic burst in the response signal to a standard waveform. 28. the control logic is configured to assert a fault signal if a mismatch exists between the acoustic burst in the response signal and the standard waveform. 29. the control logic is further configured to initiate a cleaning cycle if a mismatch exists between the acoustic burst in the response signal and the standard waveform. 30. the ultrasonic sending transducer is also the ultrasonic receiving transducer. 31. the signal processing circuit is configured to demodulate the response signal to receive a near range communication response. 32. a second receiver coupled to a second ultrasonic receiving transducer to receive a near range communication response. 33. control logic configured to determine an open channel flow rate based at least in part on the time of flight. 34. the control logic is configured to determine a closed channel flow rate based on the time-of-flight difference.

Description

BRIEF DESCRIPTION OF THE FIGURES

[0018] FIG. **1** is a plan view of an illustrative flow meter arrangement for a closed channel flow.

[0019] FIG. **2** is a perspective view an illustrative flow meter arrangement for an open channel flow.

[0020] FIG. **3** is a block diagram of an illustrative sensor controller with supporting components for ultrasonic transmission and reception.

[0021] FIG. **4**A is a block diagram of illustrative signal processing and diagnostic circuitry within the sensor controller.

[0022] FIG. **4**B is a block diagram of illustrative phase calculation circuitry that may be used within the sensor controller.

[0023] FIG. **4**C is a graph showing cosine and sine function values that may be stored in a look-up table for low-power phase calculation.

[0024] FIG. **5** is a schematic of a direct drive circuit for a piezoelectric transducer.

[0025] FIG. **6** is a graph displaying various switch signal timings and resulting voltage levels for transducer activation.

[0026] FIG. **7** is a flow diagram of an illustrative flow sensing method employing multiple independent measurements for robust sensing.

[0027] FIG. **8** is a flow diagram of an illustrative flow sensing method employing a second receive transducer for propagation speed measurement, leak detection, and/or fault monitoring.

[0028] FIG. **9** is a flow diagram of an illustrative flow sensing method employing impedance monitoring and fault detection for enhanced reliability.

[0029] FIG. **10** is a flow diagram of an illustrative near range communications method for an interrogator device.

[0030] FIG. **11** is a flow diagram of an illustrative near range communications method for a responder device.

DETAILED DESCRIPTION

[0031] It should be understood that the drawings and following description do not limit the disclosure, but on the contrary, they provide the foundation for one of ordinary skill in the art to understand all modifications, equivalents, and alternatives falling within the scope of the claim language.

[0032] To aid understanding, FIGS. **1** and **2** show illustrative contexts in which the described sensor controller and methods may be employed. FIG. **1** shows a closed-channel fluid measurement system with a pipe **102** having through which a fully confined fluid flow **104** is directed. The fluid may be a liquid, a gas, or any flowable composition including inhomogeneous mixtures with suspended solids. The pipe **102** has a predetermined cross-sectional flow area A and may be configured to provide a reasonably uniform laminar flow stream having an average flow velocity v along the pipe's longitudinal axis.

[0033] A sensor controller **106** is connected to the system, controlling the operation of ultrasonic transducers **108**, **112**. An ultrasonic sending transducer **108** is positioned on one side of the pipe **102**, emitting an acoustic burst or other acoustic signals along a propagation path **110** across a diameter of the pipe intersecting the longitudinal axis at an angle θ. On the opposite side, an ultrasonic receiving transducer **112** is situated to capture the acoustic signals sent by the sending transducer **108**. Sending transducer **108** may further be configured to receive reflections of the acoustic bursts from, e.g., bubbles, droplets, or particles entrained in the fluid flow. The sensor controller **106** processes these signals to evaluate parameters such as time of flight and phase shift as described further below.

[0034] The sensor controller **106** periodically swaps the roles of the ultrasonic transducers, such that transducer **112** may become the ultrasonic sending transducer and transducer **108** may become the ultrasonic receiving transducer, enabling the sensor controller **106** to determine parameters for opposing propagation directions along path **110**. The downstream time of flight is shortened by an amount determined by the fluid flow velocity and the upstream time of flight is similarly extended. By combining (e.g., by determining a difference between reciprocals of) the upstream and downstream measurements, the sensor controller can, in combination with other geometrical parameters (such as pipe diameter and intersection angle θ) measure the fluid flow velocity v. When combined with pipe cross section, the fluid flow velocity enables the sensor controller to determine and monitor a volumetric flow rate. If the fluid density is known or independently measured, the volumetric flow rate can be readily converted to a mass flow rate. Given the tight and well-understood correlation of fluid flow velocity, volumetric flow rate, and mass flow rate, they are each contemplated herein as being encompassed by the generic term “fluid flow rate”.

[0035] Certain enhancements to this arrangement provide enhanced reliability and robustness without unduly increasing implementation costs. These enhancements may include an integrated microphone **120** to potentially enhance sound capture capabilities for additional analysis or communication purposes. The arrangement of these components enables precise measurement and monitoring of parameters associated with fluid flow **104**.

[0036] FIG. **2** shows an open channel **200** through which fluid flow **204** is directed over a weir **202** or other obstruction. As is well understood in the civil engineering arts, the geometry of the channel and obstructions cause the fluid flow's depth to vary monotonically as a function of the fluid flow rate. Thus, by monitoring the fluid level, a suitably programmed sensor controller can determine the flow depth and thereby monitor the fluid flow rate and cumulative flow volume.

[0037] Accordingly, FIG. **2** further shows a level sensor **206** positioned above the fluid flow **204** to monitor the surface level. The illustrated level sensor **206** uses an ultrasonic sending transducer to emit an acoustic burst **208** and an ultrasonic receiving transducer (which may be the same as the sending transducer) to detect a reflection of the acoustic burst **208** from the fluid's surface. (In an alternative configuration, the level sensor **206** is positioned below the fluid's surface and oriented upward.) The level sensor **206** includes a sensor controller to measure the time of flight and the associated distance to the surface of the fluid flow **204**. With this distance, the sensor controller can use stored geometrical parameters, formulas, and/or look up tables to determine depth of the fluid flow and the associated fluid flow rate, from which a cumulative flow volume can be readily derived.

[0038] As a potential enhancement, the illustrated arrangement includes a second ultrasonic receiving transducer **210** positioned at a predetermined distance from the ultrasonic sending transducer of the level sensor **206**. This transducer **210** is designed to receive the acoustic burst **208** along a direct propagation path, enabling the sensor controller to determine a propagation speed of the acoustic burst. Because the speed of sound in air depends on temperature, pressure, and humidity, this measurement of propagation speed enables more accurate measurement of the distance to the fluid surface. Adjustments and modifications to the positions of the level sensor **206** and the ultrasonic receiving transducer **210** can be made to accommodate various fluid flow conditions, providing versatility in different operational environments.

[0039] FIG. **3** shows an illustrative sensor controller **300**, which may be implemented as a monolithic integrated circuit chip having an arrangement of interconnected components, designed to handle ultrasonic signal processing and communication tasks. At the heart of the system, the control logic **326** coordinates signal flow and processing through an internal bus **324**. The transmitter components, including transmitter **302**, transmitter **304**, and transmitter **306**, are configured to deliver drive signals to various ultrasonic sending transducers, such as ultrasonic sending transducer **352**, ultrasonic sending transducer **354**, and (via a transformer **356**) ultrasonic sending transducer **357**, generating acoustic bursts that emanate from these transducers. To offer configuration flexibility, transmitters **302**, **304** may be direct-drive transmitters using voltage drivers as described further below, while transmitter **306** may be a current driver configured to supply drive current to a transformer **356**, enabling the transformer to supply an elevated voltage signal to transducer **357**.

[0040] Transmitter **306** may further provide a sensing voltage to analog-to-digital converter (ADC) **318**, enabling the sensor controller **300** to monitor the voltage response of the ultrasonic sending transducer **357** during driving and/or post-driving reverberation. As described further below, transmitters **302**, **304** may be configured for current or impedance monitoring, enabling the sensor controller **300** to monitor the impedance of the ultrasonic sending transducers **352**, **354** during driving. Though three sending transducers are shown in FIG. **3**, most contemplated sensor arrangements will employ only one or two ultrasonic sending transducers.

[0041] Sensor controller **300** further includes a receiver **308**, receiver **310**, and receiver **312**, respectively coupled to an ultrasonic receiving transducer **358**, ultrasonic receiving transducer **360**, and microphone **362**. Transducers **358**, **360**, **362** are all shown for completeness; in practice one or more of these may be omitted. While ultrasonic receiving transducers **358**, **360** are shown and implementable as individual elements, it is contemplated that each receiving transducer may also serve as one of the ultrasonic sending transducers **352**, **354**, **357**. For example, the sensor may have a single transducer that is driven by one of the transmitters to generate an acoustic burst before being used by one of the receivers to detect a reflection of the acoustic burst. As another example, the sensor may have a transducer that is used to generate an acoustic burst and a second transducer used to receive the response. In this case, the second transducer can be used to generate a subsequent acoustic burst and the first transducer may be used to receive a subsequent response. The ultrasonic sending and receiving transducers may be piezoelectric (PZ) elements with optional supporting discrete components. Microphone **362** may similarly be a piezoelectric element, though a micro-electromechanical systems (MEMS) transducer may be preferred for higher sensitivity.

[0042] A demultiplexer **314** forwards the digital transmit signal from transmit signal generator **316** to a selected one of the transmitters **302-306** to drive the corresponding ultrasonic sending transducer to generate an acoustic burst. An arrangement of multiplexers **320**, **322** selectively couple the analog receive signals from receivers **308**, **310**, **312**, to ADC **321** and ADC **323**, which digitize the receive signals. Control logic **326** coordinates the operation of components **302-323** to deliver digital receive signals to digital signal processor (DSP) **328**, microcontroller **330**, memory **332**, and/or application specific integrated circuitry (ASIC) modules within control logic **326**. In addition to providing software or firmware instructions and programmable parameters for the signal processing components, memory **332** may provide buffering of the digital receive signals, intermediate signal streams, and measurement signals, but also may provide nonvolatile storage for logs of the measurement results that can be stored for later retrieval or delivered in real time to other components or systems.

[0043] Signal processing tasks can be allocated in various ways among the microcontroller unit (MCU) **330**, DSP **328**, and control logic **326**, which may be primarily distinguishable in terms of their balance between software and hardware implementation of their desired functionality. FIG. **3** shows the phase shift measurement circuit **334** as being implemented mainly within the digital signal processor **328**, but the disclosed modules can be distributed in other ways, with some functions implemented by the ASIC modules and others by software in the microcontroller.

[0044] FIG. **3** further shows a multiplexer **336** directing a selected analog receive signal from receivers **308**, **310** to a time-of-flight measurement circuit **344**. The time-of-flight measurement circuit **344** includes a pulse generator **338**, a comparator **340**, and a time-to-digital converter TDC **342**. When the transmit signal generator **316** operates to generate an acoustic burst, it provides an asserted Start signal to pulse generator **338**. The pulse generator **338** asserts its output signal until the Stop signal from the comparator **340** is asserted. The comparator **340** asserts the Stop signal when the selected analog receive signal exceeds a predetermined threshold voltage VT, indicating the arrival of an acoustic burst in the selected receive signal. In some alternative implementations, the pulse generator **338** incorporates a zero-crossing detector for increased precision. The pulse generator **338** de-asserts its output (1) after the envelope of the receive signal exceeds the threshold voltage, and (2) the zero-crossing detector detects a subsequent zero crossing in the receive signal. TDC **342** converts width of the pulse output by pulse generator into a digital value indicating its duration. Suitable implementation examples may include: (1) a high frequency clock counter, and (2) an integrator coupled to an analog-to-digital converter.

[0045] Sensor controller **300** may further include supporting components such as built-in self-test (BIST) circuitry **346**, a general-purpose input/output (GPIO) interface module **347**, a power supply **348**, an oscillator **349**, and a temperature sensor circuit **350**. The BIST circuitry **346** may be configured to test functionality of the various other components including the transmitters, the receivers, the signal processing circuitry, and the control logic. The GPIO interface **347** may be configured to provide digital input/output signal functionality for commands, control signals, and data. Various digital I/O and serial communications protocols may be supported including, e.g., UART, SPI, I2C, and 5V IO.

[0046] Power supply **348** provides power conditioning using one or more bandgap (BG) references, a voltage monitoring (VM) circuit, and a power-on reset (POR) module to implement the sequence of power-on operations. One or more oscillators **349** may employ a crystal to generate various on-chip clock signals for synchronizing operations of the various other components. The temperature sensor circuit **350** may be coupled to an external thermocouple or other temperature sensor to monitor environmental conditions.

[0047] An additional feature that may be offered by the sensor controller **300** is near range communication with a smart device **370** such as a smart phone or similar device having a microphone that can sense ultrasonic signals and a speaker that can transmit ultrasonic signals. As described further below, the sensor controller **300** and smart device **370** can modulate and demodulate ultrasonic signals to transmit and receive commands and responses to convey data between a sensor and a portable device, facilitating configuration of the sensor, monitoring of the sensor's performance and retrieval of sensor data.

[0048] FIG. **4**A shows a signal processing circuit **400** that incorporates various components for processing ultrasonic signals. The various components may be implemented as control logic hardware or firmware modules implemented by the DSP **328** or microcontroller **330**. Oscillator **349** supplies a carrier signal to transmit signal generator **316**, which produces the digital transmit signal TXD to generate acoustic bursts for flow rate sensing. (Optionally, transmit signal generator **316** may be further configured to modulate the digital transmit signal to produce modulated ultrasonic signals for near range communications with a smart device.) The carrier signal from oscillator **349** is also supplied to a digital quadrature mixer **402** to downcovert the digital receive signals from a given ADC into a baseband "zero intermediate frequency" ZIF signal **404** having in-phase and quadrature phase components.

[0049] A low pass filter **406** processes the ZIF signal **404** to remove noise that is out of the signal band associated with the acoustic burst and to prevent aliasing when the filtered baseband signal **410** is supplied for decimation by the decimator **412**. The low pass filter **406** may further combine the quadrature components of the filtered baseband signal to determine a phase shift measurement signal **408** that measures the digitized receive signal phase relative to the carrier signal from oscillator **349**, and may further determine a frequency measurement signal **409** that represents the frequency offset between the digitized receive signal and the carrier signal. The frequency measurement signal **409** may be a derivative of the phase shift measurement signal **408**, which in turn can be determined from the trigonometric relationship between the quadrature components. Decimator **412** reduces the sample rate of the filtered baseband signal **410** to reduce processing requirements for subsequent modules. A correlator **414** may use a correlation filter to convert the decimated baseband signal into a correlated signal, indicating when the digitized receive signal includes an acoustic burst that matches an expected waveform. A noise detection and suppression module **416** operates on the correlated signal, applying attenuation compensation to amplify peaks representing echoes and applying a nonlinear function to suppress noise. A magnitude determination module **418** converts the quadrature signal components into a magnitude signal, which may be processed by a time-of-flight measurement module **420** to determine the timing of peaks indicating the travel time of the acoustic burst. Data logging and integration with external systems is facilitated by the logging and I/O module **422**, which manages data storage and interfacing.

[0050] Additional diagnostic and noise analysis features are provided by the diagnostic module **424**, the reverberation module **426**, and the wideband noise measurement module **428**. The wideband noise measurement module **428** assesses the noise characteristics across the full spectrum of the digitized receive signal. The reverberation module **426** optionally measures the frequency and duration of the transducer's reverberation after transmission of an acoustic burst. The diagnostic module **424**, alone or in combination with modules **426**, **428**, analyzes the digitized response signal to detect and diagnose any transducer fault conditions. Some fault conditions may be indicated by, e.g., an excessively short reverberation periods (which may be due to a disconnected or defective transducer, suppressed vibration, or the like), while others may be indicated by an excessively long reverberation period (defective mounting, inadequate damping resistance, or the like). The diagnostic module **424** may detect and classify multiple such transducer fault conditions, storing the appropriate fault codes in internal registers, from whence they may be communicated to the control logic.

[0051] It is noted that modules **412-424** can be reordered or otherwise rearranged as needed to provide the desired signal processing. In at least some implementations, these modules may be disabled at least intermittently to reduce processing requirements and associated power consumption.

[0052] FIG. **4**B shows additional detail for an illustrative low-power circuit for determining phase shift measurement signal **408** and frequency measurement signal **409**. In this implementation, the oscillator **349** generates a clock signal at 8× the transmit carrier frequency to enable 8× oversampling by the ADC **321**. A frequency divider/counter **432** uses the clock signal to cycle through eight output values for a look up table **434**. As shown in FIG. **4**C, the look up table outputs correspond to cosine and sine functions. The sine function values are shifted by two table locations from the cosine function values. In some contemplated implementations, the look up table is replaced with logic that supplies the three output magnitudes 0, 0.71, and 1 with suitable sign changes.

[0053] Multipliers **435** and **436** produce products of the digitized receive signal with the cosine and sine function values, respectively, corresponding to the in-phase (I) and quadrature phase (Q) components of the receive signal. Low pass filters **437**, **438** remove noise that is out of the signal band associated with the acoustic burst and to prevent aliasing when the filtered components **410** are decimated.

[0054] A phase calculation module **440** may calculate the receive signal phase as the arctangent of the ratio between the quadrature phase component and the in-phase component. When the in-phase component is zero (or much smaller than the quadrature component), the module **440** may determine the phase to be 90 degrees. A low pass filter **442** may be used to smooth the phase measurement.

[0055] We note that the phase calculation is only meaningful when the receive signal is valid, i.e., when an acoustic burst is being received. Accordingly, a magnitude calculation module **444** may combine the in-phase and quadrature phase components to determine the receive signal magnitude. A comparator **446** provides an output to disable the phase calculation module **440** or filter **442** when the receive signal magnitude is below a predetermined threshold. In some implementations, the magnitude calculation is filtered or otherwise accumulated to ensure the magnitude is above the threshold for at least a minimum time before enabling module **440** or **442** to provide a nonzero output.

[0056] A derivative circuit **448** may operate on the phase measurement output **408** to provide a frequency measurement output **409**. The phase measurement output may be converted to a secondary time-of-flight measurement.

[0057] FIG. **5** shows an illustrative implementation of the direct drive transmitters **302**, **304**, having three switches SW**1**, SW**2**, SW**3**, that respectively couple a positive supply voltage V**1**, a negative supply voltage **502**, and an intermediate "ground" voltage to a piezoelectric ultrasonic sending transducer PZ. If all three switches are off, the driver is in a high impedance state. A current sensor or small sensing resistance R is provided in series with the transducer to enable sensing of the current flow to the transducer.

[0058] The switches may be operated in accordance with the control signal timing shown in the first three curves of FIG. **6**. Switches SW**1**, SW**2**, SW**3** conduct when their respective control signals are asserted (high), and isolate when their respectively control signals are de-asserted (low). When SW**3** conducts, the sending transducer is coupled to ground as indicated by the voltage curve Vpz. Switch SW**3** is then opened and switch SW**1** is closed to momentarily apply the positive supply voltage to the sending transducer. The voltage curve Vpz quickly converges to the positive supply voltage even as the piezoelectric element's deformation gains momentum. When the control signals have a periodicity near that of the transducer's resonant frequency, the momentum continues after the switch SW**1** is opened, causing the voltage curve Vpz to decay. For the other half of the excitation cycle, switch SW**3** couples the transducer to ground before switch SW**2** momentarily applies the negative supply voltage.

[0059] The voltage curve VR shows a voltage across the sensing resistance, which is proportional to the transducer's current flow. The voltage curve exhibits distinct peaks corresponding to the charging and discharging of the sending transducer. The charging peaks occur when the grounding switch SW**3** opens and either switch SW**1** or SW**2** closes. These peaks are consistent across a wide frequency range. However, the discharge peaks **602** created when grounding switch SW**3** closes are a strong function of frequency, reaching a minimum size when the control signals have a frequency matching the transducer's resonant frequency. A rectified and filtered version of the voltage curve

VR can thus serve as an indicator whether such resonant frequency matching has been achieved, enabling the control logic to adapt the control signals as needed to accommodate resonant frequency variations attributable to aging and changing environmental conditions.

[0060] FIG. **7** is a flow diagram of an illustrative flow sensing method employing multiple independent measurements for robust sensing. It begins in block **702**, checking for a trigger to determine whether the sensor should enter near range communications mode **704**, discussed further below. The trigger may be, for example, a button press, a detection of a beacon signal, or a period timer elapsing. Detection of the trigger causes the sensor to enter near range communications mode **704**. The method returns to the beginning when exiting near range communication mode **704**.

[0061] Otherwise, in block **706**, the sensor generates an acoustic burst with an ultrasonic sending transducer and in block **708** receives a response signal with an ultrasonic receiving transducer. In block **710**, the sensor processes the response signal to detect the arrival of the acoustic burst and to determine the associated time of flight (TOF). This can be achieved, e.g., using a time-of-flight measurement circuit **344** (FIG. **3**). In block **712**, the sensor processes the response signal to determine the phase shift of the received acoustic burst relative to the carrier frequency. This phase shift may be determined using the mixer **402** and low pass filter **406**. As discussed previously, this phase shift corresponds to the travel time of the acoustic burst and can be readily converted into a time-of-flight measurement independent of the measurement made in block **710**.

[0062] Block **714** represents an optional measurement of Doppler shift that may be obtained using the mixer **402** and low pass filter **406**. In the sensor arrangement of FIG. **1**, the flow stream may include bubbles, solids, or other causes of acoustic impedance variation that induce reflections of the acoustic burst back to the ultrasonic sending transducer. The frequency shift is essentially proportional to the flow stream velocity. Block **716** represents a repetition of blocks **706-714** with the roles of the ultrasonic sending transducer and ultrasonic receiving transducer swapped. In the sensor arrangement of FIG. **1**, this repetition enables time of flight measurements to be obtained with the acoustic burst propagating in the opposite direction of the original measurements. These measurements for the opposite direction of propagation are combined with the measurements in the original direction to obtain TOF differences proportional to the fluid flow velocity.

[0063] In block **718**, the time-of-flight measurements of blocks **710** and **712**, or the TOF differences obtained using the measurements in block **716**, are used to determine independent measurements of the fluid flow velocity. Optionally, a fluid flow velocity measurement may also be obtained from the Doppler shift measurement in blocks **714** and **716**.

[0064] In block **720**, the independent measurements are compared. If any persistent discrepancies are detected, the sensor asserts a fault signal in block **722**, which may be communicated to a user to signal a need for maintenance or repair. In block **724**, the sensor may combine the independent measurements to obtain a combined flow rate measurement. This combination process may be a selection of the measurements determined to be most accurate or consistent or may be a weighted sum configured to enhance measurement accuracy. The sensor may communicate the combined flow rate measurement to a logging service or monitoring system and/or store the combined flow rate measurement for later retrieval.

[0065] FIG. **8** is a flow diagram of an illustrative flow sensing method employing a second receive transducer for propagation speed measurement, leak detection, and/or fault monitoring. As with the method of FIG. **7**, the illustrative sensing method begins in block **802**, checking for a trigger to determine whether the sensor should enter near range communications mode **804**. Otherwise, in block **806**, the sensor generates an acoustic burst with an ultrasonic sending transducer and in block **808** receives a first response signal with a first ultrasonic receiving transducer. In block **810**, the sensor also uses a second ultrasonic receiving transducer to receive a second response signal. The second ultrasonic receiving transducer may be a piezoelectric transducer or alternatively may be a microphone having a microelectromechanical systems (MEMS) element.

[0066] In block **812**, the sensor uses the first response signal to determine a first time of flight having a dependence on the fluid flow velocity. Thereafter, the flow diagram of FIG. **8** provides three parallel paths to illustrate different ways to use the second response signal. In block **814**, the sensor uses the second response signal to determine a second time of flight that indicates the acoustic burst's propagation speed (i.e., the speed of sound) but is independent of the fluid flow velocity. To provide this measurement in an open channel system, the microphone or ultrasonic receiving transducer is positioned at a known distance from the ultrasonic sending transducer, in a direction where it can be reached without entering the fluid flow. In block **816**, the sensor determines the acoustic burst's propagation speed, enabling a more accurate determination of the surface level of the fluid flow. In block **818**, the sensor determines the flow rate measurement and conveys the measurement to the logging service or system monitor and/or stores the measurement for later retrieval.

[0067] In block **820**, the sensor processes the second response to detect the wideband “hiss” typically associated with a fluid leak from a pipe. In block **822**, the sensor determines whether the level of wideband noise exceeds a predetermined threshold, and if so, asserts a leak detection signal or some other form of alarm signal in block **824** to notify the user.

[0068] In block **830**, the sensor processes the second response to determine the amplitude or intensity of the acoustic burst. In block **832**, the sensor determines whether the amplitude or intensity falls below a predetermined threshold indicating loading or weakening of the ultrasonic sending transducer. If so, in block **834**, the sensor initiates a transducer cleaning operation and/or asserts a fault signal to notify the user of a need for maintenance or repair. In some contemplated implementations, a cleaning operation may be performed by driving the ultrasonic sending transducer with an elevated drive signal to dislodge material from the transducer's surface.

[0069] FIG. **9** is a flow diagram of an illustrative flow sensing method employing impedance monitoring and fault detection for enhanced reliability. It begins in block **902** with performing a built-in self-test BIST diagnostic on the transmitter, receiver, and signal processing components of the sensor. In block **904**, the sensor determines whether the BIST results indicate a fault, and if so, in block **906** the sensor asserted a fault signal to notify the user of a need for maintenance or repair. The sensor may then cease operation.

[0070] Otherwise, in block **908**, the sensor generates an acoustic burst using an ultrasonic sending transducer. In block **910**, the sensor measures an impedance of the sending transducer, e.g., by monitoring the current flow during acoustic burst generation with a voltage-based driver, or monitoring the voltage during acoustic burst generation with a current-based driver. In block **912**, the sensor determines whether the impedance is above a predetermined threshold, and if so, in block **914** the sensor initiates a cleaning operation to clear debris from the transducer surface. If the cleaning operation is unsuccessful, or the impedance is determined in block **916** to be outside a predetermined range, the method may proceed to block **906**. Otherwise, in block **918**, the sensor adjusts the carrier frequency, which over multiple iterations enables the sensor to determine the frequency dependence of the impedance and to find the carrier frequency that minimizes the transducer impedance.

[0071] In block **920**, the sensor uses an ultrasonic receiving transducer to receive a response to the acoustic burst. In block **922**, the sensor compares the response signal to an expected waveform to verify that the receiving transducer is operating as expected. If a mismatch is identified, the sensor returns to block **906**. Otherwise, in block **924**, the sensor detects the arrival of the acoustic burst and measures the time of flight. In optional block **926**, the sensor may repeat the operations of blocks **908-924** to determine a time-of-flight measurement for the opposite propagation direction. In block **928**, the sensor determines the flow rate measurement and conveys the measurement to the logging service or system monitor and/or stores the measurement for later retrieval.

[0072] FIG. **10** is a flow diagram of an illustrative near range communications method for an interrogator device such as a smart phone or other portable smart device **370**. In block **1002**, the device determines whether a connection should be attempted. The trigger for a connection attempt may be, e.g., the reception of an acoustic beacon signal from the sensor, a determination by a navigation or position tracking system that the user has entered the sensor's vicinity, an opening or awakening of an app on the device, a physical tap or shake of the device, or a voice command from the user. The device continues in block **1002** until a trigger is detected. Once detected, the device generates an acoustic signal containing a connection request in block **1004**.

[0073] The device checks for an acoustic signal containing a response message in block **1006**. If no valid response message is detected within a predetermined time window, the device checks whether a connection attempt timer has elapsed in block **1008**. If so, the process returns to block **1002** to await another trigger. Otherwise, another connection request message is sent in block **1004**. Once a valid response message is received in block **1006**, the device proceeds to block **1010**.

[0074] In block **1010**, the device may select a command to be sent to the sensor in block **1012**. In block **1012**, the device sends the command as an acoustic signal. In block **1014**, the device checks for an acoustic signal containing a response message. If no valid response message is detected within a predetermined time window, the device checks whether a command timer has elapsed in block **1016**. If so, the process returns to block **1002** to await another trigger. Otherwise, the command message is retransmitted in block **1012**. Once a valid response message is received in block **1014**, the device proceeds to block **1018** to determine if more commands are to be sent. If so, the device returns to block **1010**. Otherwise, the device returns to block **1002**.

[0075] The sequence of commands can vary, but may include, e.g., a diagnostic command to obtain the sensor's identifying information and status, a download command to retrieve any stored measurement data, and a configuration command to set any available configuration parameters for the sensor's operation.

[0076] FIG. **11** is a flow diagram of an illustrative near range communications method for a sensor or other responder device. In block **1102**, the sensor determines whether a connection should be attempted. The trigger for a connection attempt may be, e.g., the detection of nearby motion, detection of footsteps or other sounds, the actuation of a sensor button or control mechanism, detection of a physical knock on (or kick or jarring of) of the sensor, detection of a voice command, or detection of a connection request. The sensor continues in block **1102** until a trigger is detected. Once detected, the sensor generates an acoustic signal containing a beacon in block **1104**.

[0077] The sensor checks for an acoustic signal containing a connection request message in block **1106**. If no valid request message is detected within a predetermined time window, the sensor checks whether a connection attempt timer has elapsed in block **1108**. If so, the process returns to block **1102** to await another trigger. Otherwise, another beacon message is sent in block **1104**. Once a valid request message is received in block **1106**, the sensor proceeds to block **1110**.

[0078] In block **1110**, the sensor may send a response message to the device. The response message may include the result of a previously transmitted command, or other information. For example, the response message may include sensor status information such as whether the sensor is active, identifying information, current configuration information, the number of stored measurements, the available storage memory, current flow rate measurements, a download of stored flow rate measurements, fault alerts. Such information may be provided by default or in response to an information request command.

[0079] After sending the response message in block **1110**, the sensor may check for an acoustic signal containing another command message in block **1112**. If a valid command message is received, the sensor may attempt to execute the command in block **1114**, after which the process moves to block **1110** to communicate a response message acknowledging the command and communicating the results, e.g., whether the command was successfully performed. If no valid command message is detected within a predetermined time window, the sensor checks whether a command timer has elapsed in block **1116**. If so, the process returns to block **1102** to await another trigger. Otherwise, the previous response message is retransmitted in block **1110**.

[0080] Numerous modifications, equivalents, and alternatives will become apparent to those skilled in the art once the above disclosure is fully appreciated. It is intended that the following claims be interpreted to embrace all such modifications, equivalents, and alternatives where applicable.

Claims

1. A sensor controller comprising: a transmitter configured to provide a drive signal to an ultrasonic sending transducer to generate an acoustic burst; a first receiver configured to receive a first response signal from a first ultrasonic receiving transducer; a second receiver configured to receive a second response signal from a second ultrasonic receiving transducer at a predetermined distance from the ultrasonic sending transducer; a propagation speed circuit configured to detect a direct arrival of the acoustic burst in the second response signal and to measure a corresponding propagation speed; a level circuit configured to detect a reflected arrival of the acoustic burst in the first response signal, to measure a corresponding time of flight, and to derive a fluid level based on the time of flight and the propagation speed.
2. The sensor controller of claim 1, further comprising control logic that determines a flow rate based on the fluid level.
3. The sensor controller of claim 1, wherein the first ultrasonic receiving transducer is also the ultrasonic sending transducer.
4. The sensor controller of claim 1, wherein the second ultrasonic receiving transducer is a MEMS transducer.
5. A sensing method comprising: providing a drive signal to an ultrasonic sending transducer to generate an acoustic burst; receiving a first response signal from a first ultrasonic receiving transducer; receiving a second response signal from a second ultrasonic receiving transducer at a predetermined distance from the ultrasonic sending transducer; measuring a propagation speed based on a direct arrival of the acoustic burst in the second response signal; measuring a time of flight for a reflected arrival of the acoustic burst in the first response signal; and deriving a fluid level based on the time of flight and the propagation speed.
6. The sensing method of claim 5, further comprising determining a flow rate based on the fluid level.
7. The sensing method of claim 5, wherein the first ultrasonic receiving transducer is also the ultrasonic sending transducer, and wherein the second ultrasonic receiving transducer is a MEMS transducer.
8. A sensor controller comprising: a transmitter configured to provide a drive signal to an ultrasonic sending transducer to generate an acoustic burst; a first receiver configured to receive a first response signal from an ultrasonic receiving transducer; a second receiver configured to receive a second response signal from a MEMS transducer; and a signal processing circuit coupled to the first receiver and configured to measure a first time of flight associated with an arrival of the acoustic burst in the first response signal, and coupled to the second receiver and configured to measure at least one of: a leak noise intensity, an acoustic burst intensity, and a second time of flight associated with an arrival of the acoustic burst in the second response signal.
9. The sensor controller of claim 8, further comprising control logic configured to assert a leak detection signal when the leak noise intensity exceeds a predetermined threshold.
10. The sensor controller of claim 8, further comprising control logic configured to assert a fault signal when the acoustic burst intensity falls below a given threshold.
11. The sensor controller of claim 8, further comprising control logic configured to initiate a cleaning cycle if the second response signal indicates loading of the ultrasonic sending transducer.
12. The sensor controller of claim 8, wherein the signal processing circuit is configured to derive a propagation speed from the second time of flight.
13. The sensor controller of claim 9, wherein the control logic is further configured to swap the ultrasonic sending transducer and the ultrasonic receiving transducer to obtain a first time of flight

for each burst propagation direction, wherein the control logic determines a flow rate based on a first time of flight difference between directions.

14. A sensing method comprising: providing a drive signal to an ultrasonic sending transducer to generate an acoustic burst; receiving a first response signal from an ultrasonic receiving transducer; receiving a second response signal from a MEMS transducer; and using a signal processing circuit to measure a first time of flight associated with an arrival of the acoustic burst in the first response signal and to measure at least one of: a leak noise intensity in the second response signal, an acoustic burst intensity in the second response signal, and a second time of flight associated with an arrival of the acoustic burst in the second response signal.

15. The sensing method of claim 14, further comprising asserting a leak detection signal when the leak noise intensity exceeds a predetermined threshold.

16. The sensing method of claim 14, further comprising asserting a fault signal when the acoustic burst intensity falls below a given threshold.

17. The sensing method of claim 14, further comprising initiating a cleaning cycle if the second response signal indicates loading of the ultrasonic sending transducer.

18. The sensing method of claim 14, further comprising deriving a propagation speed from the second time of flight.

19. The sensing method of claim 15, further comprising: swapping the ultrasonic sending transducer and the ultrasonic receiving transducer to obtain a first time of flight for each burst propagation direction; and determining a flow rate based on a first time of flight difference between directions.