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(54) Title of the Invention: **Apparatus and method for measuring flow**
Abstract Title: **Apparatus and method for measuring flow**

(57) An apparatus (180) and corresponding method for measuring a flow (110) within a region (260) surrounded by a wall of a pipe (100) is provided. The apparatus (180) includes a transducer arrangement (200, 300, 510, 540) disposed substantially around an external surface of the wall of the pipe (100) for emitting a plurality of beams (250A) of acoustic radiation into the region (260) and for receiving acoustic radiation (250A, 250B) transmitted through and/or reflected from the region (260), wherein: (a) the plurality of beams (250A, 250B) are arranged to interrogate sampling points off-axis and on-axis in a cross-section of the region (260) for determining whether the flow is laminar, transitional or turbulent; (b) the plurality of beams (250A, 250B) are employed in a repetitive manner to monitor temporal fluctuations in the flow (110); (c) the sensor arrangement (300, 510, 540) is operable to sense spatially varying attenuation of the received acoustic radiation thereat for determining an occurrence of one or more gas volumes (700) present within the region (260); (d) the transducer arrangement (200, 300) is employed for performing time-of-flight measurements for propagation of the acoustic radiation within the region (260) in upstream and downstream flow directions; and (e) the transducer arrangement (200, 300, 510, 540) is coupled to a corresponding signal processing arrangement for exciting the transducer arrangement (200, 300, 510, 540) and for processing received signals generate by the transducer arrangement (200, 300, 510, 540) to provide measurement output data representative of at least one of: flow velocity within the region (260), an indication of phases present in the region (260) (gas fraction), a flow rate through the region (260). The transducer arrangement may comprise a spatially distributed array of sensors implemented using a plurality of Bragg grating filter sensors distributed along one or more optical fibres.

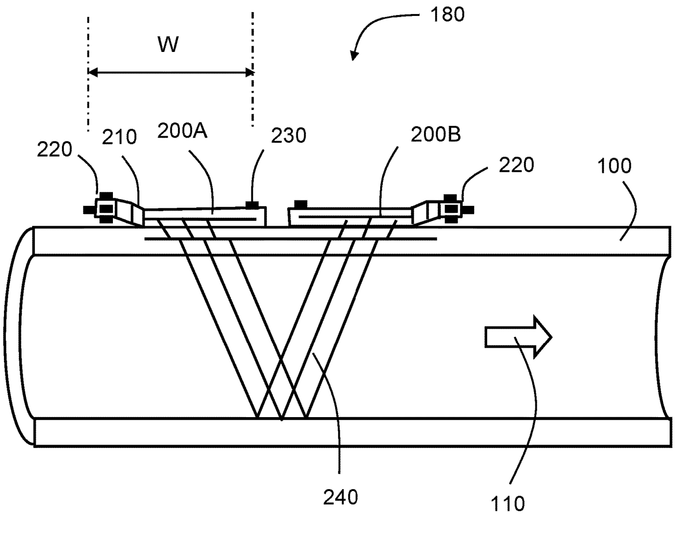

FIG. 3

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(58) Field of Search:
INT CL **G01F, G01N**
Other: **WPI, EPODOC**

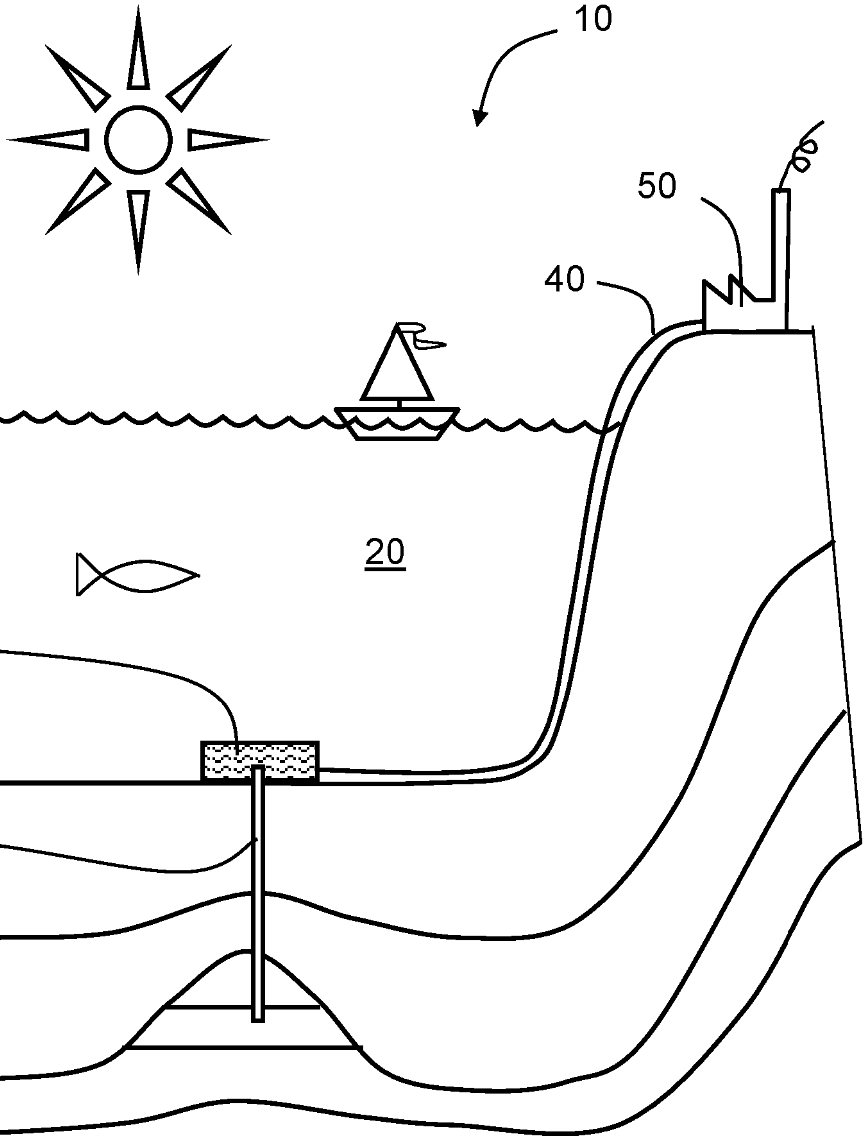

FIG. 1

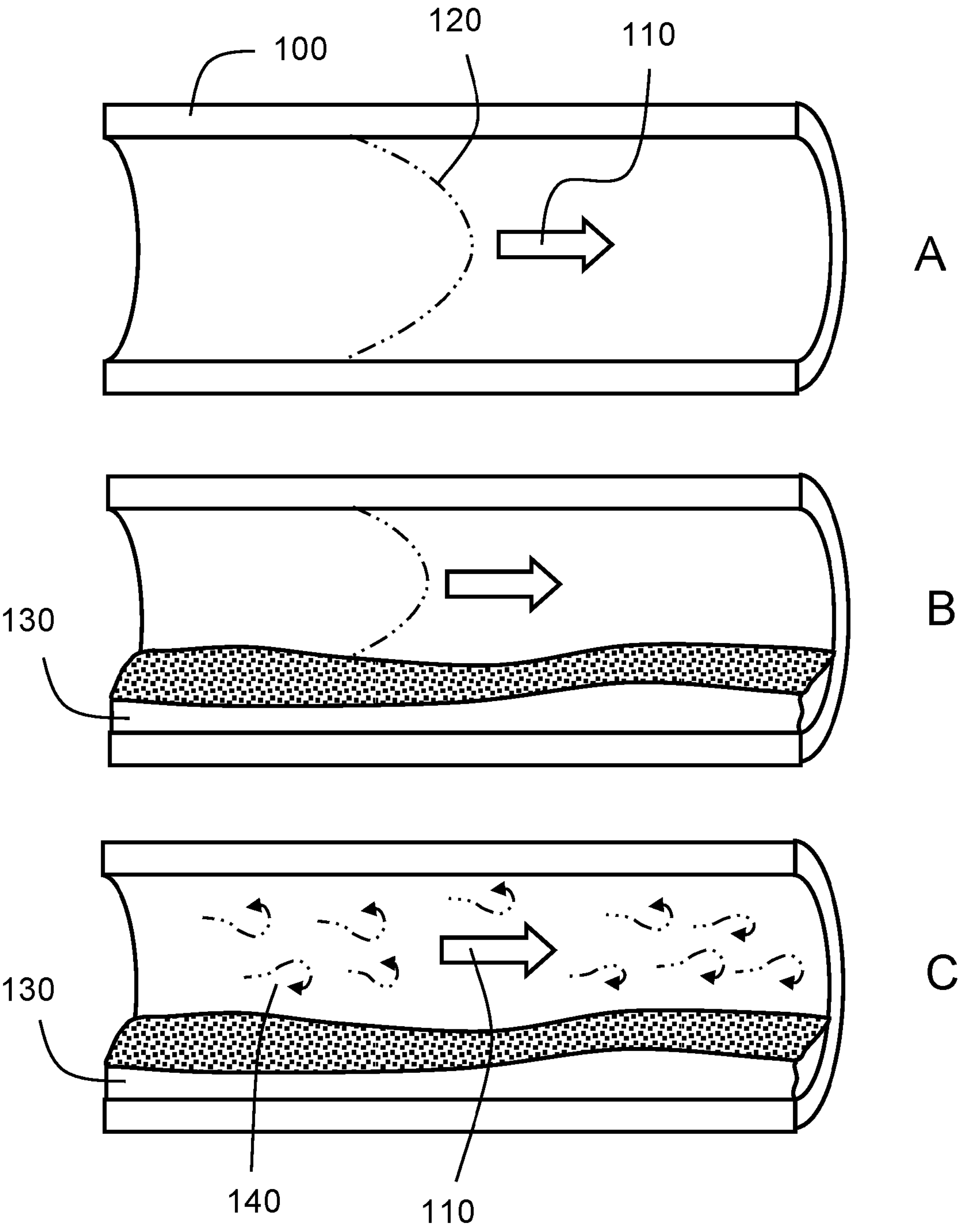

FIG. 2

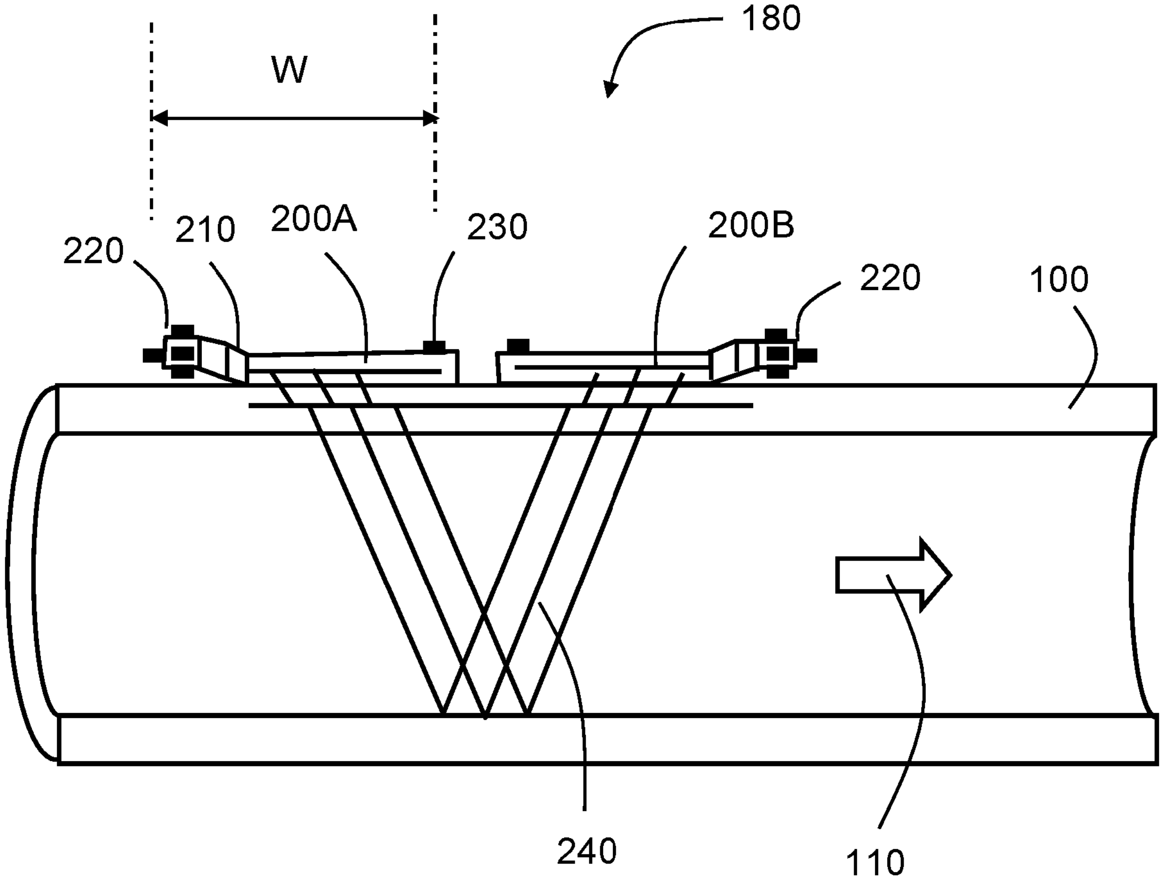

FIG. 3

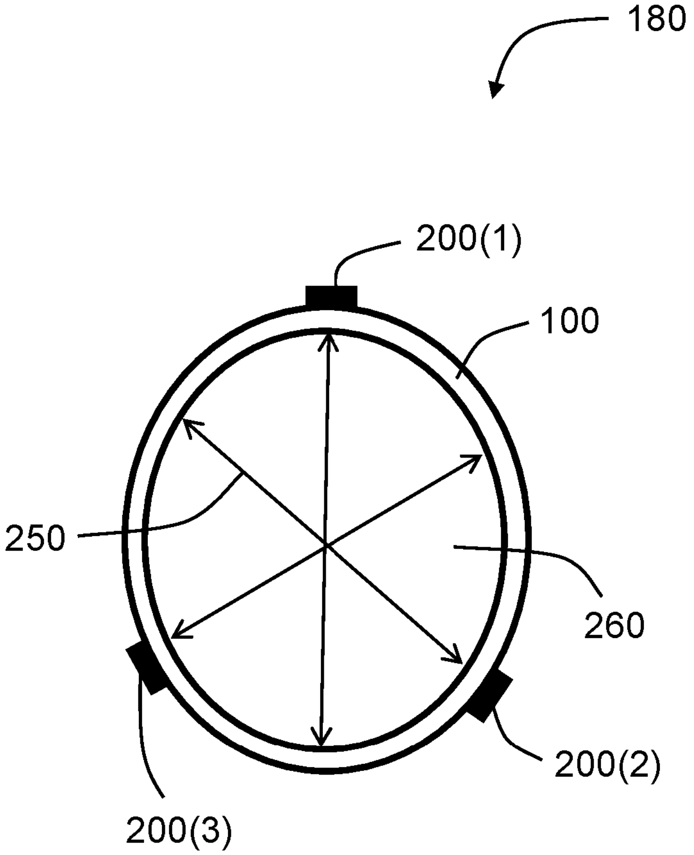

FIG. 4

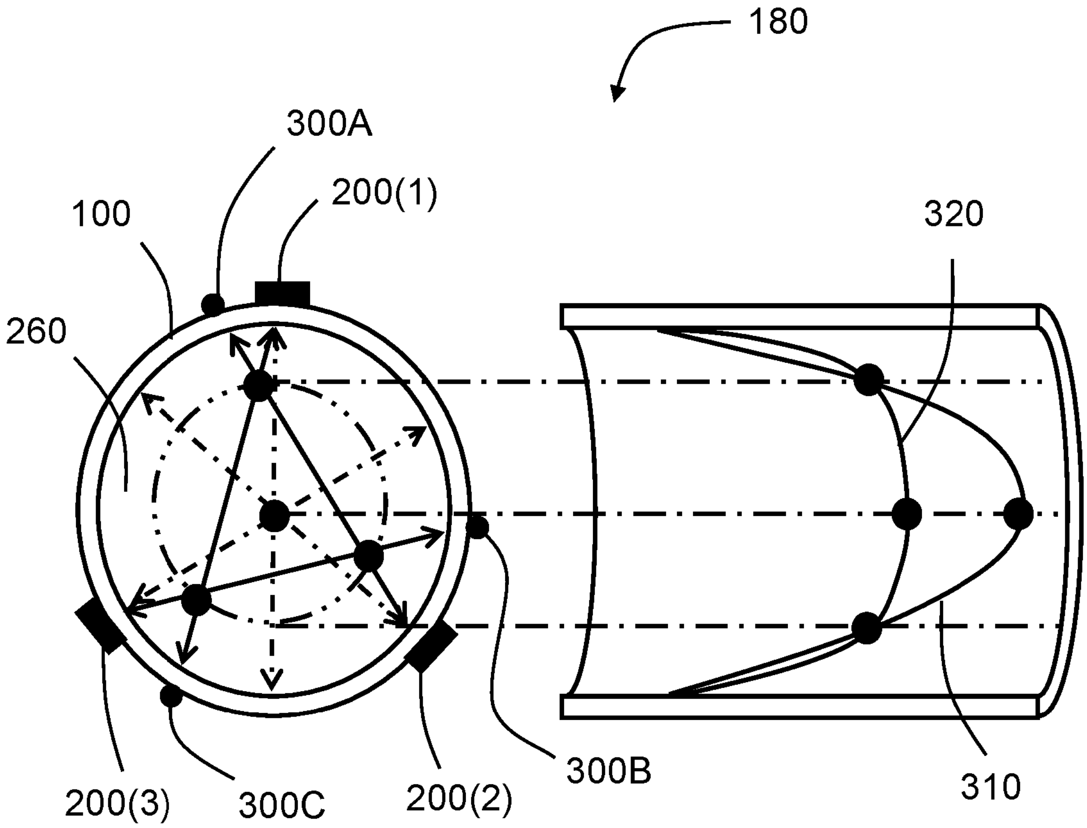

FIG. 5

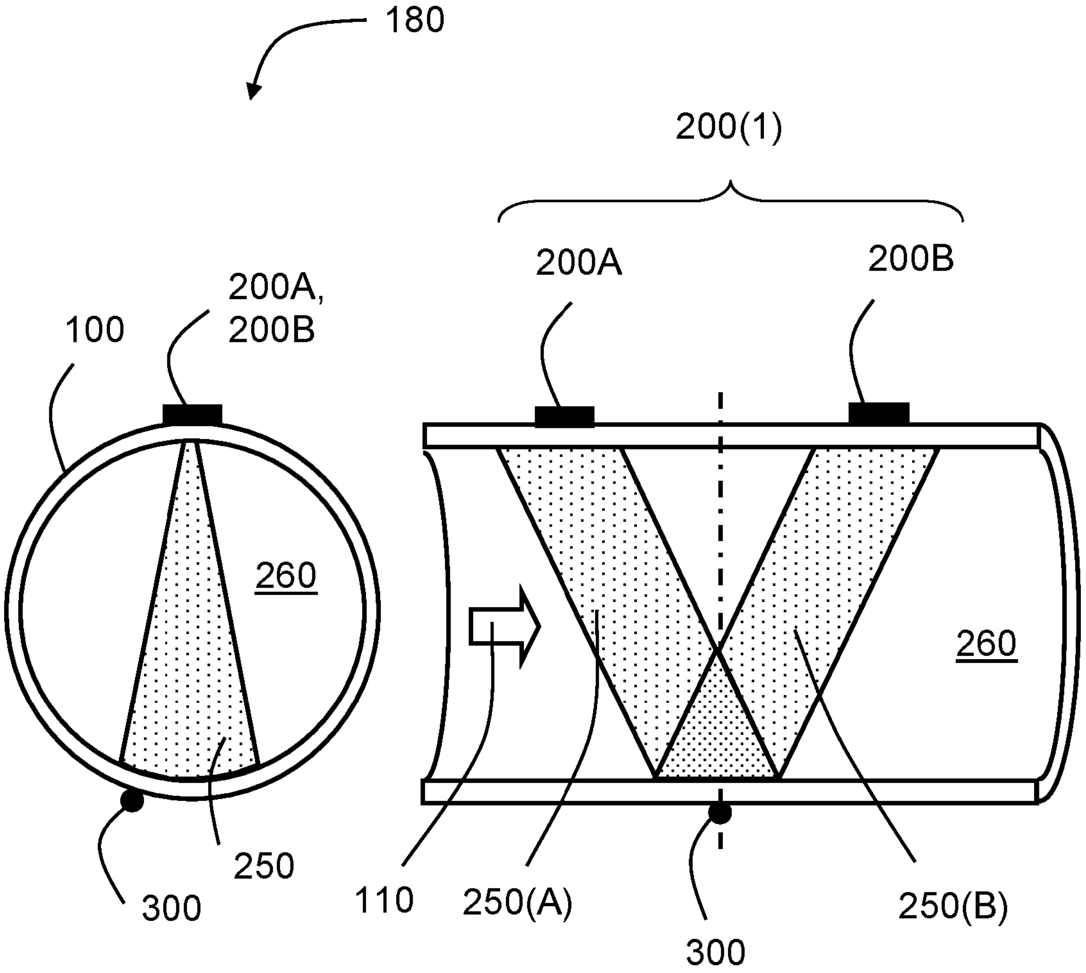
180
200(1)
200A
200B
100
200A,
200B
260
260
250
300
110
250(A)
300
250(B)

FIG. 6

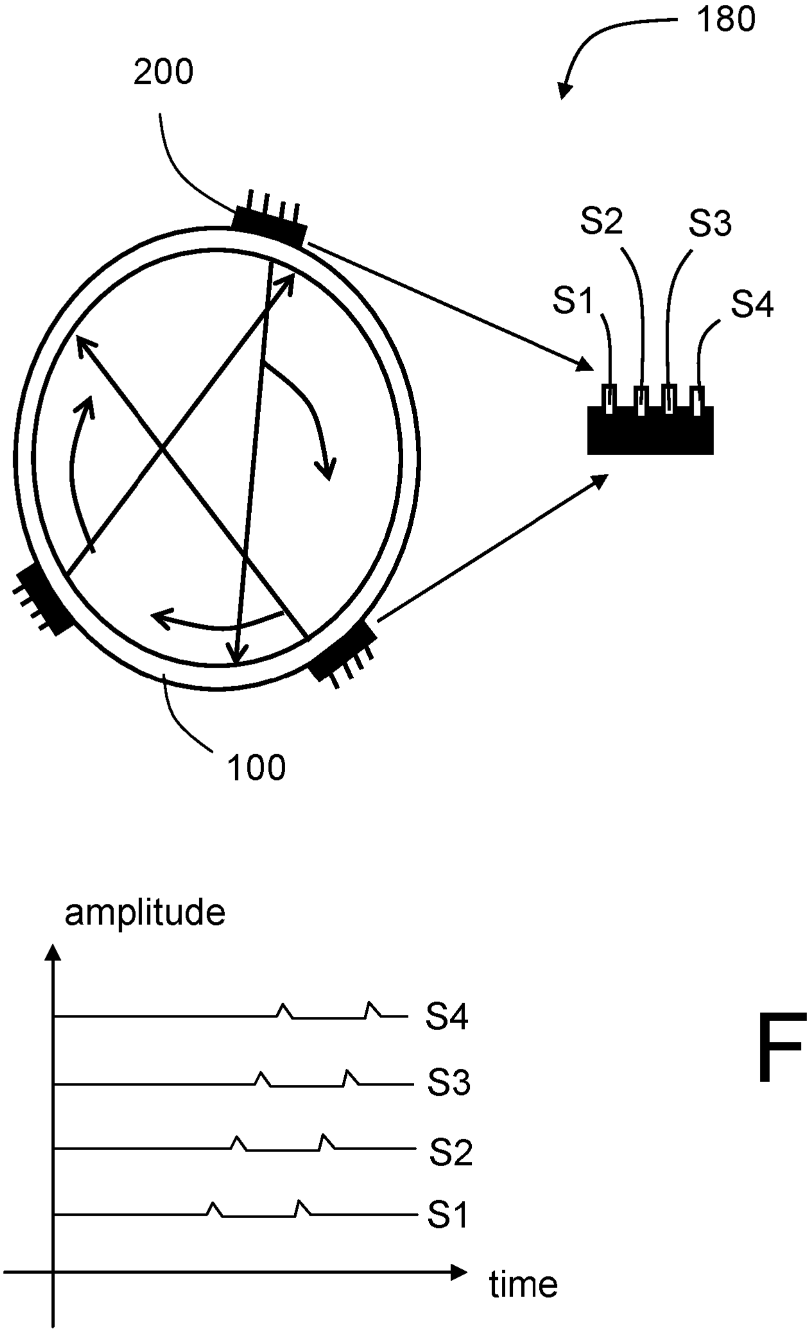

FIG. 7

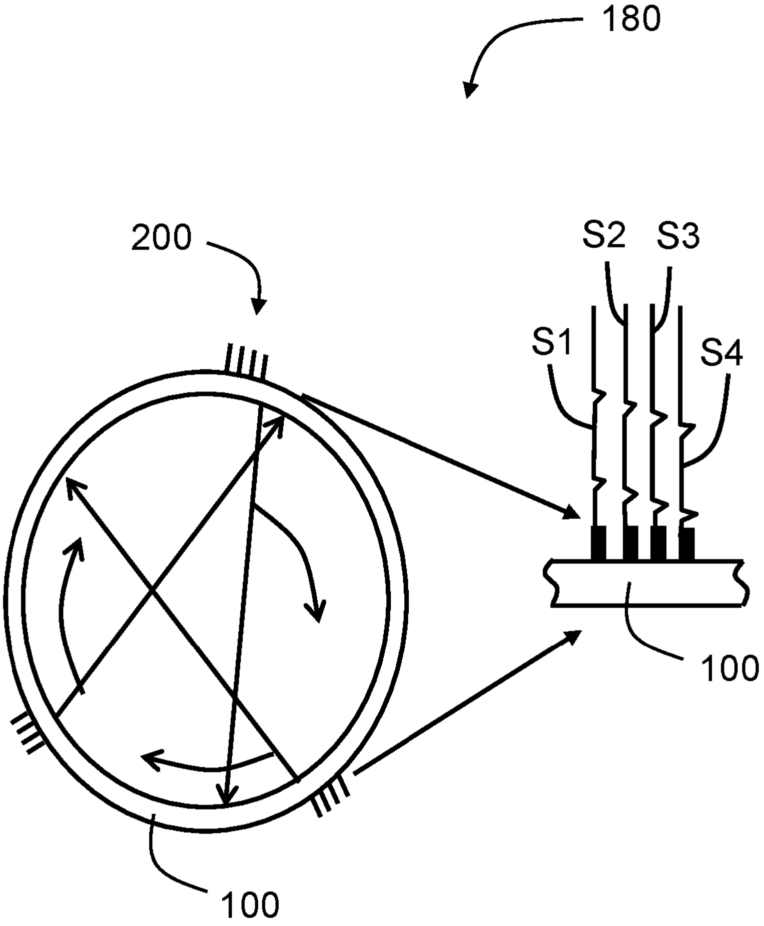

FIG. 8

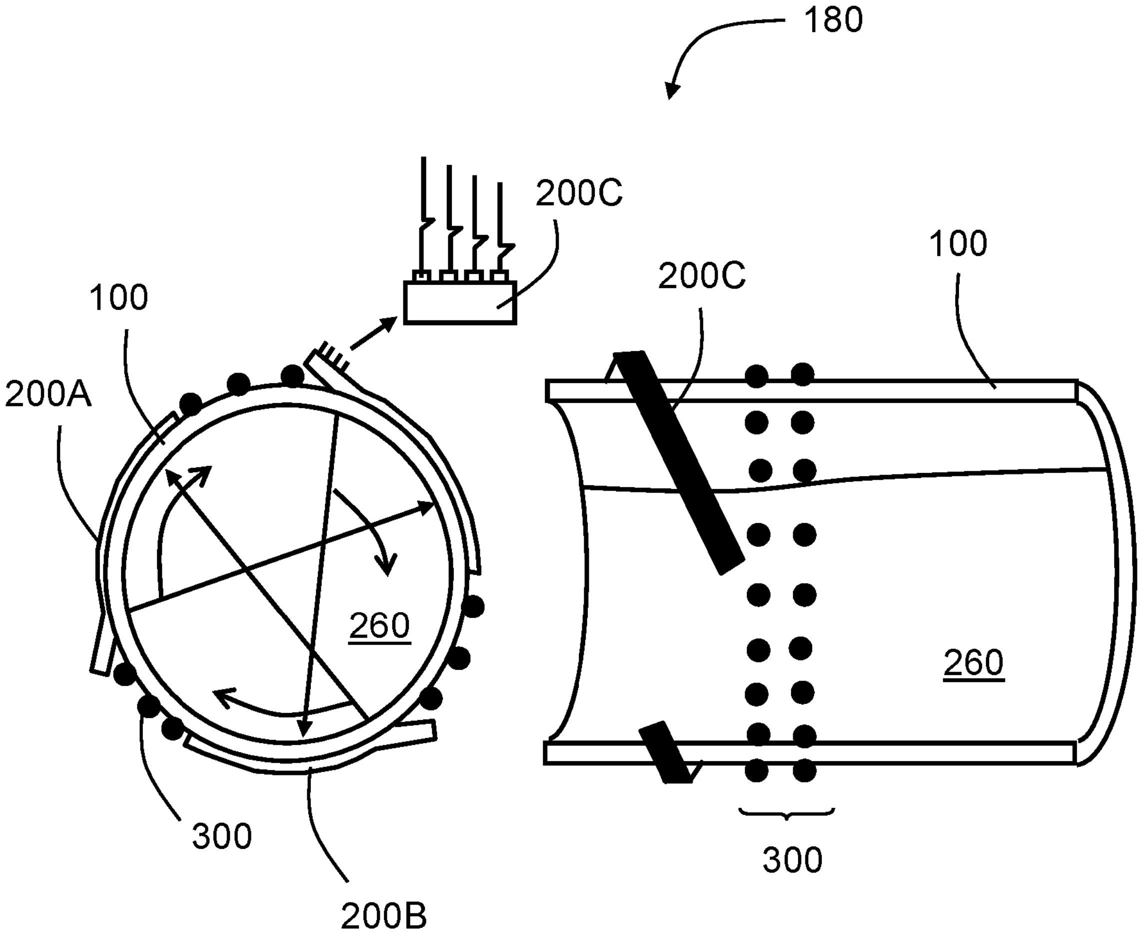

FIG. 9

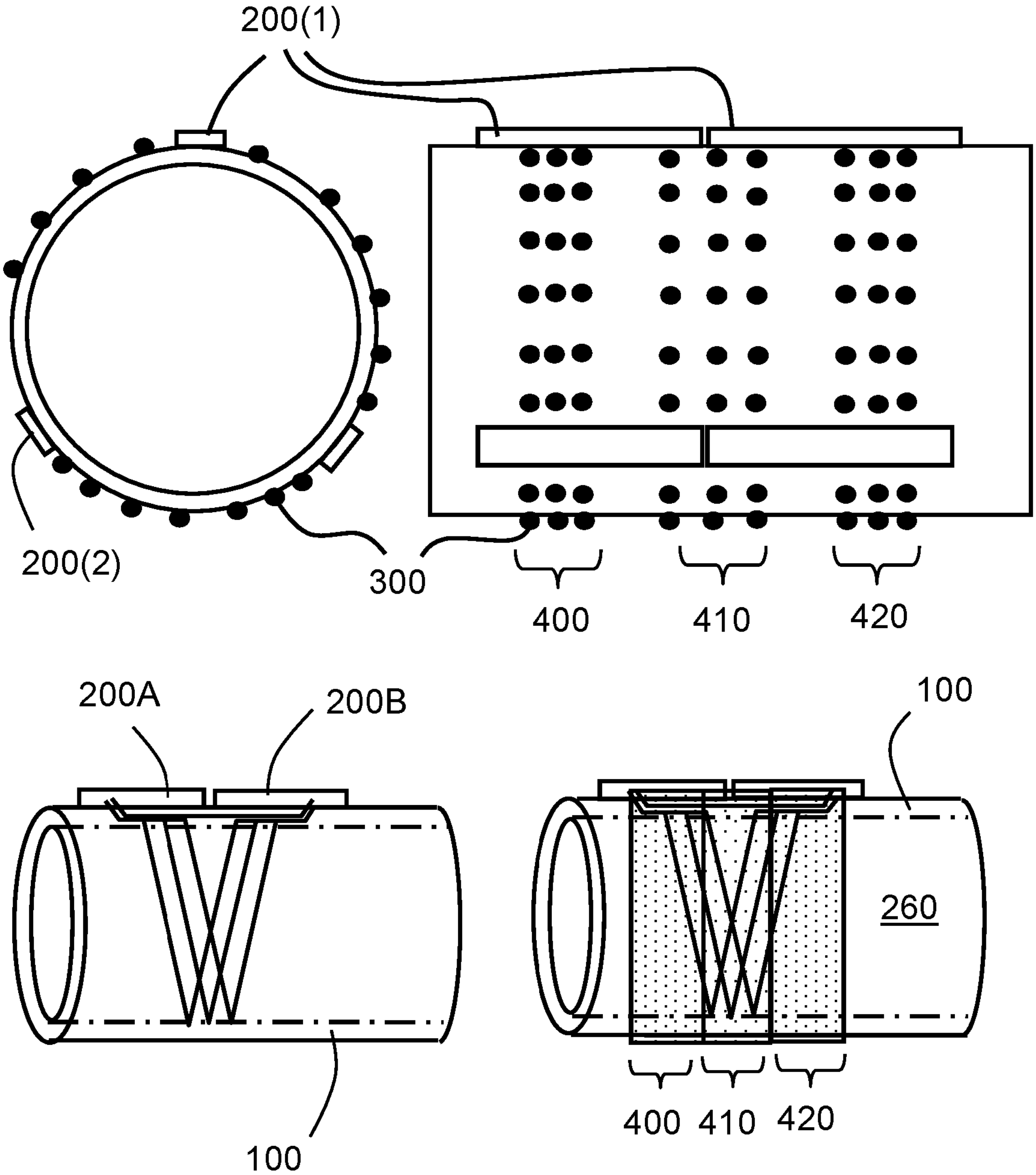

FIG. 10

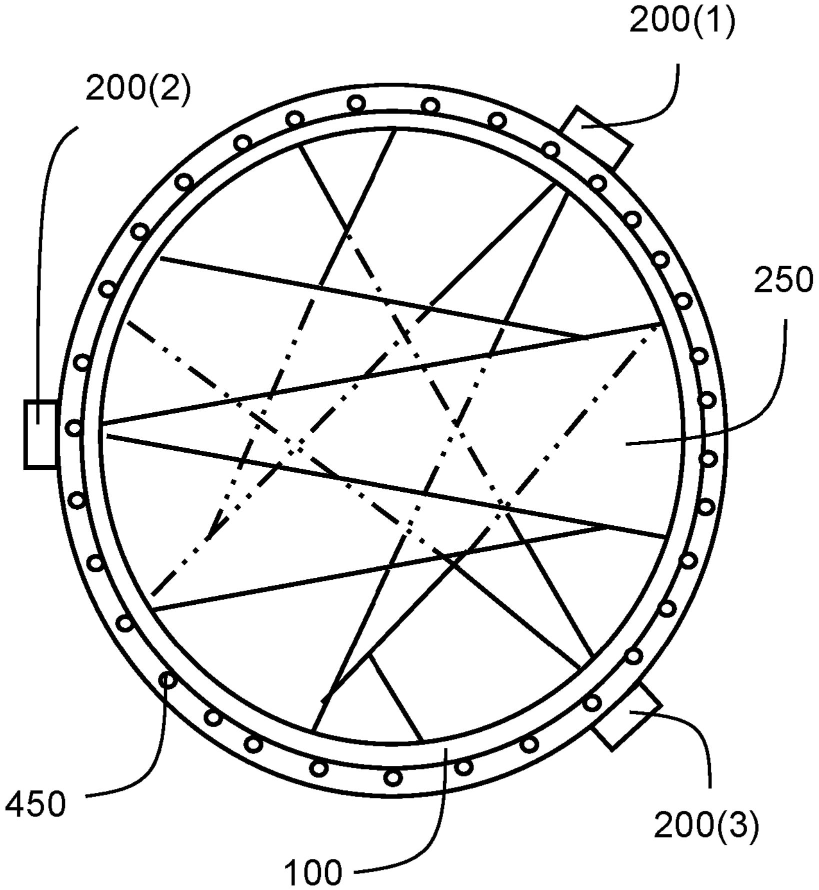

FIG. 11

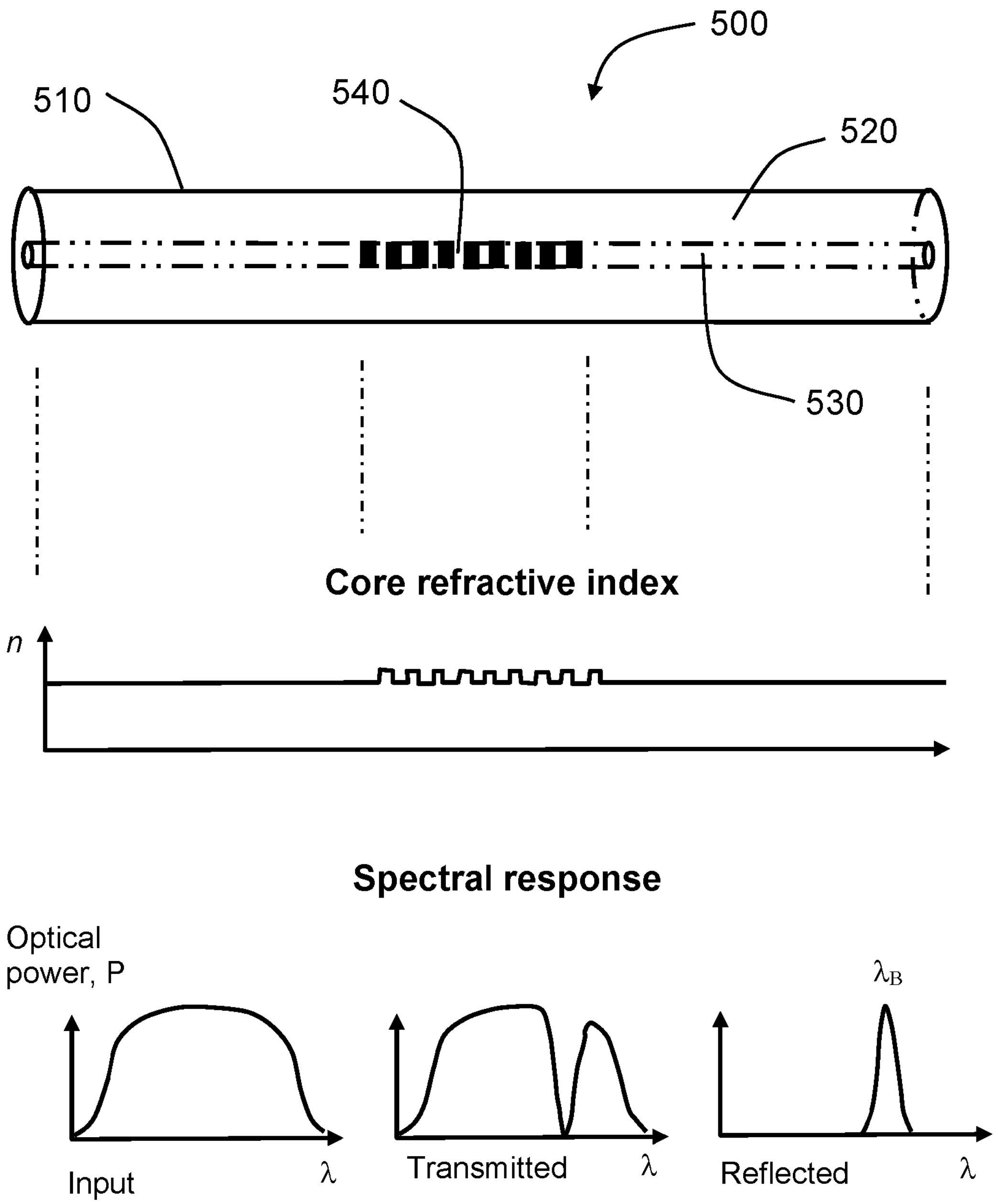
500
510
540
520
530
Core refractive index
n
Spectral response
Optical power, P
λB
Input
λ
Transmitted
λ
Reflected
λ

FIG. 12

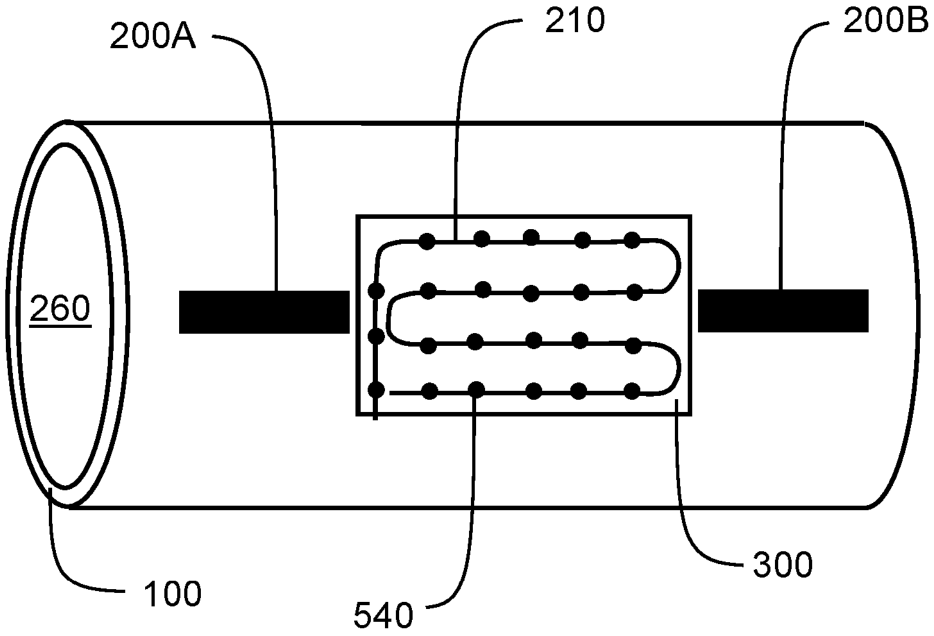

FIG. 13

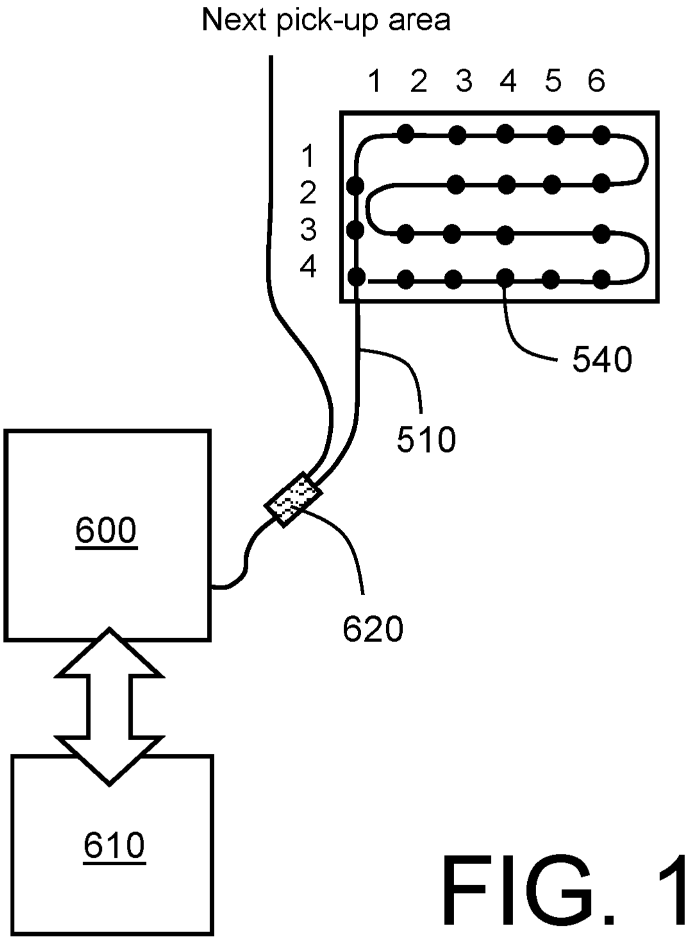

FIG. 14

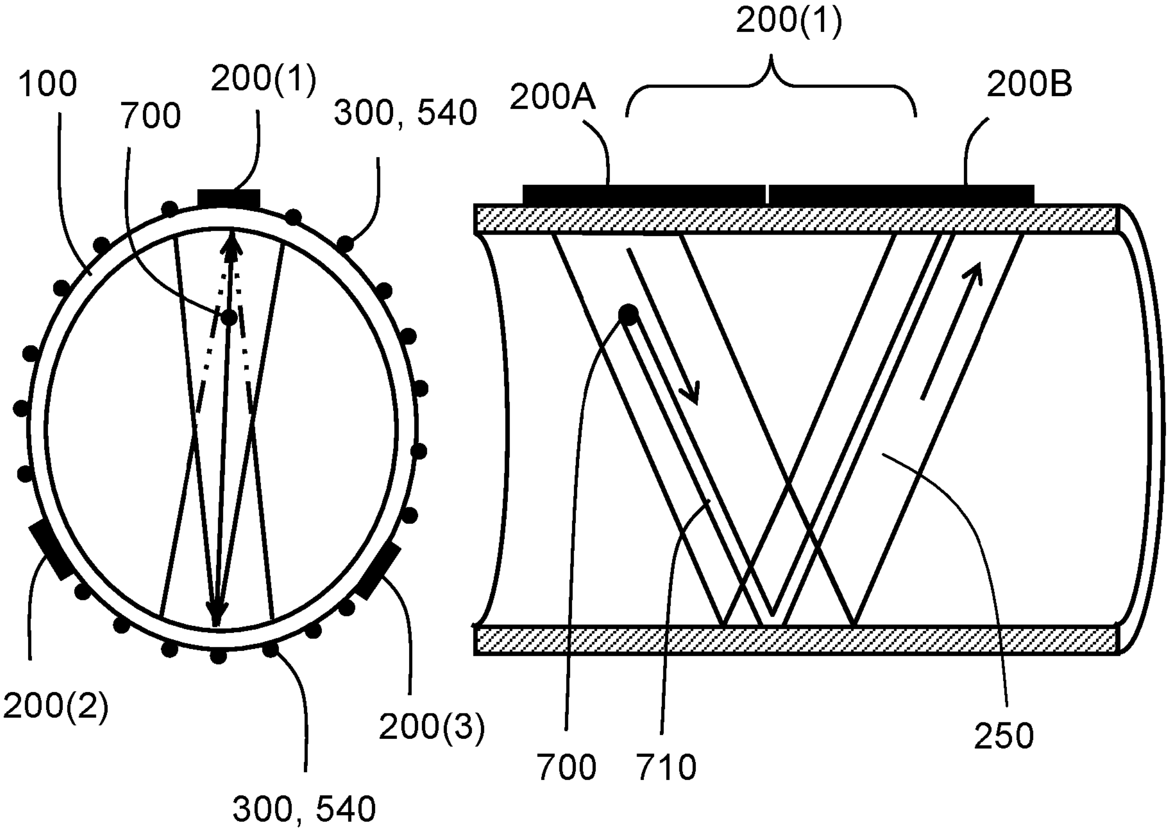
100
700
200(1)
300, 540
200(2)
200(3)
300, 540
200(1)
200A
200B
700
710
250

FIG. 15

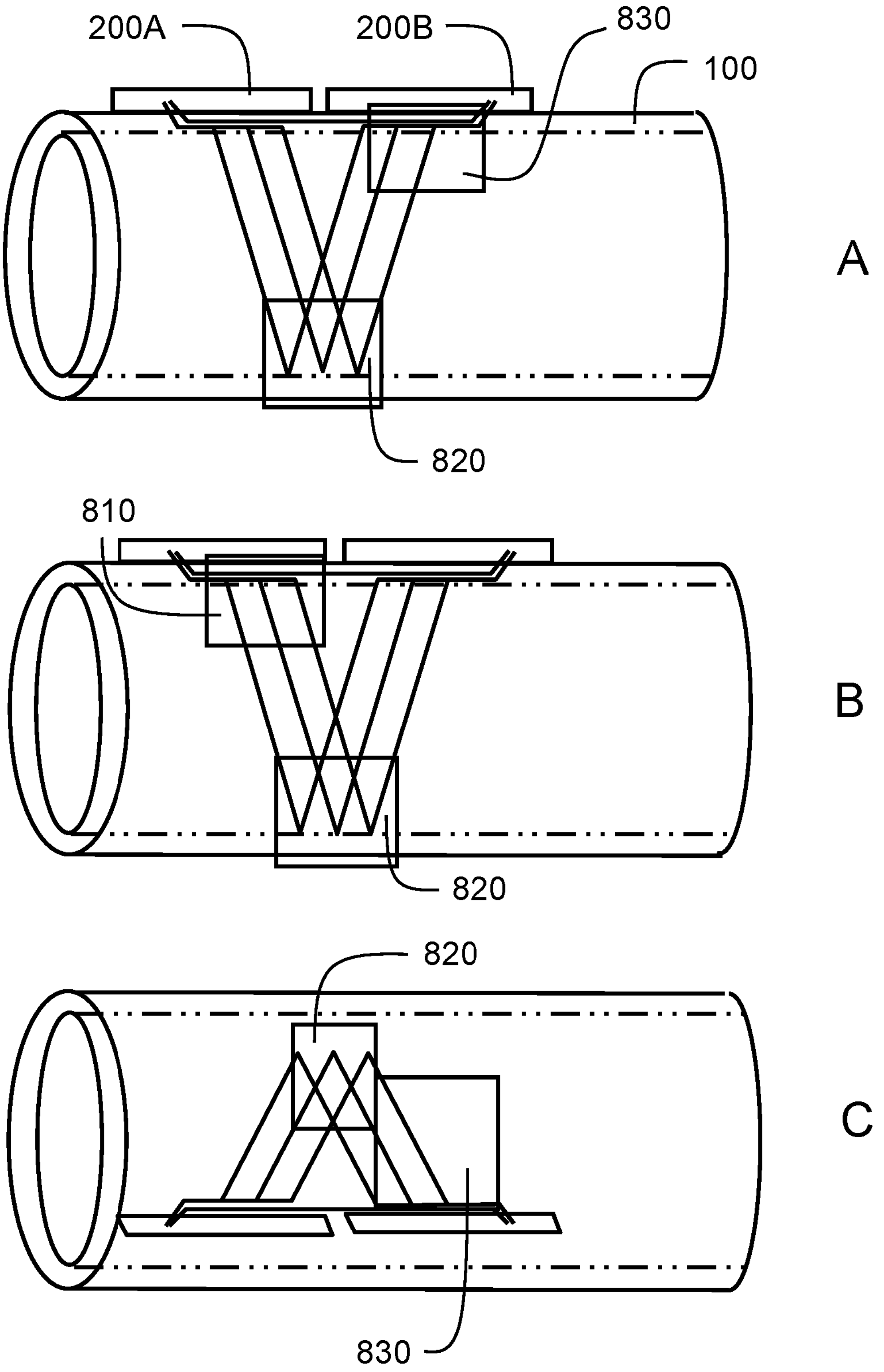

FIG. 16

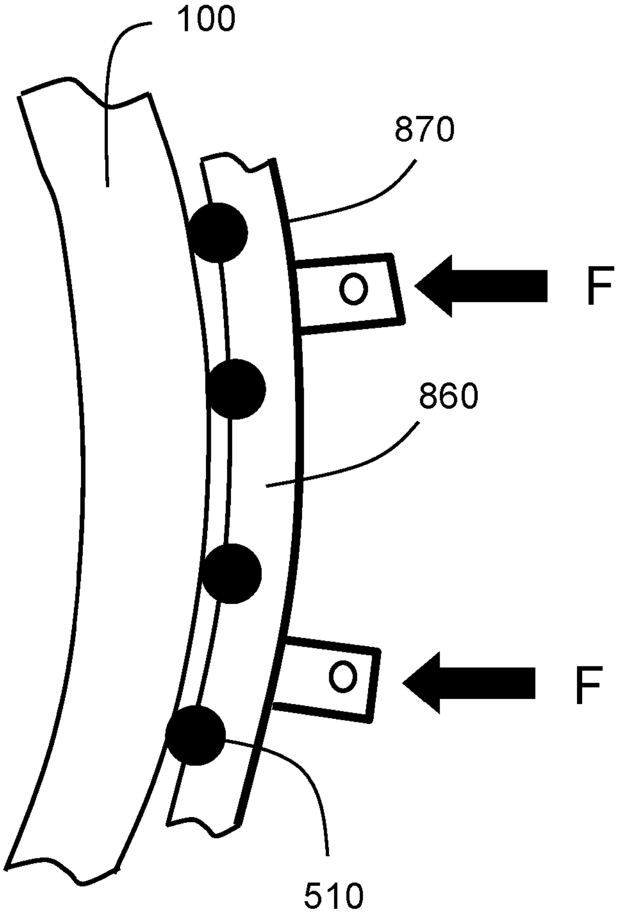

FIG. 17

APPARATUS AND METHOD FOR MEASURING FLOW

Technical Field

The present disclosure relates to apparatus for measuring flow, for example to apparatus for measuring multiphase flow. Moreover, the disclosure concerns methods of using aforesaid apparatus for measuring flow, for example to methods of measuring multiphase flow. Furthermore, the disclosure relates to software products recorded on non-transient machine-readable data storage media, wherein the software products are executable upon computing hardware for implementing aforesaid methods.

Background

Many situations in industry, for example in chemical industries, petrochemicals industry and nuclear power industry, require measurement of a flow rate of a fluid through a conduit or pipe. Moreover, when a temperature measurement and a pressure measurement across an orifice, through which the fluid flows, are made, it is feasible to infer a density and a viscosity of the fluid to be computed. However, an issue of measurement accuracy arises when the fluid flow is turbulent and/or is spatially inhomogeneous. Situations of spatial non-homogeneity arise, for example in petrochemicals industries wherein fluids pumped from an oil well often include a multiphase mixture of oil, water and sand particles. Moreover, physical characteristics of such multiphase flow are susceptible to changing considerable on an onset of turbulent flow. Many known reported flow measuring apparatus are designed to cope with non-turbulent flows, and will potentially generate erroneous flow measurements when confronted with multiphase flows and/or turbulent flows. There is a contemporary need for highly accurate non-intrusive flow measuring apparatus for monitoring flows of crude oil containing minor fractions of water and/or gas.

In a published European patent application EP 2 431 716A1 ("*A multiphase flow meter and a correction method for such a multiphase flow meter*", Applicant – Services Petroliers Schlumberger, Paris, France; inventors – Lupeau & Baker), there is described a flow meter for measuring a flow rate of a multiphase fluids mixture comprising at least one gas phase and one liquid phase, wherein the flow meter comprises:

(i) a pipe section through which the multiphase fluid mixture flows comprising a throat between an upstream part and a downstream part such as to generate a pressure drop between the upstream part and the downstream part; and

(ii) a fraction measuring device for estimating a fractional flow rate for each phase of the multiphase fluid mixture passing through the throat.

The flow meter further comprises at least one ultrasonic sensor which is operable to estimate a thickness of the liquid phase flowing as a liquid film along the wall of the pipe section, wherein the thickness is used to correct the estimated fractional flow rate for each phase when a gas liquid fraction (GLF) pertaining to the multiphase fluid mixture is such that the gas phase flows in a core of the pipe section, and the liquid phase flows along the wall of the pipe as the liquid film.

Referring to FIG. 1, an off-shore environment is indicated generally by **10**, wherein a sea-bed assembly **30** is submerged in water **20**, and is coupled via one or more sea-bed pipelines **40** to a petrochemicals processing facility **50**. The assembly **30** is alternatively, or additionally, coupled via the one or more pipelines **40** to a floating oil platform (not shown). The sea-bed assembly **30** is coupled via a bore hole **60**, for example defined by a liner tube, to a subterranean anticline including oil and/or gas resources. In many situations, the sea-bed assembly **30** is more than 1 km deep in the water **20** and is potentially subject to pressure of 150 Bar or more. It is desirable to measure to a high accuracy a flow rate of a multiphase fluid being drawn up through the bore hole **60**, for example. However, an environment experienced by the sea-bed assembly **30** is challenging for any type of precision multiphase flow meter. Although flow through the bore hole **60** may, for example, often be substantially non-turbulent, potential situations can be arise where high turbulent flow rates can occur, for example in a event of a leak or unexpected pressure surge from the anticline, wherein it is highly desirable to be able to measure flow rates of multiphase fluids, even under turbulent conditions. Known types of flow meter are not able to provide such measurement flexibility and yet be able to withstand, over a long period of use, harsh environmental conditions associated with operation of the sea-bed assembly **30**.

In a published US patent application US2008/163700A1 (*Huang Songming*), there is described a measuring apparatus for measuring properties of a flow of a fluid within a conduit including one or more walls, wherein the apparatus includes a transducer arrangement including transducers for emitting and receiving ultrasonic radiation in upstream and downstream directions in respect of the flow of fluid, and a signal processing arrangement for generating signals to excite the transducer arrangement and for processing received signals provided by the transducer arrangement for generating output signals from the signal processing arrangement indicative of properties of the flow. Moreover, there is also disclosed for the upstream and downstream directions that the apparatus is operable to perform measurements along first and second paths associated with each of the directions; for the first path, the transducer arrangement in cooperation with the conduit is operable to provide the first path solely via the one or more walls for Lamb-wave ultrasonic radiation coupling directly from a transducer for emitting ultrasonic radiation to a transducer for receiving ultrasonic radiation to generate a first received signal. Furthermore, for the second path, the transducer arrangement in cooperation with the conduit is operable to provide the second path for propagation of ultrasonic radiation within the one or more walls via Lamb waves coupling to at least a portion of the flow to propagate through the flow from a transducer for emitting ultrasonic radiation to a transducer for receiving ultrasonic radiation to generate a second received signal. The signal processing arrangement is operable to determine from the first and second signals ultrasonic radiation propagation time period through the first path and through the second path in each of the upstream and downstream flow directions, and to perform computational operations in respect of at least one of: a flow velocity (v) of the fluid in the conduit, a velocity of sound (c) through the fluid. Another published United States patent application US2008/163692A1 (*Huang Songming*) also describes a generally similar type of apparatus to that described in the aforesaid US patent application US2008/163700A1.

Summary

The present disclosure seeks to provide an improved apparatus for measuring flow, for example for measuring flows of multiphase mixture both in non-turbulent and turbulent conditions, as well as coping with spatial non-homogeneity in the aforesaid multiphase mixture.

Moreover, the present disclosure seeks to provide a method of using an improved apparatus for measuring flow, for example for measuring flows of multiphase mixture both in non-turbulent and turbulent conditions, as well as coping with spatial non-homogeneity in the aforesaid multiphase mixture.

Furthermore, the present disclosure seeks to provide a subsea non-intrusive multiphase meter accommodating a 0% to 100% gas-volume-fraction (GVF) measurement range, and providing measurement errors conforming to at least fiscal standards when operating in a single-phase mode.

According to a first aspect, there is provided an apparatus as defined in appended claim 1: there is provided an apparatus for measuring a flow within a region surrounded by a wall of a pipe, characterized in that the apparatus includes a transducer arrangement disposed substantially around an external surface of the wall of the pipe for emitting a plurality of beams of acoustic radiation into the region and for receiving acoustic radiation transmitted through and/or reflected from the region, wherein:

(a) the plurality of beams are arranged to interrogate sampling points off-axis and on-axis in a cross-section of the region for determining whether the flow is laminar, transitional or turbulent;

(b) the plurality of beams are employed in a repetitive manner to monitor temporal fluctuations in the flow;

(c) the sensor arrangement is operable to sense spatially varying attenuation of the received acoustic radiation thereat for determining an occurrence of one or more gas volumes present within the region;

(d) the transducer arrangement is employed for performing time-of-flight measurements for propagation of the acoustic radiation within the region in upstream and downstream flow directions; and

(e) the transducer arrangement is coupled to a corresponding signal processing arrangement for exciting the transducer arrangement and for processing received signals generate by the transducer arrangement to provide measurement output data representative of at least one of: flow velocity within the region, an indication of phases present in the region (gas fraction), a flow rate through the region).

The invention is of advantage in that the apparatus is capable of measuring flows of multiphase mixtures and spatially inhomogeneous mixtures more accurately on account of interrogating the flows in a more comprehensive manner using acoustic radiation.

Methods of interrogating a flow in upstream and downstream directions by way of performing a differential measurement are described in an international PCT patent application PCT/NO2010/000480 (*Tecom AS and Christian Michelsen Research AS*), the contents of which are hereby incorporated by reference.

Optionally, in the apparatus, the transducer arrangement includes a plurality of sets of waveguide transducers ("*modeline*") for generating and receiving the plurality of beams in cooperation with acoustic radiation propagation via the wall of the pipe, wherein the waveguide transducers include an elongate waveguide, and one or more transducer elements disposed at at least one end of the waveguide, and wherein a side portion of the waveguide is mounted in operation to an external surface of the wall of the pipe for coupling acoustic radiation to and from the wall of the pipe.

More optionally, in the apparatus, at least one waveguide of the transducer arrangement includes a first end thereof and a second end thereof, wherein an array of transducer elements is disposed at the first end and are individually excitable in a phase-array manner for steering the one or more beams within the region, and the one or more transducer elements are disposed at the second end for monitoring integrity of operation of the waveguide and/or for enabling a temperature compensation to be applied by the signal processing arrangement for operation of the waveguide.

Optionally, in the apparatus, the transducer arrangement includes a spatially distributed array of sensors disposed on an external surface of the wall of the pipe for receiving acoustic radiation coupled through the wall of the pipe thereto.

More optionally, in the apparatus, the spatially distributed array of sensors is implemented using a plurality of Bragg grating filter sensors distributed along one or more optical fibres, wherein the Bragg filter sensors are optically interrogated in operation via optical radiation guided through the one or more optical fibres and selectively reflected and/or transmitted at the Bragg grating filter sensors (FBG).

More optionally, in the apparatus, the spatially distributed array of sensors is interspersed between waveguides of the transducer arrangement for generating the plurality of beams.

According to a second aspect, there is provided a method of using an apparatus for measuring a flow within a region surrounded by a wall of a pipe, wherein the apparatus includes a transducer arrangement disposed substantially around an external surface of the wall of the pipe for emitting a plurality of beams of acoustic radiation into the region and for receiving acoustic radiation transmitted through and/or reflected from the region, characterized in that the method includes:

(a) using the plurality of beams to interrogate sampling points off-axis and on-axis in a cross-section of the region for determining whether the flow is laminar, transitional or turbulent;

(b) employing the plurality of beams in a repetitive manner to monitor temporal fluctuations in the flow;

(c) using the sensor arrangement to sense spatially varying attenuation of the received acoustic radiation thereat for determining an occurrence of one or more gas volumes present within the region;

(d) employing the transducer arrangement to perform time-of-flight measurements for propagation of the acoustic radiation within the region in upstream and downstream flow directions; and

(e) using a corresponding signal processing arrangement coupled to the transducer arrangement for exciting the transducer arrangement and for processing received signals generate by the transducer arrangement to provide measurement output data representative of at least one of: flow velocity within the region, an indication of phases present in the region (gas fraction), a flow rate through the region.

According to a third aspect, there is provided a software product recorded on non-transient machine-readable data storage media, wherein the software product is executable upon computing hardware of the apparatus of the first aspect for implementing the method of the second aspect.

It will be appreciated that features of the invention are susceptible to being combined in various combinations without departing from the scope of the invention as defined by the appended claims.

Description of the diagrams

Embodiments of the present invention will now be described, by way of example only, with reference to the following diagrams wherein:

FIG. 1	is an illustration of an off-shore environment in which characteristics of a multiphase flow are to be measured;
FIG. 2	is a schematic illustration of spatially inhomogeneous multiphase flows within a conduit or pipe;
FIG. 3	is a schematic illustration of a transducer arrangement employed in an apparatus for measuring flow rate within a conduit or pipe, pursuant to the present disclosure;
FIG. 4	is a schematic cross-section illustration of the conduit or pipe of FIG. 3, wherein a radial disposition of transducers for measuring flow rate is shown;
FIG. 5	is an illustration of the conduit or pipe of FIG. 4, wherein a measurement method is shown for measuring flow velocity at a central-axis position and at three off-axis positions, for a laminar flow condition and also for a situation approaching an onset of turbulence;
FIG. 6	is an illustration of the conduit or pipe of FIG. 3, wherein upstream and downstream measurement positions are shown;
FIG. 7	is an illustration of a manner in which off-axis interrogating beams of ultrasonic radiation are generated by employing phase-array ultrasonic transducers excited by mutually phase-shifted and/or time delayed excitation signals S1 to S4;
FIG. 8	is an illustration of an alternative manner in which off-axis interrogating beams of ultrasonic radiation are generated by employing phase-array

ultrasonic transducers excited by mutually phase-shifted and/or time delayed excitation signals S1 to S4;

FIG. 9	is an illustration of a manner in which emitting transducers and receiving transducers are disposed around the conduit or pipe of FIG. 3;
FIG. 10	is an illustration of an alternative manner in which emitting transducers and receiving transducers are disposed around the conduit or pipe of FIG. 3;
FIG. 11	is an illustration of measuring fields of the transducers and their associated receiving transducers of FIG. 9 and FIG. 10;
FIG. 12	is an illustration of a Bragg-grating optical sensor which is employable for implementing the receiving transducers of FIG. 9 and FIG. 10;
FIG. 13	is an illustration of an arrangement for emitting transducers and receiving transducers for measuring flow within the conduit or pipe of FIG. 3;
FIG. 14	is an illustration of an optical-fibre connection and data processing arrangement for use with the receiving transducers shown in FIG. 9 to FIG. 13;
FIG. 15	is an illustration of ultrasonic radiation propagation paths within the conduit or pipe of FIG. 3, in a presence of a particle within the conduit of pipe;
FIG. 16	is an illustration of different sensing strategies employable within apparatus pursuant to the present disclosure; and
FIG. 17	is an illustration of a manner in which receiving transducers are mounted to the conduit or pipe of FIG. 3.

In the accompanying diagrams, an underlined number is employed to represent an item over which the underlined number is positioned or an item to which the underlined number is adjacent. A non-underlined number relates to an item identified by a line linking the non-underlined number to the item. When a number is non-underlined and accompanied by an associated arrow, the non-underlined number is used to identify a general item at which the arrow is pointing.

Description of embodiments

In overview, an apparatus **180** pursuant to the present disclosure beneficially employs "*CMR Guided Wave*" technology as described in Norwegian patent NO331687 and corresponding GB patent GB2479115B, PCT patent application WO2011/078691A2 and US patent US8141434B2, which are hereby incorporated by reference. Moreover, the apparatus **180** pursuant to the present disclosure includes additional features:

(i) "*Modeline*": acoustic emitting transducers, for example ultrasonic transducers, employed in the apparatus **180** are elongate and include an acoustic waveguide which is coupled to an external surface of a conduit or pipe in which flow is to be measured. Moreover, such a "*modeline*" approach enables the apparatus **180** to achieve more accurately mode selection and suppression, thereby increasing measurement accuracy and reliability. Furthermore, such a "*modeline*" approach is capable of reducing effects of temperature changes compared to known wedge-shaped acoustic coupling element technology, and which is also capable of providing for single or multiple piezo-element positions along geometrical x-, y- and z-axes, as will be described in more detail later in this disclosure;

(ii) "*Off-centre beam*": the apparatus pursuant to the present disclosure employs non-intrusive ultrasonic guided wave transmission, wherein an acoustic beam excitation is employed at an angle which propagates outside a central region of the cross-section of the conduit or pipe of FIG. 3; and

(iii) "*Spatial detector grid*": an array of acoustic receiving sensors which are disposed in a grid-like manner around an external surface of the conduit or pipe of FIG. 3, wherein the spatial detector grid enables multiple point velocity and attenuation measurements to be performed in operation across a fluid cross-section of the conduit or pipe of FIG. 3, thereby enabling fluid dynamic monitoring to be performed in cross-section slices or as a cross-section "*3D volume*". Such measurement enables spatially inhomogeneous multiphase mixtures within the conduit or pipe of FIG. 3 to be characterized.

There is thereby achieved a non-invasive flow meter capable of providing more accurate flow rate measurements for any combination of oil, water and gas, as well as providing flow measurement conforming to a fiscal accuracy for pure and gas phases.

In the following description, the term "*acoustic*" is to be construed broadly to include any acoustic signals, for example in a frequency range of 300 Hz to 50 MHz, and more optionally in a range of 500 Hz to 100 kHz, for example aforesaid ultrasonic radiation.

The apparatus pursuant to the present disclosure is beneficially operable to employ following measurement regimes:

(i) a wide-beam acoustic interrogation for monitoring gas in a liquid flow within the conduit or pipe of FIG. 3;

(ii) a wide-beam acoustic interrogation for monitoring liquid in a gas flow within conduit or pipe of FIG. 3;

(iii) a wide-beam acoustic interrogation in combination with a liquid flow velocity based liquid fraction computation, for monitoring water in oil flow within conduit or pipe of FIG. 3; and

(iv) a wide-beam acoustic interrogation in combination with a liquid flow velocity based liquid fraction computation, for monitoring oil in water flow within conduit or pipe of FIG. 3.

Referring next to FIG. 2, there is shown example of flow, denoted by an arrow **110**, through a conduit or pipe denoted by **100**, namely hereinafter "*pipe* ***100***". In a situation A, the flow **110** is laminar, namely non-turbulent, wherein a spatial velocity of the flow **110** decreases as a function of a radial distance from a central elongate axis of the pipe **100**. It will be appreciated from the situation A that a single flow measurement for the pipe **100** corresponds to a form of aggregate of spatial flow velocities in various spatial regions of the tube **100**. For example, a lower flow velocity occurring locally at an inside wall of the pipe **100** can, for example, give rise to deposition, for example formation of scale on the inside wall, over a prolonged period of operation. The flow **110** can be a multiphase flow, for example spatially substantially homogeneous, or spatially inhomogeneous as illustrated in situation B, wherein a spatial region **130** has a different composition to a remainder of the flow **110** within the pipe **100**. However, when the flow **110** exceeds its Reynolds number R_e, see Equation 1 (Eq. 1) below, turbulent flow occurs, resulting potentially in vortices **140** and other instabilities, wherein a broadened spectrum of flow velocities within the pipe **100** occurs. It will be appreciated, especially in the situation C, that a single aggregate flow measurement for the pipe **100** is insufficient to describe complexities of the flow **110** occurring with the pipe **100**. The present disclosure describes the apparatus **180** which is both capable of providing a very accurate measurement of the flow **110** in situation A, for example to less than 0.2%

measurement error, as well as being able to cope with providing a set of measurements of the flow **110** in the situation C. The apparatus **180** achieves such accurate measurement by acquiring a series of acoustic measurements, for example ultrasonic measurements, in various operating configurations of the apparatus **180**, and then applying various analytical computations to the series of acoustic measurements, as will be described in greater detail later in this disclosure.

Referring next to FIG. 3, there is shown an apparatus **180** including an arrangement of transducers for implementing an instrument pursuant to the present disclosure. The arrangement of transducers includes a first transducer including an elongate waveguide **200A** having a length W measuring from a cluster of acoustic elements **220** disposed at a first end of the waveguide **200A**, namely "*modeline*", via a coupling neck region **210**, to a monitoring element **230** disposed at a second end of the waveguide **200A**. The arrangement of transducers further includes a second elongate waveguide **200B** disposed in a mirror orientation to the first elongate waveguide **200B**, in a manner as illustrated. Sides of the waveguide **200A**, **200B** are attached to an external surface of the pipe **100** for coupling acoustic radiation into a wall of the pipe **100** and therefrom to an interior region of the pipe **100** in which the flow **110** occurs in operation. The acoustic radiation is denoted by **240**. Optionally the Figures showing the modeline could beneficially have transducers further apart so that the pipe **100** is used as part of the transducers emitting acoustic energy into the measured fluid.

In operation, measurements are made with the acoustic radiation **240** projected in upstream and downstream directions relative to the flow **110**, and a differential computation is performed thereby removing many sources of measurement error in the apparatus **180**. The monitoring elements **230** are beneficially employed to monitor acoustic radiation coupled from the cluster of acoustic elements **220** to the waveguide **200A**, thereby enabling correction of element characteristics to be compensated, for example changes in piezo-electric coupling coefficient of the elements of the cluster as a function of operating temperature and/or time. For example, the piezo-electric elements have a coupling coefficient which slowly reduces as a function of time, for example as a result of piezo-electric element depolarization. Alternatively, in another embodiment the differential computation is performed on received phase shirted, namely Doppler shifted acoustic radiation. Similarly, the speed of sound may optionally be used for WLR, which combined with the attenuation measurements will give a multiphase measurement.

The elongate waveguides **200A**, **200B** provides "*modeline*" transducers which are superior to known acoustic transducers employing wedge-shaped acoustic coupling elements. Such superiority pertains, for example, to improved guided wave properties and better beam formation of the acoustic radiation **240**, for example ultrasonic radiation. Thus, the elongate waveguides **200A**, **200B** are operable to provide improved directing and shaping of selected acoustic mode transmission within the pipe **100**, for example for optimal utilization of transmitted acoustic radiation. Moreover, the elongate waveguides **200A**, **200B** are operable to provide improved suppression of acoustic modes which have not been selected for use in the apparatus, thereby enhancing measurement signal-to-noise ratio of the apparatus **180**. Furthermore, in comparison to known wedge-coupling-element technology, the elongate waveguides **200A**, **200B**, namely "*modeline*", additionally results in less signal drift caused by thermal wedge material expansion and contraction, as well as increased transducer foot-print area onto the external surface of the pipe **100**, namely more acoustic radiation coupled into the pipe **100**. Additionally, the waveguides **200A**, **200B** have an extended physical length, in comparison to known wedge-design transducers, which enables additional acoustic pickup, for performing following functions:

(i) acoustic energy is coupled into a sensing direction of a correspondingly shaped receiving transducer, thereby improving measurement signal-to-noise performance of the apparatus **180**; and

(ii) acoustic energy is focused in a direction and shape of a receiving array of sensors, for example Bragg-grating sensors, as will be described in greater detail later

Spatial free ends of the waveguides **200A**, **200B** are provided with the monitoring elements **230** which are beneficially employed in a feedback manner to control drive signals to the cluster of acoustic elements **220** to optimize their operation, for example for achieving an enhanced measurement signal-to-noise ratio. Optionally, the cluster of elements **220** are installed in a same plane or at different angles along x-, y- and z-axes, and controlled individually with respect of signal wave phase, namely in a manner of a phased array:

(i) for achieving an optimal operating signal-to-noise ratio;

(ii) for controlling acoustic transmission angle excitation in respect of the pipe **100** and one or more phases flowing within the pipe **100**; and

(iii) for achieving sequential transmission angles for the acoustic radiation **240**, as well as signal shape and/or signal quality for exciting various types of signals on demand, for example a given number of pulses X in a first given transmission angle for the radiation **240**, followed by a given number of pulses Y in a second given transmission angle for the radiation **240**, then returning to the given number of pulses X in the first given transmission angle, and so forth; there is thereby obtained two sets of measurements representing mutually different fluid properties by employing only one set of transducers, as illustrated in FIG. 1.

The apparatus **180** of the disclosure described above provides numerous benefits in comparison to known flow meters. In a known ultrasonic "*clamp-on*" type flow meter, namely single-phase meters, acoustic radiation is transmitted in a radial manner in a cross-section of a given pipe, and at an angle determined by a wedge-element geometry employed in the known flow meters. As a result, measurement occurs primarily at a central region of the given pipe, such that, when the given pipe is gas-filled at its centre and a remainder of the pipe is liquid-filled, transmission of acoustic radiation is severely affected, potentially resulting an no flow measurement being possible to obtain. Apparatus pursuant to the present disclosure are thus capable of providing major benefit in comparison to known single-phase flow meters.

Referring to FIG. 4, a transverse cross-section illustration of the pipe **100** of FIG. 3 is shown, wherein three sets of waveguides **200(1)**, **200(2)**, **200(3)**, namely *modeline* transducers, are disposed at 120° intervals around an external circumference of the pipe **100**; each set includes two transducers, for example as illustrated in FIG. 3. The pipe **100** encloses a volume **260** in which the flow **110** occurs in operation. The three sets of waveguides **200(1)**, **200(2)**, **200(3)** in temporal sequence are operable to emit beams, for example denoted by **250**, of acoustic radiation, for example ultrasonic radiation but not limited thereto, into the volume **260** for use in characterizing the flow **110**.

Referring to FIG. 4, a combination of acoustic beams propagating through a central axis of the pipe **100**, and also through regions of the volume **260** away from the central axis of the pipe **100**, excited at a plurality of different angles, provide a measurement of spatial fluid flow velocity for an entire cross-section of the volume **260**, wherein the measurement provides an indication of flow velocities as a function of spatial position within the volume **260**. When the apparatus **180** is suitably designed, the measurement is capable of being within a fiscal measurement error or 0.15%, for example in laminar flow conditions devoid of turbulent flow.

The apparatus **180** illustrated in FIG. 3 and FIG. 4, with its associated signal processing arrangement, is capable of measuring the flow **110** in both laminar flow conditions and turbulent flow conditions, for example by suitably reconfiguring itself, as will be described in more detail later. An onset of turbulence occurs in the flow **110** when its Reynolds number R_e exceeds a threshold value, as will next be elucidated. The Reynolds number R_e is susceptible to being computed from Equation 1 (Eq. 1):

$$R_e = \frac{\rho V D}{\mu} \qquad \text{Eq. 1}$$

wherein

R_e = Reynolds number, wherein a value $R_e < 2300$ corresponds to a laminar flow, a value $2300 < R_e < 4000$ corresponds to a transitional flow, and a value $R_e > 4000$ corresponds to a turbulent flow;

V = fluid velocity of the flow **110**;

ρ = a density of a fluid present within the volume **260**;

μ = a fluid velocity the fluid present in the volume **260**; and

D = a diameter of the pipe **100**.

By employing off-centre acoustic beams, for example ultrasonic beams, for interrogating the volume **260**, information is obtained from the volume **260** which enables the aforesaid signal processing arrangement to perform uncertainty reduction computations, wherein:

(i) by employing interpolation of a detailed flow profile of the flow **110** for Reynolds number computation, an accurate flow profile calculation is possible, for example for determining whether the flow **110** is laminar or turbulent, also including a viscosity computation; and

(ii) computations can be performed for static and dynamic uneven flow velocities, for example for performing compensations for swirl and similar types of fluid motion within the volume **260**.

Referring next to FIG. 5, an illustration of where measurements are performed within the volume **260** is shown. In addition to the sets of waveguides **200(1)**, **200(2)**, **200(3)**, there are mounted receiving transducers **300A**, **300B**, **300C** which are also disposed at angles of 120° around the external surface of the pipe **100**. The waveguides **200** and the transducers **300** are operable to enable the apparatus **180** to sample in respect of at least four spatial points for performing flow rate computations and therefrom determining whether the flow **110** is laminar, represented by a curve profile **310**, or turbulent, represented by a curve profile **320**. Thus, spatial measurements of flow at on-axis and multiple off-axis positions within the volume **260** enables more information to be obtained regarding whether or not the flow **110** is laminar, transitional or turbulent.

Thus, in FIG. 5, there is shown a process pipe, denoted by the pipe **100**, with three sets of acoustic transducer positions. Dotted lines with arrow ends within the process pipe represent three transducer acoustic beam paths, wherein all the paths propagate through a central axis of the process pipe. Moreover, solid lines with arrow heads represent three transducer beam paths which are off-centre in respect of the aforesaid central axis. Laminar flow **310** as depicted in FIG. 5 is generally approximately similar to the turbulent flow **320**, unless a spatial distribution of the flow **110** become temporally uneven, for example as a result of vortex generation. Flow velocities computed for the three off-axis positions provide sufficient information for the flow velocity profile to be determined in operation. FIG. 5 pertains both the liquid and gas flows within the pipe **100**.

In comparison, a known type of flow meter will generally propagate acoustic beams in a direction orthogonal to a wall of the pipe **100**; the apparatus **180** pursuant to the present disclosure employs non-orthogonal direction acoustic beams in addition of orthogonal acoustic beams, and thereby is able to extract more information from the flow **110** to determine its nature, for example whether it is laminar or turbulent. Any gas introduced into a liquid phase present in the pipe **100** will result in an attenuation of the aforesaid acoustic beams; such measurement pertains:

(i) in situations of a liquid flow within the pipe **100**;
(ii) in situations wherein multiphase flows occur within the pipe **100**; and
(iii) in situations wherein gas flow with liquid fraction occurs in the pipe **100**.

Thus, both off-centre and on-centre acoustic beam interrogation of the volume **260** is required for performing flow rate measurement involving a gas fraction in liquid, *mutatis mutandis* a liquid fraction present in a gas.

The apparatus **180** pursuant to this disclosure is beneficially operable to employ at least three different strategies for non-invasive acoustic beam interrogation of the volume **260** by employing off-centre acoustic beams, namely:

(a) an acoustic wide-beam interrogation of the volume **260**, wherein "*wide beam*" corresponds for example to a beam **250** divergent angle of greater than 10^{o};
(b) a steered phase-array interrogation of the volume **260**; and
(c) a measurement of transducer geometry and mounting orientation onto the pipe **100**.

Optionally, shear-mode acoustic radiation generation is employed when implementing one or more of (a) to (c) within the apparatus **180**.

When wide-beam excitation is employed in the apparatus **180**, Lamb wave propagation is beneficially employed, wherein Lamb wave or wide beam sensors operate by emitting acoustic energy at various frequencies through the pipe **100** for locating a frequency which most closely matches a natural propagation frequency of acoustic radiation within a wall of the pipe **100**. When the transducers **200**, **300** are operated at such a matched frequency, acoustic radiation substantially at the matched frequency is transmitted into the flow **110** within the volume **260**, with the wall of the pipe **100** functioning as a waveguide. As aforementioned, the wide beam of acoustic radiation travels outside the central axis of the pipe **100**, and can be received at a convenient location using one or more of the transducers **300A**, **300B**, **300C**. Optionally, as will be elucidated in greater detail later, the transducers **300A**, **300B**, **300C** are beneficially implemented using Bragg-filter-grating transducers.

Referring to FIG. 6, the transducers **200A**, **200B** are operable to emit acoustic radiation beams **250(A)**, **250(B)** in forward and backward directions respectively relative to the flow **110**, so that a differential measurement of the flow **110** can be performed, using the transducer **300** as a receiving transducer. The transducer **300** is within the wide-angle emitted beams **250(A)**, **250(B)** as illustrated. Beneficially, phased-array transducers are employed for implementing the transducers **200A**, **200B** so that they are able to be used to measure flow velocities at various off-axis positions, for example as illustrated in FIG. 5.

Acoustic radiation beam emissions from the transducers **200** illustrated in FIG. 7 are beneficially steered within the volume **260** by implementing the transducers **200** as phased arrays of acoustic emitting elements, for example driven by a plurality of signals S1 to S4 which are temporally shifted relative to one another to define a given angle of the beam **250** relative to the pipe **100** and its internal volume **260**. Optionally, one or more elements of the phased arrays of elements forming the transducers **200** are assembled directly onto the external surface of the pipe **100**, as illustrated in FIG. 8, or are assembled together into a transducer unit which is attached to the external surface of the pipe **100**, for example as illustrated in FIG. 7.

Referring next to FIG. 9, an embodiment of the apparatus **180** is shown, wherein phased-arrays of elements are coupled to waveguides **200A**, **200B**, **200C** to couple acoustic radiation into the volume **260** of the pipe **100** for steering acoustic radiation beams within the volume **260** in operation, for example for providing one or more on-axis beams traversing the central axis of the pipe **100**, as well as one or more off-axis beams. Receiver transducers **300** are beneficially implemented in an array format, for example using a network of Bragg-grating-sensors based upon use of optical fibre components, as will be described in greater detail later. The waveguides **200A** are optionally mounted in a spiral manner around the external surface of the pipe **100**, as illustrated. Thus, the present disclosure includes adding guided-wave sensors in a grid configuration around the pipe **100** for picking up guided-wave signals from, for example, three sets of guided-wave transducers **200** in a 0^o, 120^o and 240^o formation around the pipe **100**, as illustrated.

Referring next to FIG. 10, there is shown an illustration of an alternative embodiment of the apparatus **180**, wherein three sets of guided wave transducers **200**, namely "*modeline*" transducers, are disposed at 120^o angular positions around the pipe **100**. Moreover surface mounted receiver transducers **300** are mounted at intervals around a circumference of the pipe **100** at a plurality of locations along a length of the pipe **100**. The guide wave transducers **200** are intermingled with the receiver transducers **300**, as illustrated. The receiver transducers **300** are beneficially implemented as a grid network of Bragg-grating filter transducers, for example mounted against the external surface of the pipe **100**, or partially embedded into the external surface, for example in conformal reference indentations.

The receiver transducers **300**, namely surface detectors, are located in three bands **400**, **410**, **420**, substantially extending around a circumferential region of the pipe **100**. First and third bands **400**, **420** of the surface detectors are located areas from which guided acoustic waves from the transducers **200** of the transducers sets **200(1)**, **200(2)**, **200(3)** hit the wall of the pipe **100** after reflection. A second band **410** of the surface detectors is located in an area in which the acoustic guided waves hit an opposite wall of the pipe **100**.

Referring next to FIG. 11, there is shown an illustration of the receiver transducers **300** for sensing an arrival of a wide acoustic beam emitted from the guided wave transducers **200**; by "wide", is meant greater than 5^o beam divergence angle, more optionally greater than 10^o divergence angle. On account of the receiver transducers **300** being disposed in a circumferential manner around the external surface of the pipe **100** as shown, acoustic beams emitted from the three sets of transducers **200(1)**, **200(2)**, **200(3)** are susceptible to being detected by the receiver transducers **300**. Optionally, the receiver transducers **300** are implemented, as aforementioned, as a surface detector grid consisting of a plurality of acoustic detectors **450** having physical contact with the external surface of the wall of the pipe **100**. Beneficially, the acoustic detectors **450** are connected to a signal processing arrangement, for example to a control unit wherein each detector **450** has an individual signal channel associated therewith. The acoustic detectors **450** are optionally implemented using aforesaid Bragg-grating filter sensors (Fibre Bragg Gratings, “FBG”), but are susceptible to being implemented in alternative manners, for example utilizing one or more of:

(i) piezo-electric transducers;
(ii) accelerometers;
(iii) microfabricated electronic mechanical devices (MEMs), for example micromachined microfabricated Silicon accelerometers and/or microphones;
(iv) any other type of substantially point sensor which is operable to detect acoustic radiation;
(v) any other type of spatially discriminating fibre optic sensing method which is operable to detect acoustic radiation.

Bragg-grating filter sensors are especially beneficial in that multiple acoustic sensing points can be established along a length of a single optical fibre which is attached to the external surface of the pipe **100** to form a grid or band of sensors. Optical fibres are susceptible to high temporal rates of sensing, are insensitive to local electrical interference in operation, and are potentially very compact. Such compactness enables the acoustic detectors to be implemented using a plurality of optical fibres, thereby providing inbuilt redundancy in an event that one of the optical fibres were to fail when in service, for example in a sea-bed location, potentially several kilometres deep with ambient pressures in an order of 150 Bar or more.

Referring next to FIG. 12, there is shown a schematic illustration of a Bragg filter grating sensor indicated generally by **500**; this sensor is also referred as being a “*fibre Bragg grating sensor*” (FBG). An optical fibre **510** includes an optical cladding **520** and an optical core **530**. In operation, optical radiation propagates along the optical core **530** to which it is substantially confined by internal reflection occurring on account of the cladding **520** and the optical core **530** having refractive indexes n_2, n_1 respectively, wherein n_2 and n_1 are mutually different. The optical fibre **510** is optionally multi-mode optical fibre, alternatively mono-mode optical fibre. An optical grating **540** can be formed in the optical core by removing a portion of the cladding **520** in a region of the grating **540** to expose the optical core **530**, by processing the optical core **530**, for example by photolithographic steps followed by chemical or ion-beam milling, to modify its refractive index to form the grating **540**, and then the removed cladding **520** restored by adding a polymer or glass material having a refractive index of substantially n_2. The grating **540** has a spatially varying refractive index having a period of λ, wherein optical radiation propagating in the optical core **530** have a wavelength therein similar to the period λ experiences a point optical impedance mismatch, resulting in a portion of the optical radiation being reflected back along the optical fibre **510** as illustrated, and a correspondingly reduced amount of optical radiation being transmitted further along the optical fibre **510**. As the grating **540** is stretched and compressed by acoustic radiation acting thereupon, the wavelength at which partial reflection of optical radiation occurs at the grating **540** is modified. Such a shift in wavelength, which is modulated by the received acoustic radiation at the grating **540**, is detected in the aforesaid signal processing arrangement to generate a signal representative of the acoustic radiation received at the grating **540**.

Referring next to FIG. 13, there is shown an illustration of the optical fibre **510** disposed upon the external surface of the pipe **100**, disposed in a spatial region between the transducers **200A** and **200B**, wherein the transducers **200A**, **200B** corresponding to a set of transducers **200(1)**. The optical fibre **510** has a plurality of gratings **540** therealong. By meandering the optical fibre **510**, a grid of detection points is established on the pipe **100** for detecting acoustic radiation thereat in operation. Beneficially, the optical fibre **510** is folded in a radius of curvature at ends of meanders which is greater than substantially fifteen times a diameter d of the optical fibre **510**. Thus, one optical fibre is capable of addressing many individually-addressable acoustic radiation sensor points. Moreover, the optical fibre **510** can be coupled to the signal processing arrangement which is remote, for example a distance of 1 km or more remote from the gratings **540**. A free-end of the optical fibre **510** which is remote from the signal processing arrangement is beneficially terminated in a substantially non-reflecting optical load, to prevent spurious reflections back-and-forth between ends of the optical fibre **510**.

Referring next to FIG. 14, the signal processing arrangement if represented by a light source and sensor **600**, for example a solid-state laser, coupled to a photodiode detector, alternatively a Mach-Zender-based optical detector. Beneficially, the source and sensor **600** is coupled to a signal controller **610** for handling signals being input to and output from the source and sensor **600**. As illustrated, the data processing arrangement, via an optical junction **620**, is able to service several optical fibre **510** detector arrays attached to the external surface of the pipe **100**. The optical fibre **510** is beneficially employed in petrochemical environments to reduce a risk of explosion hazard which may pertain to transducers which require directly-applied electrical signals for their operation. A 6 x 4 grid of gratings **540** is shown. The source and sensor **600**, in combination with the signal controller **610** constitute a signal processing arrangement. The signal processing arrangement is beneficially, at least in part, implemented using computing hardware, for example one or more high-speed low-power-consumption RISC processors, for example manufactured by Arm (UK), which are able to process acoustic radiation signals in real-time, for example performing time-of-flight computations, correlations, convolutions and such like. The computing hardware is beneficially operable to execute one or more software products recorded on non-transient machine-readable data storage media, for example solid-state data memory, for implementing one or more algorithms for enabling the apparatus **185** to function as described.

Thus, a sensor mounted sensor network as illustrated in FIG. 14 covers a significant number of positions around a cross-section of the pipe **100** in combination with three or more wide-beam transducers **200**, for example *modeline* transducers as described in the foregoing, thereby sensing at many points within the region or volume **260**. Information obtained from each wide-beam traverse enables the data processing arrangement to detect one or more of:

(i) a fluid velocity of the flow **110**;
(ii) a diameter of the pipe **100**, for example for detecting corrosion on an inside surface of the pipe **100**; and
(iii) a speed of acoustic radiation propagation within the region or volume **260**.

In-line flow meters often include a pipe spool-piece for use when sensors are to be installed. Such spool-pieces beneficially have an optimal inner diameter manufacturing tolerances for their defined cross-section, which provide a reference for implementing fluid flow rate measurements. Aforesaid acoustic flow measuring meters, for example as aforementioned, are beneficially individually calibrated with their associated spool-pieces, to ensure a high measurement accuracy, for example to within fiscal standards.

Ultrasonic “clamp-on” flow meters are designed for non-invasive installation on process pipes, for example the pipe **100**. However, in practice, pipe dimensional tolerances can vary greatly. An ASME 831.3 standard for process piping, for example for use in petrochemical industries, define as defined in Table 1.

Table 1: ASME process pipe tolerances

Feature	Deatil
Pipe outer diameter	Nominal diameter +/- 1%
Pipe wall thickness	Nominal wall thickness (WT) +15% to -12.5 %
2 inch (50 mm) process pipe Sch40	DeltaA = +/- 4.2%
6 inch (150 mm) process pipe Sch40	DeltaA = +/- 2.4%
10 inch (250 mm) process pipe Sch40	DeltaA = +/- 2.1%

Such variations potentially have an influence of measurement calibration of the apparatus **180** when mounted thereto, requiring individual calibration of the apparatus **180**.

As flow rate Q is defined by Equation 2 (Eq. 2):

$$Q = v * A \qquad \text{Eq. 2}$$

wherein

A = cross section area; and

v = flow velocity.

An error in computing A, namely internal area of the pipe **100**, and the flow rate v as measured by the apparatus **180**, potentially results in an error when computing the flow rate Q. In order to account for tolerances of the pipe **100**, for example in a retrofit situation, it is desirable to perform a calibration of the apparatus **180**. However, for new applications, it may be feasible to control dimensions of the pipe **100** more precisely, thereby potentially avoiding a need for such calibration of the apparatus **180**. However, it will be appreciated that the mounted sensor network provided by the optical fibre **510** in combination with three or more wide beams generated by the sets of transducers **200** enables such calibration to be implemented more precisely and reliably. Situation potentially arise for the apparatus **180** that solid build-up in the pipe **100** occurs, resulting in a considerable change in effective pipe cross-section area, for example as illustrated in FIG. 2, situation C; for example, a 1 mm solid build up in a 2 inch (50 mm) diameter pipe represents a 4% reduction in the cross-sectional area of the pipe **100**, and hence a corresponding 4% error in measurement of the flow rate Q. However, the apparatus **180** is capable of correcting for such cross-sectional area by monitoring a dynamic effective cross-section of the pipe **100** by way of its multiple approaches to interrogating the region or volume **260**.

The apparatus **180** is capable of enabling a quantitative analysis of received acoustic signal attenuation when a gas fraction is present within the pipe **100**, for example caused by a gas volume **700** present in the pipe **100**, as illustrated in FIG. 15.

Referring next to FIG. 16, there is shown an illustration of three pairs of Lamb-wave transducer configurations, for example using three sets of aforesaid *modeline* transducers **200**. Each pair of transducers **200** are operable to excite acoustic beams **250** in up-flow and down-flow directions, for example for making a differential measurement. When the flow **110** is homogeneous in which a gas bubble, for example the gas bubble **700** in FIG. 15, moves with a liquid flow, the apparatus **180** is operable to perform following actions:

(i) to identify whether the fluid is predominantly water or oil, or a mixture of two liquid fractions;
(ii) to measure a flow velocity of the fluid flow **110**;
(iii) to perform a liquid flow rate measurement through liquid velocity measurement, less gas bubble volume/velocity influences;
(iv) to identify any non-homogeneity as a gas bubble, for example the bubble **700**; and
(v) a velocity of the gas bubble, for example the gas bubble **700**.

The gas bubble **700**, and any other similar gas bubbles present in the region or volume **260** of the pipe **100** will attenuate and/or scatter Lamb wave energy which is coupled from the transducer **200** through the wall of the pipe **100** into the region or volume **260**. Beneficially, a pure liquid flow velocity is computed for a given situation by a computation of acoustic radiation transit time between transmitting and receiving transducers, namely between transducers **200A**, **200B** or **200**, **300** as appropriate. A size of the bubble **700** is determined by a size of acoustic "*shadow*" generated behind the bubble **700**, as illustrated in FIG. 15; such shadow is beneficially detected spatially using the transducer **300**, namely grid array of gratings **540** disposed around the external surface of the pipe **100**.

The transducer **300**, for example implemented as the grid of grating sensors **540**, enables spatial monitoring of the cross-section of the pipe **100** to be achieved, for example to detect regions of oil, water and gas. Such cross-section monitoring, namely "*tomographic monitoring*", is achieved using multiple acoustic beams **250** from the three or more sets of transducers **200**. Beneficially, following measurements are made using the apparatus **180** when in operation:

(i) a volume **810** between the transducer **200A** and an area of reflection **820** at an opposite inside wall of the pipe **100**; and

(ii) a volume **830** between the area of reflection **820** and an area whereat reflected acoustic radiation is received, for example at the transducer **200B**.

Beneficially, such measurement is made for at least all three sets of transducers **200(1)**, **200(2)**, **200(3)**, thereby mapping six different regions of the region or volume **260**, by way of the acoustic radiation being reflected at the inside wall of the pipe **100**, as illustrated.

Referring again to FIG. 16, in a situation A, wide-angle beams of acoustic radiation excited from the transducer **200A**, namely of the set **200(1)**, spreads out and is reflected at an opposite wall of the pipe **100** at the region **820**, defining a first volume interrogated by the acoustic radiation. The acoustic radiation hitting the wall of the pipe **100** in the region **820** is detected by sensors **300** thereat, for example implementing using aforementioned grating sensors **540**. The acoustic radiation is reflected at the region **820** and propagates to the transducer **200B** and associated surrounding transducers **300**, defining a second volume interrogated by the acoustic radiation. In a situation B, a measurement similar to situation A is performed, but in an opposite direction in relation to the direction of flow **110** within the pipe **100**. In a situation C, measurement of the situations A and B are repeated for other sets of transducers, for example for the sets of transducers **200(2)** and **200(3)**.

Operation of the apparatus **180** to measure a multiphase flow within the pipe **100** will now be described in greater detail:

(a) Liquid fraction measurement, for example oil and water: the acoustic radiation velocity for each wide angle acoustic radiation beam **250** is calculated for a large number of beams **250**, for example using time-of-flight measuring techniques, to an extent that this represents an acoustic radiation velocity profile for an actual fluid volume present in the pipe **100** for a specific duration of time. The acoustic radiation velocity profile represents a profile for a presence of oil and water, and hence a volumetric fraction of water and oil can be calculated therefrom in the apparatus **180**;

(b) Gas fraction measurement: information derived from multiple excited acoustic radiation beams is employed for performing such measurements, wherein significant attenuation or complete attenuation is indicative of a presence of gas. Beneficially, in the apparatus **180**, such information is obtained from a large number of acoustic radiation beams **250**, providing representative information of gas being present within the region or volume **260**;

(c) Liquid fraction velocity measurement: such measurements are beneficially performed by employing time-of-flight of one or more beams **250** of acoustic radiation to propagate within the volume or region **260**, with the sets of transducers **200** being excited in forward and reverse direction relative to a direction flow **110** within the pipe **100**; alternatively, or additionally, cross-correlation measurements based of liquid-fraction acoustic radiation propagation velocity as a signature is employed for monitoring movement of the liquid fraction for determining its corresponding velocity or movement; and

(d) Gas fraction velocity: this is computed as described in the foregoing.

Optionally, the multiphase flow is defined a continuous liquid based upon given percentages of acoustic radiation signals received at the transducers **300**, for a signal attenuation less than a defined threshold, expressing no influence of gas upon the measurement. Optionally, sequential shift between two or more acoustic radiation frequencies is beneficially employed to enhance contrast in signal attenuation experienced between liquid and gas phases present in the pipe **100**.

Next, measurement of a continuous gas multiphase flow within the pipe **100** will be described. When implementing such measurement:

(e) Gas fraction measurement: the acoustic radiation propagation velocity within the region or volume **260** of the pipe **100** is computed for a large number of acoustic radiation beams **250**, to an extent that this represents an acoustic radiation velocity profile for an actual fluid volume during a specific duration of time. Such acoustic radiation propagation represents a profile for the presence of oil and water, thereby enabling a volumetric fraction of water and oil within the region or volume **260** of the pipe **100** to be computed;

(f) Liquid fraction measurement, for example a flow of mist: information pertaining to multiple acoustic radiation beams **250** propagating within the region or volume **260** of the pipe **100**, at one or more points of expected arrival is utilized; any significant attenuation, or complete attenuation, is indicative of a presence of a liquid. Beneficially, such information is obtained from a large number of acoustic radiation beams **250**, wherein representative information is employed to determine gas presence in the region or volume **260** of the pipe **100**; and

(g) Gas fraction velocity: gas fraction velocity if computed from time-of-flight measurements using acoustic radiation beams **250** propagating with and against the flow **110** of gas within the region or volume **260** of the pipe **100**.

Optionally, different frequencies for the acoustic radiation employed in the beams **250** can be employed in such measurements to increase contrast, and hence measurement accuracy.

Next, measurement of transitional flows within the region of volume **260** of the pipe **100** will be described. When implementing such measurement:

(h) liquid and gas fractions are measured via measurement of acoustic radiation propagation velocities, for example by performing one or more time-of-flight measurements using the apparatus **180**; and

(i) fluid velocity measurements are performed by employing cross-correlation based on profile of acoustic radiation propagation pertaining to movement in the region or volume **260** is the pipe **100**, for a defined time.

In the data processing arrangement of the apparatus **180**, for example as shown in FIG.14, a flow computer computes information for aforementioned measurement strategies (a) to (i) in a parallel manner, namely:

(i) a single-phase liquid flow measurement computation;
(ii) a single-phase liquid flow measurement computation, namely including computation of gas impurities;
(iii) a dual-phase liquid flow measurement computation;
(iv) a liquid-continuous multiphase flow measurement computation;
(v) a transitional flow computation;
(vi) a gas-continuous multiphase flow measurement computation;
(vii) a single-phase gas flow measurement computation, taking into account a potential presence of one or more liquids; and
(viii) a pure gas flow measurement computation.

For each of the computations pertaining to (a) to (i), a dynamic measurement uncertainty is beneficially computed in the signal processing arrangement of the apparatus **180**, in real-time, in addition to computations for determining flow fractions and flow rate information. Beneficially, such uncertainty data is compared in real-time for a selection of computed measurement results to provide an aggregate form of apparatus **180** output indicative of, for example, liquid fraction and flow rate.

In the foregoing, various strategies for the apparatus **180** to compute output indicate of flow rate and fractions present are described. In the following description, features of the apparatus **180** will be described in greater detail. Referring to FIG. 17, the optical fibre **510** and its associated Bragg grating sensors **540** are employed to provide a surface-mounted sensor network which is capable of providing secondary outputs from the signal processing arrangement of the apparatus **180**, for example:

(a) a surface temperature profile of the pipe **100**, for example for detecting a process malfunction or build-up of solid onto the inside surface of the pipe **100**; and

(b) detecting changes in guided wave signal propagation directly though the wall of the pipe, namely not via the region or volume **260**, for detecting any changes in an integrity of the pipe **100**, for example a material loss therefrom arising from erosion and/or corrosion, as well as fatigue damage, such as cracking of the wall of the pipe **100**.

Referring next to FIG. 17, there is shown an illustration of a portion of the wall of the pipe **100** to which the optical fibre and its associated Bragg grating sensors **540** have been applied. Optionally, the optical fibre **510** is supported in a compliant backing material **860**, for example fabricated from one or more polymeric materials, for example from a plastics material, which itself is supported onto a frame **870** to which a force F can be applied to ensure that the optical fibre **510** contacts onto the external surface of the pipe **100** in a stable and acoustically efficient manner. The backing material **860** is beneficially acoustically dissipative, likewise the frame **870**, so that spurious acoustic radiation signals are not generated in the apparatus **180** when in operation. In the apparatus **180**, use of the *modeline* transducers **200** potentially enhancing flow rate measuring accuracy for non-invasive acoustic radiation flow meters; such transducers **200** are beneficially also clamped or otherwise forced against the external surface of the pipe **100**.

The aforesaid apparatus **180** is capable of functioning as a pipe surface-mounted acoustic sensor grid for extending functionality of flow meters by measuring spatial flow information. As aforementioned, the apparatus **180** includes one or more, for example three, sets of transducers **200(1)**, **200(2)**, **200(3)** mounted to the external surface of the pipe **100**. The sets of transducers **200(1)**, **200(2)**, **200(3)** are operable, when supplied with suitable drive signals, to generate Lamb waves within the wall of the pipe **100**, wherein the Lamb waves are coupled into the region or volume **260** of the pipe **100** wherein fluid flows in operation, wherein the Lamb waves propagate as corresponding steered acoustic radiation in a form of one or more beams **250** which spread slightly as they propagate towards an opposite wall of the pipe **100**. At an area of the opposite wall **100** whereat the one or more beams **250** are received, there are included one or more receiver transducers **300**, for example implemented as an acoustic sensor grid implemented using Bragg grating sensors **540** formed in an optical fibre **510** as aforementioned, which are operable of sensing an arrival of a representative number of beams **250** of acoustic radiation propagating though the volume **260**. The one or more receiving sensors **300** detect differences in properties of the one or more beams **250** of the acoustic radiation which arrive, for example in respect of their received amplitude and their time-of-flight, for an entire area in which the acoustic radiation propagates.

The acoustic radiation is reflected from the opposite wall and propagates through a further spatial volume within the volume of region **260**, eventually arriving at a same side of the pipe from which the one or more beams **250** were originally emitted. On the same side, the one or more beams of acoustic radiation are received by one or more receiver transducers **300** and/or one of the transducers **200** of the sets **200(1)**, **200(2)**, **200(3)** being employed. Optionally, by measuring the amplitude of a portion of the acoustic radiation emitted out to the opposite wall of the pipe **100** that is received back on the same side of the wall of the pipe **100**, a fluid phase at a position of the transducers **200**, **300** can be determined, as more energy is reflected in a presence of gas at the inner surface of the wall of the pipe **100**.

Such a measurement procedure is repeated in an opposite direction, relative to a direction of the flow **110** through the pipe **100**. Moreover, such backward and forward measurements are executed for each of the sets of transducers **200(1)**, **200(2)**, **200(3)**, for example repetitive in a cycle of measurement which are continuously repeated to provide real-time monitoring of the flow **110** within the pipe **100**. Thus:

(a) sensed multiple-point information obtained regarding time-of-flight in a first direction of propagation is subtracted from corresponding multiple-point information for a second direction, wherein the first and second directions are mutually opposite; from such measurement a fluid velocity profile is determined;

(b) from measured time-of-flight and known corresponding time-of-flight information, for example expressed in a form of look-up table in the signal processing arrangement, acoustic radiation propagation distribution is computed for the volume or region **260** in which the acoustic radiation propagates, thereby enabling a spatial distribution of fluid phases within the pipe **100** to be determined; and

(c) the multiple point detection of the one or more steered acoustic radiation beams **250** provides information regarding acoustic radiation propagation attenuation within the volume or region **260**. A partial or complete attenuation of the propagating acoustic radiation is indicative of a local presence of process fluids having mutually significantly different densities, for example one or more gas bubbles in liquid, or one or more liquid droplets in a gas, depending upon a dominant fluid phase flowing long the pipe **100** incepted by the one or more steered acoustic radiation beams **250**. The number of sensors 300 which experience acoustic radiation attenuation is indicative of projected bubble or droplet size, for example the bubble **700** in FIG. 15.

When the apparatus **180** is employed to measure multiphase transitional flow, namely pertaining to a transition between liquid and gas continuous flows, the signal processing arrangement is beneficially operable to employ a cross-correlation measurements based in acoustic radiation information signature associated with interrogating from the fluid volume **830** to the second fluid volume **820**, or movement within the volume, measured by corresponding sensors **300**, for example Bragg grating sensors **540**, optionally replaces the fluid fraction and flow rate measurements.

Optionally, the distributed receiver transducers **300**, for example implemented as Bragg grating filter sensors **540**, detect changes in properties relating fluids flowing through the pipe **100**, for example solid transport in aforesaid fluids, wherein the solid is a wax, a hydrate, scale, in addition to a surface temperature of the pipe **100**. Such information to be derived from primary steered acoustic radiation beams, and/or from secondary acoustic radiation, for example shear mode excitation and acoustic radiation by additional transducers added to the apparatus **180**.

Optionally, the receiver transducers **300**, for example Bragg grating filter sensors **540**, are employed to detect dimension of the pipe **100**, for determining pipe degradation such as wall thinning, corrosion, erosion, cracking, pitting pipe coating thickness and other pipe integrity issues. Such information is beneficially derived primary steered acoustic radiation beams which are excited in the apparatus **180**, in addition to secondary acoustic radiation, for example shear mode excitation and acoustic radiation by additional transducers added to the apparatus **180**.

Optionally, the apparatus **180** is implemented by using one central controller for synchronizing all three or more transducers **200** and their associated surround receiver sensors **300**. Spatial information, obtained via use of these transducers **200**, **300** for interrogating the region or volume **260** of the pipe **100** through use of synchronous and repetitive excitation, enables laminar, transitional and turbulent multiphase flows within the pipe **100** to be analyzed. As described in the foregoing, at least six regions of the volume or region **260** are interrogated by the steered beams **250**, when three transducers **200** are employed; optionally, these six regions are at least partially spatially overlapping. Fluid phase fraction % and a flow rate across a full cross-section of the volume or region **260** can be determined using the apparatus **180**. When gas bubbles present within the pipe **100** causes attenuation of acoustic radiation propagating therein, the receiver transducers **300**, for example implemented as a spatially-distributed grid of sensors **540**, off-centre propagation of acoustic radiation is measured and shadowing caused by the gas bubbles is detected. Optionally, the transducers **200**, for example implemented using aforesaid "*modeline*" transducers, is beneficially excited at two or more frequencies in a sequential manner, for reducing uncertainty in measured signals, and thereby increasing measurement accuracy of the apparatus **180**.

Next, the sets of transducers **200** implemented in a "*modeline*" manner will now be elucidated in greater detail. Referring to FIG. 3, the sets of transducers **200** are operable to direct and shape selected acoustic propagation modes for the aforesaid acoustic radiation, thereby ensuring improved utilization of emitted acoustic radiation within the pipe **200**. The acoustic radiation **240**, propagating for example as beams **250**, is directed towards a similarly shaped receiving transducer **200**; for example, the transducer **200A** emits the acoustic radiation, and the transducer **200B** receives the acoustic radiation after it has been reflected from an opposite wall of the pipe **100** relative to that on which the transducers **200A**, **200B** are mounted, as illustrated. Such a *modeline* structure for the transducers **200A**, **200B** enables radiation corresponding to spurious unwanted acoustic radiation propagation modes to be rejected and thus not contribute to received acoustic radiation signals, as represented by output signals from the transducer **200B**, in this example, thus increasing measurement signal-to-noise ratio and hence enhancing measurement accuracy.

In the transducers **200A**, **200B**, the waveguide therein is substantially untapered, namely is different to a conventional wedge-shape coupling element used to couple ultrasonic transducers to an external surface of a conduit or pipe. The waveguide of the transducers **200A**, **200B** is capable of reducing signal drifts in signals obtained in the apparatus **180** that would otherwise arise if wedge-shaped coupling elements were employed. Moreover, the waveguide of the transducers **200A**, **200B** is capable of coupling acoustic radiation more efficient to and from the wall of the pipe **100**. Furthermore, the elongate length of the waveguide of the transducers **200A**, **200B**, in conjunction with associated monitoring sensors **230** enables an acoustic velocity within the transducers **200A**, **200B** to be determined, thereby enabling a temperature compensation of transducer **200** characteristics to be performed by the data processing arrangement of the apparatus **180**. Additionally, the monitoring sensors **230** enable operating integrity of the transducers **200A**, **200B** to be verified, for example equipment failure detection, which may be potentially relevant when the apparatus **180** is a critical part of a petrochemicals facility, materials processing facility, power station, nuclear facility and similar.

Modifications to embodiments of the invention described in the foregoing are possible without departing from the scope of the invention as defined by the accompanying claims. For example optionally in an embodiment the spatially attenuation is most commonly measured for a signal that has passed through the gas volumes 700 present in the region 260 and not only along the wall of the pipe 100. Expressions such as “including”, “comprising”, “incorporating”, “consisting of”, “have”, “is” used to describe and claim the present invention are intended to be construed in a non-exclusive manner, namely allowing for items, components or elements not explicitly described also to be present. Reference to the singular is also to be construed to relate to the plural. Numerals included within parentheses in the accompanying claims are intended to assist understanding of the claims and should not be construed in any way to limit subject matter claimed by these claims.

CLAIMS

We claim:

1. An apparatus (180) for measuring a flow (110) within a region (260) surrounded by a wall of a pipe (100), characterized in that the apparatus (180) includes a transducer arrangement (200, 300, 510, 540) disposed substantially around an external surface of the wall of the pipe (100) for emitting a plurality of beams (250A) of acoustic radiation into the region (260) and for receiving acoustic radiation (250A, 250B) transmitted through and/or reflected from the region (260), wherein:

(a) the plurality of beams (250A, 250B) are arranged to interrogate sampling points off-axis and on-axis in a cross-section of the region (260) for determining whether the flow is laminar, transitional or turbulent;

(b) the plurality of beams (250A, 250B) are employed in a repetitive manner to monitor temporal fluctuations in the flow (110);

(c) the sensor arrangement (300, 510, 540) is operable to sense spatially varying attenuation of the received acoustic radiation thereat for determining an occurrence of one or more gas volumes (700) present within the region (260);

(d) the transducer arrangement (200, 300) is employed for performing time-of-flight measurements for propagation of the acoustic radiation within the region (260) in upstream and downstream flow directions; and

(e) the transducer arrangement (200, 300, 510, 540) is coupled to a corresponding signal processing arrangement for exciting the transducer arrangement (200, 300, 510, 540) and for processing received signals generate by the transducer arrangement (200, 300, 510, 540) to provide measurement output data representative of at least one of: flow velocity within the region (260), an indication of phases present in the region (260) (gas fraction), a flow rate through the region (260).

2. The apparatus (180) of claim 1, characterized in that the transducer arrangement (200, 300) includes a plurality of sets of waveguide transducers ("*modeline*") for generating and receiving the plurality of beams (150A, 150B) in

cooperation with acoustic radiation propagation via the wall of the pipe (100), wherein the waveguide transducers include an elongate waveguide, and one or more transducer elements disposed at at least one end of the waveguide, and wherein a side portion of the waveguide is mounted in operation to an external surface of the wall of the pipe (100) for coupling acoustic radiation to and from the wall of the pipe (100).

3. The apparatus (180) of claim 2, characterized in that at least one waveguide of the transducer arrangement (200, 300) includes a first end thereof and a second end thereof, wherein an array of transducer elements (220) is disposed at the first end and are individually excitable in a phase-array manner for steering the one or more beams (250A, 250B) within the region (260), and the one or more transducer elements (230) are disposed at the second end for monitoring integrity of operation of the waveguide and/or for enabling a temperature compensation to be applied by the signal processing arrangement (600, 610) for operation of the waveguide.

4. The apparatus (180) of claim 1, characterized in that the transducer arrangement (300) includes a spatially distributed array of sensors disposed on an external surface of the wall of the pipe (100) for receiving acoustic radiation coupled through the wall of the pipe (100) thereto.

5. The apparatus (180) of claim 4, characterized in that the spatially distributed array of sensors (540) is implemented using a plurality of Bragg grating filter sensors (540) distributed along one or more optical fibres (510), wherein the Bragg filter sensors (540) are optically interrogated in operation via optical radiation guided through the one or more optical fibres (510) and selectively reflected and/or transmitted at the Bragg grating filter sensors (FBG, 540).

6. The apparatus (180) of claim 4, characterized in that the spatially distributed array of sensors (540) is interspersed between waveguides of the transducer arrangement for generating the plurality of beams (250A, 250B).

7. A method of using an apparatus (180) for measuring a flow (110) within a region (260) surrounded by a wall of a pipe (100), wherein the apparatus (180)

includes a transducer arrangement (200, 300, 510, 540) disposed substantially around an external surface of the wall of the pipe (100) for emitting a plurality of beams (250A) of acoustic radiation into the region (260) and for receiving acoustic radiation (250A, 250B) transmitted through and/or reflected from the region (260), characterized in that the method includes:

(a) using the plurality of beams (250A, 250B) to interrogate sampling points off-axis and on-axis in a cross-section of the region (260) for determining whether the flow is laminar, transitional or turbulent;

(b) employing the plurality of beams (250A, 250B) in a repetitive manner to monitor temporal fluctuations in the flow (110);

(c) using the sensor arrangement (300, 510, 540) to sense spatially varying attenuation of the received acoustic radiation thereat for determining an occurrence of one or more gas volumes (700) present within the region (260);

(d) employing the transducer arrangement (200, 300) to perform time-of-flight measurements for propagation of the acoustic radiation within the region (260) in upstream and downstream flow directions; and

(e) using a corresponding signal processing arrangement coupled to the transducer arrangement (200, 300, 510, 540) for exciting the transducer arrangement (200, 300, 510, 540) and for processing received signals generate by the transducer arrangement (200, 300, 510, 540) to provide measurement output data representative of at least one of: flow velocity within the region (260), an indication of phases present in the region (260) (gas fraction), a flow rate through the region (260).

8. A software product recorded on non-transient machine-readable data storage media, wherein the software product is executable upon computing hardware of the apparatus (185) of claim 1 for implementing the method of claim 7.

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Application No:	GB1323076.8	**Examiner:**	Mr Daniel Jones
Claims searched:	1-8	**Date of search:**	7 April 2014

Patents Act 1977: Search Report under Section 17

Documents considered to be relevant:

Category	Relevant to claims	Identity of document and passage or figure of particular relevance
X	1, 7 at least	US2008/156107 A1 (GEN ELECTRIC) Whole doc. is relevant.
X	1, 7 at least.	US2003/121335 A1 (LIU YI et al.) Whole doc. is relevant.
X	1, 7 at least.	US2002/053243 A1 (INTERNAT HYDROSONIC CO LTD et al.) Whole doc. is relevant.
X	1, 7 at least.	US6089104 A (CHANG HAK SOO) Whole doc. is relevant.
X	1, 7 at least.	FR2781047 A1 (FAURE HERMAN) Whole doc. is relevant.
X	1, 7 at least	CN203132615 U (UNIV ZHEJIANG) See abstract and figs.
X	1, 7 at least	GB2412966 A (WOOD GROUP LOGGING SERVICES IN) See abstract and figs. at least.
Y	1, 4, 5, 7 at least.	GB2399412 A (WEATHERFORD LAMB) See abstract and figs. at least. Not clear which doc. this 'Y' doc might be combined with at this stage - see exam report.
X	1, 7 at least.	WO2008/073673 A1 (GEN ELECTRIC et al.) See abstract and figs. at least.

Categories:

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
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Field of Search:

Search of GB, EP, WO & US patent documents classified in the following areas of the UKC^{X} :

Worldwide search of patent documents classified in the following areas of the IPC

G01F; G01N

The following online and other databases have been used in the preparation of this search report

WPI, EPODOC

International Classification:

Subclass	Subgroup	Valid From
G01F	0001/74	01/01/2006
G01F	0001/66	01/01/2006
G01N	0029/02	01/01/2006
G01N	0029/024	01/01/2006
G01N	0029/14	01/01/2006
G01P	0005/24	01/01/2006