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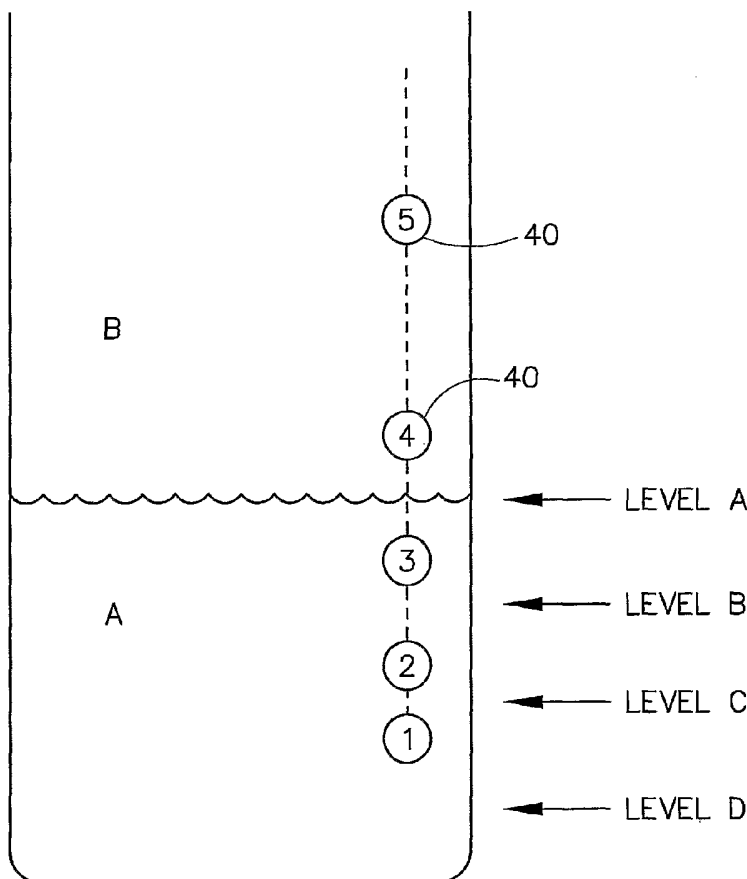
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[Continued on next page]

(54) Title: MULTI-POSITION FLUID SENSORS AND METHODS



(57) Abstract: Fluid monitoring methods, sensors and systems are disclosed. Preferred embodiments comprise two or more mechanical resonators, preferably two or more flexural resonators configured for sensing, monitoring or evaluating one or more fluids at multiple positions within one or more fluidic systems. In the methods, sensors and systems of the invention, signals generated in response to stimulation of the mechanical resonators are communicated by multiplexing over a common communication path, and then deconvoluted with respect to the position of the resonators.

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## MULTI-POSITION FLUID SENSORS AND METHODS

### BACKGROUND OF INVENTION

[0001] The present invention generally relates to the field of fluid sensors and methods, and more particularly to the field of fluid sensors and methods for sensing fluids at multiple positions in one or more fluidic systems. Such multi-position fluid sensors and methods are suitable for operation in a distributed sensing system, including for example, systems and operations involving process monitoring, process control and/or process or system servicing. The present invention relates, in preferred embodiments, to multi-position fluid sensor devices and methods adapted for level sensing, suitable for example, for operation in open and/or closed fluidic systems, such as open or closed tanks. The present invention relates, in particularly preferred embodiments, to the field of multi-position fluid sensor devices and methods for fluidic applications involving sensing fluids, monitoring fluids or determining properties of fluids, where the fluids are heat-sensitive (*e.g.*, cryogenic fluids), ignitable (*e.g.*, flammable fluids), within expansively-distributed systems and/or within space-constrained fluidic systems (*e.g.*, microfluidic systems).

[0002] Effective approaches for measuring characteristics of fluids using mechanical resonators are disclosed in commonly-owned U.S. Patent Nos. 6,401,519; 6,393,895; 6,336,353; 6,182,499; 6,494,079 and EP 0943091 B1, each of which are incorporated by reference herein for all purposes. *See also*, Matsiev, "Application of Flexural Mechanical Resonators to Simultaneous Measurements of Liquid Density and Viscosity," IEEE International Ultrasonics Symposium, Oct. 17-20, 1999, Lake Tahoe, Nevada, which is also incorporated by reference herein for all purposes. The use of a quartz oscillator in a sensor has been described as well in U.S. Patent No.'s 6,223,589 and 5,741,961, and in Hammond, et al., "An Acoustic Automotive Engine Oil Quality Sensor", Proceedings of the 1997 IEEE International Frequency Control Symposium, IEEE Catalog No. 97CH36016, pp. 72-80, May 28-30, 1997.

[0003] The use of other types of sensors is also known in the art. For example, the use of acoustic sensors has been addressed in applications such as viscosity measurement in J.W. Grate, et al, Anal. Chem. 65, 940A-948A (1993)); "Viscosity and Density Sensing

with *Ultrasonic Plate Waves*”, B.A. Martin, S.W. Wenzel, and R.M. White, *Sensors and Actuators*, A21-A23 (1990), 704-708; “*Preparation of chemically etched piezoelectric resonators for density meters and viscometers*”, S.Trolier, Q.C. Xu, R.E.Newnham, *Mat.Res. Bull.* 22, 1267-74 (1987); “*On-line Sensor for Density and Viscosity Measurement of a Liquid or Slurry for Process Control in the Food Industry*”, Margaret S. Greenwood, Ph.D. James R. Skorpik, Judith Ann Bamberger, P.E. Sixth Conference on Food Engineering, 1999 AIChE Annual Meeting, Dallas, Texas; U.S. Patent Nos. 5,708,191; 5,886,250; 6,082,180; 6,082,181; and 6,311,549; and “*Micromachined viscosity sensor for real-time polymerization monitoring*”, O.Brand, J.M. English, S.A. Bidstrup, M.G. Allen, *Transducers '97*, 121-124 (1997). See also, U.S. Patent No. 5,586,445 (“*Low Refrigerant Charge Detection Using a Combined Pressure / Temperature Sensor*”).

[0004] Multi-position sensors involving mechanical resonators are known in the art. For example, U.S. Patent No. 6,182,499 to McFarland *et al.* discloses systems and methods involving mechanical resonators for evaluating fluid properties of an array of fluids in parallel (*i.e.*, simultaneously) and sequentially (*e.g.*, by scanning). U.S. Patent No. 4,893,496 to Bau *et al.* discloses systems involving torsional resonators for measuring properties and level of fuel in an aircraft fuel tank. Level sensors employing single mechanical resonators, such as a relatively large tuning fork resonator or an ultrasonic resonator, are also known in the art, as disclosed for example by Princo Instruments, Inc. in level control product brochures at the internet website:

<http://www.princolevelcontrols.com>). See also *Meas. Sci. Technol.* 9, 1480-1491 (September 1980). See also Mohanty *et al.*, Simultaneous measurement of load and position with an embedded chirped sampled fibre grating, *J. Opt. A: Pure Appl. Opt.* 7:29-34 (2005). See also University of Toronto, Institute for Aerospace Studies, Fiber Optic Sensors and Smart Materials / Structures Research Projects, “Fiber Optic Bragg Grating Research and Development” (Internet, January 2005).

[0005] Notwithstanding the above, there remains a need in the art for alternative or improved multi-position sensor devices and methods for efficiently sensing, monitoring or evaluating one or more fluids in one or more fluidic systems, including for example in applications involving distributed sensing in process control systems, fluid distribution

systems, process tanks, storage tanks, *etc.* Examples in which such a need exists include for example, such fluidic systems used in connection with the petroleum, chemical, pharmaceutical, healthcare, environmental, military, aerospace, construction, heating, ventilating, air-conditioning, refrigeration, food, and transportation industries. In particular, there remains a need in the art for effectively sensing one or more fluids in one or more fluidic systems at multiple positions using relatively straightforward, cost-effective, scalable systems and methods, with requisite accuracy and precision. Particular needs also exist with respect to certain fluid types and/or system types. For example, significant challenges exist with respect to effectively and efficiently sensing, monitoring or evaluating fluids: that are heat-sensitive (*e.g.*, cryogenic fluids, heat-sensitive biological fluids, *etc.*); that are ignitable (*e.g.*, flammable fluids) and/or that are within space-constrained fluidic systems (*e.g.*, microfluidic systems). Generally, although many approaches have been proposed for single-position systems for such fluids and systems, such single-position systems cannot be effectively and/or efficiently applied as a multi-position sensor due to design constraints associated with these fluids and/or systems. For example, systems involving heat-sensitive fluids are typically constrained with respect to thermal loading (*i.e.*, heat generation) and thermal insulation breaches (*e.g.*, heat retention). Likewise, systems involving ignitable fluids are typically constrained with respect to sources of potential ignition. Further, systems such as microfluidic systems are space-constrained.

#### **SUMMARY OF INVENTION**

[0006] It is therefore an object of the present invention to provide improved sensor devices and methods for efficiently sensing, monitoring and/or evaluating (*e.g.*, determining properties of) fluids used in fluidic systems. In particular, it is an object of the invention to provide cost-effective, practical approaches for sensing, monitoring and/or evaluating fluids at multiple positions in one or more fluidic systems. In preferred embodiments, it is an object of the invention to provide devices and methods for sensing or monitoring fluid level, and if desired, for evaluating fluid properties in conjunction therewith.

[0007] Briefly, therefore, the present invention is broadly directed to various methods for sensing one or more fluids at multiple positions in one or more fluidic systems using a

sensor, where the sensor comprises two or more resonators such as two or more mechanical resonators. In preferred embodiments, the sensor comprises two or more resonators including at least one flexural resonator, and the sensor preferably comprises two or more flexural resonators.

**[0008]** The invention is also broadly directed to various systems for sensing one or more fluids at multiple positions, preferably in one or more fluidic systems. The systems generally comprise a sensor comprising at least two resonators. The sensor is preferably configured for operation in one or more fluidic systems, and comprises at least two resonators such as two or more mechanical resonators at multiple positions within the one or more fluidic systems. In preferred embodiments, the sensor comprises two or more mechanical resonators including at least one flexural resonator, and most preferably, the sensor comprises two or more flexural resonators.

**[0009]** In the methods and systems of the present invention, one or more fluids are sensed at multiple positions in one or more fluidic systems using multiple (*i.e.*, two or more) resonators. Generally, the methods and systems of the invention involve signal multiplexing with respect to a common communication path (concurrently or sequentially, in time), together with deconvoluting the communication-path-multiplexed signals with respect to the position of the resonators. The extent of deconvolution does not have to be absolute; rather, the signal need only be deconvoluted to an extent sufficient to obtain meaningful information about a fluidic system of interest. More specifically, in the methods and systems of the present invention, the two or more resonators are stimulated (actively or passively) to generate signals associated with the response of the resonators to the respective stimulus. Signals generated by the two or more resonators are communicated through a common communication path (*e.g.*, a conductive lead), preferably from each of the two or more resonators to a signal processing circuit. Communicated signals originating from the two or more resonators are processed (*e.g.*, in a signal processing circuit) to characterize the response of the two or more resonators (*e.g.*, with respect to one or more signal characteristics of the signals). The characterized response (*i.e.*, the processed signal) can be used in various respects, depending on the particular application of interest for the multi-position sensor. Generally, the response of the resonators can be associated with position – either

specifically (*e.g.*, associating the responses of the two or more resonators with the respective positions of the two or more resonators) or inferentially (*e.g.*, associating the responses of the two or more resonators to infer the relative position of a fluid or a fluid interface within a fluidic system). In some applications, both position-specific associations and position-inferential associations can be advantageously employed. Hence, in some applications, the response of the two or more resonators can be specifically associated with the respective resonators and/or with the respective positions of the two or more resonators, for example based on at least one of the signal characteristics of the respective characterized responses (*e.g.*, based on respective frequency). In other applications, the response of the two or more resonators can be used to inferentially identify a position of a fluid or a fluid interface within a fluidic system (*e.g.*, to identify liquid level in a tank), for example based on a fluid-dependent difference between the characterized response of two or more resonators. Such fluid-dependent differences in responses include, for example, the presence of a (detectable) response versus and essential absence of a (detectable) response, or for example, a more substantial response (*e.g.*, only minimally-damped response, for example in a vapor phase), versus a less substantial response (*e.g.*, more highly-damped response, for example in a liquid phase).

**[0010]** Without being bound by theory, the response of each of the two or more mechanical resonators during sensing operations is a function of at least (i) the resonator design (*e.g.*, resonator type, design characteristics, *etc.*), and (ii) the fluid being sensed. Accordingly, for applications that involve sensing the same fluid in one or more fluidic systems, multiple resonators with different designs (*e.g.*, design characteristics) can preferably be used to sense the fluids, with the observed resonator responses being different (*e.g.*, having differentiable characterized responses). Conversely, for applications that involve sensing different fluids in one or more fluidic systems, multiple resonators can be used with either substantially the same design (*e.g.* resonator type and design characteristics, *etc.*) or with different designs (*e.g.*, resonator type and design characteristics, *etc.*), again with the observed resonator responses being different. In both instances, differences in the observed resonator responses – characterized by signals having characteristics that are differentiable – can be used for associating resonator

responses with position (specifically or inferentially) to obtain meaningful information about the fluid within the system.

[0011] In any case, in preferred method and system approaches and embodiments, the sensor comprises two or more flexural resonators. The flexural resonators comprise a flexural resonator sensing element having a sensing surface for contacting the fluid being sensed. In operation during a sensing period, the sensing surface of a flexural resonator displaces or is displaced by at least a portion of the fluid being sensed. The flexural resonator sensor can be operated passively or actively, and if actively operated, is preferably excited using a stimulus signal. The particular nature of the stimulus signal is not critical, but in some embodiments, the stimulus signal can be a waveform having a frequency (*e.g.*, a predetermined frequency) or having a range of frequencies (*e.g.*, being swept over a determined or predetermined range of frequencies), and in each such case, having a frequency or a range of frequencies of less than about 1 MHz. In some embodiments, additional sensors (*e.g.*, such as temperature and/or pressure sensors) can be employed in the systems and methods in combination with the two or more mechanical resonators (preferably, flexural resonators). In some embodiments, alternative sensors can be employed in place of a mechanical resonator sensor. Further discussion of preferred sensors and sensor subassemblies (comprising or more components of a sensor), as well as the preferred use thereof, are described hereinafter.

#### **GENERAL OVERVIEW – METHODS**

[0012] Therefore, the inventions are generally directed, in one aspect, to a method for sensing one or more fluids at multiple positions. Preferably, the one or more fluids are associated with (*e.g.*, contained within or originating from) one or more fluidic systems. In this aspect, the method comprises contacting a sensing surface of a first mechanical resonator with fluid, and (concurrently or sequentially, in time, therewith) contacting a sensing surface of a second mechanical resonator with fluid. The first resonator has a first position (*e.g.*, associated with (*e.g.*, within) a fluidic system). The second resonator has a second position (*e.g.*, associated with (*e.g.*, within) a fluidic system). The fluid-contacted first resonator is stimulated to generate a first signal associated with a response of the first resonator (to the stimulus or stimuli). The fluid-contacted second-resonator is

stimulated to generate a second signal associated with a response of the second resonator (to the stimulus or stimuli). The first resonator and the second resonator are preferably stimulated while their respective sensing elements are in physical contact with the fluid being sensed. In some embodiments, however, the sensing elements may be contacted with fluid, removed from contact with the fluid, and thereafter, stimulated (with the sensing element outside of the fluid environment). The generated first signal and second signal are each communicated (concurrently or sequentially, in time) as multiplexed signals over a common communication path (*e.g.*, conductive lead); preferably, the first signal and second signal are communicated over a common communication path defined by at least a portion of the communication link from the first resonator and the second resonator to a signal processing circuit. The communicated first signal and second signal are processed (*e.g.*, in a signal processing circuit), to characterize the response of the first resonator and the second resonator, respectively. The characterized response preferably comprises one or more signal characteristics, such as frequency, amplitude, peak width (at a given amplitude), signal intensity, *etc.* The response of the first resonator and the response of the second resonator are associated with position.

**[0013]** Generally, in one approach, the responses of the first resonator and the second resonator are associated with corresponding respective positions of the resonators, such association being a position-specific association. Additionally or alternatively, in another approach, the responses of the first resonator and the second resonator are associated with a position of a fluid or a fluidic interface within a fluidic system, or both, with position being inferred in the context of the particular system, as described above. Further details regarding these various approaches and embodiments exemplary thereof are discussed in the following paragraphs.

**[0014]** In one embodiment within a preferred first approach with respect to this aspect of the invention, the response of the first resonator and the response of the second resonator are associated with the positions of the first resonator and the second resonator, respectively, based on at least one of the signal characteristics of the characterized response. Such association provides for effective and efficient position-specific sensing, monitoring and/or evaluating (*e.g.*, determining fluid properties) of one or more fluids in one or more fluidic systems. Preferably, in this first approach, the responses of the

resonators are associated with their respective positions based on frequency (*e.g.*, resonance frequency) and/or based on amplitude of the characterized response. A number of more specific embodiments can be realized within the context of this first approach, some of which are described below within the Summary of the Invention, and others of which are described within and/or are readily ascertainable from the context of the Detailed Description of the instant specification (including combining the various features described therein in any and all possible combinations and permutations).

**[0015]** In another embodiment within a preferred second approach with respect to this aspect of the invention, the response of the first resonator and the response of the second resonator are associated to infer the (relative or absolute) position of a fluid or a fluid interface within one or more fluidic systems. Such inference is possible, based on the particular configuration of a particular system, including for example sensing fluid level within a process tank, or for example sensing vertical phase separation (*e.g.*, stratification) or radial separation within a process region (*e.g.*, such as within a pipeline, or reactor, or tank, or groundfluid). In this second approach, a position of the fluidic interface can be identified to be between the first position and a second position based on a fluid-dependent difference between the characterized response of the first resonator and the characterized response of the second resonator. Preferably, in this second approach, the fluid-dependent difference can be the presence or essential absence of a signal and/or a difference in one or more signal characteristics of the characterized responses. A number of more specific embodiments can be realized within the context of this second approach, some of which are described below within the Summary of the Invention, and others of which are described within and/or are readily ascertainable from the context of the Detailed Description of the instant specification (including combining the various features described therein in any and all possible combinations and permutations).

**[0016]** According to a further embodiment preferred in connection with the first (position-sensitive) approach of this aspect of the invention, the invention is directed to a method for sensing a fluid to determine a profile of one or more properties of the fluid. Specifically and preferably, such embodiment can be directed to method for sensing a body of fluid at multiple positions to determine a spatial profile of one or more properties of the fluid. A sensing surface of a first mechanical resonator is contacted with the fluid,

and a sensing surface of a second mechanical resonator with contacted with the fluid. The first resonator has a first position within the body of fluid, and the second resonator has a second position within the body of fluid. The fluid-contacted first resonator is stimulated to generate a first signal associated with a response of the first resonator. The fluid-contacted second-resonator is stimulated to generate a second signal associated with a response of the second resonator. The generated first signal and second signal are communicated over a common communication path. The communicated first signal and second signal are processed to characterize the response of the first resonator and the second resonator, respectively, with the characterized response comprising one or more signal characteristics. The response of the first resonator and the response of the second resonator are associated with the positions of the first resonator and the second resonator, respectively, based on at least one of the signal characteristics of the characterized response. At least one property (*e.g.*, viscosity) of the fluid at each of the first position and the second position is determined. The at least one property is determined at the first position by correlating the response of the first resonator with the at least one property of the fluid based on the characterized response of the first resonator (*e.g.*, based on at least one of the signal characteristics of the characterized responses thereof). The at least one property is determined at the second position by correlating the response of the second resonator with the at least one property of the fluid based on the characterized response of the second resonator (*e.g.*, based on at least one of the signal characteristics of the characterized responses thereof).

[0017] According to an additional embodiment preferred in connection with the second (inferred position) approach of this aspect of the invention, the invention is directed to a method for sensing or identifying a position of a fluid or fluidic interface. More specifically, for example, the position of a fluidic interface defined between a first fluid and a second fluid can be sensed or identified in a fluidic system comprising a first mechanical resonator positioned at a first position,  $P_1$ , and a second mechanical resonator positioned at a second position,  $P_2$  (in spatial relation to the first position,  $P_1$ ). A sensing surface of the first resonator is contacted with the first fluid during a sensing period, and, a sensing surface of the second resonator is contacted with the second fluid during the sensing period. The first resonator and the second resonator are stimulated during the

sensing period to generate at least one of a first signal associated with a response of the first resonator and a second signal associated with a response of the second resonator. Preferably, the first resonator and the second resonator are stimulated during the sensing period to generate both a first signal associated with a response of the first resonator and a second signal associated with a response of the second resonator. In either case, any generated first signal and second signal are communicated over a common communication path. Preferably, the signals are communicated from each of the first resonator and second resonator, respectively, to a signal processing circuit over the common communication path. Any communicated first signal and second signal are processed (*e.g.*, in a signal processing circuit) to characterize the response of the first resonator and the response of the second resonator, respectively. The position of the fluidic interface is identified to be between the first position,  $P_1$ , and the second position,  $P_2$ , based on a fluid-dependent difference between the characterized response of the first resonator and the characterized response of the second resonator. In some embodiments of this second approach for this aspect of the invention, the fluid-dependent difference can be the presence or essential absence of a response, or a difference in amplitude of a response, in each case for example at a particular frequency or over a particular range of frequencies.

**[0018]** According to yet another preferred embodiment, the invention is directed to a method for sensing fluid level (*e.g.*, liquid level) within a fluidic system. The fluidic system preferably comprises at least two fluids, a first fluid and a second fluid. In preferred applications, the fluidic system can comprise a liquid first fluid and a second fluid. The second fluid can be a gas or a liquid. If the second fluid is a liquid second fluid, it is preferably differentiable from the liquid first fluid (*e.g.*, forms a separate differentiable phase). In this method, a sensing surface of a first mechanical resonator is contacted with the liquid first fluid during a sensing period. A sensing surface of a second mechanical resonator is contacted with the second fluid during the sensing period. The first resonator preferably has a first resonance frequency,  $f_{R1}$ , and is positioned at a first position,  $P_1$ . The second resonator preferably has a second resonance frequency,  $f_{R2}$ , with the second resonance frequency,  $f_{R2}$ , being different than the first resonance frequency,  $f_{R1}$ , in at least one of the liquid first fluid or the second fluid, and in some

embodiments, in both of the liquid first fluid and the second fluid. The second resonator is positioned at a second position,  $P_2$ . The first resonator and the second resonator are each stimulated during the sensing period to generate a first signal associated with a response of the first resonator and to, independently, generate a second signal associated with a response of the second resonator. The generated first signal and the generated second signal are communicated to a signal processing circuit over a common communication path. Preferably, the common communication path includes at least a portion of a communication path extending from each of the first and second resonators to a signal processing circuit. The communicated first signal and second signal are processed in the signal processing circuit to characterize the response of the first resonator and the second resonator, respectively, with the characterized response comprising one or more signal characteristics. The one or more signal characteristics preferably include at least frequency (*e.g.*, resonance frequency or shift in resonance frequency). The response of the first resonator and the response of the second resonator are associated with the first position,  $P_1$ , and the second position,  $P_2$ , respectively, based on frequency of the characterized response. The liquid level is identified to be between the first position,  $P_1$ , and the second position,  $P_2$ , based on a fluid-dependent difference between the characterized response of the first resonator and the characterized response of the second resonator. In some embodiments, the fluid-dependent difference can be the presence or essential absence of a response, or a difference in amplitude or other signal characteristic of a response, for example at a particular frequency or over a particular range of frequencies.

[0019] Generally, the embodiments discussed herein in connection with this (method) aspect of the invention, can be realized with many variations and/or more specifically-characterized embodiments based on specific details and features described within and/or readily ascertainable from the context of the Detailed Description of the instant specification (including combining the various features described therein in any and all possible combinations and permutations).

#### **GENERAL OVERVIEW – SENSORS AND SYSTEMS**

[0020] In another general aspect, the invention is directed to sensors and to systems comprising a sensor. The sensor is preferably configured for operation in one or more fluidic systems, and comprises at least two resonators such as two or more mechanical resonators at multiple positions within the one or more fluidic systems. In preferred embodiments, the sensor comprises two or more mechanical resonators including at least one flexural resonator, and most preferably, the sensor comprises two or more flexural resonators. The sensor further comprises an electrical circuit, preferably comprising circuitry selected from signal processing circuitry, data retrieval circuitry and combinations thereof. The electrical circuit can comprise one or more circuitry modules, as integrated or discrete circuits. The sensor further comprises a communication link for electrical communication between each of the two or more resonators and the electrical circuit. The communication link comprises a common communication path defining at least a portion of the communication link between each of the two or more resonators and the electrical circuit. In some embodiments, the communication link between each of the two or more resonators and the electrical circuit can consist essentially of the common communication pathway.

[0021] In one preferred embodiment, this aspect of the invention is directed to a system for sensing one or more fluids at multiple positions in one or more fluidic systems. The system comprises a sensor configured for operation in the one or more fluidic systems. The sensor comprises two or more mechanical resonators at multiple positions within the one or more fluidic systems, an electrical circuit and a communication link comprising two or more conductive paths such as conductive wires. The electrical circuit comprises signal activation circuitry for generating electronic stimulus for stimulating the two or more resonators. The electrical circuit further comprises at least one of signal conditioning circuitry, data derivation circuitry or data retrieval circuitry, for processing or retrieving a signal representing data originating from the two or more resonators. The communication link provides for electrical communication between each of the two or more resonators and the electrical circuit (including integrated circuitry or common associated discrete circuitry modules). The communication link comprises a common communication path defining at least a portion of the communication link between each of the two or more resonators and the electrical circuit. In this embodiment, the common

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communication path comprises two conductive leads for providing the electronic stimulus to each of the two or more resonators (*e.g.*, the electronic stimulus being generated using the signal activation circuitry), and for receiving signals associated with the responses of the two or more resonators (*e.g.*, into at least one of the signal conditioning circuitry, data derivation circuitry or data retrieval circuitry).

**[0022]** In another preferred embodiment directed to this aspect of the invention, a system for sensing one or more fluids at multiple positions in one or more fluidic systems is provided. The system comprises a sensor configured for operation in one or more fluidic systems, with the sensor comprising three or more mechanical resonators at multiple positions within the one or more fluidic systems, an electrical circuit, a communication link comprising at least two conductive leads, and a third conductive shielding lead. More specifically, the electrical circuit comprises signal activation circuitry for generating electronic stimulus for stimulating the three or more resonators. The electrical circuit also comprises (intergrally, or as separate discrete associate circuits) at least one of signal conditioning circuitry, data derivation circuitry or data retrieval circuitry for processing or retrieving a signal representing data originating from the three or more resonators. The communication link provides for electrical communication between each of the three or more resonators and the electrical circuit. The communication link comprises a common communication path defining at least a portion of the communication link between each of the three or more resonators and the electrical circuit, with the common communication path comprising first and second conductive leads for providing the electronic stimulus to each of the three or more resonators and for receiving signals associated with the responses of the three or more resonators. The sensor further comprises a third conductive lead configured substantially proximate to each of the first and second conductive leads for shielding to at least reduce, and preferably to substantially eliminate wire-to-wire interference (*e.g.*, capacitance) between the first and second conductive leads.

**[0023]** In general, the system of the invention (including with respect to each of the aforementioned embodiments), can be effective for sensing a fluid, monitoring a fluid (*e.g.*, as part of a process-control schema) and/or evaluating a fluid (*e.g.*, determining one or more properties of a fluid in a fluidic system). Each of the mechanical resonators of

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the sensor can comprise sensing element (*e.g.*, a flexural resonator) having a sensing surface adapted for or configured for contacting the fluid, and being responsive to changes in one or more properties of a fluid.

[0024] An apparatus of the invention can be useful in connection with fluidic systems for sensing, monitoring or evaluating one or more fluids within the one or more fluidic systems, especially for example tanks, process lines, reactors, condensers, heat-exchangers, and other unit-operation equipment involving fluids, some of which are described in connection with the methods of the invention.

[0025] Generally, the embodiments discussed herein in connection with this (system) aspect of the invention, can be realized with many variations and/or more specifically-characterized embodiments based on specific details and features described within and/or readily ascertainable from the context of the Detailed Description of the instant specification (including combining the various features described therein in any and all possible combinations and permutations).

#### ADVANTAGES

[0026] Generally, the various approaches and embodiments of the methods and systems of the invention as summarized hereinbefore and described in further detail hereinafter are particularly advantageous with respect to many diverse types of fluids in many diverse types of applications. As noted above, the various methods and systems are generally advantageous with respect to sensing, monitoring and/or evaluating (*e.g.*, determining one or more properties) fluids, as well as particularly in connection with process control applications, of one or more fluids in one or more fluidic systems. In general, commercial benefit is realized by relative simplicity and lower costs with respect to sensor deployment, sensor operation, sensor maintenance, sensor repair and/or replacement. Further advantages are also realized with respect to particular applications, some of which are described herein and in the Detailed Description of the invention.

[0027] The methods and systems of the present invention offer significant advantages over previously-known approaches for sensing, monitoring and/or evaluating one or more fluids at multiple points in fluidic system(s). In particular, the invention offers substantial flexibility to configure devices and methods that are effective, efficient and

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affordable for generating data associated with a fluid, and especially with one or more properties of a fluid at multiple points or positions, and thereby providing a more comprehensive dataset from which various decisions, such as process control and/or servicing decisions can be made. This flexibility allows for applications of the devices and methods of the invention across diverse industries, including for example, across industries such as the petroleum, chemical, pharmaceutical, healthcare, environmental, military, aerospace, construction, heating, ventilating, air-conditioning, refrigeration, food, and transportation industries. Significantly, the present invention also offers the advantage for servicing fluidic systems where such fluidic systems comprise heat-sensitive fluids, comprise ignitable fluids, are spatially expansive fluidic systems and/or are spatially constrained fluidic systems. The present invention offers substantial advantage over conventional sensor systems, in that not only can fluid position be determined (*e.g.*, fluid level), but also fluid properties – using the same sensor.

**[0028]** With respect to heat-sensitive fluids such as cryogenic fluids, for example, the use of a common communication path (*e.g.*, single set of conductive leads, the set including for example two-wire or three-wire conductive lead configurations as described in connection with the systems of the invention) provides a basis for minimizing thermal loadings due to resistive heating within a cryogenic fluidic system. The use of relatively low voltages and currents in connection with these methods and systems (*e.g.*, for stimulating the resonators, for communicating, and/or for processing and/or retrieving a signal representing data originating from the three or more resonators) independently also provides a basis for minimizing thermal loadings within the cryogenic system.

**[0029]** With respect to ignitable fluids such as flammable liquids or gasses, for example, the use of a common communication path (*e.g.*, single set of conductive leads, the set including for example two-wire or three-wire conductive lead configurations as described in connection with the systems of the invention) provides a basis to minimize the amount of communication link (*e.g.*, minimizes the length of wire) and thereby help reduce the chance of ignition due to failure thereof within an ignitable-fluid system. The use of relatively low voltages and currents in connection with these methods and systems (*e.g.*, for stimulating the resonators, for communicating, and/or for processing and/or retrieving

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a signal representing data originating from the three or more resonators) provides a basis for making the ignitable-fluid system inherently more safe.

[0030] With respect to large-scale applications, such as spatially expansive large-scale distributed sensing systems for one or more fluidic systems over longer distances (*e.g.*, more than ten meters), the relatively simplicity of the sensor and the relative cost-effectiveness of the communication-path-multiplexed configuration provides substantial commercial benefits.

[0031] With respect to space-constrained applications, such as microfluidic systems, the relatively simplicity of the sensor and the capability to employ very small mechanical resonators, such as micromachined mechanical resonators and micromachined common communication path (*e.g.*, in each case, the resonators and common communication path being integrally formed in a substrate or in one or more microchip bodies mounted on a substrate) provide a basis for efficient and effective multi-position sensing.

[0032] Other features, objects and advantages of the present invention will be in part apparent to those skilled in art and in part pointed out hereinafter. All references cited in the instant specification are incorporated by reference for all purposes. Moreover, as the patent and non-patent literature relating to the subject matter disclosed and/or claimed herein is substantial, many relevant references are available to a skilled artisan that will provide further instruction with respect to such subject matter.

### **BRIEF DESCRIPTION OF THE DRAWINGS**

[0033] FIG.'s 1A through 1B are schematic representations of the general methods and systems of the invention as applied in connection with a single fluidic system (designated "I"), where the single fluid system comprises: a single fluid / phase (Fig. 1A); and multiple fluids / phases (Fig. 1B).

[0034] FIG.'s 2A through 2D are schematic representations of the general methods and systems of the invention as applied in connection with two fluidic systems (designated as "I" and "II"), where the two fluidic systems comprise: a single fluid / phase of a same type of fluid (*e.g.*, same composition) in each fluidic system (Fig. 2A); a single fluid / phase of a different type of fluid (*e.g.*, different composition) in each fluidic system (Fig. 2B); a single fluid / phase in a first of the two fluidic systems, and multiple fluids / phases

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in the second of the two fluidic systems, one of the multiple fluids / phases in the second system being of the same type as the fluid in the first system (Fig. 2C), and multiple fluids / phases, each of different types, in each of the two fluidic systems (Fig. 2D).

[0035] FIG.'s 3A through 3B are schematic representations of the general methods and systems of the invention illustrating an embodiment in which a sensor comprising multiple mechanical resonators (designated by circled numbers 1, 2, 3 and 4) at multiple, spatially discrete positions linked through a common communication path is deployed in a body of fluid (designated as "A") such as within a process region (Fig. 3A), and an associated set of characterized responses of the mechanical resonators (Fig. 3B).

[0036] FIG.'s 4A through 4B are schematic representations of the general methods and systems of the invention illustrating an embodiment in which a sensor comprising multiple mechanical resonators (designated by circled numbers 1, 2, 3, 4 and 5) at multiple, spatially discrete positions linked through a common communication path is deployed in a fluidic system (*e.g.*, a pipeline) comprising a first fluid / phase (designated as "A") and a second fluid / phase (designated as "B") having a fluidic interface therebetween (Fig. 4A), and an associated set of characterized responses of the mechanical resonators (Fig. 4B).

[0037] FIG.'s 5A through 5B are schematic representations of the general methods and systems of the invention illustrating an embodiment in which a sensor comprising multiple mechanical resonators (designated by circled numbers 1, 2, 3 and 4) at multiple, spatially discrete positions linked through a common communication path is deployed in a fluidic system (*e.g.*, a tank), for example as a level sensor, with the fluidic system comprising a first fluid (*e.g.*, a liquid first fluid) (designated as "A") and a second fluid / phase (*e.g.*, a vapor space above the liquid first fluid) (designated as "B") (Fig. 5A), and an associated set of characterized responses of the mechanical resonators (Fig. 5B).

[0038] FIG.'s 6A through 6B are schematic representations of the general methods and systems of the invention illustrating an embodiment in which a sensor comprising multiple mechanical resonators (designated by circled numbers 1, 2 and 3) at multiple, spatially discrete positions linked through a common communication path is deployed in a fluidic system (*e.g.*, a pipeline or tank) comprising a first fluid / phase (designated as "A"), a second fluid / phase (designated as "B") and a third fluid / phase (designated as

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“C”) depicted as being vertically phase-separated and having respective fluidic interfaces therebetween (Fig. 6A), and an associated set of characterized responses of the mechanical resonators (Fig. 6B).

[0039] FIG.'s 7A through 7C are schematic representations of the general methods and systems of the invention illustrating an embodiment in which a sensor comprising multiple mechanical resonators (designated by circled numbers 1, 2 and 3) at multiple, spatially discrete positions linked through a common communication path is deployed in a fluidic system (*e.g.*, a vertical riser pipeline) comprising a first fluid / phase (designated as “A”) and a second fluid / phase (designated as “B”) depicted as being radially phase-separated and having respective fluidic interfaces therebetween, showed in both longitudinal cross-section (Fig. 7A) and radial cross-section (Fig. 7B) and an associated set of characterized responses of the mechanical resonators (Fig. 7C).

[0040] FIG.'s 8A through 8D are schematic representations of the general methods and systems of the invention illustrating an embodiment in which a sensor comprising multiple mechanical resonators (designated by circled numbers 1, 2, 3 and 4) at multiple, spatially discrete positions linked through a common communication path is deployed in a fluidic system (*e.g.*, a settling tank) comprising – at a first time,  $t_1$ , a substantially uniform single phase fluid made up of a mixture (*e.g.*, liquid-in-liquid; liquid-in-gas; solid-in-liquid; solid-in-gas, *etc.*) of four components (designated as “A-B-C-D”) as a substantially homogeneous dispersion, suspension, fluidization, *etc.* (Fig. 8A), and comprising – at a second time,  $t_2$ , the four components as phase-separated first fluid / phase (designated as “A”), second fluid / phase (designated as “B”), third fluid / phase (designated as “C”) and fourth fluid / phase (designated as “D”), depicted as being vertically phase-separated and having respective fluidic interfaces therebetween (Fig. 8B), and further illustrating associated sets of characterized responses of the mechanical resonators at the first time,  $t_1$  (Fig. 8C), and at the second time,  $t_2$  (Fig. 8D).

[0041] FIG.'s 9A through 9H illustrate sensors suitable for use in connection with the general methods and systems of the invention, including schematic representations illustrating: an embodiment in which a sensor comprises multiple mechanical resonators (designated by circled numbers 1, 2, 3 and 4) arranged in a linear array, linked in communication with one or more circuits through a common communication path (Fig.

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9A); an embodiment representing a detailed configuration of the embodiment of Fig. 9A in which the multiple mechanical resonators are electrically coupled in parallel using two conductive leads, and as shown, including an optional third conductive lead for capacitance shielding (Fig. 9B); an embodiment representing an alternative detailed configuration of the embodiment of Fig. 9A in which the multiple mechanical resonators are electrically coupled in series using two conductive leads, and as shown, including an optional third conductive lead for capacitance shielding (Fig. 9C); an alternative embodiment in which a sensor comprises multiple mechanical resonators arranged in a linear array, linked in communication with multiple circuits through a common communication path (Fig. 9D); an embodiment in which a sensor comprises multiple mechanical resonators (designated by circled numbers 1, 2 and 3) arranged in a curvilinear array, linked through a common communication path (Fig. 9E); an embodiment in which a sensor comprises multiple mechanical resonators (designated by circled numbers 1 through 5) arranged in a geometrically-shaped array such as a pentagonal array (as shown), linked through a common communication path (Fig. 9F); an embodiment in which a sensor comprises multiple mechanical resonators (designated by circled numbers 1 through 17) arranged in a star-patterned array, linked through a common communication path and supported on a star-shaped support frame (Fig. 9G); and an embodiment in which a sensor comprises multiple mechanical resonators (designated by circled numbers 1 through 12) arranged in a three-dimensional array such as a helical array (as shown), linked through a common communication path (Fig. 9H).

**[0042]** FIG.'s 10A through 10D are schematic representations of the general methods and systems of the invention illustrating embodiments in which a sensor comprising multiple mechanical resonators at multiple, spatially discrete positions is deployed outside of (but nonetheless in general association with) one or more fluidic systems, including: an embodiment in which a sensor comprising multiple mechanical resonators (designated by circled numbers 1 through 4) linked through a common communication path is deployed between two walls of a double-wall tank (*e.g.*, double-walled fluid-storage tank or fluid-transport tank) for example for spatially-sensitive leak detection (Fig. 10A); an embodiment in which a sensor comprising multiple mechanical resonators (designated by circled numbers 1 through 5) linked through a common communication path is deployed

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in the ground beneath a storage tank (*e.g.*, a storage tank comprising a hazardous material such as a fuel) for example for spatially-sensitive detection of leaks and/or of ground-water contamination (Fig. 10B); an embodiment in which a sensor comprising multiple mechanical resonators (designated by circled numbers 1 through 8) linked through a common communication path is deployed above ground in the atmosphere surrounding one or more chemical processing units (*e.g.*, hydrocarbon refining operations) for example for spatially-sensitive detection of air contamination (Fig. 10C); and an embodiment in which a sensor comprising multiple mechanical resonators (designated by circled numbers 1 through 4) linked through a common communication path is deployed within a well casing and externally adjacent to a well-pipe (*e.g.*, a residential or commercial water well) for monitoring ground-water level associated with the well (Fig. 10D).

[0043] Figures 11A through 11D illustrate sensors suitable for use in connection with the general methods and systems of the invention, including schematic representations illustrating embodiments in which a sensor comprises multiple mechanical resonators (designated by circled numbers 1, 2 and 3) linked in communication with one or more circuits through a common communication path, with the circuits comprising signal processing circuitry and/or data retrieval circuitry, generally (Fig. 11A), with various detailed configurations (Fig. 11B and Fig. 11C), and with the one or more circuits being configured to be partially local and partially remote (for example, as a ported sensor subassembly) (Fig. 11D).

[0044] FIG's 12A through 12I are schematic representations of a fluidic system (Fig. 12A) and of several configurations for flexural resonator sensing elements (Fig. 12B through 12I).

[0045] FIG.'s 13A through 13C are a schematic representation of an equivalent circuit for a sensor comprising a flexural resonator sensing element (Fig. 8A) and of equations relating thereto (Fig. 8B and Fig. 8C).

[0046] FIG.'s 14A through 14E are schematic representations of one preferred approach for circuitry that can be used in connection with the various embodiments of the invention, at least a portion of the circuitry being realized in an application specific integrated circuit (ASIC).

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[0047] FIG.'s 15A through 15D are schematic representations of alternative approaches for realizing circuitry in an ASIC.

[0048] FIG.'s 16A through 16C are tables listing preferred application areas (fields of use) (Fig. 16A), fluidic systems (Fig. 16B) and fluids (Fig. 16C) for which the methods, systems and apparatus of the inventions can be employed.

[0049] FIG.'s 17A through 17F are photos, schematic representations and graphs relating to experiments employing the methods and systems of the invention for measuring the level of liquid hexane in a container, including: a photograph depicting a portion of a sensor comprising five tuning-fork resonators arranged in a linear array linked through a common communication path and supported by a support rod (Fig. 17A); a photo of an oscilloscope showing the data representing the characterized responses of the five tuning fork sensors when positioned in the gas-phase above the hexane liquid phase (Fig. 17B); a schematic representation of the experimental set-up (Fig. 17C); a graph showing four sets of data from four measurements taken with the hexane liquid phase at four different levels (designated as "Level A", "Level B", "Level C" and "Level D"), the four sets of data representing the characterized responses of the five tuning forks for each respective measurement, shown with the four data sets being overlaid without offset (Fig. 17D); a graph showing the four sets of data of Figure 17D, shown with the four data sets being offset with respect to the y-axis value (to allow for greater ease in comparative interpretation between the four data sets) (Fig. 17E); the schematic as shown in Figure 17C depicting the sensor comprising the five tuning fork resonators in association with the four sets of data of Figure 17E depicting the characterized responses of the mechanical resonators for the measurements taken with the hexane liquid phase at the four different levels (designated as "Level A", "Level B", "Level C" and "Level D") (Fig. 17F).

[0050] The invention is described in further detail below with reference to the figures, in which like items are numbered the same in the several figures.

### **DETAILED DESCRIPTION OF THE INVENTION**

[0051] The following paragraphs describe certain features and combinations of features that can be used in connection with each of the various methods, sensors and systems of

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the invention, as generally described above. Also, particular features described hereinafter can be used in combination with other described features in each of the various possible combinations and permutations. As such, the invention is not limited to the specifically described embodiments.

**[0052]** The method of the invention, described with reference to Figures 1A and 1B, 2A through 2D, 3A and 3B, 4A and 4B, 5A and 5B, 6A and 6B, 7A through 7C and 8A through 8D, is a method for sensing one or more fluids (designated in the various figures as fluids or phases "A", "B", "C", "D", *etc.*) at multiple positions using mechanical resonators 40 (designated generally collectively using the reference numeral "40", with multiple resonators designated more specifically in the various figures as resonators with circled numbers 1, 2, 3, *etc.* and in the associated text herein as 40-1, 40-2, 40-3, *etc.*). In many applications, the fluid(s) being sensed are contained within, constrained by, originated from, or otherwise associated with one or more fluidic systems 100 (with multiple fluidic systems being designated in the various figures as systems "I", "II", *etc.*, and in the associated text as 100-I, 100-II, *etc.*). Sensing surfaces of each of the multiple resonators 40 are contacted with fluid(s) at the multiple positions, preferably during a sensing period. The multiple resonators 40 are each stimulated, preferably during the sensing period and while their sensing surfaces are in contact with the fluid. The multiple resonators 40 can be stimulated actively (*e.g.*, using an electrical activating signal) or passively (*e.g.*, without an activating signal) to generate signals associated with the respective resonator responses. The generated signals are communicated (as multiplexed signals) over a common communication path 65 (indicated generally in the various figures using dashed lines linking each of the multiple resonators 40) to electrical circuitry 20 / 30 for signal processing and/or data retrieval. The multiplexed signals are then deconvoluted, by processing the signals to characterize the responses, and then associating the characterized responses of the resonators with position – with specific positions of respective resonators, or with positions of fluids or fluid interfaces within the particular fluidic system(s).

**[0053]** In preferred methods, the characterized responses of the resonators 40 are also used to determine one or more properties of the fluid being sensed. Fluid properties can be advantageously determined using flexural resonators such as tuning forks, for example

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(*e.g.*, to determine viscosity, density, dielectric and conductivity). Generally, at least one property, and preferably two or more properties of the fluid at each of the multiple positions is determined. Typically, the at least one property is determined at multiple positions by correlating the respective responses associated with each resonator with the at least one property of the fluid, for example, based on at least one of the signal characteristics of the characterized responses of the resonators.

[0054] With reference generally to Figures 9A through 9G, a preferred sensor 10 for use in connection with the methods and systems of the invention comprises at least two resonators such as two or more mechanical resonators 40 at multiple positions, preferably associated with one or more fluidic systems 100. The sensor 10 also includes one or more electrical circuits such as signal processing circuitry 20 and/or data retrieval circuitry 30. Electrical communication between each of the two or more resonators 40 and the electrical circuit(s) 20 / 30 is provided by a communication link that comprises a common communication path 65 defining at least a portion of the communication link between each of the two or more resonators 40 and the electrical circuit(s) 20, 30. In some embodiments, the communication link between each of the two or more resonators and the electrical circuit can consist essentially of the common communication path 65.

[0055] As noted above, many advantages of the sensor are realized in the methods and systems of the invention by multiplexing signals representing the responses of the multiple spatially discrete mechanical resonators over a common communication path, and decoupling the multiplexed signals to obtain meaningful information about the fluid(s) being sensed – *e.g.*, about the fluid(s) *per se*, such as fluid properties thereof, or about the fluid(s) in relation to and in the context of the fluidic system(s) with which the fluid(s) is associated.

#### **COMMON COMMUNICATION PATH**

[0056] Generally, with reference again to the several above-noted figures, the signals generated in association with the responses of the mechanical resonators 40 are communicated over a common communication path 65. The particular nature of the common communication path is not narrowly critical. The common communication path 65 can typically comprise for example, a plurality of a conductive paths 66a, 66b (Fig.'s

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9B and 9C) such as conductive wires, conductive thin-film connectors or other conductive connectors). Alternatively, however, the common communication path 65 can be realized (over its entirety or over a portion thereof) using for example acoustic paths (*e.g.*, solid waveguides, such as solid rods), magnetic paths (*e.g.*, inductive coupling, such as across a fluidic barrier 110), electromagnetic paths (*e.g.*, electromagnetic radiation such as microwave radiation, visible light radiation, infrared radiation, *etc.*, typically applied in connection with a wave guide such as a fiber optic, *etc.*).

[0057] Regardless of the particular manner in which the common communication path 65 is realized, the mechanical resonators 40 can be configured in any suitable manner with respect to electrical connection to the common communication path 65. The particular configuration will depend upon the type of mechanical resonators 40 employed, including for example, the number of electrodes and the configuration of the electrodes associated with the resonators, how the resonators are stimulated (*e.g.*, actively versus passively), *etc.* Preferred configurations for mechanical resonators 40 generally, and especially for resonators such as tuning fork resonators or other flexural resonators, can include a parallel configuration, for example as shown in Figure 9B, or alternatively a series configuration, for example as shown in Figure 9C. As shown in Figures 9A and 9B, conductive paths 66a, 66b are electrically connected with terminals 67 (*e.g.*, illustrated as input terminal 67a and output terminal 67b) that are electrically connected with electrodes of the mechanical resonators 40 to form a circuit that includes the mechanical resonator – with the resonators being included in the circuit either in parallel (Fig. 9B) or in series (Fig. 9C). An alternative series configuration is shown in Figure 9D, in which a common communication path 65 provides electrical communication link between a first circuit comprising for example a signal processing circuit 20 (*e.g.*, comprising signal activation circuitry), each of the multiple mechanical resonators 40-1, 40-2, 40-3, 40-4 and a second circuit, comprising for example one or both of a signal processing circuit 20 and a data retrieval circuit 30. These and other configurations can be adapted by persons of ordinary skill in the art to accommodate particular types of mechanical resonators.

[0058] In any case, the common communication path 65 can be further enhanced to optimize sensor performance by reducing, minimizing or preferably eliminating electrical

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effects that can interfere with the signals associated with the responses of the resonators  
40. In preferred embodiments, for example, in which the common communication path  
65 comprises a plurality of conductive paths 66a, 66b, the sensor can further comprise  
another conductive lead (*e.g.*, a third conductive lead 66c as shown in Figures 9B and 9C)  
configured substantially proximate to each of the first and second conductive leads 66a,  
66b for shielding to reduce or minimize wire-to-wire interference (*e.g.*, capacitance)  
between the first and second conductive leads 66a, 66b. The third conductive lead 66c  
can be grounded, as shown in Figures 9B and 9C.

[0059] The timing of communication of the generated signals is not critically significant  
to the invention. Generated signals originating from each of the plurality of mechanical  
resonators of can be communicated over the common communication path 65  
concurrently (*i.e.*, having at least some overlap in signal as considered with respect to  
time) or substantially concurrently (*i.e.*, the signals being communicated over the  
common communication path 65 at substantially the same time, within a common  
sensing period where the differences in time are attributed to the physics of the  
communication over the communication path (*e.g.*, the physics of the electrons being  
communicated in a conductive path). In some embodiments (*e.g.* where multiple  
resonators are stimulated passively by the fluidic environment in which the sensing  
surface of the resonator resides), the signals associated with the response of the  
resonators may be communicated sequentially in time over the common communication  
path, in correspondence with a sequential timing of the passive stimulus associated with  
respective resonators.

#### **DECOUPLING**

[0060] In the context of the present invention (methods and systems), decoupling of the  
multiple signals being communicated is generally based (typically *a priori*) knowledge  
about either (i) the mechanical resonators (*e.g.*, design characteristics thereof), or (ii) the  
configuration of the resonators with respect to a particular fluidic system, or (iii) both of  
the above items (i) and (ii). Generally, decoupling is effected by processing the signals  
received over the common communication path (typically using signal processing

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circuitry) to characterize the responses of the mechanical resonators. The characterized responses are then associated with position.

**[0061]** In one approach, the characterized responses are associated specifically with the positions of respective resonators. This association is preferably based on observing one or more signal characteristics (*e.g.*, frequency, amplitude, *etc.*) of characterized responses and then correlating the observed signal characteristic(s) for each particular response with a particular one of the resonators (and therefore with its corresponding position within the fluidic system), typically for example based on knowledge about that particular resonator (*e.g.*, based on a specific design characteristic(s) thereof). With reference to Figure 3A for example, signals generated by stimulating the four mechanical resonators 40-1, 40-2, 40-3 and 40-4 in a body of fluid A are communicated over the common communication path 65 and processed to characterize the response of the resonators, with the characterized responses being illustrated in Figure 3B. A signal characteristic, for example the frequencies of the characterized responses, can be observed. In the illustrated example shown in Figures 3A and 3B, the observed frequency of each characterized response can be correlated to each specific resonator based on the designed resonance frequency of each resonator. That is, for example, if the resonance frequencies of the four mechanical resonators 40-1, 40-2, 40-3 and 40-4 are  $f_{R1}$ ,  $f_{R2}$ ,  $f_{R3}$ , and  $f_{R4}$ , respectively, then the observed signal having the frequency of  $f_{R1}$  can be correlated to resonator 40-1 (and the position thereof). Similarly, the observed signal having the frequency of  $f_{R2}$  can be correlated to resonator 40-2 (and the position thereof); the observed signals having the frequency of  $f_{R3}$  can be correlated to resonator 40-3 (and the position thereof); and the observed signal having the frequency of  $f_{R4}$  can be correlated to resonators 40-4 (and the position thereof).

**[0062]** Hence, generally, as illustrated in the approach described and exemplified in the immediately preceding paragraph, in some applications it is desirable that each of the mechanical resonators 40 are different from each other with respect to at least one design characteristic. Preferably, the difference in design characteristic imparts a differentiable resonator response and a corresponding difference with respect to at least one signal characteristic of the characterized response associated with the multiple resonators 40. In the context for example of using frequency as a signal characteristic for deconvolution,

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the sensor can comprises two or more resonators having different frequencies such as different resonance frequencies. Specifically, for example, the sensor can comprise a first resonator having a first resonance frequency,  $f_{R1}$ , and a second resonator having a second resonance frequency,  $f_{R2}$ , where the second resonance frequency,  $f_{R2}$ , is different than the first resonance frequency,  $f_{R1}$ , in one or more of the fluids being sensed. In some embodiments, it may be preferred to design the resonators 40 such that the second resonance frequency,  $f_{R2}$ , is different than the first resonance frequency,  $f_{R1}$ , in each of two or more fluids being sensed. The difference in frequencies can be known *a priori* in absolute terms (*e.g.*, particular frequency values for each resonator) or in relative terms (*e.g.*, which resonator has the highest frequency, which has the next highest frequency, which has the then next highest frequency, *etc.*). Also, the frequency value being considered can be a set particular frequency (presence of a response or not) or a range of frequencies or a change in frequency relative to some standard or a resonance frequency (as described above) or a change in resonance frequency versus some standard.

**[0063]** Further, although described herein specifically in the context of resonators 40 having designed frequency differences (for correlating based on frequency of the observed resonator response), resonator design characteristics can likewise be controlled to effect resonators differences that impart differentiable resonator responses and corresponding differences with respect to other signal characteristics (besides frequency) of the characterized response, including for example differences in signal amplitude, peak width (*e.g.*, at a particular percentage (*e.g.*, 50%, *e.g.*, 70%) of the maximum amplitude), signal intensity, *etc.*

**[0064]** With respect to the approach described and exemplified in the immediately preceding paragraphs, the degree of difference in design characteristics of the resonators is not narrowly critical. The desired degree in difference (*e.g.*, in resonance frequency) depends primarily on the extent of difference desired for the characterized response, which itself depends on the type of fluid(s), the purpose of the sensing operation, the type of resonators and the quality of the resonators, the signal processing circuitry, *etc.*, among other factors. Accordingly, a person of ordinary skill in the art can design the differences in resonators to achieve a differentiable characterized response based on known design implications. Generally, for example, for deconvolution approaches involving frequency

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tuning of the multiple resonators 40, it may be desirable to design mechanical resonators 40 having differences in resonance frequencies ranging from about 1x (one times) to about 5x (five times) the width of the resonance peak (*e.g.*, as measured at 70% of the maximum amplitude) in the fluid being sensed or in a standard fluid, and preferably from about 2x (two times) to about 3x (three times) the width of the resonance peak (*e.g.*, as measured at 70% of the maximum amplitude) in the fluid being sensed or in a standard fluid. Hence for preferred flexural resonators such as tuning fork resonators having sensing operations of less than about 1 MHz, differences in designed resonance frequencies of at least about 0.1 Hz, preferably of at least about 0.5 Hz, and more preferably of at least about 1 Hz. In many applications, greater differences are preferred, including for example differences of at least about 5 Hz, at least about 10 Hz, at least about 20 Hz, at least about 50 Hz or at least about 100 Hz. In some embodiments, even higher differences can be reasonably employed, including for example 200 Hz, 400 Hz or 1 kHz. Similar considerations can be considered in the context of other types of mechanical resonators and/or with respect to other signal characteristics, such as amplitude or peak width.

[0065] Generally, in applications involving fluidic systems having more than one type of fluids A, B (*e.g.*, in a level-sensing application as illustrated in Figures 5A and 5B), a skilled person can also consider the potential for change or shift in signal characteristic resulting sensing operations in different fluids, and then design the resonators to have different characteristics that do not mask or otherwise interfere with deconvolution based on recognizing the fluid-dependent change in characterized response. In the context of level sensing for example (in a system oriented with a heavier first fluid situated below a lighter second fluid), one may want to select designed differences in signal characteristics (*e.g.*,  $\Delta f$ ) (used for deconvoluting, as described herein) so that the differences observed due to fluid-dependency is not offset by an equal and opposite designed differences. In the level sensing system of Figures 5A and 5B, where for example, frequency is being used a signal characteristic for deconvolution, one can expect the sensing of heavier fluid A to shift the frequency to a lower frequency, thereby widening the difference between the frequency of resonator response in fluid A and the adjacent

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frequency response for the fluid B, and thereby avoiding potential masking / offset / overlap of signals..

[0066] As noted above, decoupling can be effected in another approach, based on observed differences in the characterized responses of the resonators considered together with inferences drawn from (typically *a priori*) knowledge about the configuration of the resonators with respect to a particular fluidic system. In this approach the characterized responses are associated with position, for example with positions of the fluid(s) or fluidic interfaces for a particular fluidic system, based on differences (*e.g.*, especially fluid-dependent differences) in the characterized responses of the resonators. This inferential association is preferably based on observing characterized responses and then correlating the observed responses with a status of the fluid or fluidic interface within the fluidic system. With reference to Figure 4A for example, signals generated by stimulating the five mechanical resonators 40-1, 40-2, 40-3, 40-4 and 40-5 in a system comprising two fluids / phases A,B (*e.g.*, moving in a direction through a pipeline) are communicated over the common communication path 65 and processed to characterize the response of the resonators, with the characterized responses being illustrated in Figure 4B. The characterized responses can be observed to identify the relative position of fluid A versus fluid B (or by inference, the fluidic interface between fluid A and fluid B). Specifically, in the illustrated example shown in Figures 4A and 4B, the observed characterized responses can be used to identify the position of the fluids A and B by inference where fluid A is known to damp the resonator response more than fluid B and where the sensor as deployed in this fluidic system has five mechanical resonators. Based on this information, one can infer that two of the five resonators 40-1, 40-2, 40-3, 40-4 and 40-5 are in contact with fluid A and that three of the five resonators 40-1, 40-2, 40-3, 40-4 and 40-5 are in contact with fluid B. Where the fluids are moving in a particular direction (*e.g.*, due to pressure differentials along the pipeline), then one can definitively identify the fluidic interface to lie between resonators 40-2 and 40-3 in the system as illustrated. Hence, one can obtain meaningful information about the position of the fluids A and B within this system – even without specifically correlating each particular resonator (and its associated position) with each particular characterized response on a one-to-one basis.

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[0067] As another example of such inferential association, with reference to Figure 5A for example, signals generated by stimulating the four mechanical resonators 40-1, 40-2, 40-3 and 40-4 in a system comprising two fluids / phases A,B (*e.g.*, as a level sensor for a tank having a heavier (*e.g.*, liquid) fluid A and a lighter (*e.g.*, vapor) fluid B thereabove) are communicated over the common communication path 65 and processed to characterize the response of the resonators, with the characterized responses being illustrated in Figure 5B. The characterized responses can be observed to identify the relative position (*e.g.*, the level) of fluid A versus fluid B (or by inference, the fluidic interface between fluid A and fluid B). Specifically, in the illustrated example shown in Figures 5A and 5B, the observed characterized responses can be used to identify the level of fluid A by inference where fluid A is known to substantially completely damp the resonator response (without generating a detectable signal, at least in the electronic circuits as tuned) whereas fluid B provides a detectable response and where the sensor as deployed in this fluidic system has four mechanical resonators 40. Based on this information, one can infer that three of the four resonators 40-1, 40-2, 40-3 and 40-4 are in contact with fluid B (the lighter fluid) and that one of the four resonators 40-1, 40-2, 40-3 and 40-4 is in contact with fluid A. Since fluid A is known to be heavier, one can definitively identify the level to lie between resonators 40-1 and 40-2 in the system as illustrated. This example further illustrates that one can obtain meaningful information about the position of the fluids A and B within this system – even without specifically correlating each particular resonator (and its associated position) with each particular characterized response on a one-to-one basis. In fact, in the illustrated system applied for level sensing operations, it is sufficient in some applications to only detect the number of the characterized responses associated with one or both of the two fluids / phases A, B.

[0068] The nature of the differences in the characterized responses of the resonators 40 is not narrowly critical. Generally, the differences in the characterized response (as compared between resonators 40) is a fluid-dependent difference – that is, a difference at least partially attributable to differences in the types of or fluid properties (*e.g.*, viscosity, density, dielectric, conductivity). Hence, for example, the differences in characterized responses of resonators 40 can be the presence versus the essential absence of characterized response (or versus the essential absence of a detectable characterized

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response) in the system and system electronic circuitry as configured and used in a sensing operation. As another example, the differences in characterized responses of resonators 40 can be a comparative difference with respect to one or more signal characteristics (*e.g.*, frequency, amplitude, peak width (*e.g.*, at some percentage of maximum amplitude, as described previously), intensity, *etc.*). For example, differences in amplitude can be associated with relative degree of damping of a mechanical resonators by different fluids (*e.g.*, oil / water) and/or different phases (*e.g.*, liquid / vapor, liquid / solid, solid / vapor). Further, differences in characterized responses of resonators 40 can be a comparative difference in a fluid property, where the value of the fluid property is derived from one or more signal characteristics. The differences in characterized responses of two or more resonators 40 can be ascertained by direct comparison (*e.g.*, for example, comparing a resonator response associated with a first resonator at a first position directly with a resonator response associated with a second resonator at a second position). Alternatively, the differences in characterized responses of two or more resonators 40 can be ascertained by indirect comparison using a third resonator (*e.g.*, for example, comparing resonator responses associated with each of a first resonator and a second resonator with a resonator response associated with a third resonator, thereby indirectly providing for comparison between the first and second resonators).

**[0069]** As noted in the Summary of the Invention, the response of each of the multiple mechanical resonators 40 during sensing operations is a function of at least (i) the resonator design (*e.g.*, resonator type, design characteristics, *etc.*), and (ii) the fluid being sensed. Because of this, the multiple resonators 40 deployed in connection with a particular sensor 10 can be substantially the same or can be different, in each case with respect to resonator type and/or resonator design characteristics. One consideration in designing the sensor is therefore the type of fluidic system(s) including the number of and nature of fluid(s) to be sensed. Another consideration is the amount and type of information that is desired from the sensing operation. Deconvoluting using the position-specific approach based on correlating observed signal characteristics (as described above) to designed differences in the mechanical resonators can be generally applied, with substantially universal application with respect to types of fluidic systems and with

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respect to numbers and types of fluids. This approach is particularly well-suited for applications involving sensing a single fluid type or within a single body of fluid (*e.g.*, as illustrated schematically in connection with Figures 1A, 2A and 3A). In contrast, sensors comprising multiple resonators 40 having substantially the same design (*e.g.* resonator type and design characteristics, *etc.*) are well-suited for applications that involve sensing different fluids. With reference to Figures 6A and 6B, for example, each of the three resonators 40-1, 40-2 and 40-3 could be substantially identical with respect to resonator type and design characteristics and therefore with respect to response to a particular stimulus in sensing operation for a given fluid. In the illustrated application however, the resonance frequency of these three resonators could vary in the three different fluids A, B and C, allowing for deconvolution of the multiplexed signals. With reference to Figure 6B, for example, it would be apparent that the three characterized responses identify the presence of three different fluids / phases in the context of the fluidic system illustrated in Figure 6A. Further, it is notable that sensors comprising multiple resonators 40 having substantially the same design (*e.g.* resonator type and design characteristics, *etc.*) could also be employed in connection with applications involving only a single fluid type, with deconvolution based on other signal characteristics of the characterized responses – such as signal intensity (*e.g.*, where signal frequency, signal amplitude and/or signal bandwidth do not provide a differentiable characterized response).

#### FLUIDIC SYSTEMS

[0070] The methods and systems of the invention typically involve applications of a sensor (as generally and specifically described herein) in association with one or more fluidic systems. Generally, the fluidic system can be an open fluidic system or a closed fluidic system. An open fluidic system can comprise one or more fluids and having one or more fluidic surfaces that are exposed to an open uncontrolled atmosphere. For example, an open fluidic system can be an open container such as an open-top tank or an open well of a reactor or of a parallel reactor (*e.g.*, microtiter plate). Alternatively, the fluidic system can be a closed fluidic system. A closed fluidic system can comprise one or more fluids that are generally bounded by a barrier so that the fluids are constrained. For example, a closed fluidic system can include a pipeline (*e.g.*, for oil and/or gas

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transport), a reactor, or a recirculating fluidic system, such as an oil system associated with an engine, or a refrigerant or coolant system associated with various residential, commercial and/or industrial applications. A closed fluidic system can be in fluid communication with an open fluidic system. The fluid communication between a closed fluidic system and an open fluidic system can be isolatable, for example, using one or more valves. Such isolation valves can be configured for uni-directional fluid flow, such as for example, a pressure relief valve or a check valve. In general, the fluidic system (whether open or closed) can be defined by manufactured (*e.g.*, man-made) boundaries comprising one or more barriers. The one or more barriers defining manufactured boundaries can generally be made from natural or non-natural materials. Also, in general, the fluidic system (whether open or closed) can be a flow system such as a continuous flow system or a semi-continuous flow (*e.g.*, intermittent-flow) system, a batch system, or a semi-batch system (sometimes also referred to as a semi-continuous system). In instances, fluidic systems that are flow systems are closed fluidic systems. In other instances, fluidic systems that are batch systems are open fluidic systems (*e.g.* open tanks) or closed fluidic systems (*e.g.*, closed tanks).

**[0071]** With further reference to Figures 1A and 1B for example, methods and systems can comprise a sensor 10 deployed in association with a single fluidic system 100-I, where the fluid system comprises a single fluid / phase (Fig. 1A) or multiple fluids / phases (Fig. 1B).

**[0072]** Referring to FIG.'s 2A through 2D, methods and systems of the invention can comprise a sensor 10 applied in association with two or more fluidic systems 100-I, 100-II where the two fluidic systems comprise a single fluid / phase of a same type of fluid (*e.g.*, same composition) in each fluidic system (Fig. 2A), a single fluid / phase of a different type of fluid (*e.g.*, different composition) in each fluidic system (Fig. 2B), a single fluid / phase in a first of the two fluidic systems, and multiple fluids / phases in the second of the two fluidic systems, one of the multiple fluids / phases in the second system being of the same type as the fluid in the first system (Fig. 2C), and multiple fluids / phases, each of different types, in each of the two fluidic systems (Fig. 2D).

**[0073]** In any case, the fluidic system(s) 100-I (100-II) can comprise one or more couplings 60 for interfacing the sensor across a fluidic barrier 110. Although illustrated

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generally with circuits 20, 30 external to the fluid being sensed, in some applications the circuits 20, 30 (and indeed the entire sensor 10) is situated internal to the fluidic system and exposed to the fluid; thereby obviating the need for the coupling 60. Packaging approaches are known in the art for such internally-situated electronics circuits 20, 30.

[0074] Generally, the configurations as illustrated in Figures 1A and 1B and Figures 2A through 2D may be applicable, for example, for: property profiling of a single fluid A spatially across process region(s) of fluidic system(s); for property profiling of two fluids A, B spatially across a process region(s) of fluidic system(s), for identifying the presence (or absence) of two fluids / phases A, B and/or C, D within the process region(s), for identifying the position of the interface(s) between the two fluids / phases A, B and/or C, D within the process region(s) and/or for sensing the level of one or both fluids A, B and/or C, D within the process region(s).

[0075] In any case, the single or multiple fluidic systems may be any type of fluidic system, without limitation, including research-scale systems (*e.g.*, high-throughput experimentation systems such as parallel batch reactors or parallel flow reactors), pilot-plant scale systems and/or industrial scale (commercial) systems. Particularly preferred systems and applications of commercial significance are described below.

[0076] Each of the aforementioned generally described fluidic systems can be applied independently or in combination with each other, in each of the possible various permutations. Also, each of the aforementioned generally preferred approaches can be applied in further combination with more particular aspects, including particular protocols and/or particular systems or sensor features, as described herein.

#### **GENERAL APPLICATIONS**

[0077] Generally, the methods and systems of the invention can be deployed in connection with many applications. Some (non-limiting) applications of particular interest include, for example, process monitoring, process control, quality control / quality assurance, enterprise management, servicing, research, *etc.*

[0078] Referring briefly to FIG.'s 3A through 3B, the general methods and systems of the invention can be applied for sensing, monitoring or evaluating (*e.g.*, determining one or more fluid properties) a body of fluid A at multiple positions. A sensor 10 comprising

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multiple mechanical resonators 40 at multiple, spatially discrete positions are linked through a common communication path 65 within a process region comprising the body of fluid (Fig. 3A). The sensor is operatively employed to obtain an associated set of characterized responses of the mechanical resonators (Fig. 3B). The set of characterized responses can be associated with specific mechanical resonators 40 (as described above). Such sensor operations can be used for spatially profiling one or more properties of the fluid A. For example, in embodiments in which resonators 40-1, 40-2, 40-3 and 40-4 are position-correlated specifically to frequencies  $f_{R1}$ ,  $f_{R2}$ ,  $f_{R3}$ , and  $f_{R4}$ , respectively, (as described above), and the one or more signal characteristics (*e.g.*, amplitude) correlate to a particular property of interest, then a variation (*e.g.*, an increasing gradient) with respect to that property can be observed.

**[0079]** FIG.'s 4A through 4B are representative of applications involving multiple fluids / multiple phases moving through a process region (*e.g.* a process line such as a pipeline), and the methods and systems of the invention can be applied for sensing, monitoring or evaluating (*e.g.*, determining one or more fluid properties) fluids A, B at multiple positions as they move through the process region. Such applications are common, for example, in connection with oil exploration and/or hydrocarbon refining. Typical applications can involve a lighter fluid / phase (*e.g.*, oil) and a heavier fluid / phase (*e.g.* water). A sensor comprises multiple mechanical resonators 40 at multiple, spatially discrete positions linked through a common communication path 65 as described above. A first fluid / phase A and a second fluid / phase B having a fluidic interface therebetween are moved through the process region by a motive force, such as a pressure differential. As shown in Figure 4B, an associated set of characterized responses of the mechanical resonators 40 can be observed. The characterized responses can be used to identify the location of fluids A and B (or the associated fluidic interface) within the process region and/or to profile one or more properties of the fluids A and B spatially across the process region.

**[0080]** As discussed above, a level-sensing application is schematically represented by FIG.'s 5A and 5B, in which a process region (*e.g.* tank, reactor, *etc.*) (*e.g.*, open or closed) includes a sensor 10 comprising multiple mechanical resonators 40 positioned at multiple, spatially discrete positions and linked through a common communication path

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65. Typically, the process region (*e.g.*, tank, reactor) comprises a first fluid / phase A (*e.g.*, a liquid first fluid) and a second fluid / phase B (*e.g.*, a vapor space above the liquid first fluid). The process region can also include a single fluid, as a homogeneous or a non-homogeneous fluid (comprising *e.g.*, slurry, fluidized particles or static particles). The level of the fluid A (or fluid B) may be sensed based on an associated set of characterized responses of the mechanical resonators 40, as shown in Figure 5B. Advantageously, in addition to level sensing, the sensor 10 can also be used effectively for evaluating the fluid(s) A, B with respect one or more fluid properties.

[0081] FIG.'s 6A and 6B schematically represent applications of the methods and systems of the invention in connection with a fluidic system having a process region (*e.g.*, a pipeline or tank) comprising a first fluid / phase A, a second fluid / phase B, and a third fluid / phase C that are phase-separated, typically vertically phase-separated, and that can have respective fluidic interfaces therebetween. Vertical phase-separation (*e.g.*, stratification) can occur in process regions comprising flowing fluids (*e.g.*, process lines such as pipe lines) and/or static fluids (*e.g.*, process tanks), typically due to gravitational effects acting on fluids having different densities. In the illustrated embodiment, a sensor 10 comprises multiple mechanical resonators 40 positioned at multiple, spatially discrete positions and linked through a common communication path 65. The presence or absence or extent of vertical phase separation (*e.g.*, stratification), the identity of various fluids A, B, C and/ or the positions (relative positions or actual positions) of the various fluids A, B and/or C can be variously determined based on the associated set of characterized responses of the mechanical resonators, for example as shown in Figure 6B. Advantageously, in addition, the sensor 10 can also be used effectively for evaluating the fluid(s) A, B, C with respect one or more fluid properties.

[0082] FIG.'s 7A through 7C schematic represent applications of the general methods and systems of the invention in connection with a fluidic system having a process regions (*e.g.*, vertically-oriented process line such as a vertical riser pipe) comprising a first fluid / phase A and a second fluid / phase B that are radially phase-separated, and that can have a respective fluidic interface therebetween. Figure 7A shows a longitudinal cross-section of the process region (*e.g.*, vertical riser); Figure 7B shows a radial cross-section thereof. Radial phase-separation can occur for example in process regions comprising flowing

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fluids (*e.g.*, process lines such as pipe lines; *e.g.*, channeling in flow reactors such as fixed bed reactors or fluidized bed reactors). In some cases, such radial phase-separation can occur due to gravitational effects acting on fluids having different densities. In the illustrated embodiment, a sensor 10 comprises multiple mechanical resonators 40 positioned radially across the process region at multiple, spatially discrete positions and linked through a common communication path 65. The presence or absence or extent of radial phase separation, the identity of various fluids A, B and/ or the positions (relative positions or actual positions) of the various fluids A, B can be variously determined based on the associated set of characterized responses of the mechanical resonators, for example as shown in Figure 7C. Advantageously, in addition, the sensor 10 can also be used effectively for evaluating the fluid(s) A, B with respect one or more fluid properties.

[0083] Although the various applications for the methods and systems of the invention have been primarily described heretofore in the context of sensing at a particular time during the process, the methods and systems have substantial advantageous applications for sensing, monitoring and/or evaluating (*e.g.* determining a fluid property) at various multiple times, typically defined by various multiple discrete sensing periods (separated in time by non-sensing periods). Such sensing, monitoring and/or evaluating may be applied in connection with process control systems, for example. Alternatively, it may be of commercial or industrial or research interest to evaluate one or more fluidic systems at multiple positions at several discrete sensing periods in order to evaluate the change in one or more fluids or in a process comprising such one or more fluids. This aspect of the methods and systems of the invention is illustrated in FIG.'s 8A through 8D, for example, in connection with a fluidic system (*e.g.*, a settling tank) having a process region. At a first time,  $t_1$ , the process region can comprise a substantially uniform single phase fluid made up of a mixture A-B-C-D (*e.g.*, liquid-in-liquid; liquid-in-gas; solid-in-liquid; solid-in-gas, *etc.*) of four fluids as a substantially homogeneous dispersion, suspension, fluidization, *etc.* (Fig. 8A). Such mixtures are common, for example, in some polymerization protocols (*e.g.* emulsion polymerization) and in industrial applications (*e.g.*, waste-water treatment). At a second time,  $t_2$ , the process region can comprise the four fluid components as phase-separated first fluid / phase A, second fluid / phase B, third fluid / phase C and fourth fluid / phase D, illustrated herein as being vertically

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phase-separated and having respective fluidic interfaces therebetween (Fig. 8B). The sensor 10 comprises multiple mechanical resonators 40 at multiple, spatially discrete positions and linked through a common communication path 65. Associated sets of characterized responses of the mechanical resonators 40 are obtained during a first sensing period at the first time,  $t_1$  (Fig. 8C), and subsequently during a second sensing period at the second time,  $t_2$  (Fig. 8D). Using the methods and systems of the invention, the presence or absence or extent of vertical phase separation (*e.g.*, stratification) can be identified, as well as the timing associated with the onset or the completion of such phase separation. The methods and systems of the invention can also be used to determine the identity of various fluids A, B, C, D and/ or the positions (relative positions or actual positions) of the various fluids A, B, C, D (over time). Advantageously, in addition, the sensor 10 can also be used effectively for evaluating the fluid(s) A, B, C, D with respect one or more fluid properties.

[0084] In any case, the fluidic system(s) as disclosed in such various applications can comprise one or more couplings 60 for interfacing the sensor across a fluidic barrier 110. Although illustrated generally with circuits 20, 30 external to the fluid being sensed, in some applications the circuits 20, 30 (and indeed the entire sensor 10) is situated internal to the fluidic system and exposed to the fluid; thereby obviating the need for the coupling 60. Packaging approaches are known in the art for such internally-situated electronics circuits 20, 30.

[0085] In any case, the single or multiple fluidic systems may be any type of fluidic system, without limitation, including research-scale systems (*e.g.*, high-throughput experimentation systems such as parallel batch reactors or parallel flow reactors), pilot-plant scale systems and/or industrial scale (commercial) systems.

[0086] Other applications that are not as closely linked with fluidic systems are also contemplated in connection with the sensors, systems and methods of the invention. Specifically, FIG.'s 10A through 10D are schematic representations of the general methods and systems of the invention illustrating embodiments in which a sensor comprising multiple mechanical resonators at multiple, spatially discrete positions is deployed outside of (but nonetheless in general association with) one or more fluidic systems. In one embodiment, a sensor 10 comprising multiple mechanical resonators 40

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linked through a common communication path 65 is deployed between two walls of a double-wall tank (*e.g.*, double-walled fluid-storage tank or fluid-transport tank) – for example for spatially-sensitive leak detection (Fig. 10A). In another embodiment, a sensor 10 comprising multiple mechanical resonators 40 linked through a common communication path 65 is deployed in the ground beneath a storage tank – for example, a storage tank comprising a hazardous material such as a fuel - for example for spatially-sensitive detection of leaks and/or of ground-water contamination (Fig. 10B). In an additional embodiment, a sensor 10 comprising multiple mechanical resonators 40 linked through a common communication path 65 is deployed above ground in the atmosphere surrounding one or more chemical processing units (*e.g.*, hydrocarbon refining operations) – for example for spatially-sensitive detection of air contamination (Fig. 10C). In a further embodiment a sensor 10 comprising multiple mechanical resonators 40 (designated by circled numbers 1 through 4) linked through a common communication path 65 is deployed within a well casing and externally adjacent to a well-pipe (*e.g.*, a residential or commercial water well) – for example for monitoring ground-water level associated with the well (Fig. 10D).

[0087] Each of the aforementioned generally described applications for the systems and methods of the invention can be applied independently or in combination with each other, in each of the possible various permutations. Also, each of the aforementioned generally preferred approaches can be applied in further combination with more particular aspects, including particular protocols and/or particular systems or sensor features, as described herein.

#### SENSOR CONFIGURATIONS

[0088] The particular configuration of the multiple mechanical resonators 40 as deployed in connection with the sensors 10 in the methods and systems of the invention is not narrowly critical.

[0089] With reference to Figures 9A through 9H, for example, a sensor 10 suitable for use in connection with the methods and systems of the invention can include multiple mechanical resonators 40 arranged in a linear array (Fig. 9A), arranged in a curvilinear array (Fig. 9E), arranged in a geometrically-shaped array such as a pentagonal array (as

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shown) (Fig. 9F), arranged in a star-patterned array, linked through a common communication path and supported on a star-shaped support frame 64 (Fig. 9G), and/or arranged in a three-dimensional array such as a helical array (as shown) (Fig. 9H), in each case linked through a common communication path 65.

[0090] The number of mechanical resonators 40 used in a particular application is likewise not narrowly critical. Generally, the number of resonators 40 can depend upon the particular application of interest, and the degree of resolution desired within that application (e.g. in a level-sensing application, the number of resonators may depend upon the number of different intermediate levels desired to be detected). The number of resonators 40 can generally be two or more, preferably three or more and preferably four or more. In some applications, higher numbers of resonators 40 can be employed in connection with a sensor 10, including 10 or more, 20 or more, 30 or more, 40 or more, 50 or more, 70 or more, 100 or more, 400 or more, 1000 or more, 10,000 or more, 100,000 or more, 500,000 or more or 1,000,000 or more. Very high numbers of resonators 40 can be realized, for example, especially using micro-sensors formed (e.g., micromachined) in a substrate or in a microchip body mounted on a substrate. The number of resonators 40 can vary, therefore, generally ranging for example, from 2 to about one million, and preferably from 2 to about 500,000 or from 2 to about 100,000. In preferred embodiments, the number of resonators can vary from 2 to about 10,000, from 2 to about 1000, from 2 to about 400, from 2 to about 100, from 2 to about 70 or from 2 to about 50. In especially preferred embodiments, the number of resonators can vary from 3 to about 40, from 3 to about 20 or from 3 to about 10.

[0091] The physical spacing of mechanical resonators 40 for a sensor generally likewise depends upon the particular application of interest, and the degree of spatial resolution desired within that application, as well as on the type of mechanical resonators, the size of the mechanical resonators and the number of mechanical resonators being used in connection with a sensor 10. For some applications for example, it may be advantageous to employ micro-resonators with a spacing of not more than about 1 micron, or not more than about 10 microns or not more than about 100 microns or not more than about 1 mm. In more typical applications, it may be advantageous to employ resonators with a spacing of about 1 mm or more, and not more than about 5 mm or not more than about 1 cm, or

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not more than about 5 cm or not more than about 10 cm or not more than about 20 cm or not more than about 40 cm or not more than about 70 cm. For sensors 10 deployed as distributed sensors in a larger fluidic system(s), the spacing between mechanical resonators may be at least or more than about 1 m, and not more than about 2 m or not more than about 4 m or not more than about 10 m. For sensors 10 deployed as expansively distributed sensors in expansive fluidic system(s), the spacing between mechanical resonators may be more than about 10 m, and not more than about 20 m or not more than about 40 m or not more than about 100 m. Larger spacings are of course possible, and within the discretion of the skilled person.

[0092] Each of the aforementioned generally described sensor configurations for the systems and methods of the invention can be applied independently or in combination with each other, in each of the possible various permutations. Also, each of the aforementioned generally preferred approaches can be applied in further combination with more particular aspects, including particular protocols and/or particular systems or sensor features, as described herein.

#### **SENSING, MONITORING AND/OR EVALUATING FLUIDIC SYSTEMS – GENERAL**

[0093] In each of the aforementioned generally preferred approaches and/or embodiments of the methods and sensors and systems of the invention, the sensor(s) can be employed for sensing, monitoring and/or evaluating one or more fluids in one or more fluidic systems.

#### ***Fluids***

[0094] Generally, for example, mechanical resonators such as flexural resonators can be used in connection with liquids or gasses having a wide range of fluid properties, such as a wide range of viscosities, densities and/or dielectric constants (each such property being considered independently or collectively as to two or more thereof). For example, liquid fluids can generally have viscosities ranging from about 0.1 cP to about 100 000 cP, and/or can have densities ranging from about 0.0005 g/cc<sup>3</sup> to about 20 g/cc<sup>3</sup> and/or can have a dielectric constant ranging from about 1 to about 100. Gaseous fluids can, for example, generally have viscosities ranging from about 0.001 to about 0.1 cP, and/or can have densities ranging from about 0.0005 to about 0.1 g/cc<sup>3</sup> and/or can have a dielectric

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constant ranging from about 1 to about 1.1. The fluids can be ionic fluids or nonionic fluids. As an example, ionic fluids can have a conductivity ranging from about 1 Ohm.cm to about 1 GOhm cm. The fluids of the invention can include relatively pure liquid or gaseous elements (*e.g.*, liquid N<sub>2</sub>, gaseous O<sub>2</sub>, gaseous or liquid H<sub>2</sub>) or relatively pure liquid or gaseous compounds (*e.g.*, liquid H<sub>2</sub>O, gaseous CH<sub>4</sub>).

[0095] The fluids of the inventions can also be single-phase or multi-phase mixtures of gases, liquids and/or solids, including for example: mixtures of gasses; mixtures of liquids (*e.g.*, solutions); two-phase mixtures of a first liquid and a second liquid (*e.g.*, liquid-liquid emulsion); two-phase mixtures of liquids and gasses (*e.g.*, a liquid having gas sparging or bubbling, *e.g.*, a liquid nebulized through a gaseous environment); two-phase mixtures of liquids and solids (*e.g.*, colloidal solutions; dispersions; suspensions); two-phase mixtures of solids and gases (*e.g.*, fluidized bed systems); and/or three-phase mixtures of gasses, liquids and solids. Particular examples of preferred fluids are described herein, including in discussion below regarding preferred applications of the methods and devices of the invention. The fluids can be of the same type (*e.g.*, compositionally) and/or can be of a different type (*e.g.*, compositionally). As noted above, the fluids can generally be single phase fluids or multiple-phase fluids such as two-phase fluids. Single-phase fluids can be liquids or gasses. Single-phase fluids can also include single-phases fluids in contact with one or more non-fluidic phases, such as solids – including for example liquid-solid phases (*e.g.*, slurries, suspensions or dispersions of particles within a liquid media, including uniform or non-uniform slurries, suspensions or dispersions of particles within a liquid media), as well as for example gas-solid phases (*e.g.*, uniformly or non-uniformly fluidized particles within a gaseous media, or static particles within a gaseous media). Multiple-phase fluids such as two-phase fluids can include for example, liquid-liquid phases (*e.g.*, liquid-liquid emulsions, liquid-liquid stratified phases), liquid-gas phases (*e.g.*, aerosols, liquid-gas stratified phases) and gas-gas phases (*e.g.*, gas-gas stratified phases).

[0096] In multi-phase fluid systems comprising two or more identifiable fluid phases, the two or more fluid phases can have a fluidic interface separating one fluid phase from another fluid phase. The fluidic interface can have a composition that is detectable different from each of the first phase and the second phases between which it is defined.

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The fluidic interface can be a distinct interface (*e.g.*, comprising a substantial step-change from one phase to the next phase), or a more gradual interface (*e.g.*, comprising a gradient change from one phase to the next phase). Quantitatively, in some embodiments, the fluidic interface can have a substantially narrow volume with respect to the corresponding volumes of the adjacent fluid phases (*e.g.*, preferably not more than about 40%, more preferably not more than about 25% and most preferably not more than about 15%, by volume, relative to the volumes of the adjacent fluid phases).

### ***Operating Conditions***

[0097] The operating conditions of the fluid in the fluidic system is not narrowly critical to the invention. Generally, the fluids within a particular fluidic system and/or fluids in different fluidic systems can have widely varying process conditions, such as temperature, pressure flowrate. Generally, the temperature can range from about or below the freezing point of the fluid to above the vaporization temperature, including for example to superheated temperatures and/or for supercritical fluids. Particular temperature ranges can be preferred for particular fluids. Generally, the pressure within a fluidic system can likewise cover a wide range, including for example ranging from about vacuum conditions to about 25,000 psig. In preferred applications, the pressure can be lower, ranging from vacuum conditions to about 15,000 psig, from vacuum conditions to about 10,000 psig, from vacuum conditions to about 5,000 psig, from vacuum conditions to about 1,000 psig, from vacuum conditions to about 500 psig, or from vacuum conditions to about 100 psig. In an alternative embodiment, the pressure range in each of the aforementioned ranges can have lower pressure limit of about 1 psig or about 10 psig or about 20 psig.

### ***Monitored Property/Properties***

[0098] In the methods and systems and apparatus of the invention, the particular property being monitored is not narrowly critical. In general, the property of interest will depend on the fluid and the significance of the monitoring with respect to a particular fluidic system in a particular commercial application. The property being monitored for a particular fluidic system may also depend to some extent on the type of sensor. Significantly, some properties of fluids (both liquids and gasses) are of general importance across a wide range of commercial applications. For example, the viscosity

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of a fluid is of near universal interest for many fluidic systems. Likewise, the density of a fluid is also of great general interest for many fluidic systems. It is especially advantageous to be able to monitor both viscosity and density of a fluid – based on the same monitoring event (*e.g.*, concurrently or simultaneously, using the same sensing element, on the same fluid sample). Significantly, flexural resonators such as tuning forks, unimorphs (*e.g.*, disc benders), bimorphs, torsional resonators, *etc.* have been demonstrated by Matsiev *et al.* to have the capability of such concurrent or simultaneous monitoring of both viscosity and density. *See Matsiev, "Application of Flexural Mechanical Resonators to Simultaneous Measurements of Liquid Density and Viscosity," IEEE International Ultrasonics Symposium, Oct. 17-20, 1999, Lake Tahoe, Nevada, which is incorporated by reference herein for all purposes, and see also commonly-owned U.S. Patent Nos. 6,401,519; 6,393,895; 6,336,353; 6,182,499; 6,494,079 and EP 0943091 B1, each of which are incorporated by reference herein for all purposes.* Dielectric constant is also a very significant property of interest for many commercial applications – particularly for applications involving ionic liquids. *See Id.* Other properties can also be of interest, alternatively to or in addition to the aforementioned properties. For example, temperature and/or pressure and/or flow rate are similarly of near-universal interest across a wide range of commercial applications. Parallel resistance can also be of interest.

### **Sensors**

[0099] In general, as noted above, the particular sensing element of the sensor of the methods and systems and apparatus of the present invention is not limited. Generally, the sensing elements useful in connection with this invention are adapted to monitor one or more properties of a fluid – that is, to generate data associated with one or more properties of the fluid. The data association with a property in this context means data (typically obtained or collected as a data stream over some time period such as a sensing period), including both raw data (directly sensed data) or processed data, can be directly informative of or related to (*e.g.*, through correlation and/or calibration) an absolute value of a property and/or a relative value of a property (*e.g.*, a change in a property value over time). In many applications, the raw data can be associated to a property of interest using one or more correlations and/or using one or more calibrations. Typically such

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correlations and/or calibrations can be effected electronically using signal processing circuitry, either with user interaction or without user interaction (*e.g.*, automatically).

**[00100]** Particular sensing elements for the sensor 10 can be selected based on needed or desired property (or properties) of interest, and on required specifications as to sensitivity, universality, fluid-compatibility, system-compatibility, as well as on business considerations such as availability, expense, *etc.* Because of the substantial universal nature of viscosity and/or density and/or dielectric properties for many diverse fluidic systems, sensor elements that are suited for monitoring these properties are preferred. There are many sensor elements known in the art for measuring one or more of viscosity, density and/or dielectric. Accordingly, the selection of one or more of such sensor element types is not critical to the invention.

**[00101]** Preferably, the sensor 10 comprises a mechanical resonator sensor. The mechanical resonator can include, for example, flexural resonators, surface acoustic wave resonators, thickness shear mode resonators and the like. Various types of flexural resonators can be employed, including for example tuning forks, cantilevers, bimorphs, unimorphs, membrane resonators, disc benders, torsion resonators, or combinations thereof. Flexural resonator sensing elements comprising tuning fork resonators are particularly preferred. The tuning fork resonator can have two tines (*e.g.*, binary-tined tuning fork) or more than two tines, such as three tines (*e.g.*, a trident tuning fork) or four tines (*e.g.*, a quaternary-tined tuning fork). In some applications, a tuning fork resonator may be configured (*e.g.*, with respect to geometry and electrode configuration) for resonating within a single plane. For some applications, a tuning fork may be may be configured (*e.g.*, with respect to geometry and electrode configuration) for resonating in two or more different planes relative to each other, such as in two planes perpendicular to each other.

**[00102]** Such flexural resonator sensors are well known in the art. *See Matsiev, "Application of Flexural Mechanical Resonators to Simultaneous Measurements of Liquid Density and Viscosity," IEEE International Ultrasonics Symposium, Oct. 17-20, 1999, Lake Tahoe, Nevada, which is incorporated by reference herein for all purposes, and see also commonly-owned U.S. Patent Nos. 6,401,519; 6,393,895; 6,336,353; 6,182,499; 6,494,079 and EP 0943091 B1, each of which are incorporated by reference*

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herein for all purposes. More recent advances include those described in co-pending applications, such as U.S. Ser. No. 10/452,264 entitled "Machine Fluid Sensor And Method" filed on June 2, 2003 by Matsiev *et al.* (co-owned, describing applications involving flexural resonator technologies in machines, such as transportation vehicles); U.S. Ser. No. 60/505,943 entitled "Environmental Control System Fluid Sensing System and Method" filed on September 25, 2003 by Matsiev *et al.* and related PCT Application No. PCT/US03/32983 entitled "Environmental Control System Fluid Sensing System and Method" filed on October 17, 2003 by Matsiev *et al.* (each co-owned, describing applications involving flexural resonator technologies in heating, ventilation, air-conditioning and refrigeration systems and in machines such as engine systems related thereto); US Appl. No. 2002/0178805 A1 (describing applications involving flexural resonator technologies in down-hole oil well applications such as well-logging systems); U.S. Ser. No. 10/804,446 entitled "Mechanical Resonator" filed on March 19, 2004 by Kolosov *et al.* (co-owned, describing various advantageous materials and coatings for flexural resonator sensing elements); U.S. Ser. No. 10/804,379 entitled "Resonator Sensor Assembly" filed on March 19, 2004 by Kolosov *et al.*, and PCT Application. No. PCT/US04/08552 entitled "Resonator Sensor Assembly" filed on March 19, 2004 by Kolosov *et al.* (each co-owned, describing various advantageous packaging approaches for applying flexural resonator technologies); and U.S. Ser. No. 10/394,543 entitled "Application Specific Integrated Circuitry For Controlling Analysis For a Fluid" filed on March 21, 2003 by Kolosov *et al.*, and PCT Application. No. PCT/US04/008555 entitled "Application Specific Integrated Circuitry For Controlling Analysis For a Fluid" filed on March 19, 2004 by Kolosov *et al.* (each co-owned, describing electronics technologies involving application-specific integrated circuit for operating flexural resonator sensing elements), each of which are incorporated herein by reference for all purposes, and each of which includes descriptions of preferred embodiments for flexural resonator sensors and use thereof in connection with the methods and apparatus and systems of the present invention. Further details regarding flexural resonator sensors and/or flexural resonator sensing element are described below, but are generally applicable to each approach and/or embodiment of the inventions disclosed herein.

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[00103] Generally, each of the mechanical resonators 40 of the sensor 10 can comprise one or more sensing surfaces 50 that can be exposed to a fluid during a sensing operation. The sensor can also comprise one or more additional sensing elements 51, and in some embodiments, each of the multiple mechanical resonators 40 can be employed together with corresponding additional sensing elements 51 such as additional temperature sensing elements 51. With reference briefly to Figure 11D, the sensing surfaces 50 of the mechanical resonators 40 can be optionally situated in a sensing element housing 52 such that a sensing surfaces 50 can be exposed to the fluid (e.g., via housing window 54).

[00104] Although much of the description is presented herein in the context of flexural resonator sensors, various aspects of the invention are not limited to such sensors. Hence, other types of sensors (or sensor subassemblies) can also be used in place of mechanical resonators. In addition, other sensors (or sensor subassemblies) can be used in combination with the mechanical resonator sensor or other types of sensors mentioned above. Particularly preferred sensors for use in combination with mechanical resonators, such as flexural resonators, include temperature sensors, pressure sensors, flow sensors, conductivity sensors, thermal conductivity sensors, among others.

#### ***Barrier Interface***

[00105] With further reference to Figure 11D, for example, the installed sensor 10 can also optionally comprise a coupling 60 providing electrical or mechanical access across the fluidic barrier 110. The coupling 60 can comprise a set of conductive paths (not shown) providing electrical communication through the barrier 110 to a signal processing circuit 20 or data retrieval circuit 30, preferably situated on the external side of the barrier 110 of the fluidic system 100 (e.g., mounted on the external side of the coupling 60, as shown).

[00106] As described above, the sensor 10 can be interfaced with the fluidic system(s) across a barrier 110 that defines at least a portion of the fluidic system(s). Preferably, the sensor 10 is interfaced across the barrier without substantially compromising the integrity of the fluid system. With further reference to the various figures discussed above, a sensor 10 can be interfaced with a fluidic system 100 across a barrier 110 using a coupling 60. The coupling 60 can generally be a mechanical

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coupling, an electrical coupling and/or a magnetic coupling. In one approach, the coupling 60 can comprise one or more bodies having a first surface on the internal fluid-side of the barrier 110, and an opposing second surface on the external side of the barrier 110. The body of the coupling 60 can be affixed to (*e.g.*, fixedly mounted on, fixedly attached to) the barrier 110. Alternatively, the body of the coupling 60 can be integrally formed with the barrier 110. The body of the coupling 60 can alternatively be removably engaged with the barrier 110. In any case, the coupling 60. As noted, the coupling 60 can further comprise one or more conductive paths (*e.g.*, wired electrical leads) extending through the body thereof. The one or more conductive paths can each have corresponding end terminals preferably exposed at one or more surfaces of the body, and adapted for providing electrical connection across the barrier 110 between the mechanical resonators 40 (and other sensing element 51) and signal processing circuitry and/or data retrieval circuitry. The terminals can comprise, for example, contact pins or contact pads.

#### ***Sensor Circuitry***

[00107] With reference to Figures 11A through 11D, the sensor 10 further comprises one or both of a signal processing circuit 20 or a data retrieval circuit 30.

[00108] The sensor 10, as shown in Figure 11A, can comprise two or more mechanical resonators 40 (*e.g.*, a flexural resonators) linked by a common communication path 65 to a circuit. The circuit preferably comprises either a signal processing circuit 20 (*e.g.*, comprising amplifier circuitry), or a data retrieval circuit 30 (*e.g.* comprising data memory circuitry, perhaps adapted for recording raw data received from the mechanical resonators 40). In a generally more preferred embodiment the sensor 10 can comprise two or more installed mechanical resonators 40 (*e.g.*, two or more flexural resonators) commonly communicating with both signal processing circuitry 20 and data retrieval circuitry 30.

[00109] Generally, the signal processing circuit 20 can comprise one or more of signal conditioning circuitry 24 and data derivation circuitry 26, separately or in combination. If the mechanical resonators 40 are to be actively stimulated using an electronic stimulus, the signal processing circuit 20 can further comprise optional signal activation circuitry 22.

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[00110] Generally, referring further to Figures 11A and 11B, the signal processing circuit 20 can comprise one or more circuits (or circuit modules) for activating sensing surfaces 50 of mechanical resonators 40 and/or for processing data originating with a sensing surface 50 of a resonator 40. Generally for example, the signal processing circuit can comprise: a signal activation circuit 22 (generally optional, *e.g.*, for providing an electronic stimulus to the sensing element during active sensing, as discussed in more detail below); a signal conditioning circuit 24 for processing data originating from the sensing element (generally preferred, *e.g.* for altering an electronic characteristic of a data signal, typically resulting in a conditioned data or data stream); and/or a data derivation circuit 26 for processing data originating from the sensing element (generally preferred, *e.g.*, for identifying, selecting or interpreting a particular electronic characteristic of a data signal, typically resulting in derived data or data stream that is more closely related to the property (or properties) of interest (*e.g.*, has higher information content and/or greater information value) than a raw data stream and/or a conditioned data or data stream).

[00111] In particular, with further reference to Figures 11C, the signal processing circuit 20 can comprise one or more circuits (or circuit modules) as signal conditioning circuits 24, such as for example: signal input circuitry 24a (*e.g.*, for receiving a response signal from the sensing surface 50 of the resonator 40); amplifying circuitry 24b (*e.g.* including pre-amplifiers and amplifiers, for amplifying a signal); biasing circuitry 24c (*e.g.*, for offsetting or otherwise changing a reference frame relating to the signal, including such as for reducing analog signal offsets in the response signal); converting circuitry 24d (*e.g.*, analog-to-digital (A/D) converting circuitry for digitizing data or a data stream); microprocessor circuitry 24e (*e.g.*, for microprocessing operations involving data originating from the sensing element and/or user-defined data); signal-processing memory 24f (*e.g.*, typically being accessible to one or more signal processing circuits or circuit modules for providing data thereto, such as for example system-specific and/or sensing-element-specific identifying indicia, user-defined data for signal conditioning, *etc.*); and/or signal output circuitry 24g (*e.g.*, for outputting a conditioned signal to another circuit module (*e.g.*, to a data derivation circuit and/or to a data retrieval circuit)).

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[00112] Referring again to Figure 11C, the signal processing circuit 20 can comprise one or more circuits (or circuit modules) as data derivation circuits 26, such as for example: signal input circuitry 26a (*e.g.*, for receiving a response signal from the sensing surface 50 of the resonator 40 or from one or more data conditioning circuits 24); signal detection circuitry 26b (*e.g.*, for identifying and/or detecting one or both of phase data and/or amplitude data and/or frequency data of the response signal); microprocessor circuitry 26c (*e.g.*, for microprocessing operations involving data originating from the sensing element, typically involving a microprocessor configured for processing one or more software operations such as software algorithms or firmware algorithms (*e.g.*, a data-fitting algorithm) for determining a parameter of the fluid that is associated with a property thereof, and/or typically for processing user-defined data (*e.g.*, predefined data and/or substantially concurrently-defined data) in conjunction with the data originating from the sensing element, and/or typically involving user-initiated, user-controllable, and/or user-interactable processing protocols, typically for determining a parameter using a calibration with a fitting algorithm, for determining a parameter using a correlation algorithm, for determining a change in a detected signal characteristic (*e.g.*, frequency, amplitude) or for determining a a determined parameter); signal-processing memory 26d (*e.g.*, typically including electronic data storage media, such as non-volatile memory (*e.g.*, ROM, PROM, EE-PROM, FLASH memory, *etc.*), typically being pre-loaded with and/or being accessible for loading user-defined data (*e.g.*, calibration data, correlation data, data defining approximated fluid properties, system-specific information, sensing-element specific information such as an identifying indicia, and/or typically being accessible to one or more signal processing circuits (or circuit modules) for use thereof; and/or signal output circuitry 26e (*e.g.*, for outputting a conditioned signal to another circuit module (*e.g.*, to a data derivation circuit and/or to a data retrieval circuit).

[00113] The data retrieval circuit 30 can comprise data storage circuitry 32 and/or data display circuitry 24, separately or in combination. The data retrieval circuitry 30 can likewise comprise data transmission circuitry 36.

[00114] The data storage circuitry 32 of the data retrieval circuit can comprise memory for capturing raw data stream or a data stream generated by the signal processing circuit (*e.g.*, a conditioned data stream or a derived data stream). In such a case, in

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operation, collected data residing in the installed memory circuit can be transmitted to and either displayed in or stored in a ported unit, for later collection and/or analysis at a remote data repository. For example, a memory stick (jump drive) can be used to transfer data to a remote data repository.

**[00115]** The data retrieval circuit 30 can comprise (additionally or alternatively to the data storage circuit) data display circuitry 34 such as a light (*e.g.*, an light-emitting diode (LED)) for indicating a status of a fluid under test) or such as a readout (*e.g.*, an LED readout display) or such as a graphical user interface (*e.g.*, computer monitor).

**[00116]** Likewise, in any of the aforementioned and/or following mentioned approaches and embodiments, referring again to 11 A through 11B, the data retrieval circuitry 30 can comprise one or more modules for retrieving data – whether raw data or processed data. Generally, the data retrieval circuit 30 can comprise one or more circuits (or circuit modules), including a data storage circuit 32, a data display circuitry 34 and/or a data transmission circuitry 36. The data retrieval circuit 30 can be in electrical communication with the sensing element directly, or alternatively, via a signal processing circuit 20 that processes (*e.g.*, amplifies, biases, converts, *etc.*) raw data coming from the sensing element.

**[00117]** With further reference to Figures 11C, the data storage circuit 32 can typically comprise: signal input circuitry 32a (*e.g.*, for receiving raw data or a raw data stream from the sensing element, and/or for receiving conditioned data or a conditioned data stream from one or more data conditioning circuits 24, and/or for receiving derived data or a derived data stream from one or more data derivation circuits 26); a data storage media 32b (*e.g.*, such as non-volatile memory (*e.g.*, ROM, PROM, EE-PROM, FLASH memory *etc.*); and, signal output circuitry 32c (*e.g.*, for outputting a stored data or stored data stream to another circuit module (*e.g.*, to a data derivation circuit and/or to a data transmission circuit and/or to a data display circuit).

**[00118]** Data display circuit 34 as shown in Figure 11C can configured to be effective for displaying data associated with one or more properties of a fluid, or for displaying a status of the fluid, where such status is based on data associated with a property of the fluid. Hence, data display circuit 34 can include a display device, and can typically comprise: signal input circuitry 34a (*e.g.*, for receiving raw data or a raw data

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stream from the sensing element, and/or for receiving conditioned data or a conditioned data stream from one or more signal conditioning circuits 24, and/or for receiving derived data or a derived data stream from one or more data derivation circuits 26, and/or for receiving stored data or stored data stream from one or more data storage circuits 32); a data-display memory 34b (*e.g.*, such as non-volatile memory (*e.g.*, ROM, PROM, EEPROM, FLASH memory, *etc.*, or random access memory (RAM), in either case typically for temporarily storing a data or data stream to-be-displayed); a microprocessor circuit 34c (*e.g.*, for processing / modifying data, such as stored, to-be-displayed data); a visual display circuit 34d (*e.g.*, digital computer monitor or screen; *e.g.*, a status light such as a LED status light, *e.g.*, a printer, *e.g.*, an analog meter, *e.g.*, a digital meter, *e.g.*, a printer, *e.g.*, a data-logging display device, *e.g.*, preferably in some embodiments a graphical user interface, *etc.*); and, signal output circuitry 34e (*e.g.*, for outputting a stored data or stored data stream – such as to another circuit module (*e.g.*, to a data derivation circuit and/or to a data transmission circuit and/or to a data display circuit).

[00119] Data transmission circuit 36 as shown in 11 C can be configured to be effective for transmitting data originating from the sensing element. Specifically, for example, the data transmission circuit 36 can include: signal input circuitry 36a (*e.g.*, for receiving raw data or a raw data stream from the sensing element, and/or for receiving conditioned data or a conditioned data stream from one or more data conditioning circuits 24, and/or for receiving derived data or a derived data stream from one or more data derivation circuits 26, and/or for receiving stored data or stored data stream from one or more data storage circuits 32); an optional microprocessor circuit 36b (*e.g.*, for processing / modifying data, such as stored, to-be-transmitted data, and/or for controlling data transmission protocols); transmission protocol circuitry 36c (*e.g.*, for effecting and coordinating communication protocols, such as for example a hard-wired interface circuit (*e.g.*, TCP/IP, 4-20 mA, 0-5V, digital output, *etc.*), or a wireless communication circuit involving an electromagnetic radiation (*e.g.*, such as radio frequency (RF) short range communication protocols (*e.g.*, Bluetooth™, WiFi - IEEE Standard 80211 *et seq.*, radio modem), land-based packet relay protocols, satellite-based packet relay protocols, cellular telephone, fiber optic, microwave, ultra-violet and/or infrared protocols), or a wireless communication circuit involving magnetic fields (*e.g.*, magnetic induction

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circuits); and signal output circuitry 36d (*e.g.*, for outputting a transmission of stored data or stored data stream – such as to another circuit module (*e.g.*, to a data derivation circuit and/or to a data storage circuit and/or to a data display circuit).

**[00120]** Data transmission is particularly preferred using a data transmission circuit 36 in connection with a ported sensor subassembly that comprises a signal-processing memory and the data transmission circuit. Where the signal-processing memory comprises user-defined data, such data can be configured to be accessible to the data transmission circuit for communicating the user-defined data from the ported sensor subassembly to the fluidic system or to a remote data repository. In another preferred approach, the ported sensor subassembly can comprise a data transmission circuit for communicating data associated with one or more properties of the fluid from ported sensor subassembly to the fluidic system or to a remote data repository. In another method, the ported sensor subassembly can comprise a data storage media accessible for storing data associated with one or more properties of the fluid, and in combination therewith, a data transmission circuit for communicating stored data from the data storage media to the fluidic system or to a remote data repository, in either case preferably using a wireless communication protocol.

**[00121]** In any event, preferably, generated data is stored (*e.g.*, in memory), displayed (*e.g.*, in a graphical user interface or other display device) or (meaning additionally or alternatively) transmitted (*e.g.*, using hard-wired or wireless communications protocols) using the data retrieval circuit of the interfaced sensor. Although listed and represented in the figures in a particular (*e.g.*, linear) order, there invention is not limited to use of such circuit modules in any particular order or configuration, and a person of ordinary skill in the art can determine a suitable circuit design for a particular fluidic system and a particular sensor, in view of the general and specific teaching provided herein.

**[00122]** With reference to Figure 11D, illustrating a particularly preferred embodiment, the signal processing circuit 20 includes a signal conditioning circuit 24 that comprises (or in some embodiments consists essentially of) an amplifier circuit comprising one or more amplifiers or one or more preamplifiers, effective for or configured for amplifying one or more input signals received from one or both of the

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mechanical resonator 40 or the additional sensing elements 51. The sensor 10 of this embodiment preferably further comprises at least a data retrieval circuit 30, but most preferably comprises both a signal processing circuit 20 and a data retrieval circuit 30. This embodiment further comprise, an installed memory media, preferably such as a signal-processing memory as an accessible portion of a signal conditioning circuit 24 (not shown) and/or as an accessible portion of a data derivation circuit 26 (as shown) and/or as data storage circuit 32 (not shown). In a preferred approach, for example, the memory media can comprise electronic data storage media, such as non-volatile memory (*e.g.*, ROM, PROM, EE-PROM, FLASH memory *etc.*), and can typically be pre-loaded with and/or accessible for loading user-defined data (*e.g.*, calibration data, correlation data, data defining approximated fluid properties) as well as pre-loaded and/or accessible for loading user defined data that is system-specific information and/or sensing-element specific information, in each case such as an identifying indicia. The signal processing circuit 20 of this embodiment can further comprise (either as installed circuitry or as a ported circuitry subassembly) an optional signal activation circuit 22, a signal conditioning circuit 24 and a data derivation circuit 26, wherein the data derivation circuit 26 comprises microprocessor circuitry 26c configured for processing data originating from the mechanical resonators 40 and/or the additional sensing elements 51 such as additional temperature sensing elements in conjunction with user-defined data (*e.g.*, calibration data) accessible from the installed memory media. The data retrieval circuit 30 of the sensor 10 of this particularly preferred embodiment preferably comprises, at least a data storage circuit 32 and preferably also either or both of a data display circuit 34 or a data transmission circuit 36.

**[00123]** The particular location of the signal processing circuitry 20 and/or data retrieval circuitry 30 of the installed sensor 40 is not critical. In some embodiments (*e.g.*, in applications involving high-temperature and/or flammable fluids), it may be advantageous to provide the preinstalled circuitry 20, 30 external to the fluidic system (*e.g.*, fixedly mounted on a surface of barrier 110 opposing the fluid-side surface of the barrier 110), and in electrical communication with one or more of the resonators 40 of sensor 10. In other embodiments the circuitry 20, 30 can be mounted on the fluid-side surface of the barrier 110.

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### **SENSING OPERATIONS**

[00124] The sensor can be advantageously applied to sense the fluid by collecting data, and typically a data stream that is fluid dependent, and that can be processed to identify and evaluate particular fluid property characteristics. The methods and systems and apparatus of the invention can be used to monitor fluidic systems for various purposes. The inventions can be advantageously used, for example, to monitor fluids in any of the following field applications: materials or process research, materials or process development, materials or process quality assurance (QA), process monitoring / evaluation, process control, and service applications involving any of the foregoing.

[00125] As described above in connection with the generally preferred approaches and systems, the sensor is interfaced with one or more fluidic systems. The sensor is operational for monitoring a property of a fluid within the fluidic system. The fluid property can be monitored in real time, in near real time, or in time-delayed modes of operation. Further details of preferred fluidic systems, fluids, properties, sensors and monitoring, including specific methodology approaches and apparatus features thereof are described herein (above and below), and each of the herein-described details are specifically considered in various combinations and permutations with the generally described aspects in this subsection of the specification.

[00126] In any of the aforementioned and/or following-mentioned approaches and embodiments, the signal processing circuitry can comprise one or more circuit modules for processing data originating from the resonators 40 (generally, directly or indirectly). The signal processing circuitry can comprise each such circuit module alone (*i.e.*, individually) or in various combinations and permutations. The data being processed can be raw data (previously unprocessed data) typically coming either directly from the sensing element or from a data storage media (*i.e.*, data memory circuitry) that captured the data directly from the sensing element. Alternatively, the data being processed by one or more circuit modules of the signal processing circuit can be previously processed data (*e.g.*, from another module thereof).

#### ***Active/Passive Sensing Operations***

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[00127] Regardless of the particular configuration for the interfaced sensor, the fluid is sensed, actively or passively, using the interfaced sensor during a first sensing period to generate data associated with one or more properties of the fluid. In passive sensing mode of operation, the flexural resonator sensing element is displaced by the fluid to generate a signal (*e.g.*, such signal being generated by piezoelectric material of sensing element, with appropriate electrodes), without application of an electronic input stimulus to the flexural resonator. In an active sensing mode of operation, an electronic stimulus (*e.g.*, input signal having a voltage and/or frequency) is provided to the flexural resonator sensing element to initiate (via piezoelectric properties) a mechanical response in the sensing element such that at least a portion of the sensing surface of resonator displaces at least a portion of the fluid. The mechanical response is fluid dependent, and the extent of that dependence can be measured electronically, as is known in the art. With further reference to Figures 11A through 11C, a signal activation circuit 22 can comprise, for an active sensing mode of operation, a signal input circuitry 22a (*e.g.*, for receiving a data or a data stream or instructions on active sensing signals) one or more user-defined or user-selectable signal generators, such as a frequency generator circuitry 22b, and/or such as a voltage spike generator circuitry 22c, and in each case, *e.g.*, for providing an electronic stimulus to the sensing element, in an active sensing configuration; and signal output circuitry 22d.

[00128] In a preferred operation involving an active sensing mode, a stimulus signal (*e.g.*, such as a variable frequency signal or a spike signal) can be intermittently or continuously generated and provided to the sensing element. A property-influenced signal, such as a frequency response, is returned from the sensing element. The return signal (*e.g.*, frequency response) can be conditioned and components of the signal (*e.g.*, frequency response) can be detected. The method can further includes converting the frequency response to digital form, such that the digital form is representative of the frequency response received from the sensing element. Then, first calibration variables can be fetched from a memory. As used herein, the term "fetch" should be understood to include any method or technique used for obtaining data from a memory device. Depending on the particular type of memory, the addressing will be tailored to allow access of the particular stored data of interest. The first calibration variables can define

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physical characteristics of the sensor or sensing element. Second calibration variables can also be fetched from memory. The second calibration variables define characteristics of the sensor or sensing element in a known fluid. The digital form is then processed when the sensing element is in the fluid under-test, and the processing uses the fetched first and second calibration variables to implement a fitting algorithm to produce data that relates to the fluid properties or fluid characteristics of the fluid under-test.

**[00129]** In some embodiments involving an active sensing mode and using a mechanical resonator sensing element (such as a flexural resonator sensing element), it may be preferably to employ an active sensing mode of operation involving an input stimulus signal having a frequency of not more than about 1MHz, and preferably not more than about 500 kHz, and preferably not more than about 200 kHz, and most preferably not more than about 100 kHz. In some embodiments, even lower frequencies can be employed in the operation of the mechanical resonator sensing element, including for example frequencies of not more than about 75 kHz. Specific operational ranges include frequencies ranging from about 1 kHz to about 1MHz, preferably from about 1kHz to about 500 kHz, preferably from about 1kHz to about 200 kHz, preferably from about 1kHz to about 100 kHz, preferably from about 1 kHz to about 75 kHz, more preferably from about 1 kHz to about 50 kHz, more preferably still from about 5 kHz to about 40 kHz, even more preferably from about 10 kHz to about 30 kHz and most preferably from about 20 kHz to about 35 kHz. In such embodiments, it may be preferably to provide an input stimulus signal that has a frequency that varies over time. In such embodiments, it may be preferably to provide two or more cycles of varying a frequency over time over a predetermined range of frequencies, and preferably over a frequency range that includes the resonant frequency for the flexural resonator sensing element. Such frequency sweeping offers operational advantages that are known in the art.

**[00130]** In a preferred operation involving a passive sensing mode, the mechanical resonators such as a flexural resonator, interacts with the fluid to generate a property-influenced signal. The signal from the sensing element is intermittently or continuously observed and/or retrieved by the signal processing circuit. The signal can be conditioned and components of the signal (*e.g.*, frequency response, voltage, *etc.*) can be detected.

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The method can further include converting the response to digital form, such that the digital form is representative of the signal received from the sensor. Then, as above in the active mode, first and/or second calibration variables can be fetched from a memory. The first calibration variables can define physical characteristics of the sensor or sensing element. Second calibration variables can also be fetched from memory. The second calibration variables can define characteristics of the sensor or sensing element in a known fluid. The digital form can then be processed when the sensing element is in the fluid under-test, and the processing uses the fetched first and second calibration variables to implement a fitting algorithm to produce data that relates to the fluid properties or fluid characteristics of the fluid under-test.

[00131] In preferred embodiments, one or more circuit modules of the signal processing circuit and/or the data retrieval circuit can be implemented and realized as an application specific integrated circuit (ASIC). *See*, for example, above-referenced U.S. Ser. No. 10/394,543 entitled "Application Specific Integrated Circuitry For Controlling Analysis For a Fluid" filed on March 21, 2003 by Kolosov *et al.*, and PCT Application No. PCT/US04/008555 entitled "Application Specific Integrated Circuitry For Controlling Analysis For a Fluid" filed on March 19, 2004 by Kolosov *et al.*. Particularly preferred circuit configurations are described below, but should be considered generally applicable to each approach and embodiment of the inventions described herein.

***USER-DEFINED DATA (E.G., CALIBRATION, IDENTIFYING INDICIA)***

[00132] Generally relevant to each of the methods, systems and apparatus of the inventions, user-defined data such as calibration data, correlation data, signal-conditioning data can be employed as part of a signal processing circuit (*e.g.*, signal conditioning and/or data derivation circuitry). Likewise, additionally or alternatively, identifying indicia such as bar-codes, electronic signatures (*e.g.*, 64-bit serial numbers) can be used to identify one or more of: particular fluidic systems, particular locations within a fluidic system; particular fluid types; particular sensors; and/or particular sensing elements (including sensing element types (*e.g.*, tuning fork flexural resonator), sensing element lot numbers for a set of co-manufactured sensing elements, and specific particular individual sensing elements). Such user-defined identifying indicia can be particularly useful in combination with user-defined calibration, correlation and/or signal

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conditioning data since such data can be specific to the fluidic system, the location, the fluid type; the sensor (type or individual sensor) and/or the particular sensing elements (including sensing element types (*e.g.*, tuning fork flexural resonator), sensing element lot numbers for a set of co-manufactured sensing elements, and specific particular individual sensing elements). The user-defined data can be fluid-property (*e.g.*, temperature dependent), and therefore, there can be interaction between one or more sensing elements (*e.g.*, temperature sensing element) and a user-defined data (*e.g.*, calibration data) for a particular fluid in a particular system using a particular resonator. The user-defined data can generally be pre-defined data or can be concurrently-defined data, and the defining can be done by a person and/or by a computer.

**[00133]** The level of specificity of any particular user-defined data to any particular fluidic system, fluid, sensor or sensor element will depend on the particular user-application, the property of interest, the sensor type, the required degree of accuracy, *etc.*

**[00134]** In a preferred methods, apparatus and systems, in which a flexural resonator sensing element is employed alone or in conjunction with one or more other systems, it is preferable to have accessible user-defined calibration data that includes at least (i) flexural resonator sensing element-specific (*e.g.*, calibration) data, as well as (ii) application-specific (*e.g.*, fluid type) data (*e.g.*, calibration data). It is also preferable to have specific user-defined identifying indicia.

**[00135]** In general, there are several approaches for managing a network of interfaced sensors across multiple fluidic systems, where each sensor / system may require its own specific signal conditioning data (*e.g.*, offset information) and/or its own specific user-defined input to a data derivation circuitry (*e.g.* calibration data or correlation data or approximate fluid property values, *etc.*).

**[00136]** In one approach, discussed for example in connection with Figure 11D, each installed sensing element can have a locally installed signal-processing memory module for storing the required user-defined data. A person porting a ported sensor subassembly can then initiate a sensing operation (or retrieve an accumulated or stored data stream) using signal processing circuitry of the ported sensor subassembly. The ported signal processing circuitry can communicate with the locally-installed signal-

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processing memory module to get the user-defined data (*e.g.* calibration data) specific for sensing the fluid at that location of that fluidic system using that particular sensing element.

[00137] In an additional or alternative approach, a signal-processing memory module for storing user-defined data for data derivation can be included within the ported sensor subassembly. In some embodiments, the data can be a standard data set with a set of varying corrections for particular sensors or fluids or fluid conditions. Some sort of identifying indicia is preferably available at the site of the interfaced sensor for identifying it with particularity. In this instance, a person porting a ported sensor subassembly can then initiate a sensing operation (or retrieve an accumulated or stored data stream) by first interrogating (querying) the identifying indicia, and then using the read identifying indicia within the ported sensor subassembly to obtain the relevant user-defined data set for the fluid at that location of that fluidic system using that particular sensing element.

[00138] Other variations on this approach can likewise be beneficially applied.

#### SENSORS HAVING FLEXURAL RESONATOR SENSING ELEMENTS AND OPERATION THEREOF

[00139] As seen in FIG. 12A, one embodiment involves the incorporation of a sensor 10 according to the present invention into a fluidic system 1000, such as an environmental control system, that includes one or more unit operation devices 1020, 1040, 1060 such as a compressor, an expansion valve, a condenser and an evaporator through which a thermal change fluid can be cycled via one or more passages, such as in a conduit. Other components may also be employed as desired, such as one or more suitable pumps, a filter, a dryer, a suitable flow cell, or a combination of two or more thereof. Likewise, any of the above components may be omitted from a system of the present invention. Suitable valving and process monitoring instrumentation may also be employed in the fluidic system 1000.

[00140] One or more of the sensors 10 according to the present invention is adapted for permanent or temporary placement with multiple resonators 40 positioned within one of the system components or between one of the system components. For

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example one or more resonators 40 may be situated between various unit operation devices 1020, 1040, 1060. Likewise, one or more resonators 40 may additionally or alternatively be incorporated in another component, such as a conduit, coil, filter, nozzle, dryer, pump, valve or other component, or positioned upstream or downstream therefrom. The resonators may be located in the flow path of the fluid (e.g., in a conduit), a headspace or both. In a particular embodiment, the sensor resonators 40 are included along with (and optionally integrated therewith) a condition monitoring device such as a temperature measurement device, a pressure measurement device, a mass flow meter, or combinations of two or more of such devices. Without limitation, an example of a combined pressure and temperature sensor is discussed in U.S. Patent No. 5,586,445 (incorporated by reference).

**[00141]** Sensing in accordance with the present invention is particularly attractive for evaluating one or more of properties of the fluid, such as the level of a fluid (e.g., indicative of a system leak, a blockage in the system, or the like), the superheat condition of a fluid (e.g., the level of superheat), subcooling of a fluid, concentration of a desired component (e.g., refrigerant) in the fluid, or the presence or absence or concentration of an undesired component (e.g., contaminants) in the fluid. In particular, the sensor is effectively employed to monitor (continuously or periodically) small changes in conditions of the fluid, such as viscosity, density, viscosity/density product, dielectric constant, conductivity or combinations of two or more thereof, which are indicative of a change of one or more of the above-noted properties, or of a change in state of the fluid or the presence of contaminants, and to output the results thereof.

**[00142]** Optionally, the mechanical resonators can be in signaling communication with a processing unit 1100 (which may include a user interface) for controlling operation of the fluidic system. The processing unit 1100 may be microprocessor integrated with the sensor 10, for example, as part of the signal processing circuitry as described above. The processing unit 1100 optionally can optionally also be in signaling communication with a condition monitoring device 1120 (shown as part of an integrated assembly with the sensor 10). Thus, data obtained from the sensor 10 may be processed along with other data to assist in monitoring and establishing operating conditions of the fluidic system.

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[00143] Thus, for example, in one aspect of the present embodiment, the sensor 10 according to the present invention is employed to monitor at least one property of a fluid (e.g., the simultaneous monitoring of viscosity and density). Data generated from the sensor, along with other data (e.g., temperature, pressure, flow rate, or combinations thereof), for example, from the condition monitoring device 1120, can be sent to the processing unit 1100. From the data provided, the processing unit 1110, which typically will be programmed with a suitable algorithm, will process the data. In a process control embodiment, the processing unit can effect least one operation of the fluidic system selected from switching a subsystem of the fluidic system (e.g., a unit operation device 1020, 1040, 1060) or one or more components thereof between an "on" or "off" state, shutting or opening a valve in the fluidic system, changing a flow rate of the fluid, changing a pressure of the fluid, changing the operating speed or condition of one or more components of the fluidic system, or otherwise controlling operation of the fluidic system or a component thereof, providing a visual output signal, providing an audible output signal, or a combination thereof.

[00144] It will be appreciated that the above configuration of FIG. 12A permits the use of one or more modes of active sensing operations, such as excitation at one or more frequencies around resonance frequency of the resonator, or the time decay of oscillation after an electrical or mechanical impulse (e.g., a voltage spike). Passive operations can include, for example, observing passive oscillations due to ambient noise, vibrations, electromagnetic interference, *etc.*

[00145] The monitoring of fluid properties according to the invention may be performed under normal operating conditions of the machine into which the present sensor is placed. The present invention is particularly advantageous in that it operable over a broad range of temperatures. Thus, in one specific aspect, it is contemplated that the monitoring step occurs at a temperature below  $-40^{\circ}\text{C}$  or possibly the monitoring step occurs at a temperature above  $400^{\circ}\text{C}$ . Generally the monitoring will occur between these extremes.

It is also possible that during or following monitoring, the response of the sensor is compared against another value, such as a prior response of the resonator, a response of another resonator located elsewhere in the system, a known reference value for the fluid,

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or a combination of two or more such comparisons. The observed response may be stored in memory or otherwise recorded. It may also be possible to have data about a particular fluid stored in memory of a suitable processor, which can be retrieved in response to a triggering event, such as inputting by a technician or reading of a fluid type by an optical detector, such as a bar code scanner.

**[00146]** As the fluid property changes over time, analysis can be made and the response compared with those of the fresh fluid. The identification of a difference between responses could then be used as a trigger or other output signal for communicating with diagnostics hardware, which would provide an audible or visual signal to the operator. It is also possible that a signal is outputted to a remote telemetry device, such as one located external of the system. Thus, as with any of the embodiments herein a "wireless" communications system might be employed, pursuant to which a signal that is outputted may be a radiofrequency signal or another electromagnetic signal. Comparison against reference values from the original fluid is not the only approach for generating a communication to a user about the fluid condition. It may be possible, for example, to pre-program certain expected values into a device, which then compares the real-time values obtained. Moreover, it is possible that no comparisons are made, but rather upon obtaining a certain threshold response, an output signal is generated for triggering a user notification, for triggering a system control unit to alter one or more functions of the system or a combination thereof. It is also contemplated that a sensor in a controlled fluid sample may be employed as an internal reference.

**[00147]** It is also possible that the response obtained from the monitoring is stored in a memory, with or without communicating the response to the user. In this manner, a service technician can later retrieve the data for analysis.

**[00148]** Turning now to Figure 12B there is shown an illustration of one preferred resonator element 1140 in accordance with the present invention. The resonator element 1140 preferably includes a base 1160 that has at least two tines 1180 having tips 1200 that project from the base. The shape of the tines and their orientation relative to each other on the base may vary depending upon the particular needs of an application. For example, in one embodiment, the tines 1180 are generally parallel to each other. In another embodiment the tines diverge away from each other as the tips are approached. In

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yet another embodiment, the tines converge toward each other. The tines may be generally straight, curved, or a combination thereof. They may be of constant cross sectional thickness, of varying thickness progressing along the length of the tine, or a combination thereof.

**[00149]** Resonator sensing element(s) are suitably positioned in an element holder. Alternatively, the elements (with or without a holder) may be securably attached to a wall or barrier or other surface defining one of the fluidic systems or passages into which it is placed. In yet another embodiment, the element is suitably suspended within a passage such as by a wire, screen, or other suitable structure.

**[00150]** Element holders may partially or fully surround the sensing elements as desired. Suitable protective shields, baffles, sheath or the like may also be employed, as desired, for protection of the elements from sudden changes in fluid flow rate, pressure or velocity, electrical or mechanical bombardment or the like to help locate an element relative to a fluid or combinations thereof. It should be appreciated that resonator elements may be fabricated from suitable materials or in a suitable manner such that may be employed to be re-useable or disposable.

**[00151]** Examples of approaches to materials combinations, or the packaging of sensing elements that may be employed in accordance with the present invention are disclosed, without limitation in commonly-owned U.S. Provisional Application Serial Nos. 60/456,767 and 60/456,517 (both filed March 21, 2003) (and incorporated by reference). Thus, one particular approach contemplates affixing a sensing element having a exposed sensing surface to a platform, wherein a spaced relationship is created between the exposed sensing surface and the platform. A suitable protective layer may be applied to cover the platform and/or the sensing element while maintaining an exposed sensing surface. The latter exposed sensing surface may be prepared by the use of a consumable protective layer (e.g., a polymer, starch, wax, salt or other dissolvable crystal, low melting point metal, a photoresist, or another sacrificial material) that is used to block the exposed sensing surface prior to applying the protective layer.

**[00152]** A plurality of the same type or different types of resonators of resonators can be used in combination. For example, a low frequency resonator may be employed

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with a high frequency resonator. In this manner, it may be possible to obtain a wider range of responses for a given sample.

**[00153]** The size of the sensing elements, especially mechanical resonator sensing elements such as flexural resonator sensing elements is not critical to the invention. In some applications, however, it should be appreciated that one advantage of the present invention is the ability to fabricate a very small sensor using the present resonators. For example, one preferred resonator has its largest dimension smaller than about 2 cm, and more preferably smaller than about 1 cm. One resonator has length and width dimensions of about 3 mm by 8 mm, and possibly as small as about 1 mm by 2.5 mm. Geometry of the resonator may be varied as desired also. For example, the aspect ratio of tines of the tuning forks, or geometrical factors of other resonators can be optimized in order to achieve better sensitivity to the properties of the gas phase, liquid phase or its particular components (e.g., a lubricant). For example, the aspect ratio of a tuning fork tine may range from about 30:1 to about 1:1. More specifically, it may range from about 15:1 to about 2:1.

**[00154]** It is thus seen that a preferred resonator is configured for movement of a body through a fluid. Thus, for example, as seen in FIG. 12B, the resonator may have a base and one or a plurality of tines projecting from the base. It is preferred in one aspect that any tine has at least one free tip that is capable of displacement in a fluid relative to the base. FIG. 12C illustrates a cantilever 1220 having a base 1240 and a free tip 1260. Other possible structures, seen in FIGS. 12D and 12E contemplate having a disk 1280, a plate 1300 or the like that is adapted so that one portion of it is displaceable relative to one or more variable or fixed locations 1320 (1320'). As seen in Fig. 12F, in yet another embodiment a resonator 1340 is contemplated in which a shear surface 1360 of the resonator has one or more projections 1380 of a suitable configuration, in order that the resonator may be operated in shear while still functioning consistent with the flexural or torsional resonators of the present invention, by passing the projections through a fluid.

**[00155]** In still other embodiments, and referring to Fig. 12G, 12H and 12I, it is contemplated that a resonator 2000 may include an elongated member 2020 supported on its sides 2040 by a pair of arms 2060. As shown respectively in Figs. 12G through 12I,

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the elongated member may be configured to oscillate side-to-side, back and forth, in twisting motions or combinations thereof.

[00156] The flexural resonator, such as the embodiment of FIG. 12B, may be constructed as a monolithic device. Yet another structure of the present invention contemplates the employment of a laminate or other multi-layer body that employs dissimilar materials in each of at least a first layer and a second layer, or a laminate comprised of layers of piezoelectric material of different orientations or configurations. According to this approach, upon subjecting one or more of the layers to a stimulus such as temperature change, an electrical signal or other stimulus, one of the materials will respond different than the other and the differences in responses will, in turn, result in the flexure of the resonator. In yet another embodiment, it is contemplated that plural resonators can be assembled together with an electrode at least partially sandwiched therebetween. In this manner, it may be possible to further protect electrodes from harsh conditions, while still achieving the desired flexure. One specific example might include a two or more lithium niobate or quartz tuning forks joined together with a gold electrode therebetween. Other configurations (e.g., an H-shaped resonator) and material combinations may be employed as well, as disclosed in U.S. Provisional Application Serial Nos. 60/456,767 and 60/456,517 (both filed March 21, 2003), incorporated by reference.

[00157] As can be seen, the selection of the specific resonator material, structure, or other characteristic will likely vary depending upon the specific intended application. Nonetheless, it is preferred that for each application, the resonator is such that one or a combination of the following features (and in one highly preferred embodiment, a combination of all features) is present: a coating, if placed upon the resonator in a thickness greater than about 0.1 micron, will not substantially detract from resonance performance; the resonator is operable and is operated at a frequency of less than about 1 MHz, and more preferably less than about 100 kHz; the resonator is substantially resistant to contaminants proximate to the sensor surface; the resonator operates to displace at least a portion of its body through a fluid; or the resonator responses are capable of deconvolution for measuring one or more individual properties of density, viscosity, viscosity/density product, conductivity or dielectric constant.

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**[00158]** The resonator may be uncoated or coated or otherwise surface treated over some or all of its exterior surface. A preferred coating is a metal (e.g., a conductive metal similar to what may be employed for electrodes for the sensor, such as silver, gold, copper, aluminum or the like), plastic, ceramic or composite thereof, in which the coating material is substantially resistant to degradation from the fluid to which it is to be exposed or to surface build-up, over a broad temperature range. For example, one preferred embodiment, contemplates the employment of a base resonator material and a performance-tuning material. Among the preferred characteristics of the resonators of the present invention is the base material is generally thermally stable. For example, in one preferred embodiment, the material exhibits a dielectric constant that is substantially constant over a temperature range of about 0°C to about 100°C, more preferably about -20°C to about 150°C, and still more preferably about -40°C to about 200°C. For example, it is contemplated that a preferred material exhibits stability to a temperature of at least about 300°C, and more preferably at least about 450°C. In another aspect, the dielectric constant of the performance-tuning material preferably is greater than that of quartz alone, such as by a factor of 5 or more, more preferably by a factor of 10 or more and still more preferably by a factor of 20 or more.

**[00159]** Figure 13A illustrates a circuit diagram 11220 for a tuning fork equivalent circuit 11222 and a read-out input impedance circuit 11224. The frequency generator is coupled to the tuning fork equivalent circuit 11222 to a parallel connection of a capacitance  $C_p$  as well as a series connection of a capacitor  $C_s$ , a resistor  $R_o$ , an inductor  $L_o$ , and an equivalent impedance  $Z(\omega)$ . The read-out impedance circuit includes a parallel resistor  $R_{in}$  and a capacitor  $C_{in}$ . The output voltage is thus represented as  $V_{out}$ .

**[00160]** The equations shown in Figure 13B can define the equivalent circuit. In equation (2), the  $V_{out}$  of the equivalent circuit is defined. In equations (3) and (4), the impedance  $Z_{in}$  and  $Z_{tf}$  are derived. Equation (5) illustrates the resulting impedance over frequency  $Z(\omega)$ . As can be appreciated, the voltage  $V_{out}$ , graphed verses the frequency  $Z(\omega)$ , necessitates the determination of several variables.

**[00161]** The variables are defined in equation (1) of Figure 13B. In operation, the tuning fork's frequency response near the resonance is used to determine the variables that will define the characteristics of the fluid-under-test. The algorithm that will be used

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to determine the target fluid under-test characteristic parameters will require knowledge of data obtained during calibration of a tuning fork. In addition to access to calibration data, the algorithm will also utilize a data fitting process to merge approximated variables of the target fluid under-test, to the actual variable characteristics (i.e., density, viscosity, dielectric constant) for the fluid under-test.

[00162] In the circuit, it is assumed that  $C_s$ ,  $R_o$ ,  $L_o$  are equivalent characteristics of a preferred resonator in a vacuum,  $C_p$  is the equivalent parallel capacitance in a particular fluid under-test,  $\rho$  is the fluid density,  $\eta$  is fluid viscosity,  $\omega$  is oscillation frequency.  $C_p$  is a function of  $k$ , as shown in equations (6) through (10). The constant "k" is, in one embodiment, a function of the tuning fork's geometry, and in one embodiment, defines the slope of a curve plotting ( $C_{p\text{measured}}$ ,  $C_{p\text{cal}}$ , and  $C_{p\text{vacuum}}$ ) verses ( $\epsilon_{\text{measured}}$ ,  $\epsilon_{\text{cal}}$ , and  $\epsilon_{\text{vacuum}}$ ), respectively. In a physical sense, the constant "k" is a function of the tuning fork's geometry, the geometry of the tuning fork's electrode geometry, the tuning fork's packaging (e.g., holder) geometry, the material properties of the tuning fork, or a combination of any of the above factors. The resulting value of  $C_p$  will be used to determine the dielectric constant  $\epsilon$  as shown by the equations.

[00163] Further, it can be appreciated that that viscosity and density can be de-convoluted based on the equations defined in Figure 13C. For some sensors, the value of  $C_{p\text{measured}}$  is typically on the order of about 1 to 3 orders of magnitude greater than the value of  $C_s$ . Accordingly, in order to improve the ability to measure  $Z(\omega)$ , desirably trimming circuitry is employed as part of or in association with the signal conditioner, such as a trimming circuits. In order to more efficiently process the signal being received from the tuning fork, the signal 232 is signal conditioned to eliminate or reduce the signal offset and thus, increase the dynamic range of the signal produced by the tuning fork. Thus, the data being analyzed can be more accurately processed.

[00164] Figures 14A through 14C and 15A through 15D represent one set of preferred approaches and embodiments for realizing a signal processing circuitry for a flexural resonator sensor. In particular, the described approaches and embodiments are considered in the context of an interfaced sensor applied with a fluidic system within an engine, and in particular, in combination with an engine control unit (ECU), which directs overall control of multiple aspects of engine operation. This should be understood

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as being an example demonstrating an application and manner of realizing the present inventions, and should not be limiting on the inventions described herein.

**[00165]** Figure 14A illustrates a block diagram of the circuit formed, for example, in an application specific integrated circuit (ASIC) 11118 and its components, as an example of a signal processing circuit. The ASIC 11118 is designed to provide stimulus to the tuning fork 116 and receive and process data to provide information regarding the characteristics of a fluid under-test. In one embodiment, the ASIC will include a frequency generator 11130 that is configured to provide a frequency stimulus to the tuning fork 11116 by way of communication line 11156. The generated frequency is preferably a variable frequency input signal, such as a sinusoidal wave or square wave, that sweeps over a predetermined frequency range. The sweeping range will preferably include the resonance frequency range of the sensor. Preferably, the frequency is less than 100 kHz, and more preferably, is in the range of about 5 kHz and about 50 kHz, and most preferably, is in the range of about 20 kHz to about 35 kHz.

**[00166]** The tuning fork response over the frequency range is then monitored to determine the physical and electrical properties of the fluid under-test. The response from the tuning fork 11116 is provided to a signal conditioning circuitry block 11132, by way of a communication line 11158. In one preferred embodiment, the tuning fork 11116 will also include a capacitor 11316, which will be described in greater detail below. The capacitor 11316 is also coupled to the signal conditioning circuitry 11132. The signal conditioning circuitry 11132 is provided to receive the analog form of the signal from the tuning fork 11116 and condition it so that more efficient signal processing may be performed before further processing.

**[00167]** The signal conditioning circuitry 11132 will receive the analog output from the tuning fork 11116, and is designed to substantially eliminate or reduce signal offsets, thus increasing the dynamic range of the signal that is to be further processed. In this manner, further processing can concentrate on the signal itself as opposed to data associated with the signal offset.

**[00168]** Signal detection circuitry (SDC) 11134 is also provided, and it is coupled to the signal conditioning circuitry 11132. Signal detection circuitry 11134 will include, in one embodiment, a root mean squared (RMS) to DC converter, that is designed to

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generate a DC output (i.e., amplitude only) equal to the RMS value of any input received from the signal conditioning circuitry 11132. The functional operation of a RMS-to-DC converter is well known to those skilled in the art. In another embodiment, the signal detection circuitry 11134 may be provided in the form of a synchronous detector. As is well known, synchronous detectors are designed to identify a signal's phase and amplitude when preprocessing of an analog signal is desired in order to convert the analog signal into digital form. Once the signal detection circuitry block 11134 processes the signal received from the signal conditioning circuitry 11132, the signal detection circuitry 11134 will pass the data to an analog-to-digital converter (ADC) 11136. The analog-to-digital converter 11136 will preferably operate at a sampling rate of up to 10 kHz while using a 10-bit resolution. The analog-to-digital converter (ADC) can, of course, take on any sampling rate and provide any bit resolution desired so long as the data received from the signal detection circuitry is processed into digital form.

[00169] The ADC 11136 will also receive information from the temperature sensor 11117 to make adjustments to the conversion from the analog form to the digital form in view of the actual temperature in the fluid under-test 11114. In an alternative embodiment, the temperature sensor 11117 can be omitted, however, the temperature sensor 11117 will assist in providing data that will expedite the processing by the ASIC 11118.

[00170] The digital signal provided by the analog-to-digital converter 11136 is then forwarded to a digital processor 11138. The digital processor 11138 is coupled to memory storage 11140 by way of a data bus 11150 and a logic bus 11152. Logic bus 11152 is also shown connected to each of the frequency generator 11130, the signal conditioning circuitry 11132, the signal detection circuitry 11134, and the analog-to-digital converter 11136. A digital logic control 11142 is directly coupled to the logic bus 11152. The digital logic control 11142 will thus communicate with each of the blocks of the ASIC 11118 to synchronize when operation should take place by each one of the blocks. Returning to the digital processor 11138, the digital processor 11138 will receive the sensed data from the tuning fork 11116 in digital form, and then apply an algorithm to identify characteristics of the fluid under-test 11114.

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[00171] The algorithm is designed to quickly identify variables that are unknown in the fluid under-test. The unknown variables may include, for example, density, viscosity, the dielectric constant, and other variables (if needed, and depending on the fluid). Further, depending on the fluid under-test 11114 being examined, the memory storage 11140 will have a database of known variables for specific calibrated tuning forks. In one embodiment, the memory storage 11140 may also hold variables for approximation of variables associated with particular fluids. In another embodiment, the memory storage 11140 will store serial numbers (or some type of identifier) to allow particular sets of data to be associated with particular tuning forks. In such a serial number configuration, the storage memory can hold unique data sets for a multitude of unique tuning forks. When a tuning fork is sold, for example, the purchaser need only input its assigned serial number into an interface, and the data set associated for that tuning fork will be used during operation. From time to time, it may be necessary to upload additional data sets to the storage memory 11140, as new tuning forks (with unique serial numbers) are manufactured.

[00172] The process for using variable data from prior calibrations and from fluids that may closely resemble the fluid under-test, will be described in greater detail below. In general, however, the digital processor 11138 may quickly access the data from the memory storage 11140, and digitally process an algorithm that will generate and output variables that define the fluid under-test 11114.

[00173] The digital processor will then communicate through the digital logic control 11142 and communication line 11154, the identified variables that characterize the fluid under-test 11114 to the local machine electronics 11120 (or some recipient computer, either locally or over a network). In one embodiment, the local machine electronics 11120 will include an engine control unit (ECU) 11121, that directly receives the data from the digital logic control 11142 through signal 11154. The engine control unit 11121 will then receive that data and, in accordance with its programmed routines, provide feedback to the local machine user interface 11122.

[00174] For example, the engine control unit 11121, may set a different threshold for when the fluid under-test 11114 (*i.e.*, engine oil), has degraded. For example, different car manufacturers, and therefore, different engine control units for each car will

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define a particular viscosity, density and dielectric constant (or one or a combination thereof) that may be indicative of a need to change the oil. However, this programmable threshold level setting will differ among cars. Thus, the engine control unit 11121 will provide the local machine user interface 11122 the appropriate signals depending on the programming of the particular automobile or engine in which the engine control unit 11121 is resident.

[00175] The ASIC 11118 has been shown to include a number of component blocks, however, it should be understood that not all components need be included in the ASIC as will be discussed below. In this example, the digital processor 11138 may be physically outside of the ASIC 11118, and represented in terms of a general processor. If the digital processor 11138 is located outside of the ASIC 11118, the digital logic control 142 will take the form of glue logic that will be able to communicate between the digital processor 11138 that is located outside of the ASIC 11118, and the remaining components within the ASIC 11118. In the automobile example, if the processor 11138 is outside of the ASIC, the processor will still be in communication with the engine control unit 11121.

[00176] Figure 14B illustrates an example when the digital processor 11138 is outside of the ASIC 11118. In such an embodiment, the digital processor 11138 may be integrated into a printed circuit board that is alongside of the ASIC 11118, or on a separate printed circuit board. In either case, the ASIC 11118 will be in communication with the tuning fork 11116 to provide stimulus and to process the received analog signals from the tuning fork 11116. The ASIC will therefore convert the analog signals coming from the tuning fork 11116 and convert them to a digital form before being passed to the digital processor 11138.

[00177] If the ASIC 11118 is provided on an automobile, and the digital processor 138 is outside of the ASIC 11118, the digital processor 11138 will still be able to communicate with the engine control unit 11121 of the local machine electronics 11120. The engine control unit 11121 will therefore communicate with the local machine user interface 11122. In this example, the user interface may include a user display 11122b. The user display 11122b may include analog and digital indicators 11122d. The analog and digital indicators 11122d may indicate the qualities of the fluid under-test (e.g.,

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engine oil), and can be displayed in terms of a gauge reading to indicate to the user when the fluid under-test has degraded or needs to be changed.

**[00178]** In another embodiment, the user display 11122b may include a digital display 11122c (e.g., monitor) that may provide a digital output or display of the condition of the engine oil to the user through an appropriate graphical user interface (GUI). The user interface 11122 may also include a user input 11122a. The user input 11122a may be an electronic interface that would allow a service technician, for example, to provide updated calibration information for a tuning fork that is inserted in a particular vehicle, or provide adjusted approximations for new engine oils that may just have come onto the market.

**[00179]** By way of the user input 11122a, a service technician will be able to input new data to the ASIC 11118 through the engine control unit 11121. As mentioned above, the ASIC 11118 will include a memory storage 11140 for storing calibration data, and in some embodiments, storing approximated characteristics for fluids that may undergo sensing by tuning fork 11116.

**[00180]** Figure 14C illustrates another detailed block diagram of the ASIC 11118, in accordance with one embodiment of the present invention. In this example, the ASIC 11118 shows a number of blocks that may be integrated into or kept out of, the ASIC 11118. Blocks that may be kept outside of the ASIC include blocks 11175. As a high level diagram, the tuning fork 11116 is connected to an analog I/O 11160. The analog I/O is representative of blocks 11132, 11134, and 11136, in Figure 9A above. The analog I/O block 11160 therefore performs signal conditioning and conversion of the data received from the tuning fork 11116.

**[00181]** Frequency generator 11130, as discussed above, will provide the variable frequency input signal to the tuning fork 11116 through the analog I/O 160. Glue logic 11162 is provided to integrate together the various circuit blocks that will reside on the ASIC 11118. As is well known, glue logic will include signaling lines, interfacing signals, timing signals, and any other circuitry that is needed to provide inputs and outputs to and from the chip that defines the ASIC 11118. All such glue logic is standard and is well known in the art. The ASIC 11118 further includes user defined data (ROM) 11140'. As mentioned above, the user-defined data 11140' may include calibration data,

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as well as approximated variable data for particular fluids that may become fluids under-test. The user defined data to be stored in this memory can come from any source. For example, the data may be obtained from a fluid manufacturer, a tuning fork manufacturer, a contractor party, etc. Still further, the data may be obtained in the form of a data stream, a database or over a network.

[00182] For example, Figures 14D and 14E provide exemplary data that may be stored within the user-defined data 11140'. As shown in Figure 9D, a tuning fork 1.1 (designated as such to emphasize varieties in tuning forks) may provide calibration variables, as well as approximated fluid characteristics for a particular type of fluid. In the example of Figure 14D, the selected oil type 3 has approximated fluid characteristics for density, viscosity, and dielectric constant for a particular temperature, which is depicted in this figure to be 25° C. As used herein, the term "approximated fluid characteristics" represent starting point values of fluid characteristics before the fitting algorithm is started. Thus, the starting point values are initial values defined from experience, previous tests, or educated guesses. Consequently, the starting point values, in one embodiment, approximate the actual fluid characteristic values of the fluid under-test. In this manner, convergence to the actual fluid characteristics can be expedited.

[00183] In still another embodiment, it may be possible to start with the approximated fluid characteristics at some set of fixed values (which can be zero, for example). From each fixed value, the fitting algorithm can move the value until the actual fluid characteristic value is ascertained.

[00184] Continuing with the example, the approximated fluid characteristics for the same oil type 3 may have different approximated fluid characteristics due to the rise in temperature to 40° C, in Figure 14E. The calibration variables will also be updated to reflect the values for a particular temperature for the tuning fork 1.1. As new oil types become available to the market, it may be necessary to update the approximated fluid characteristics for the different temperature ranges so that the user-defined data can be updated in the ASIC 11118.

[00185] Referring back to Figure 14C, a digital I/O 11140' is provided to interface with a computer 11123, and a test I/O interface 11164 is provided to enable testing of the ASIC 11118 during design simulation, during test bench testing, during pre-market

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release, and during field operation. The ASIC 11118 will also include a timer 11172 to provide coherent operation of the logic blocks contained in ASIC 11118. As mentioned above, the ROM block 11166, the RAM block 11168, the CPU core 11170, and the clock 11174, can optionally be included in the ASIC 11118 or removed and integrated outside of the ASIC 11118. The ROM 11166 will include programming instructions for circuit interfaces and functionality of the ASIC 11118, the RAM 11168 will provide the CPU core 11170 with memory space to read and write data being processed by the CPU core 11170, and the clock 11174 will provide the ASIC with proper signal alignment for the various signals being processed by the blocks of the ASIC 11118.

[00186] Figures 15A through 15D depict alternative configurations for various circuit modules of the ASIC 11118.

#### **DOWNSTREAM DATA PROCESSING**

[00187] The methods and systems and apparatus of the invention can be used as described herein to monitor fluids in fluidic systems to generate data associated with one or more properties of the fluids. The data generated can be used directly, for example, as described herein for status evaluation, fluid property logging, fluid property tracking, *etc.*, among other uses. Such data can also be subsequently further processed for further subsequent uses (*i.e.*, downstream) for various purposes. Such downstream processing of the data or data stream (represented for example by a signal or signal stream), typically but not necessarily in connection with other data from other independent sources, can be effectively applied to generate higher level information or knowledge based on the directly generated data, for example for purposes such as one or more of: process monitoring, process control (*e.g.*, involving automated or manual control schemes, such as feedback or feed forward control schemes), fluid maintenance (*e.g.*, fluid replacement (whole or partial), fluid enhancement (*e.g.*, adding one more additives or removing one or more contaminants), fluid operating conditions (*e.g.*, temperature, pressure, flowrate, *etc.*), predictive maintenance, materials or process research, materials or process development, quality control, fluid analysis, and especially maintenance or service applications involving any of the foregoing, among others.

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#### SPECIFIC END-USE APPLICATIONS

[00188] The methods and systems and apparatus of the invention can be used to monitor fluidic systems for various purposes. The inventions can be advantageously used, for example, to monitor fluids in any of the field applications and/or fluidic systems and/or fluid types as shown in Figures 16A through 16C.

[00189] Particularly preferred applications involve heating, ventilating, air conditioning and refrigeration (HVAC&R) applications. In these applications, the fluidic systems can include circulating fluids such as circulating refrigerants, circulating coolants, circulating lubricants and circulating oils. In general, many fluids used in HVAC&R fluidic systems can be collectively referred to as thermal change fluids – fluids which have a thermal property change within the fluidic system, for example, typically within each cycle of a fluidic system, including for example, changes due to one or more unit operations (*e.g.*, fluid compression, fluid expansion, heat transfer, *etc.*). Hence, a thermal change fluid can include: refrigerants, coolants, lubricants, oils and mixtures thereof. For example, coolant being compressed in an HVAC&R fluidic system can include compressor lubricant or oil. Also, the engines driving such compressors or other device can have their own isolated fluidic systems (*e.g.*, circulating oil fluidic system).

[00190] Transportation vehicles are also particularly preferred.

[00191] Fluidic systems in heavy machinery, such as engines and compressors are also particularly preferred.

[00192] Fluidic systems involving heat-sensitive fluids (*e.g.*, cryogenic fluids), or fluid systems involving ignitable fluids (*e.g.*, flammable fluids) are likewise advantaged by the systems and methods of the invention.

#### EXAMPLES

[00193] Experiments employing the methods and systems of the invention were performed for measuring the level of liquid hexane in a container. Five quartz tuning fork resonators, each originally having a mean frequency approximately around 31 kHz were modified with respect to resonance frequency by trimming the tuning fork tines using sandpaper. The modified tuning forks had resonance frequencies varying by about

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100 – 200 Hz. Each of the tuning forks was connected in parallel to two conductive wire leads used as a common communication path. A third conductive lead situated as a middle line between the two conductive leads of the common communication path was grounded as a shield to improve signal quality as described above. The tuning fork resonators were spatially arranged along the common communication path in order of increasing resonance frequency: the tuning fork resonator having the lowest resonance frequency,  $f_{R1}$ , was at one end, the tuning fork resonator having the highest resonance frequency,  $f_{R5}$ , was at the other end, and the remaining three tuning forks situated therebetween having increasing resonance frequencies,  $f_{R2}$ ,  $f_{R3}$ , and  $f_{R4}$ . The tuning forks and associated conductive wires leads are shown, together with a support rod, in Figure 17A.

[00194] The array of tuning fork resonators was connected via the two conductive wire leads to a network analyzer configured for providing a varying-frequency activation signal to stimulate the tuning fork resonators, and to process the signal generated by the tuning fork response thereto. In a scoping run, the network analyzer provided an activation signal with a frequency over the spectrum of frequencies covering all five tuning forks. When stimulated in the gas phase (*i.e.*, air and partial hexane vapor), the tuning fork resonators response was characterized to obtain the characterized responses shown in Figure 17B. When stimulated in the liquid phase (hexane), the response of the tuning fork resonators was negligible at the circuitry settings (*e.g.*, gain) employed in the experiment. When the tuning fork resonators were removed from the liquid phase back into the gas phase, the gas-phase signal was restored in about 1 second.

[00195] The array of tuning forks was oriented vertically in a hexane-containing container, substantially as shown in the schematic representation of Figure 17C, with the tuning fork resonator having the lowest resonance frequency situated closest to the bottom of the container. As shown, the tuning fork resonators are depicted as resonators 40-1, 40-2, 40-3, 40-4 and 40-5, having corresponding resonance frequencies,  $f_{R1}$ ,  $f_{R2}$ ,  $f_{R3}$ ,  $f_{R4}$  and  $f_{R5}$ , respectively. Measurements were taken with the hexane liquid phase at four different levels - Level A, Level B, Level C and Level D. With hexane at the highest level, Level A, three of the tuning fork resonators were submersed in the hexane, and two of the tuning forks were in the gas phase above the hexane liquid phase. When

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the hexane level was lower, at Level B, two of the tuning fork resonators were submersed in the hexane, and three of the tuning forks were in the gas phase above the hexane liquid phase. When the hexane level was again lower, at Level C, one of the tuning fork resonators were submersed in the hexane, and four of the tuning forks were in the gas phase above the hexane liquid phase. Finally, when the hexane level was at its lowest level, at Level D, none of the tuning fork resonators were submersed in the hexane; rather all five of the tuning forks were in the gas phase above the hexane liquid phase.

**[00196]** Figure 17D is a graph showing four sets of characterized response data from the corresponding four sets of measurements at the four different hexane levels. As shown in this figure, the four data sets are overlaid without offset. Figure 17 E is another graph showing the same four sets of data of Figure 17D, but with the data sets being offset with respect to the y-axis value (to allow for greater ease in comparative interpretation between the four data sets).

**[00197]** Figure 17F shows the data from Figure 17E (rotated 90 degrees counterclockwise) juxtaposed together with the experimental set-up of Figure 17C. With reference to Figure 17F, the characterized responses of the tuning fork resonators for the measurements taken with the hexane liquid phase at the four different levels was associated with the specific tuning fork resonators and their corresponding positions based on frequency of the observed response. In these experiments, since the resonance frequencies of the five tuning fork resonators 40-1, 40-2, 40-3, 40-4 and 40-5 was  $f_{R1}$ ,  $f_{R2}$ ,  $f_{R3}$ ,  $f_{R4}$  and  $f_{R5}$ , respectively, then the observed signal having the frequency of  $f_{R1}$  was correlated to resonator 40-1 (and the position thereof). Similarly, the observed signal having the frequency of  $f_{R2}$  was correlated to resonator 40-2 (and the position thereof); the observed signals having the frequency of  $f_{R3}$  was correlated to resonator 40-3 (and the position thereof); the observed signal having the frequency of  $f_{R4}$  was correlated to resonator 40-4 (and the position thereof); and the observed signal having the frequency of  $f_{R5}$  was correlated to resonator 40-5 (and the position thereof).

**[00198]** Based on this association, with further reference to Figure 17F, the hexane levels were identified based on the characterized responses. With hexane at the highest level, Level A, characterized responses were observed only at  $f_{R4}$  and  $f_{R5}$ , with a substantial absence of an observed characterized response at  $f_{R1}$ ,  $f_{R2}$  and  $f_{R3}$ , thereby

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indicating that the hexane level was between  $f_{R3}$  and  $f_{R4}$ , and therefore, between the positions of resonators 40-3 and 40-4. Similarly, when the hexane level was lower, at Level B, characterized responses were observed at  $f_{R3}$ ,  $f_{R4}$  and  $f_{R5}$ , with a substantial absence of an observed characterized response at  $f_{R1}$  and  $f_{R2}$ , thereby indicating that the hexane level was between  $f_{R2}$  and  $f_{R3}$ , and therefore, between the positions of resonators 40-2 and 40-3. When the hexane level was again lower, at Level C, characterized responses were observed at  $f_{R2}$ ,  $f_{R3}$ ,  $f_{R4}$  and  $f_{R5}$ , with a substantial absence of an observed characterized response at  $f_{R1}$ , thereby indicating that the hexane level was between  $f_{R1}$  and  $f_{R2}$ , and therefore, between the positions of resonators 40-1 and 40-2. Finally, when the hexane level was at its lowest level, at Level D, characterized responses were observed at each of  $f_{R1}$ ,  $f_{R2}$ ,  $f_{R3}$ ,  $f_{R4}$  and  $f_{R5}$ , thereby indicating that the hexane level was below  $f_{R1}$ , and therefore, below the positions of resonator 40-1.

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[00199] In light of the detailed description of the invention and the examples presented above, it can be appreciated that the several objects of the invention are achieved.

[00200] The explanations and illustrations presented herein are intended to acquaint others skilled in the art with the invention, its principles, and its practical application. Those skilled in the art may adapt and apply the invention in its numerous forms, as may be best suited to the requirements of a particular use. Accordingly, the specific embodiments of the present invention as set forth are not intended as being exhaustive or limiting of the invention.

## WE CLAIM:

1. A method for sensing one or more fluids at multiple positions, the method comprising
  - contacting a sensing surface of a first mechanical resonator with fluid, the first resonator having a first position,
  - contacting a sensing surface of a second mechanical resonator with fluid, the second resonator having a second position,
  - stimulating the fluid-contacted first resonator to generate a first signal associated with a response of the first resonator,
  - stimulating the fluid-contacted second-resonator to generate a second signal associated with a response of the second resonator,
  - communicating the generated first signal and second signal over a common communication path,
  - processing the communicated first signal and second signal to characterize the response of the first resonator and the second resonator, respectively, the characterized response comprising one or more signal characteristics, and
  - associating the response of the first resonator and the response of the second resonator with the positions of the first resonator and the second resonator, respectively, based on at least one of the signal characteristics of the characterized response.
  
2. A method for sensing a body of fluid at multiple positions to determine a spatial profile of one or more properties of the fluid, the method comprising
  - contacting a sensing surface of a first mechanical resonator with the fluid, the first resonator having a first position within the body of fluid,
  - contacting a sensing surface of a second mechanical resonator with the fluid, the second resonator having a second position within the body of fluid,
  - stimulating the fluid-contacted first resonator to generate a first signal associated with a response of the first resonator,

stimulating the fluid-contacted second-resonator to generate a second signal associated with a response of the second resonator,

communicating the generated first signal and second signal over a common communication path,

processing the communicated first signal and second signal to characterize the response of the first resonator and the second resonator, respectively, the characterized response comprising one or more signal characteristics,

associating the response of the first resonator and the response of the second resonator with the positions of the first resonator and the second resonator, respectively, based on at least one of the signal characteristics of the characterized response, and

determining at least one property of the fluid at each of the first position and the second position, the at least one property being determined at the first position by correlating the response of the first resonator with the at least one property of the fluid based on the characterized response of the first resonator, the at least one property being determined at the second position by correlating the response of the second resonator with the at least one property of the fluid based on the characterized response of the second resonator.

3. A method for sensing the position of a fluidic interface between a first fluid and a second fluid, the method comprising

contacting a sensing surface of a first mechanical resonator with the first fluid during a sensing period, the first resonator being positioned at a first position,  $P_1$ ,

contacting a sensing surface of a second mechanical resonator with the second fluid during the sensing period, the second resonator being positioned at a second position,  $P_2$ , in spatial relation to the first position,  $P_1$ ,

stimulating the first resonator and the second resonator during the sensing period to generate at least one of a first signal associated with a response the first resonator and a second signal associated with a response of the second resonator,

communicating any generated first signal and second signal over a common communication path from the first resonator and second resonator, respectively, to a signal processing circuit,

processing any communicated first signal and second signal in the signal processing circuit to characterize the response of the first resonator and the second resonator, respectively, and

identifying the position of the fluidic interface to be between the first position,  $P_1$ , and the second position,  $P_2$ , based on a fluid-dependent difference between the characterized response of the first resonator and the characterized response of the second resonator.

4. The method of claim 3 wherein the first resonator has a first resonance frequency,  $f_{R1}$ , and the second resonator has a second resonance frequency,  $f_{R2}$ , the second resonance frequency,  $f_{R2}$ , being different than the first resonance frequency,  $f_{R1}$ , in at least one of the first fluid or the second fluid.

5. The method of claim 4 comprising

contacting the sensing surface of the first resonator with the first fluid and stimulating the first resonator during the sensing period, the first fluid allowing the first resonator response such that a detectable first signal is generated,

contacting the sensing surface of the second resonator with the second fluid and stimulating the second resonator during the sensing period, the second fluid allowing the second resonator response such that a detectable second signal is generated,

communicating the generated first signal and second signal to the signal processing circuit over the common communication path,

processing the communicated first signal and second signal in the signal processing circuit,

correlating the processed first signal and second signal to the first position,  $P_1$ , and the second position,  $P_2$ , respectively, and

identifying the position of the fluidic interface to be between the first position,  $P_1$ , and the second position,  $P_2$ , based on the difference between the response of the first resonator and the response of the second resonator, the difference being determined by comparing at least one characteristic of the processed first signal at the first resonance

frequency,  $f_{R1}$ , to at least one corresponding characteristic of the processed second signal at the second resonance frequency,  $f_{R2}$ .

6. The method of claim 4 comprising
  - contacting the sensing surface of the first resonator with the first fluid and stimulating the first resonator during the sensing period, the first fluid allowing the first resonator response such that a detectable first signal is generated,
  - contacting the sensing surface of the second resonator with the second fluid and stimulating the second resonator during the sensing period, the second fluid allowing the second resonator response such that a detectable second signal is generated,
  - contacting the sensing surface of a third mechanical resonator with the second fluid during the sensing period, the third resonator having a third resonance frequency,  $f_{R3}$ , the third resonance frequency,  $f_{R3}$ , being different than the first resonance frequency,  $f_{R1}$ , and the second resonance frequency,  $f_{R2}$ , in at least the one of the first fluid or the second fluid, the third resonator being positioned at a third position,  $P_3$ , the second position,  $P_2$ , being between the first position,  $P_1$ , and the third position,  $P_3$ ,
  - stimulating the third resonator during the sensing period, the second fluid allowing a third resonator response such that a detectable third signal is generated,
  - communicating the generated first signal, second signal and third signal to the signal processing circuit over the common communication path,
  - processing the communicated first signal, second signal and third signal in the signal processing circuit,
  - correlating the processed first signal, second signal and third signal to the first position,  $P_1$ , the second position,  $P_2$ , and the third position,  $P_3$ , respectively, the processed third signal being correlated to the third position,  $P_3$ , based on a characteristic of the processed third signal at the third resonance frequency,  $f_{R3}$ , and
  - identifying the position of the fluidic interface to be between the first position,  $P_1$ , and the second position,  $P_2$ .
7. The method of claim 6 wherein the position of the fluidic interface is identified to be between the first position,  $P_1$ , and the second position,  $P_2$ , based the

difference between the response of the first resonator and the response of the second resonator, the difference being determined by comparing at least one characteristic of the processed first signal at the first resonance frequency,  $f_{R1}$ , to at least one corresponding characteristic of the processed second signal at the second resonance frequency,  $f_{R2}$ .

8. The method of claim 6 wherein the position of the fluidic interface is identified to be between the first position,  $P_1$ , and the second position,  $P_2$ , based on

- (i) a difference between the response of the third resonator and the response of the first resonator, the difference being determined by comparing at least one characteristic of the processed third signal at the third resonance frequency,  $f_{R3}$ , to at least one corresponding characteristic of the processed first signal at the first resonance frequency,  $f_{R1}$ , and
- (ii) a similarity between the response of the third resonator and the response of the second resonator, the similarity being determined by comparing at least one characteristic of the processed third signal at the third resonance frequency,  $f_{R3}$ , to at least one corresponding characteristic of the processed second signal at the second resonance frequency,  $f_{R2}$ .

9. The method of claim 4 comprising

- contacting the sensing surface of the first resonator with the first fluid and stimulating the first resonator during the sensing period, the first fluid damping the first resonator response such that a detectable first signal is not generated,
- contacting the sensing surface of the second resonator with the second fluid and stimulating the second resonator during the sensing period, the second fluid allowing the second resonator response such that a detectable second signal is generated,
- communicating the generated second signal to the signal processing circuit over the common communication path,
- processing the communicated second signal in the signal processing circuit,
- correlating the processed second signal to the first position,  $P_2$ , and
- identifying the position of the fluidic interface to be between the first position,  $P_1$ , and the second position,  $P_2$ , based on the difference between the response of the first

resonator and the response of the second resonator, the difference being determined by the essential absence of the processed first signal at the first resonance frequency,  $f_{R1}$ , and the presence of the second signal at the second resonance frequency,  $f_{R2}$ .

10. A method for sensing liquid level within a fluidic system comprising a liquid first fluid and a second fluid, the method comprising
  - contacting a sensing surface of a first mechanical resonator with the liquid first fluid during a sensing period, the first resonator having a first resonance frequency,  $f_{R1}$ , the first resonator being positioned at a first position,  $P_1$ ,
  - contacting a sensing surface of a second mechanical resonator with the second fluid during the sensing period, the second resonator having a second resonance frequency,  $f_{R2}$ , the second resonance frequency,  $f_{R2}$ , being different than the first resonance frequency,  $f_{R1}$ , in at least one of the liquid first fluid or the second fluid, the second resonator being positioned at a second position,  $P_2$ ,
  - stimulating the first resonator and the second resonator during the sensing period to generate a first signal associated with a response the first resonator and a second signal associated with a response of the second resonator,
  - communicating the generated first signal and second signal to a signal processing circuit over a common communication path,
  - processing the communicated first signal and second signal in the signal processing circuit to characterize the response of the first resonator and the second resonator, respectively, the characterized response comprising one or more signal characteristics including at least frequency, and
  - associating the response of the first resonator and the response of the second resonator with the first position,  $P_1$ , and the second position,  $P_2$ , respectively, based on frequency of the characterized response,
  - identifying the liquid level to be between the first position,  $P_1$ , and the second position,  $P_2$ , based on a fluid-dependent difference between the characterized response of the first resonator and the characterized response of the second resonator.

11. The method of claim 3 wherein the characterized response comprises one or more signal characteristics, the method further comprising associating the response of the first resonator and the response of the second resonator with the positions of the first resonator and the second resonator, respectively, based on at least one of the signal characteristics of the characterized response.

12. The methods of any of claims 1, 2 or 11 wherein the characterized response comprises one or more signal characteristics that includes frequency, and the response of the first resonator and the response of the second resonator is associated with the positions of the first resonator and the second resonator, respectively, based on frequency of the characterized responses.

13. The methods of any of claims 1, 2, 11 or 12 wherein the characterized response comprises one or more signal characteristics that includes amplitude, and the response of the first resonator and the response of the second resonator is associated with the positions of the first resonator and the second resonator, respectively, based on amplitude of the characterized responses.

14. The methods of any of claims 1, 2, 11, 12 or 13 wherein the characterized response comprises one or more signal characteristics that includes peak width, and the response of the first resonator and the response of the second resonator is associated with the positions of the first resonator and the second resonator, respectively, based on peak width of the characterized responses.

15. The methods of any of claims 1, 3 or 4 further comprising determining at least one property of the fluids at multiple positions,

the at least one property being determined at the first position by correlating the response of the first resonator with a property of the fluid in contact therewith at the first position, based on the characterized response of the first resonator,

the at least one property being determined at the second position by correlating the response of the second resonator with a property of the fluid in contact therewith at the second position based on the characterized response of the second resonator.

16. The methods of any of claims 2 or 15 wherein the determined at least one fluid property is selected from the group consisting of viscosity, density, dielectric and conductivity.

17. The methods of any of claims 2 or 15 wherein the determined at least one fluid property comprises at least two properties selected from the group consisting of viscosity, density, dielectric and conductivity.

18. The methods of any of claims 2 or 15 wherein the determined at least one fluid property comprises at least viscosity and density.

19. The method of any of claims 1 through 18 wherein the generated first signal and second signal are communicated over a common communication path extending from the first and second mechanical resonators to an electrical circuit comprising signal processing circuitry or data retrieval circuitry.

20. The method of any of claims 1 through 19 wherein the first resonator and the second resonator are stimulated with an electronic stimulus.

21. The method of any of claims 1 through 20 wherein the first resonator and the second resonator are stimulated with an electronic signal originating from signal activation circuitry and communicated to the first resonator and the second resonator over the common communication path.

22. The method of any of claims 1 through 21 wherein the communicated first signal and second signal are processed in signal processing circuitry comprising signal conditioning circuitry and data derivation circuitry.

23. The method of any of claims 1 through 22 wherein the communicated first signal and second signal are multiplexed over the common communication path from the first mechanical resonator and the second mechanical resonator to a circuit comprising signal processing circuitry or data retrieval circuitry, the circuit being located internal to fluidic system(s) comprising the fluid(s) contacting the respective surfaces of the first mechanical resonator and the second mechanical resonators.

24. The method of any of claims 1 through 23 wherein the communicated first signal and second signal are multiplexed over the common communication path from the first mechanical resonator and the second mechanical resonator to a circuit comprising signal processing circuitry or data retrieval circuitry, the circuit being located external to fluidic system(s) comprising the fluid(s) contacting the respective surfaces of the first mechanical resonator and the second mechanical resonators.

25. The method of any of claims 1 through 24 wherein the sensor further comprises at least one temperature sensing element.

26. The method of any of claims 1 through 24 wherein the sensor further comprises a first temperature sensing element having a sensing surface proximate to the sensing surface of the first mechanical resonator, and a second temperature sensing element having a sensing surface proximate to the sensing surface of the second mechanical resonator.

27. The method of any of claims 1 through 26 wherein the common communication path comprises a first conductive lead and a second conductive lead for stimulating the first resonator and the second resonator with electronic stimulus and for communicating the generated first signal and second signal to signal processing circuitry, the sensor further comprising a third conductive lead configured substantially proximate to each of the first and second conductive leads for shielding to at least reduce wire-to-wire capacitance between the first and second conductive leads.

28. The method of any of claims 1 through 27 wherein the mechanical resonators are flexural resonators.

29. The method of any of claims 1 through 28 wherein the mechanical resonators are tuning fork resonators.

30. A system for sensing one or more fluids at multiple positions, the system comprising a sensor comprising  
two or more mechanical resonators at multiple positions,  
an electrical circuit comprising circuitry selected from signal processing circuitry, data retrieval circuitry and combinations thereof, and  
a communication link for electrical communication between each of the two or more resonators and the electrical circuit, the communication link comprising a common communication path defining at least a portion of the communication link between each of the two or more resonators and the electrical circuit.

31. A system for sensing one or more fluids at multiple positions in one or more fluidic systems, the system comprising a sensor configured for operation in one or more fluidic systems, the sensor comprising  
two or more mechanical resonators at multiple positions within the one or more fluidic systems,  
an electrical circuit comprising signal activation circuitry for generating electronic stimulus for stimulating the two or more resonators, and at least one of signal conditioning circuitry, data derivation circuitry or data retrieval circuitry for processing or retrieving a signal representing data originating from the two or more resonators, and  
a communication link for electrical communication between each of the two or more resonators and the electrical circuit, the communication link comprising a common communication path defining at least a portion of the communication link between each of the two or more resonators and the electrical circuit, the common communication path comprising two conductive leads for providing the electronic stimulus to each of the two

or more resonators, and for receiving signals associated with the responses of the two or more resonators.

32. The system of claim 31 wherein the sensor further comprises a third conductive lead configured substantially proximate to each of the first and second conductive leads for shielding wire-to-wire interference between the first and second conductive leads.

33. A system for sensing one or more fluids at multiple positions in one or more fluidic systems, the system comprising a sensor configured for operation in one or more fluidic systems, the sensor comprising

three or more mechanical resonators at multiple positions within the one or more fluidic systems,

an electrical circuit comprising signal activation circuitry for generating electronic stimulus for stimulating the three or more resonators, and at least one of signal

conditioning circuitry, data derivation circuitry or data retrieval circuitry for processing or retrieving a signal representing data originating from the three or more resonators,

a communication link for electrical communication between each of the three or more resonators and the electrical circuit, the communication link comprising a common communication path defining at least a portion of the communication link between each of the three or more resonators and the electrical circuit, the common communication path comprising first and second conductive leads for providing the electronic stimulus to each of the three or more resonators and for receiving signals associated with the responses of the three or more resonators, and

a third conductive lead configured substantially proximate to each of the first and second conductive leads for shielding to at least reduce wire-to-wire capacitance between the first and second conductive leads.

34. The system of any of claims 30 through 33 wherein the mechanical resonators have one or more design characteristics that differ from each other, the

different design characteristics providing differentiable characterized responses as determined in a common fluid.

35. The system of any of claims 30 through 34 wherein the mechanical resonators have resonance frequencies that differ from each other as determined in a common fluid.

36. The system of any of claims 30 through 35 wherein the mechanical resonators have resonance amplitudes that differ from each other as determined in a common fluid.

37. The system of any of claims 30 through 35 wherein the communication link between each of the two or more resonators and the electrical circuit consists essentially of the common communication path.

38. The system of claim 30 wherein the electrical circuit comprises signal activation circuitry for generating electronic stimulus for stimulating the two or more resonators.

39. The system of claim 30 wherein the electrical circuit comprises signal activation circuitry for generating electronic stimulus for stimulating the two or more resonators, and at least one of signal conditioning circuitry, data derivation circuitry or data retrieval circuitry for processing or retrieving a signal representing data originating from the two or more resonators.

40. The system of any of claims 30 through 39 wherein the electrical circuit comprises signal activation circuitry for generating electronic stimulus for stimulating the two or more resonators, and each of signal conditioning circuitry, data derivation circuitry and data retrieval circuitry for processing or retrieving a signal representing data originating from the two or more resonators.

41. The system of any of claims 30 through 40 wherein the sensor further comprises at least one temperature sensing element.
42. The system of any of claims 30 through 41 wherein the sensor further comprises a first temperature sensing element having a sensing surface proximate to a sensing surface of a first mechanical resonator, and a second temperature sensing element having a sensing surface proximate to a sensing surface of a second mechanical resonator.
43. The system of any of claims 1 through 42 wherein the mechanical resonators are flexural resonators.
44. The system of any of claims 1 through 43 wherein the mechanical resonators are tuning fork resonators.
45. The system of any of claims 1 through 44 further comprising a tank for containing one or more fluids, wherein the sensor is adapted for one or more of: sensing one or more fluids at multiple positions within the tank; sensing the position of a fluidic interface between fluids within the tank; or sensing fluid level within the tank.
46. The system of any of claims 1 through 45 further comprising a tank for containing one or more fluids, wherein the sensor is adapted for determining at least one fluid property of the one or more fluids within the tank.
47. The system of any of claims 1 through 44 further comprising a reactor for processing one or more fluids, wherein the sensor is adapted for one or more of: sensing one or more fluids at multiple positions within the reactor; sensing the position of a fluidic interface between fluids within the reactor; or sensing fluid level within the reactor.

48. The system of any of claims 1 through 44 and 47 further comprising a reactor for containing one or more fluids, wherein the sensor is adapted for determining at least one fluid property of the one or more fluids within the reactor.

49. The system of any of claims 1 through 44 further comprising a process line for one or more fluids, wherein the sensor is adapted for one or more of: sensing one or more fluids at multiple positions within the process line; sensing the position of a fluidic interface between fluids within the process line; or sensing fluid level within the process line.

50. The system of any of claims 1 through 44 and 49 further comprising a process line for one or more fluids, wherein the sensor is adapted for determining at least one fluid property of the one or more fluids within the process line.

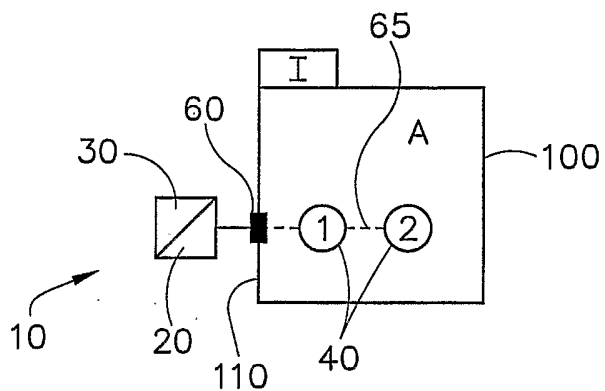


FIG. 1A

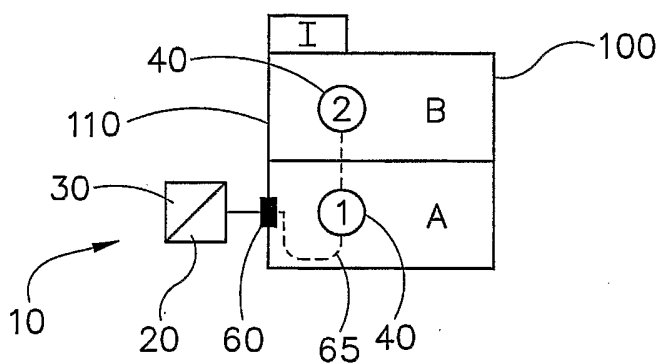


FIG. 1B

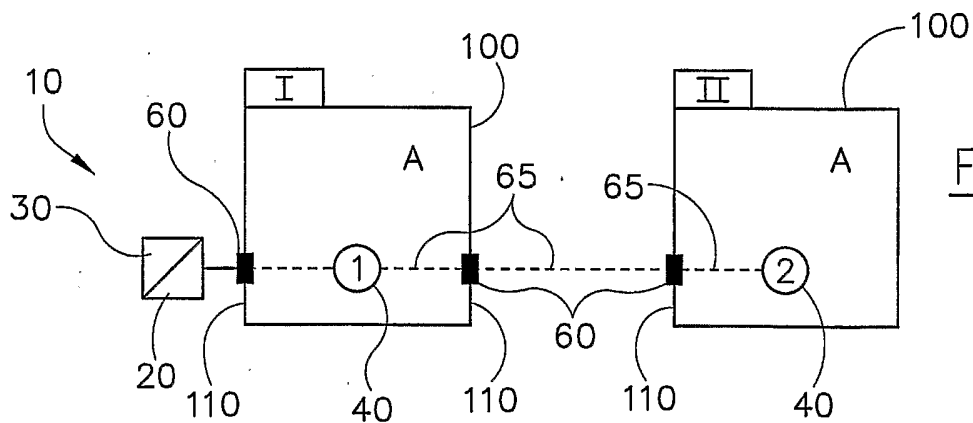


FIG. 2A

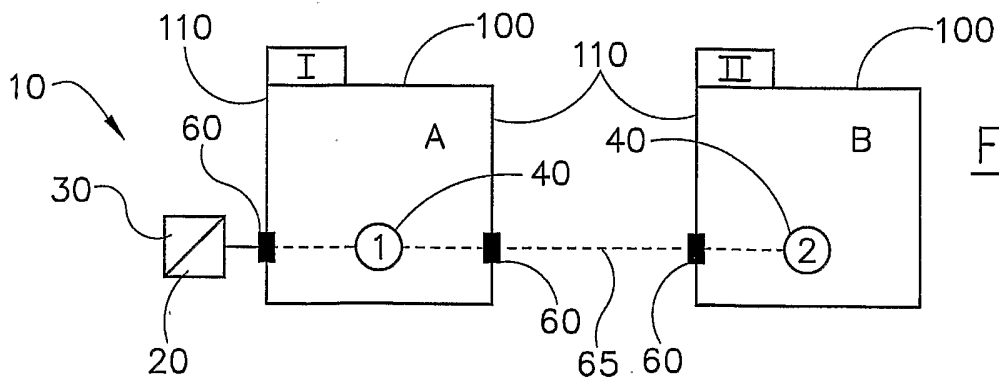


FIG. 2B

FIG. 2C

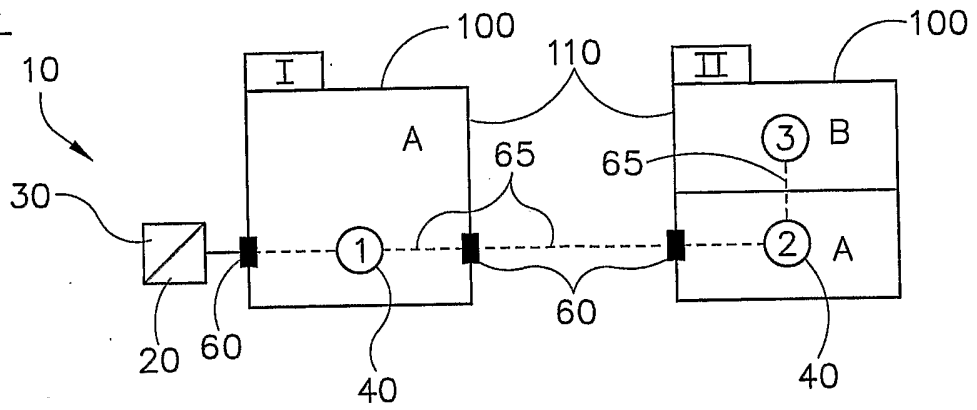


FIG. 2D

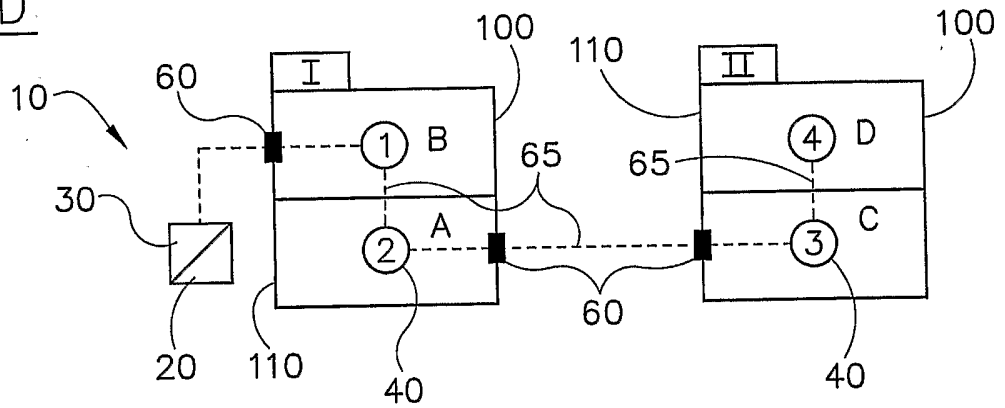


FIG. 3A

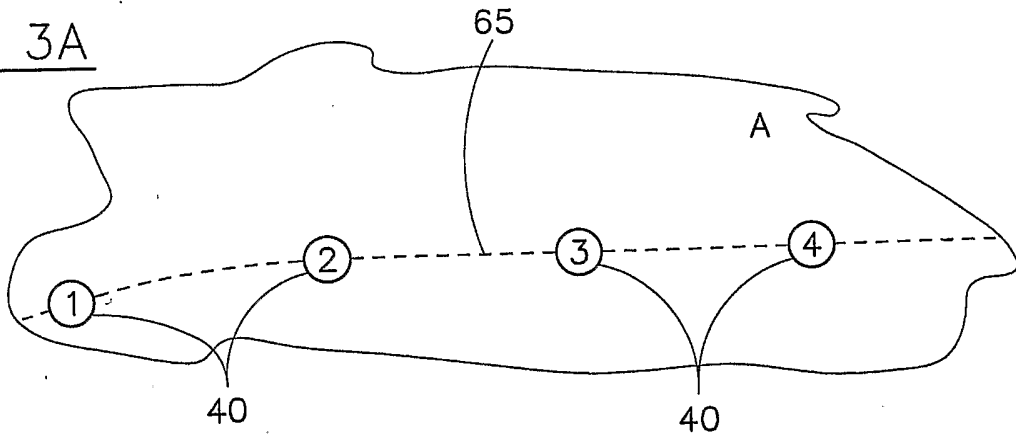


FIG. 3B

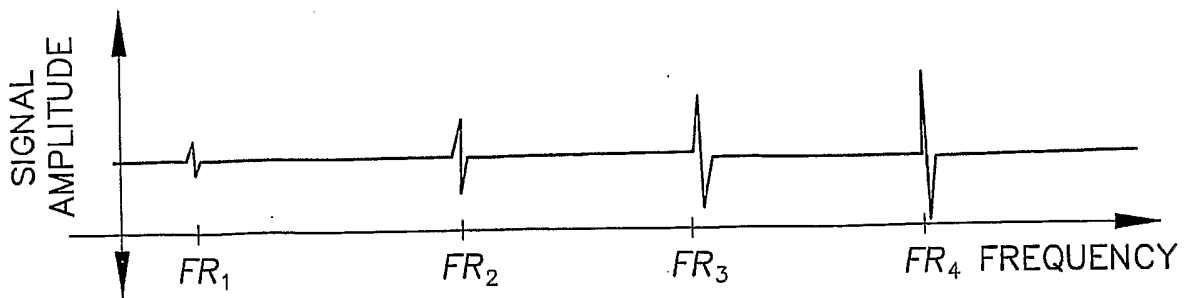


FIG. 4A

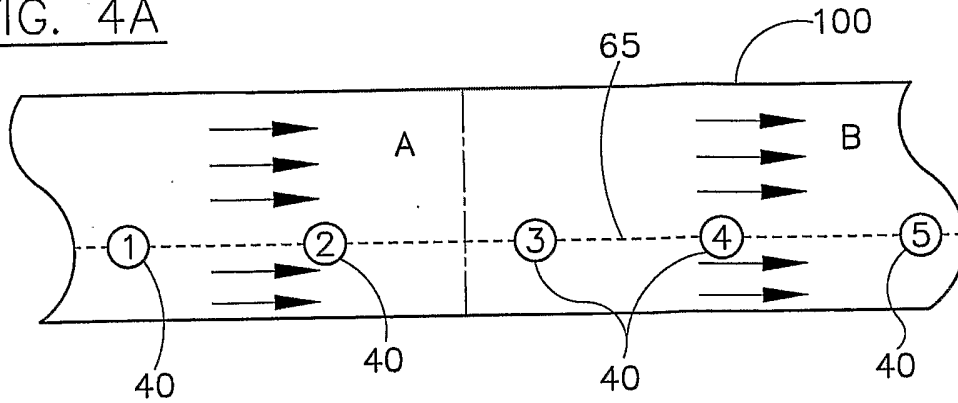


FIG. 4B

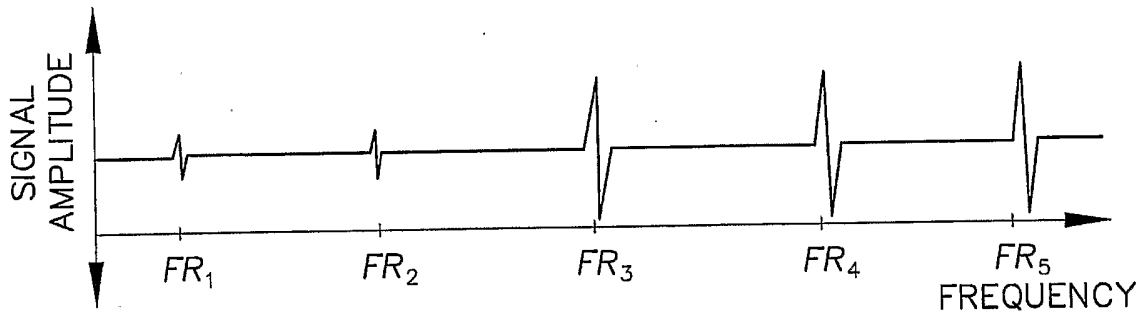


FIG. 5A

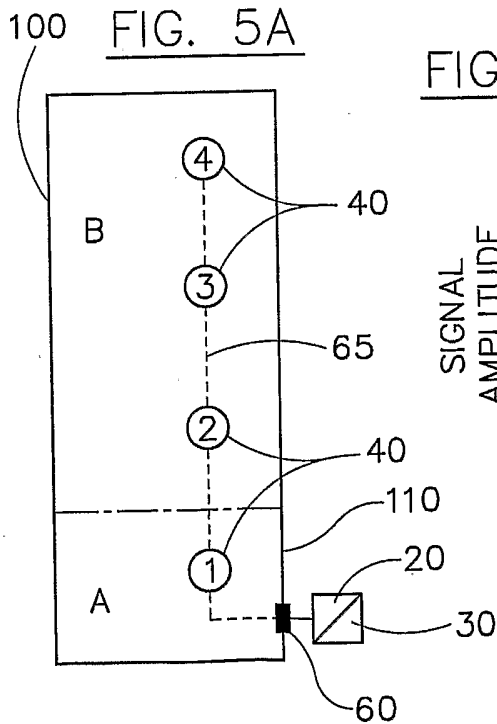
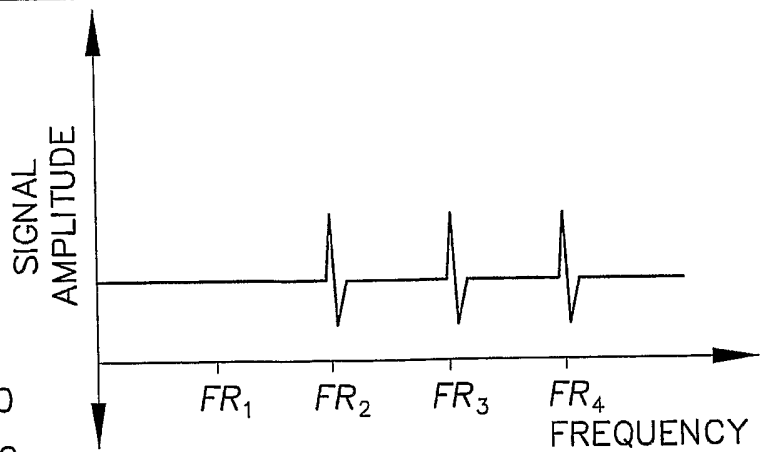


FIG. 5B



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FIG. 6A

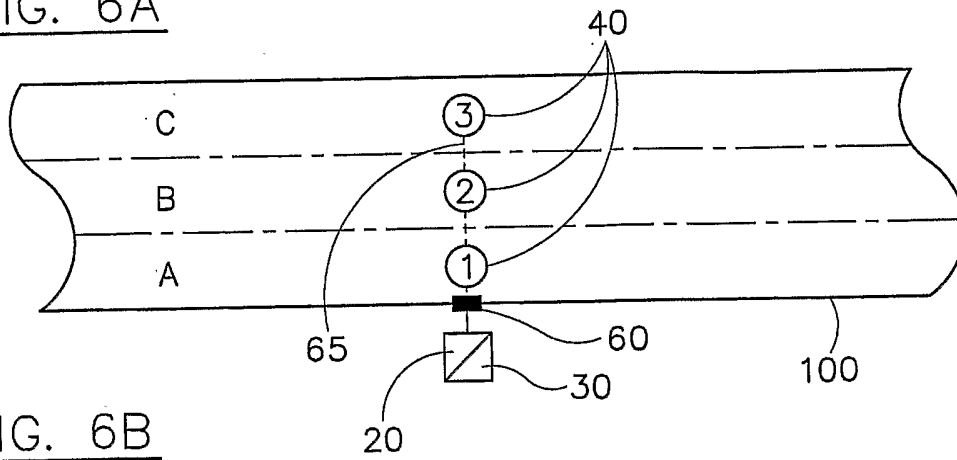


FIG. 6B

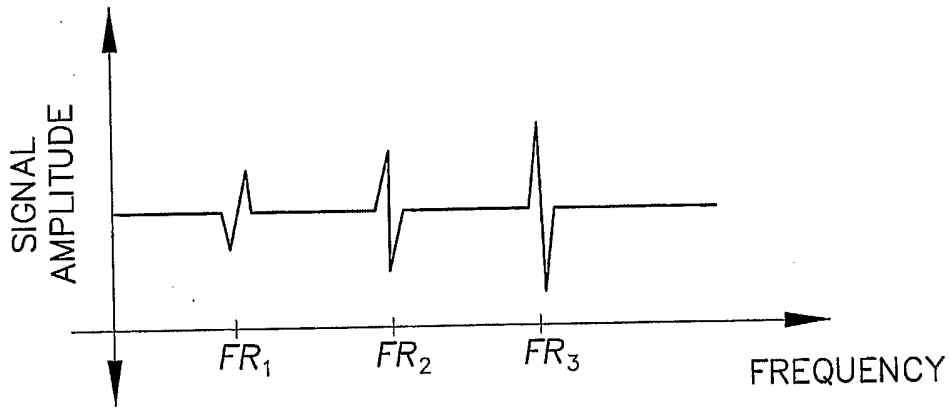


FIG. 7A

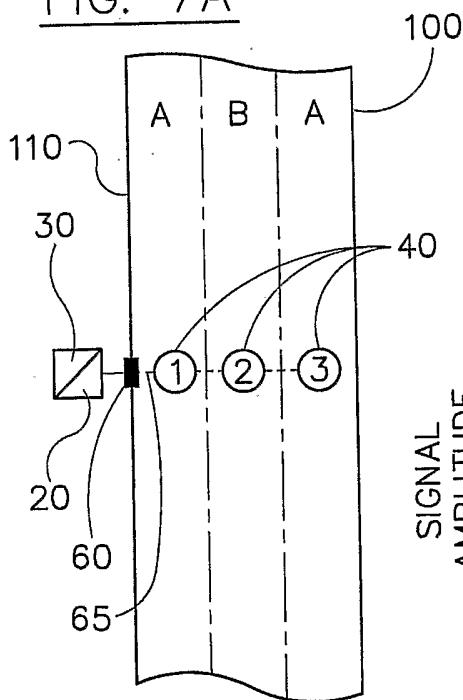


FIG. 7B

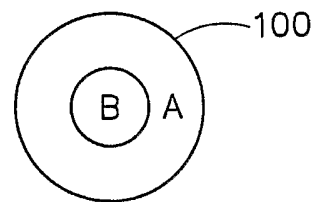
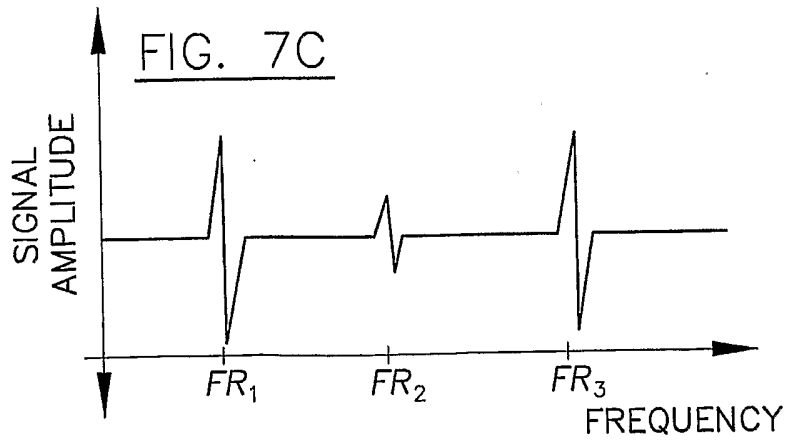


FIG. 7C



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FIG. 8A

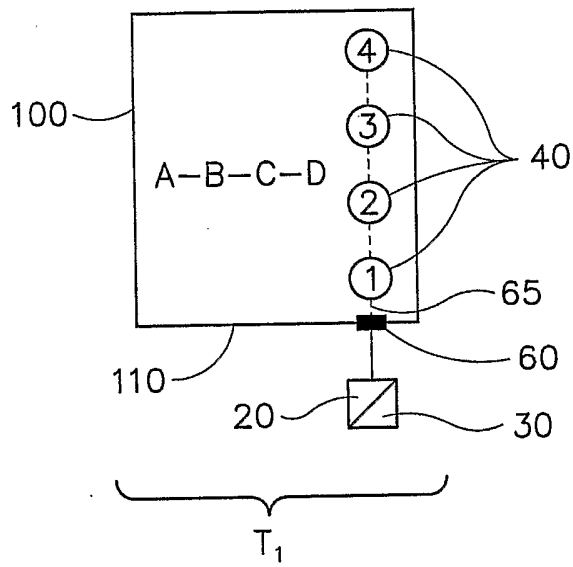


FIG. 8B

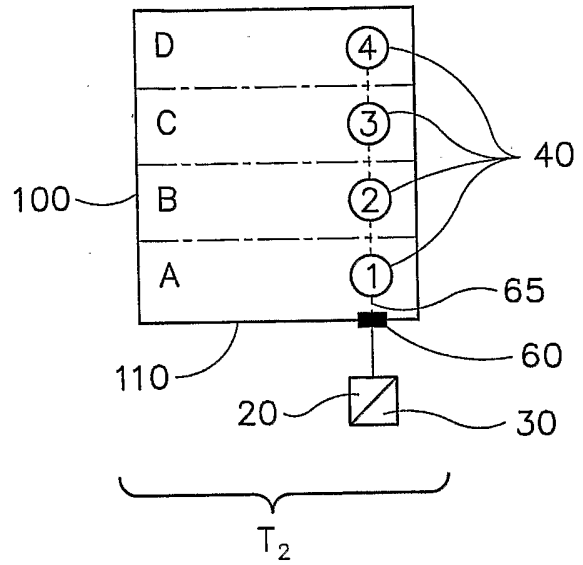


FIG. 8C

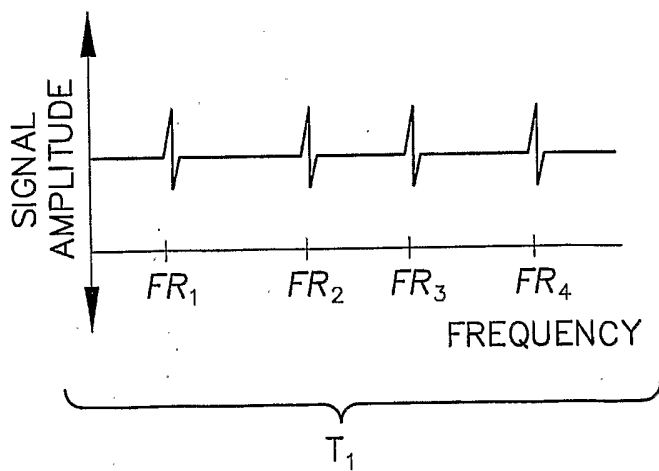
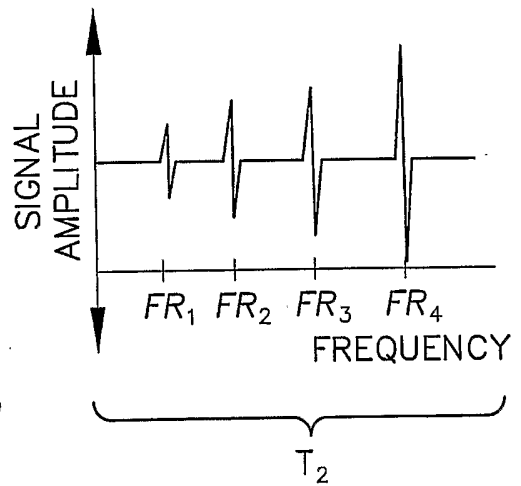
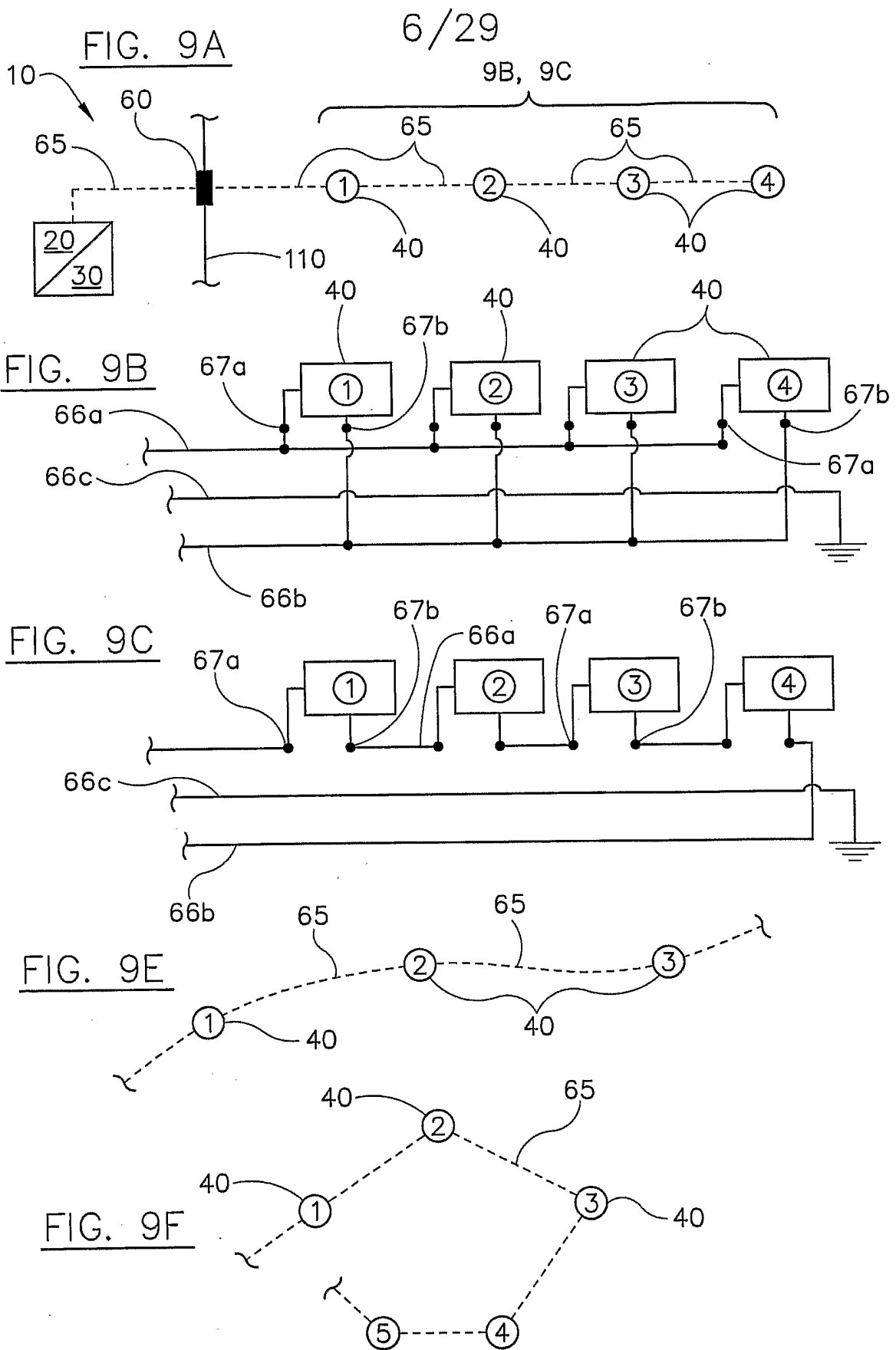


FIG. 8D





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FIG. 9G

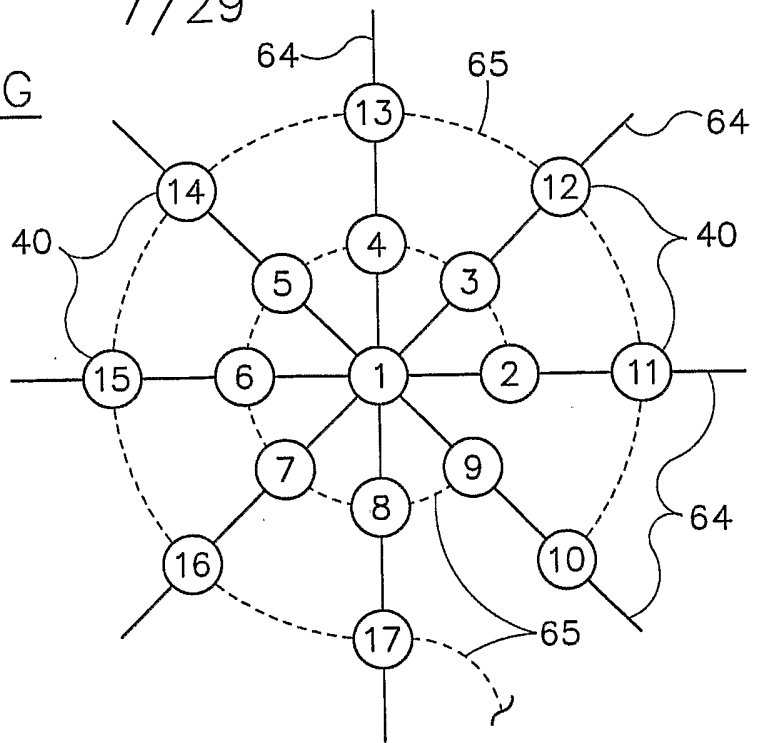


FIG. 9H

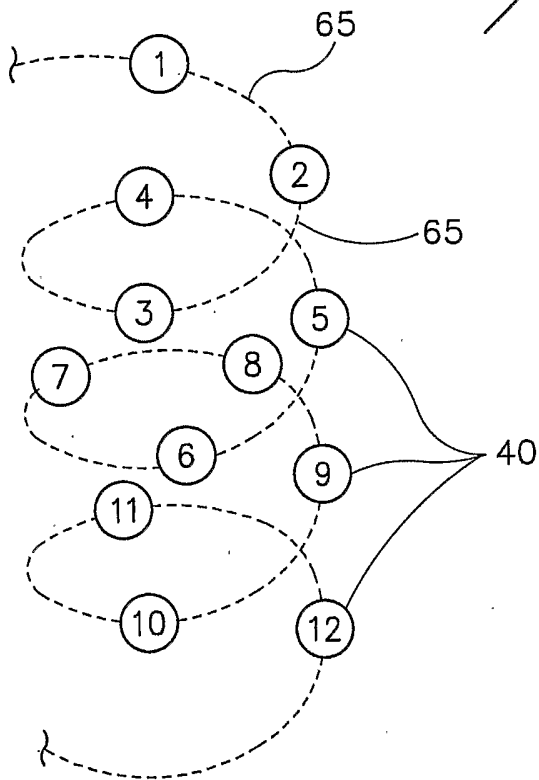


FIG. 9D

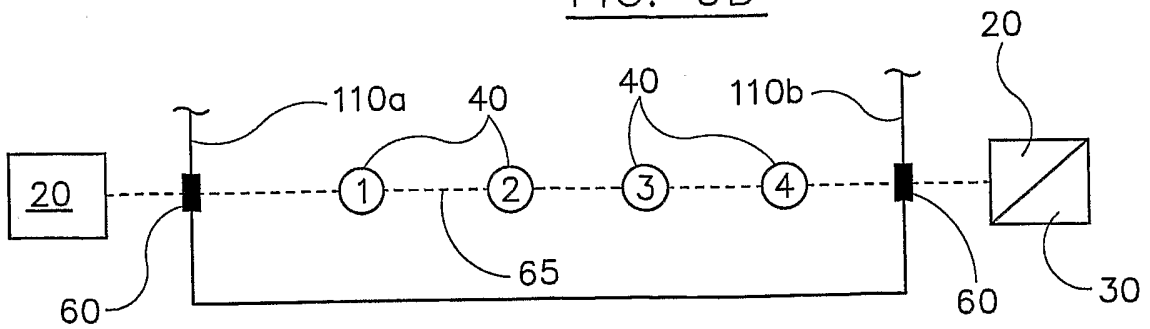


FIG. 10A

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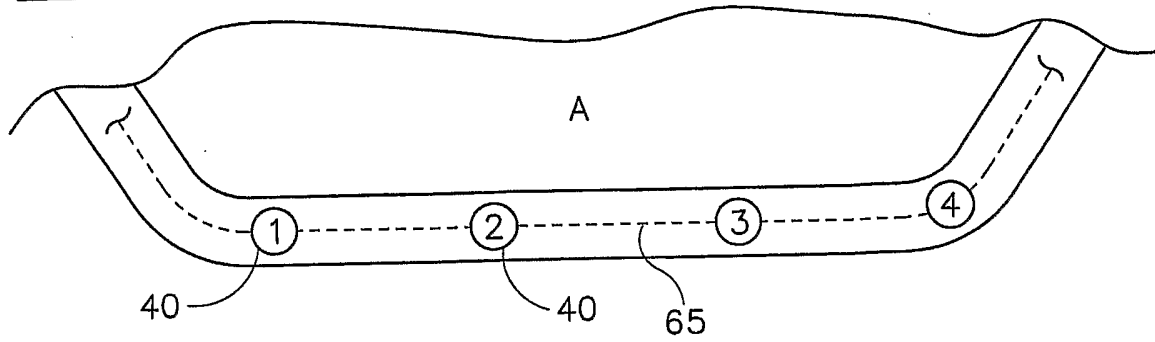


FIG. 10B

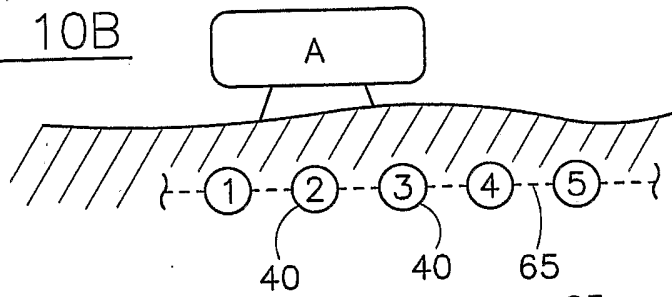


FIG. 10C

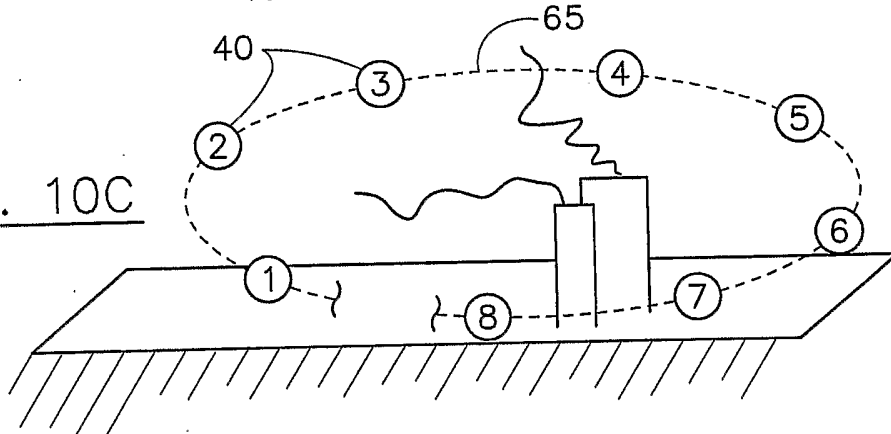
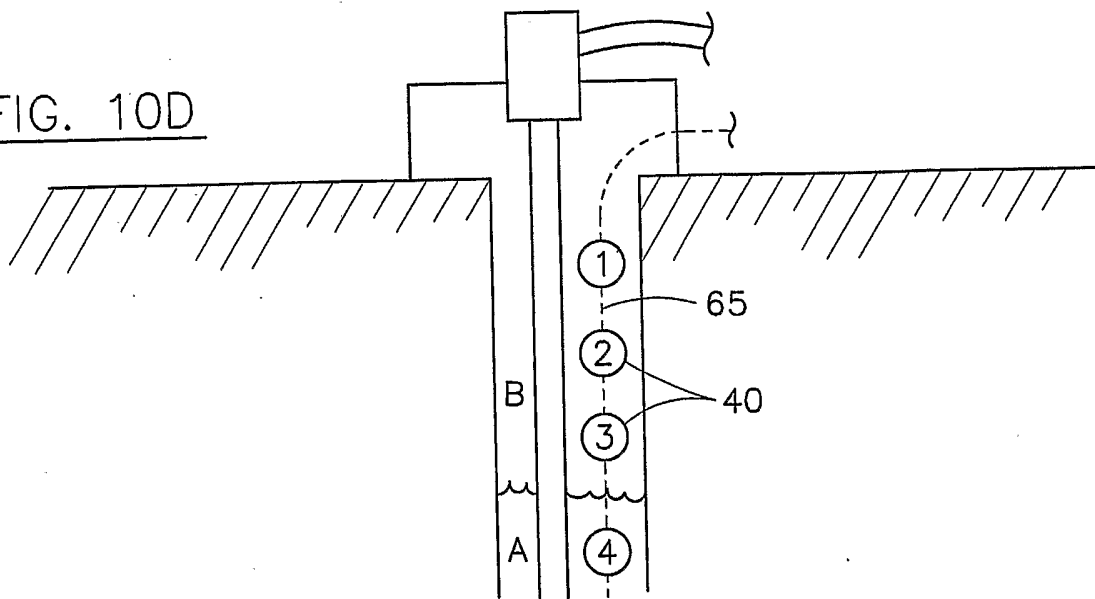


FIG. 10D



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FIG. 11A

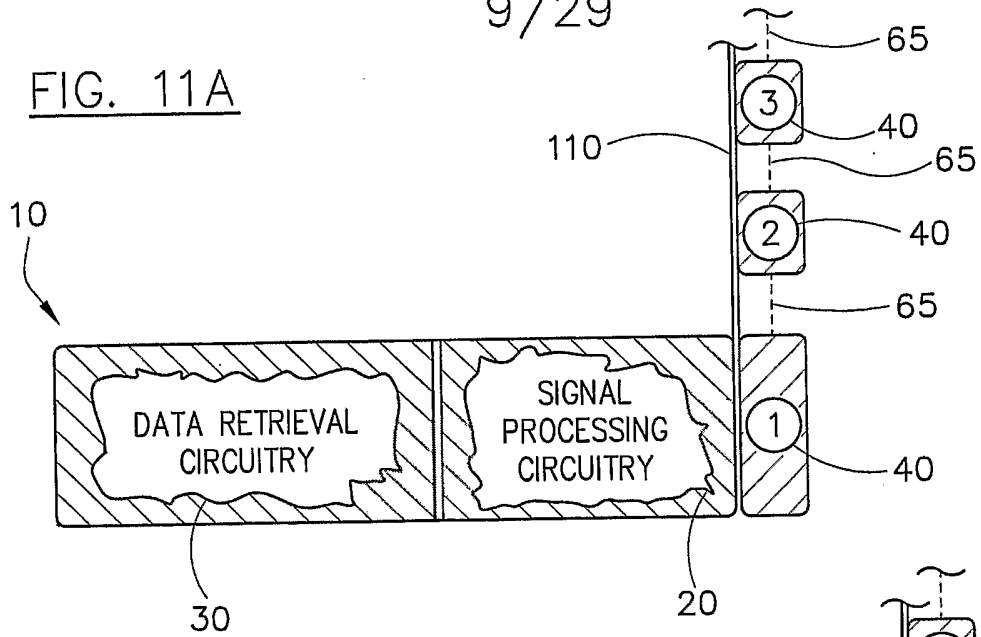


FIG. 11B

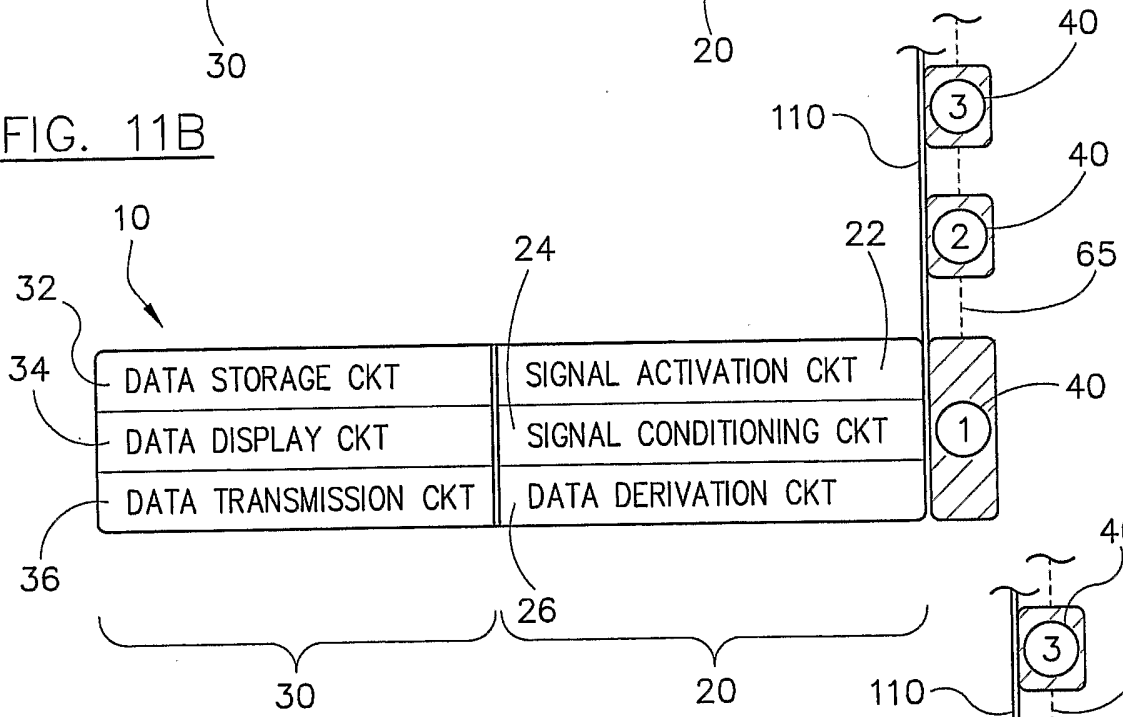
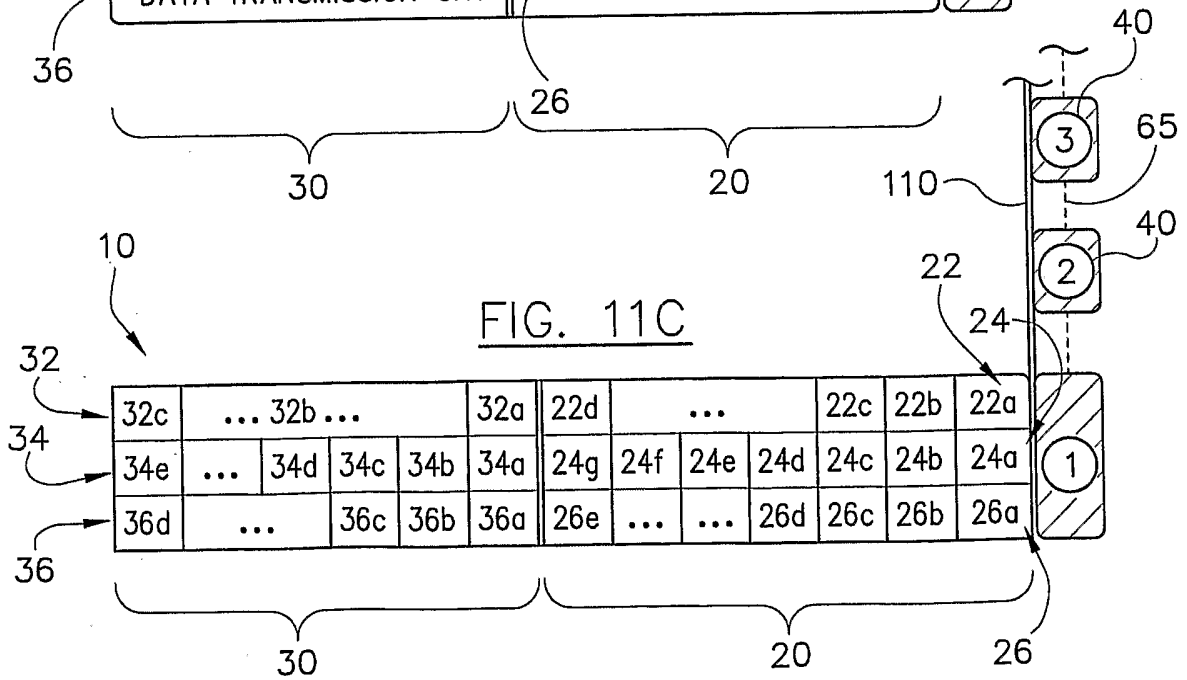
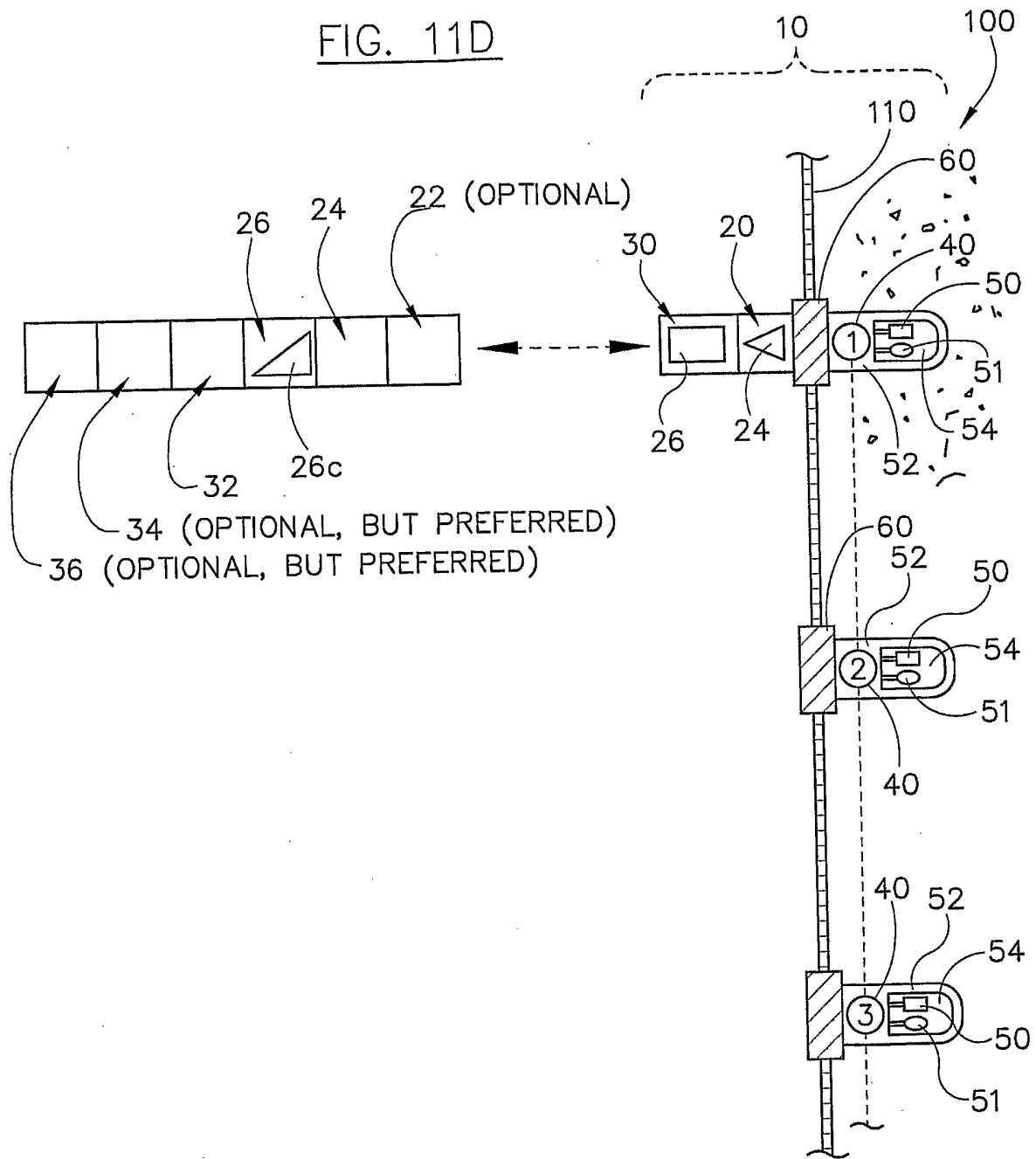


FIG. 11C



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FIG. 11D



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FIG. 12A

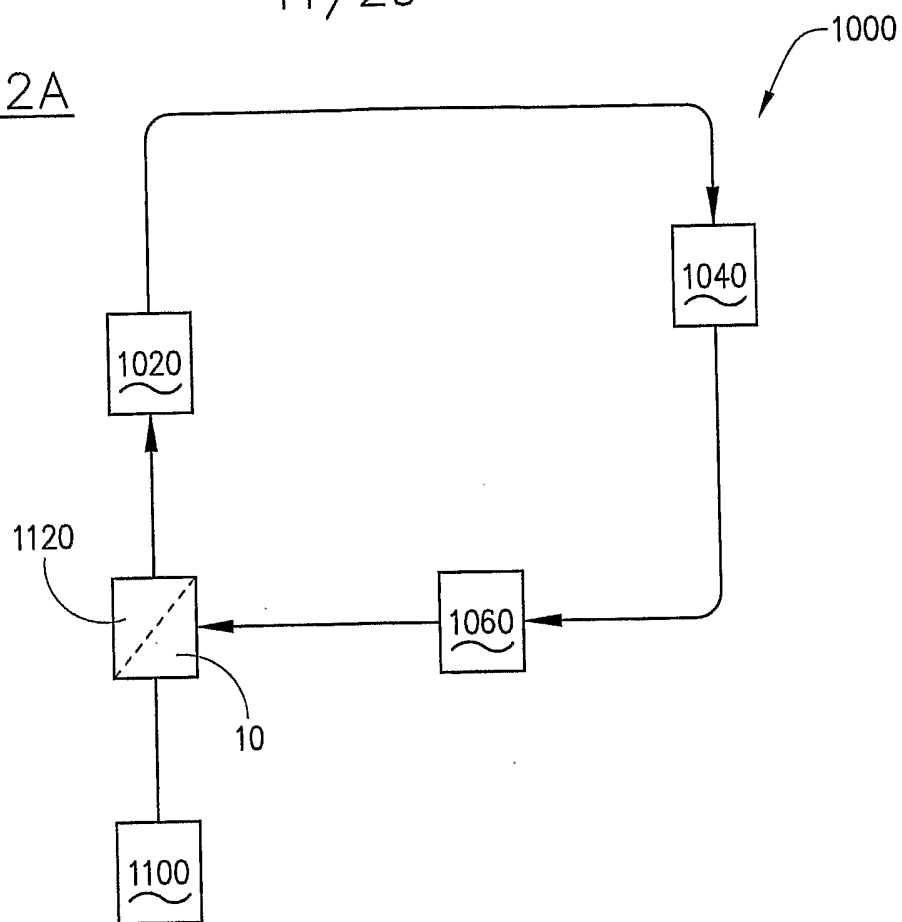
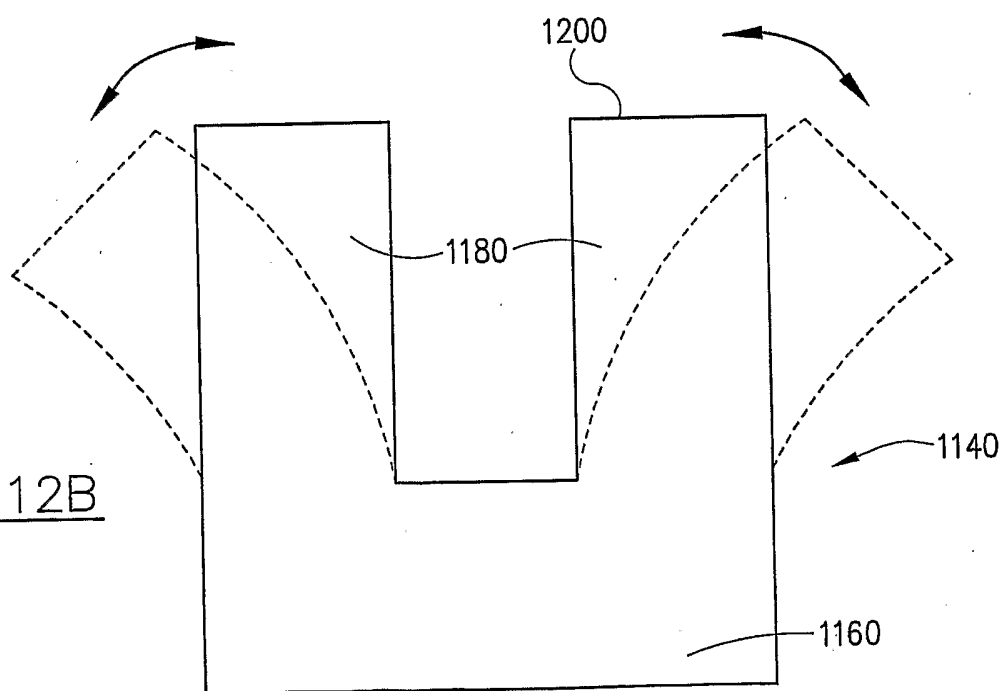


FIG. 12B



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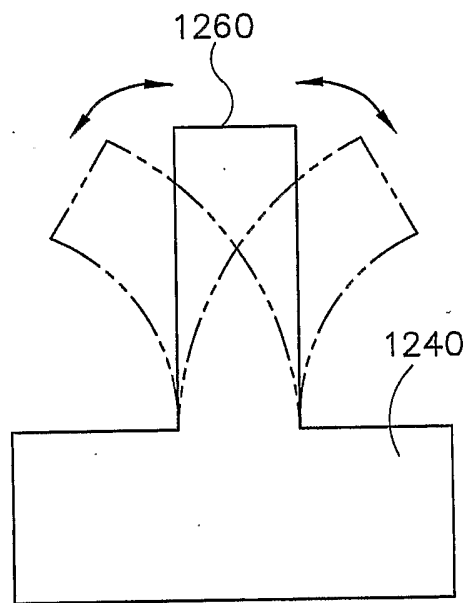


FIG. 12C

1220

FIG. 12D

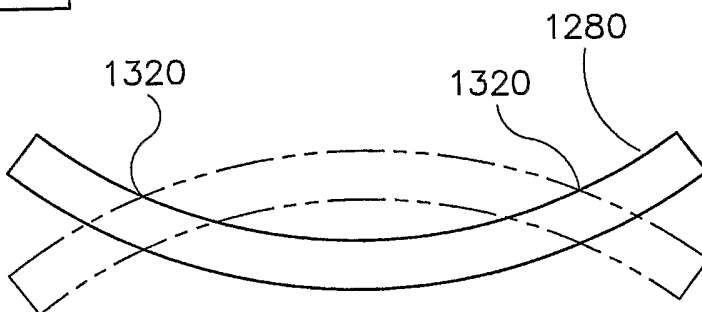


FIG. 12E

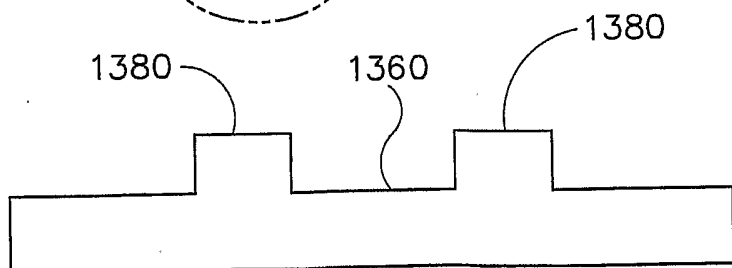
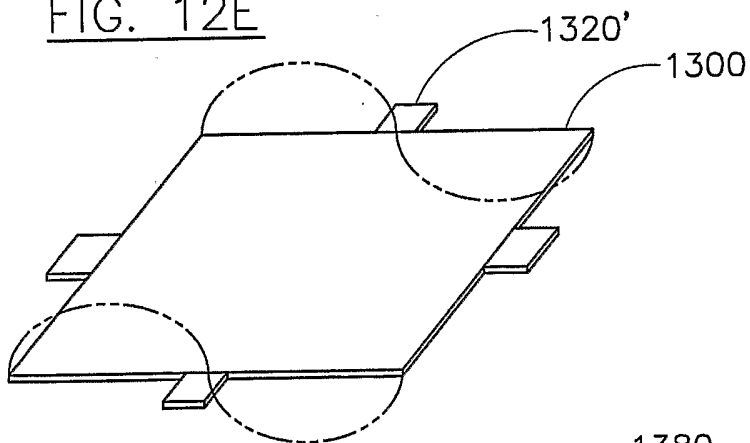


FIG. 12F

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FIG. 12G

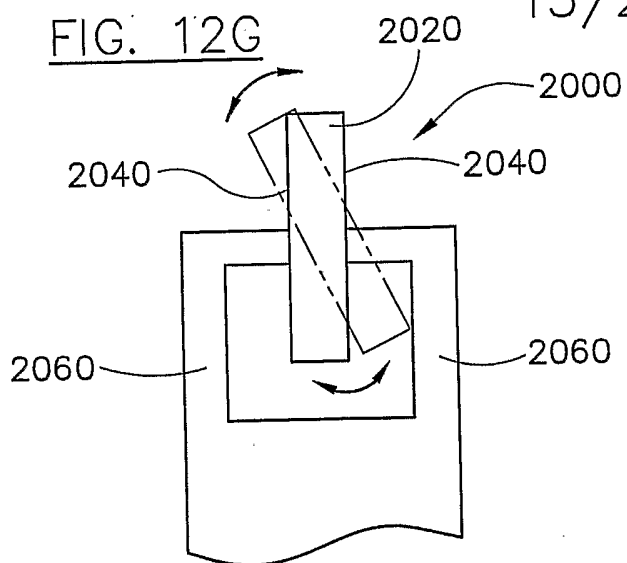


FIG. 12H

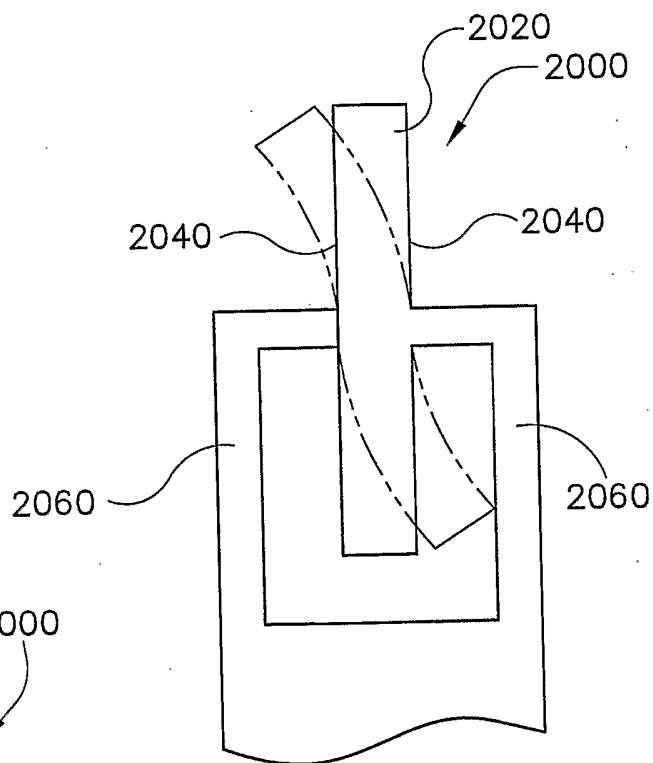


FIG. 12I

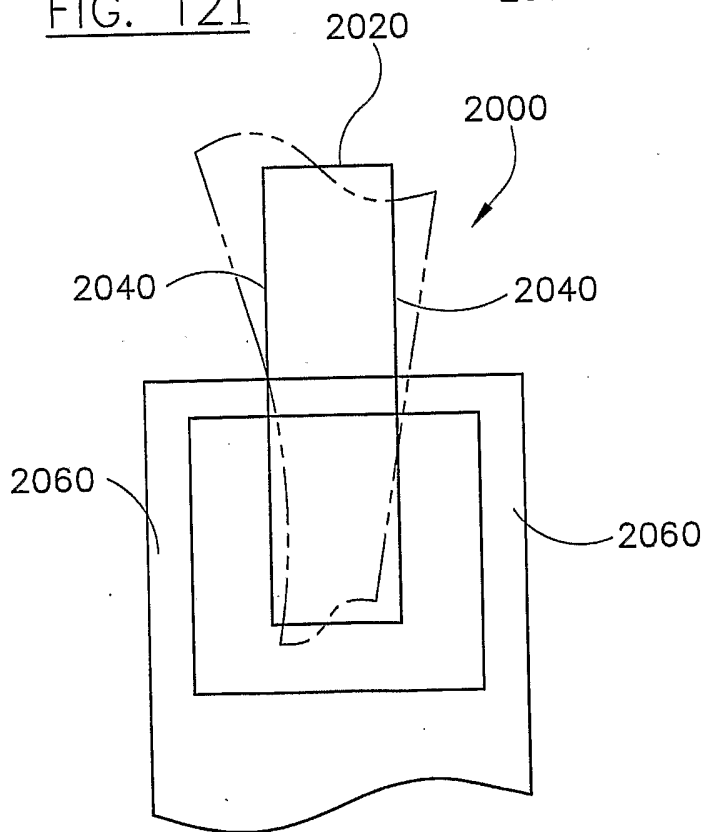
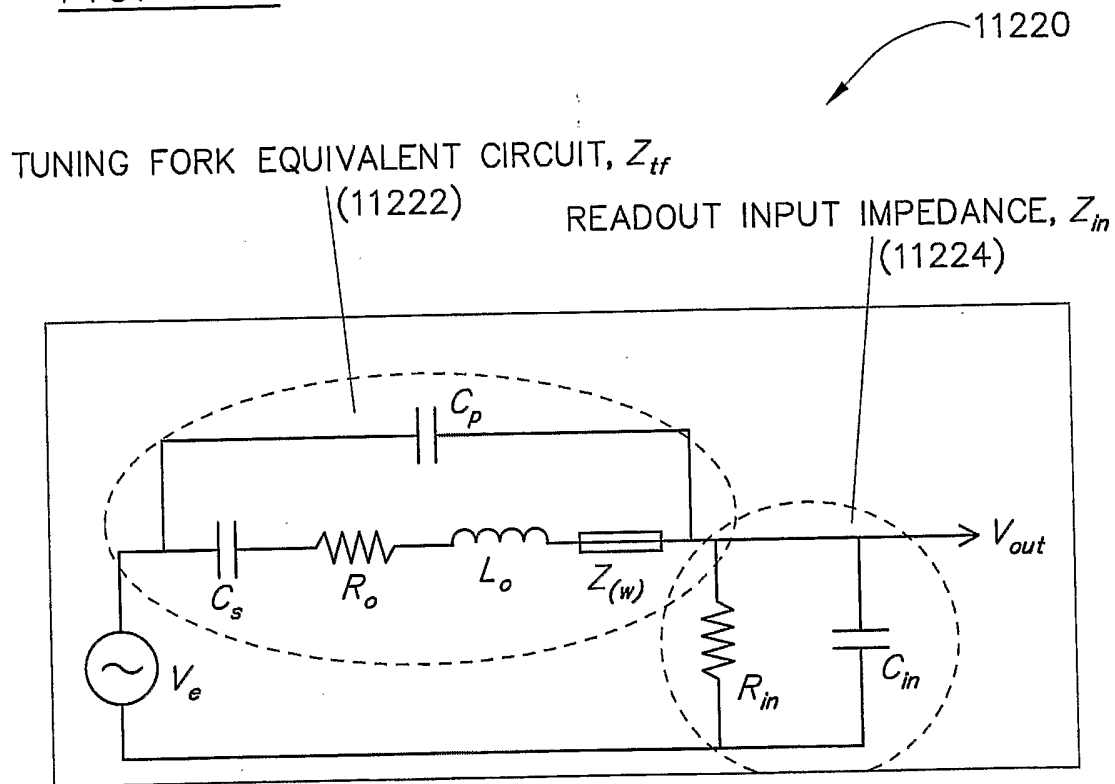


FIG. 13A



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FIG. 13B

$$V_{out}(C_o, C_p, L_o, C_s, R_o, Z(\omega), A, B, \rho, \eta, \omega, \epsilon) \quad (1)$$

$$V_{out}(\omega) = \frac{V_o(Z_{in}(\omega))}{(Z_{in}(\omega)) + (Z_{tf}(\omega))} \quad (2)$$

$$Z_{in} = R_{in} * (1/i\omega C_{in})(R_{in} + 1/i\omega C_{in})^{-1} \quad (3)$$

$$Z_{tf} = (1/i\omega C_p)(R_o + 1/i\omega C_s + i\omega L_o) \quad (4)$$

$$(1/i\omega C_p + R_o + 1/i\omega C_s + i\omega L_o)^{-1}$$

$$Z(\omega) = A i\omega p + B * (\omega \rho \eta)^{1/2} (1+i) \quad (5)$$

$$\epsilon_{measured} = a + k * C_p(\text{measured}) \quad (6)$$

$$\epsilon_{measured} = [\epsilon_{cal} - (\epsilon_{cal} - 1) * [C_{p_{cal}} / (C_{p_{cal}} - C_{p_o})]] + \quad (7)$$

$$[C_{p(\text{measured})} * [(\epsilon_{cal} - 1) / (C_{p_{cal}} - C_{p_o(\text{vacuum})})]]$$

$$a = [\epsilon_{cal} - (\epsilon_{cal} - 1) * [C_{p_{cal}} / (C_{p_{cal}} - C_{p_o})]] \quad (8)$$

$$k = [(\epsilon_{cal} - 1) / (C_{p_{cal}} - C_{p_o(\text{vacuum})})] \quad (9)$$

$$C_{p(\text{measured})} \text{ IS A FUNCTION OF "k"} \quad (10)$$

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FIG. 13C

$$Z(\omega) = A i \omega \rho + B \sqrt{\omega \rho \eta} (1+i)$$

$$Z(\omega) = i \omega \Delta L + \Delta Z \sqrt{\omega} (1+i)$$

$$\Delta L = A \rho, \quad \Delta Z = B \sqrt{\rho \eta}$$



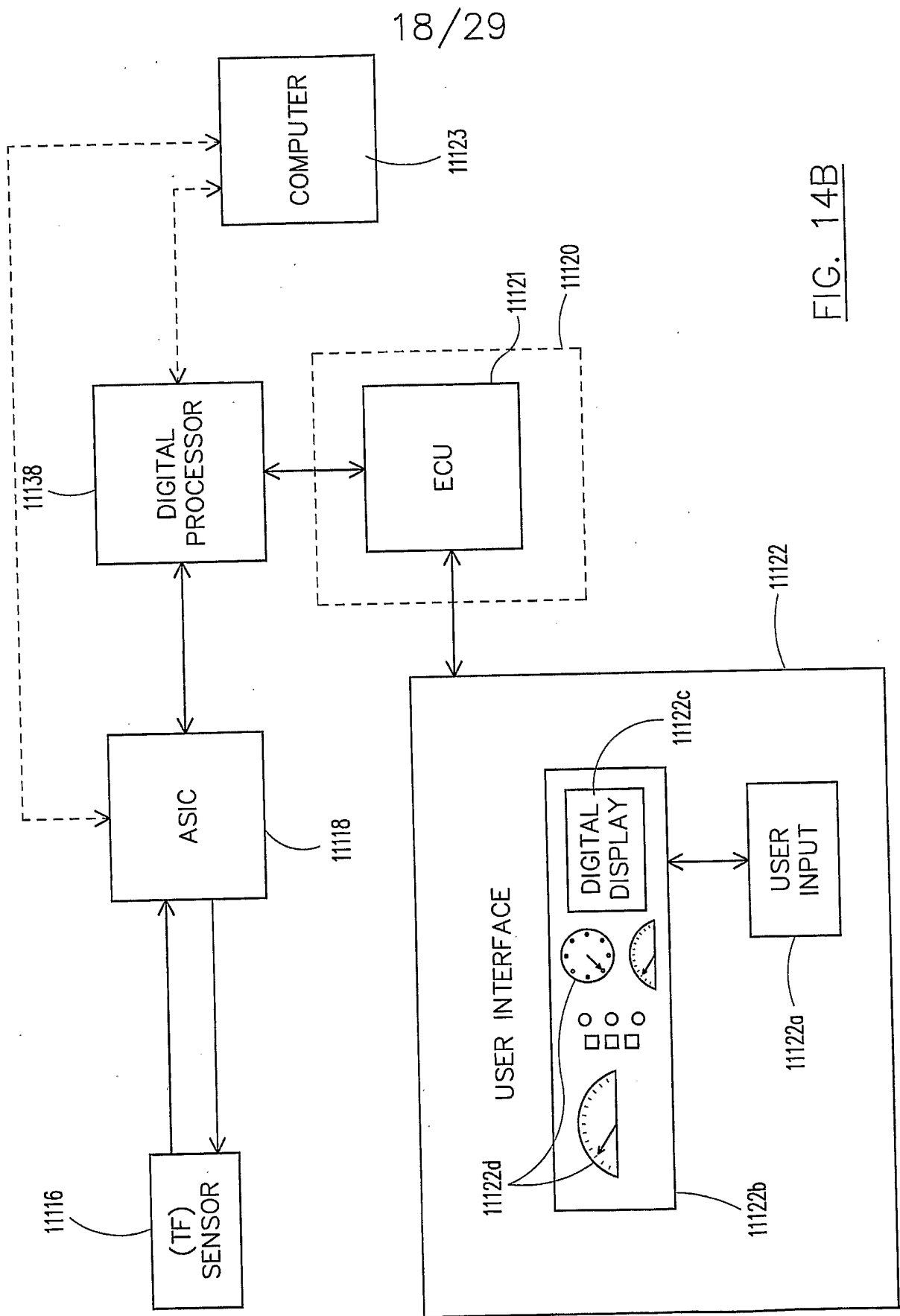


FIG. 14B

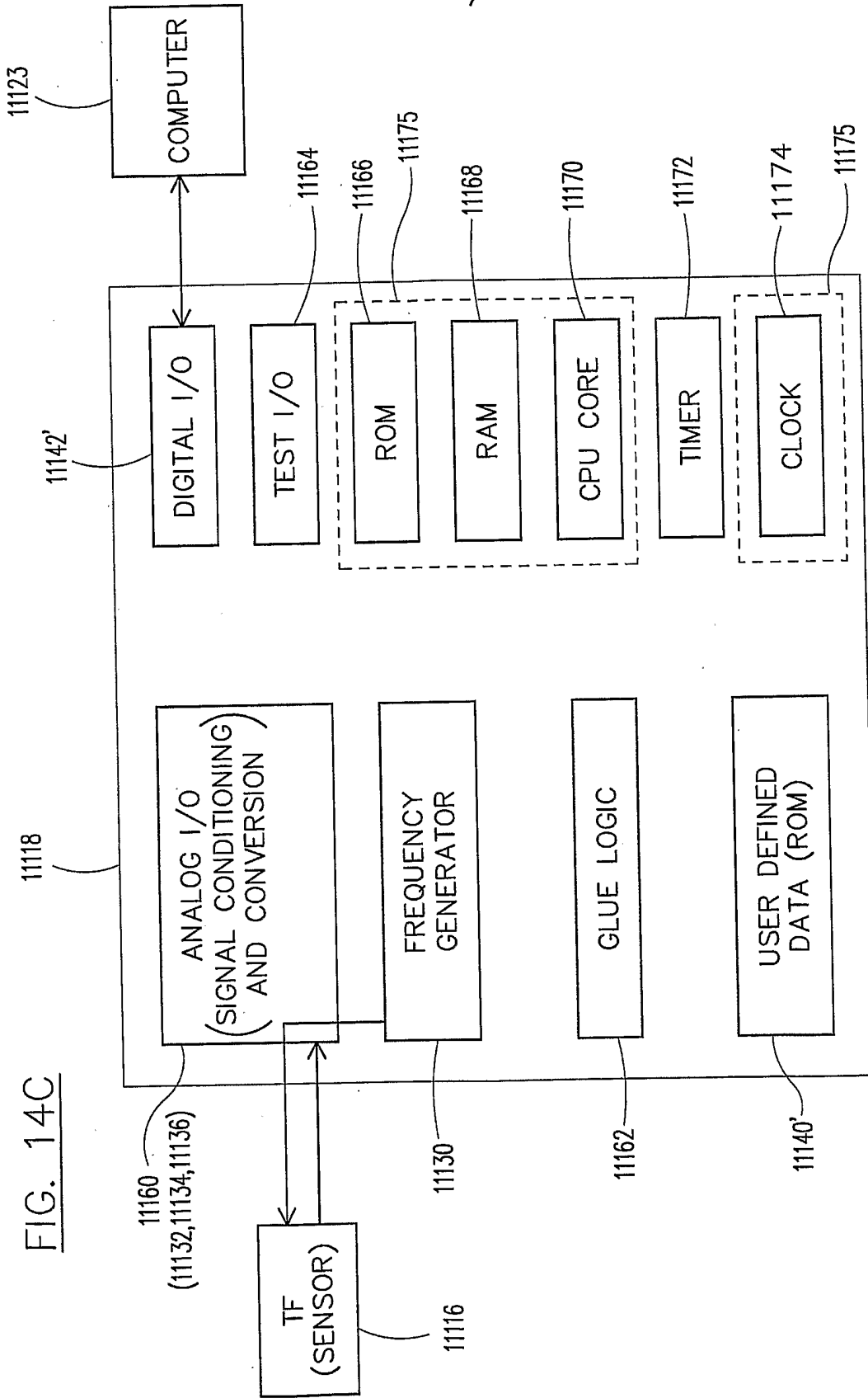


FIG. 14C

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FIG. 14D

APPROXIMATED FLUID CHARACTERISTICS

	DENSITY	VISCOSITY	DIELECTRIC CONSTANT	
TUNING FORK 1.1 TEMP. 25° C	OIL TYPE 1	$\rho$	$\eta$	$\epsilon$
	OIL TYPE 2	$\rho$	$\eta$	$\epsilon$
	OIL TYPE 3	$\rho$	$\eta$	$\epsilon$
CALIBRATION VARIABLES $V_1$ $V_2$ $V_3$ $V_4$ $V_5$ $V_6$ $V_7$	OIL TYPE 4	$\rho$	$\eta$	$\epsilon$
	OIL TYPE 5	$\rho$	$\eta$	$\epsilon$
	OIL TYPE 6	$\rho$	$\eta$	$\epsilon$
		$\vdots$	$\vdots$	$\vdots$
		$\vdots$	$\vdots$	$\vdots$
		$\vdots$	$\vdots$	$\vdots$
	OIL TYPE N	$\rho$	$\eta$	$\epsilon$

FIG. 14E

APPROXIMATED FLUID CHARACTERISTICS

	DENSITY	VISCOSITY	DIELECTRIC CONSTANT	
TUNING FORK 1.1 TEMP. 40° C	OIL TYPE 1	$\rho'$	$\eta'$	$\epsilon'$
	OIL TYPE 2	$\rho'$	$\eta'$	$\epsilon'$
	OIL TYPE 3	$\rho'$	$\eta'$	$\epsilon'$
CALIBRATION VARIABLES $V_1'$ $V_2'$ $V_3'$ $V_4'$ $V_5'$ $V_6'$ $V_7'$	OIL TYPE 4	$\rho'$	$\eta'$	$\epsilon'$
	OIL TYPE 5	$\rho'$	$\eta'$	$\epsilon'$
	OIL TYPE 6	$\rho'$	$\eta'$	$\epsilon'$
		$\vdots$	$\vdots$	$\vdots$
		$\vdots$	$\vdots$	$\vdots$
		$\vdots$	$\vdots$	$\vdots$
	OIL TYPE N	$\rho'$	$\eta'$	$\epsilon'$

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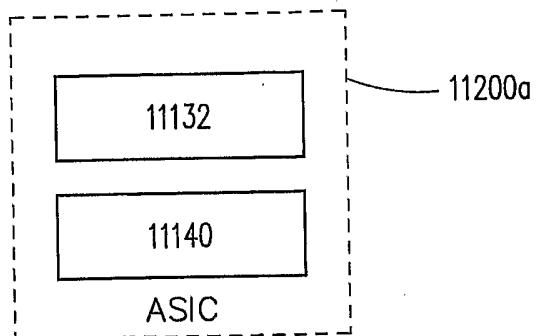


FIG. 15A

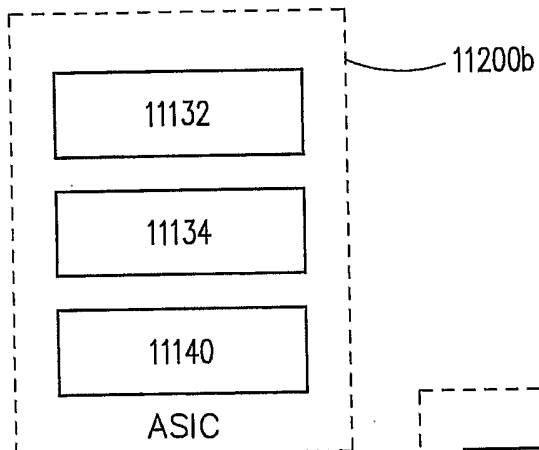


FIG. 15B

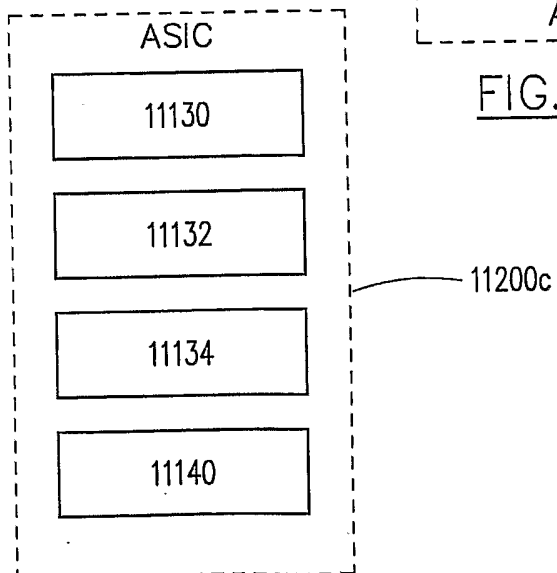


FIG. 15C

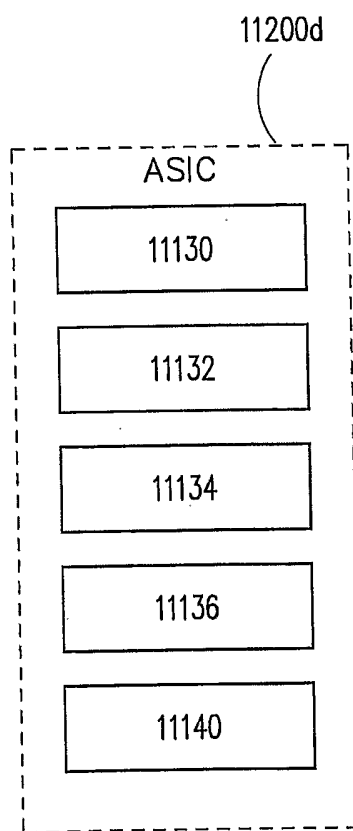


FIG. 15D

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FIG. 16A

## APPLICATIONS

- TRANSPORTATION (AIR, SEA, LAND, SPACE)
- WORKING VEHICLES (CONSTRUCTION, AGRICULTURE, MINING, SUB-SEA ROV, TRUCKING)
- MILITARY VEHICLES (HMVVE, TANKS, TRUCKS, ect)
- HEAVY MACHINERY (INDUSTRIAL, MANUFACTURING)
- INDUSTRIAL WASTEWATER
- DRINKING WATER
- OIL AND GAS EXPLORATION AND PRODUCTION  
(DRILLING, WELLBORE AND PRODUCTION LOGGING, LABORATORY OIL ANALYSIS, SEPARATION)
- FUEL AND HYDROCARBON TRANSPORTATION
- REFINING (REACTORS, CONDUITS, CONDENSERS)
- PETRO CHEMICAL (REACTORS, CONDUITS, CONDENSERS)
- CHEMICAL (REACTORS, CONDUITS, CONDENSERS)
- FOOD STORAGE AND PROCESSING
- HEAT EXCHANGERS
- CRYOGENIC SYSTEMS
- BIOSENSORS
- CHEMICAL SENSORS
- POWER GENERATION (RECIPROCAL, TURBINE, HYDRO, FUEL CELLS)
- VAPOR DETECTION (HUMIDITY, FUMES)
- MEDICAL (DEVICE AND PHARMA)
- LABORATORY (AUTOMATED, HAND-HELD)
- PRINTING (INDUSTRIAL PRINTERS, DESKJET)
- MANUFACTURING (PAINTS, INKS)
- MANUFACTURING EQUIPMENT MONITORING  
(CNC EQUIPMENT LUBRICANT, EXTRUSION POLYMER MONITORING)
- ENVIRONMENTAL HAZARD SAMPLING AND MONITORING
- HOMELAND SECURITY
- PETROCHEMICAL TRANSPORTATION

## FLUIDIC SYSTEMS

FIG. 16B

- ENGINES (RECIPROCAL, TURBINE, ELECTRIC)
- BRAKES (AUTOMOTIVE, INDUSTRIAL)
- TRANSMISSIONS (HYDRAULIC, GEAR)
- HEAT EXCHANGERS (RADIATORS, HVAC&R, COOLERS, CHILLERS)
- FUEL STORAGE AND TRANSMISSION
- PIPELINES
- STORAGE TANKS
- HVAC&R SYSTEMS
- COMPRESSORS (AIR, GAS)
- VACUUM PUMPS
- GEAR BOXES
- DEWARs
- BUILDINGS (ATMOSHERICS IN BUILDINGS AND HOUSES ..aka. HUMIDITY SENSOR)
- MAMMALIAN BODY (VEINS, LUNGS, GUT)
- WELLS (OIL, GAS, WATER)
- PRINTING PRESS
- TURBINES
- LUBRICATION SYSTEMS

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FIG. 16C

## FLUIDS

- OILS, GREASES, HYDRAULICS (SYNTHETICS AND HC)
- GASES (REACTOR FEEDS, HC'S, INORGANICS INCLUDING CRYO'S)
- HEAT EXCHANGER FLUID (WATER, GLYCOL, "DOWTHERMS", REFRIGERANTS)
- CRUDE OIL
- FUEL (GASOLINE, DEISEL, BIODEISEL, ETHANOL, METHANOL, HYDROGEN)
- MAMMALIAN (BLOOD, URINE, VAGINAL)
- FOOD (BATTER, OILS, GREASES, GELS, PASTES, ALCOHOLS)
- SOLVENTS (LABORATORY, INDUSTRIAL, HOME)
- CLEANERS (WINDSHEILD WASHER FLUID, ETC.)
- INK
- FLUIDIZED BEDS
- AMBIENT AIR
- EXHAUST GASES
- HYDROGEN
- INERT GASES

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FIG. 17A

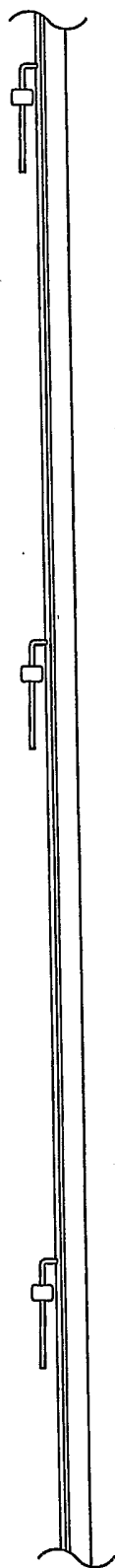


FIG. 17B

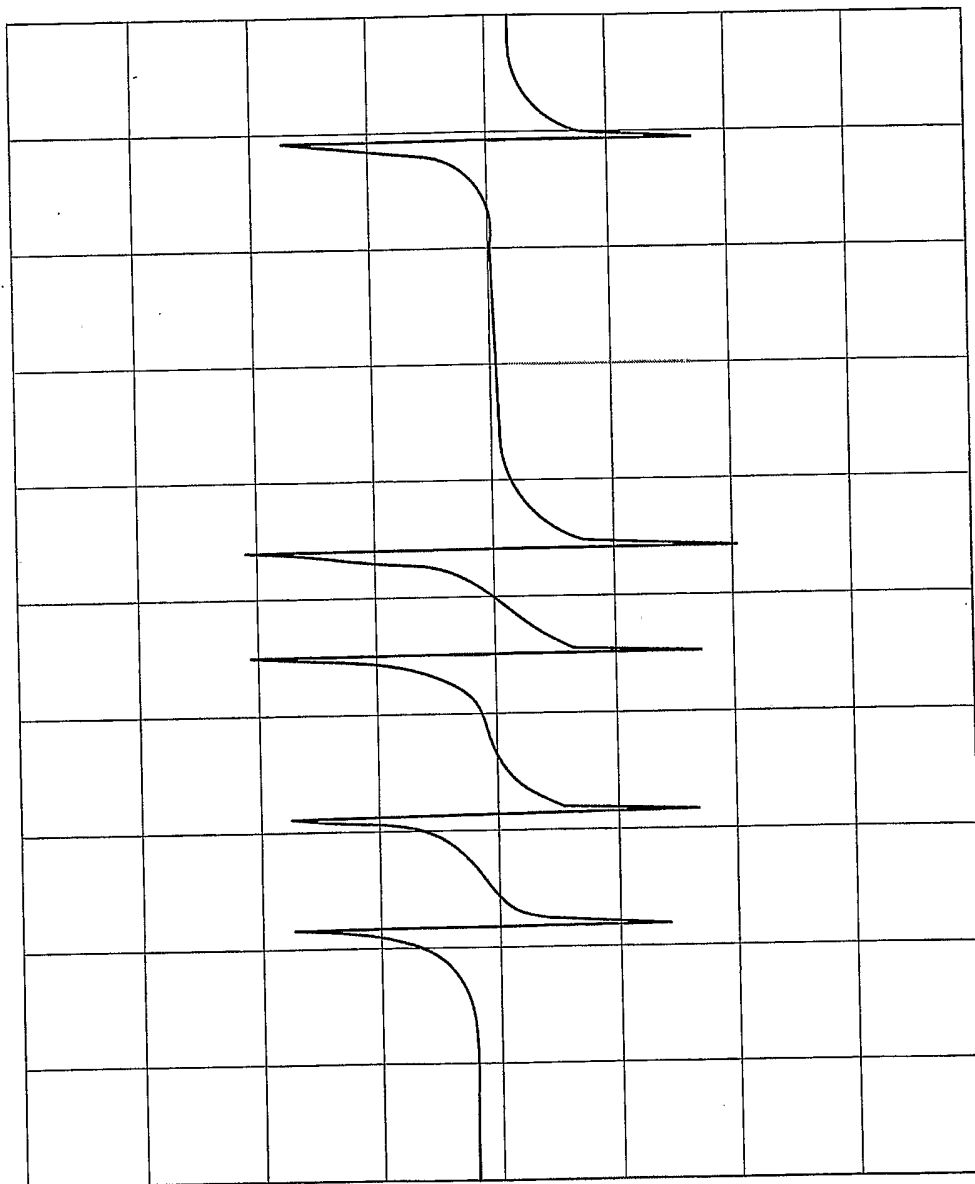


FIG. 17C

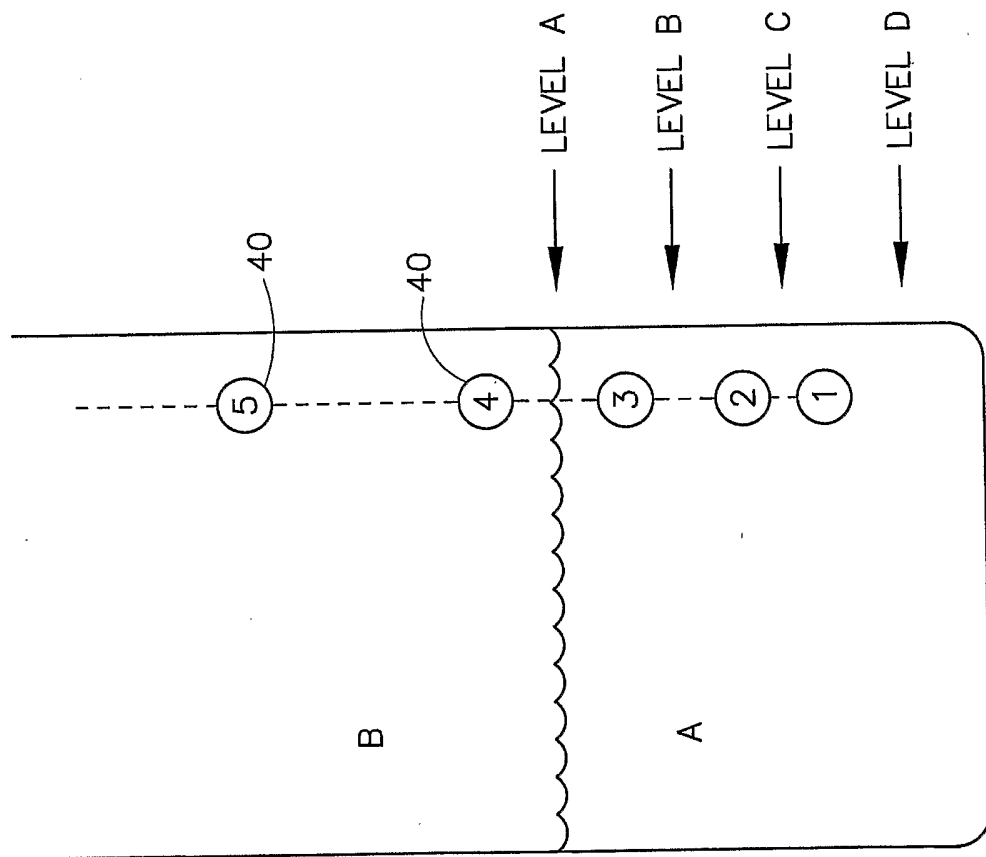


FIG. 17D

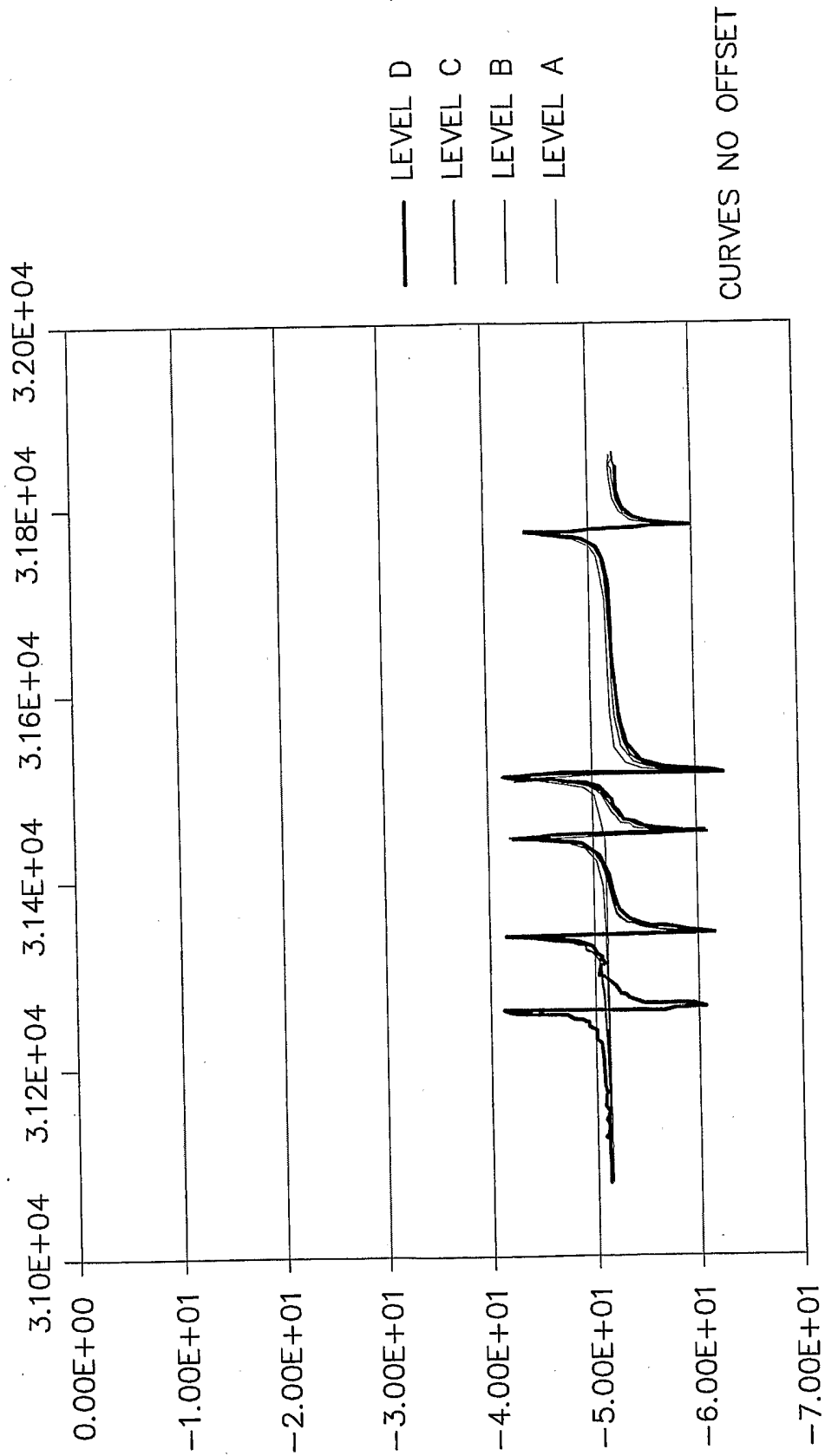


FIG. 17E

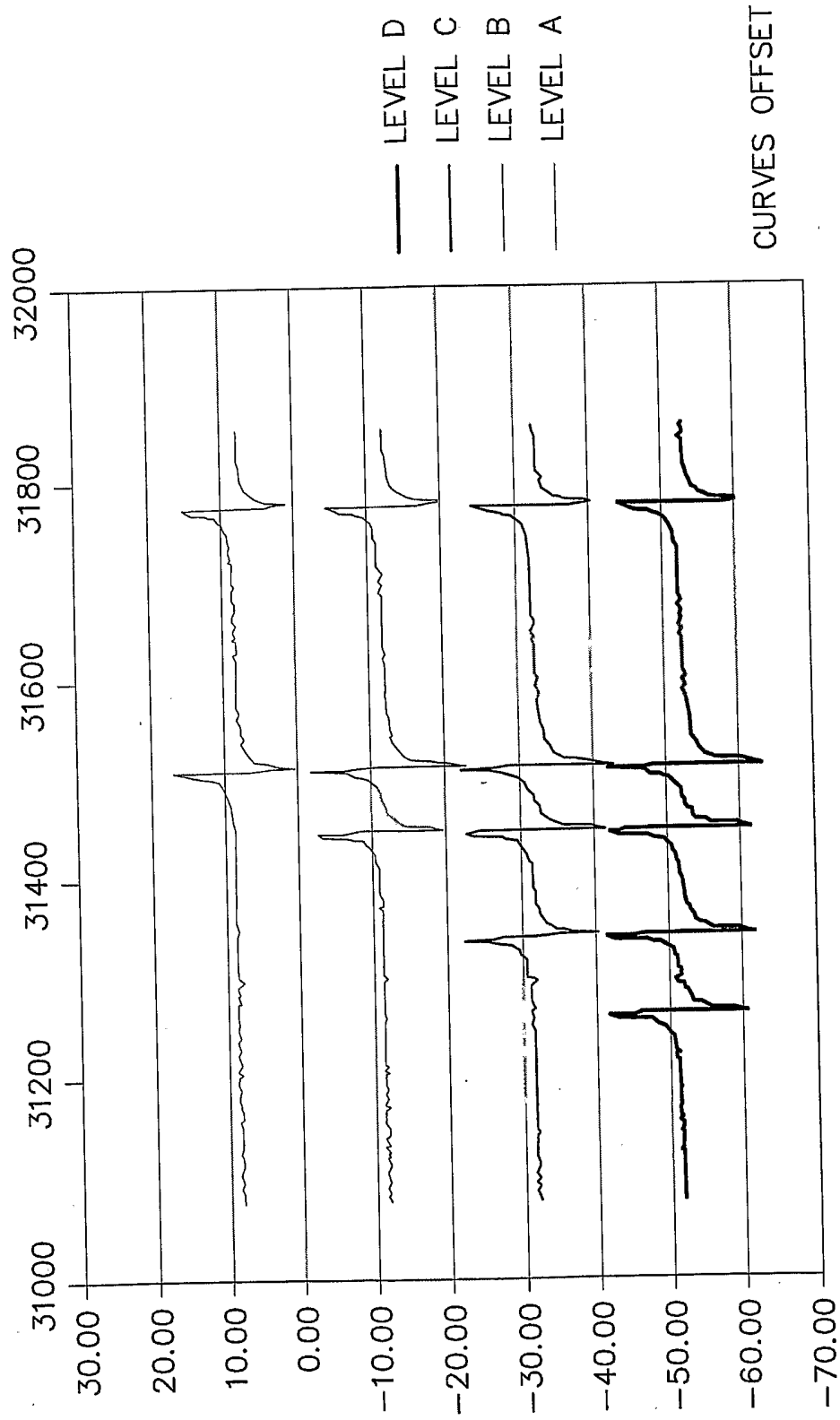


FIG. 17F

