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[Continued on next page]

(54) **Title**: SURFACE WAVE SENSOR FOR DOWNHOLE APPLICATIONS

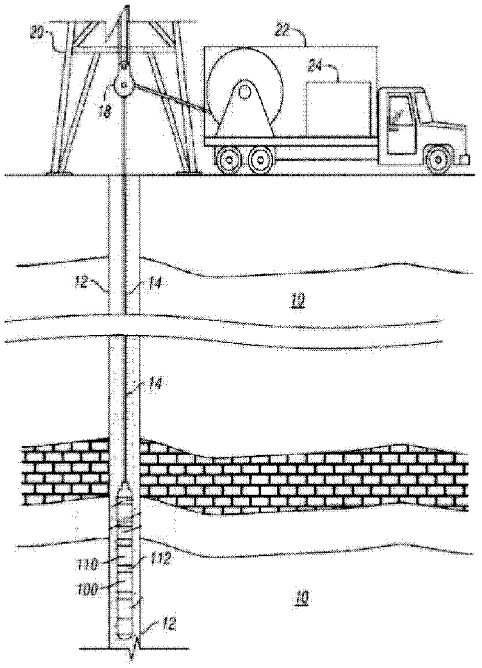

FIG. 1

(57) **Abstract**: The present disclosure relates to an apparatus and method for estimating a parameter of interest in a downhole fluid using a fluid analysis module. The fluid analysis module may include: a first transducer configured to generate a surface wave in a fluid. The first transducer may include one or more of: a piezoelectric crystal, a electromagnetic transducer, and a surface acoustic wave crystal. The apparatus may use the first transducer or a second transducer to generate a signal indicative of the dissipation of the surface wave in the fluid. The apparatus may include a compensator configured to reduce mechanical pressure on the transducer. The method may include estimating a parameter of interest of the fluid using a signal indicative of the dissipation of the surface wave.

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SURFACE WAVE SENSOR FOR DOWNHOLE APPLICATIONS

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FIELD OF THE DISCLOSURE

[0001] This disclosure generally relates to estimating properties of downhole fluids. In certain aspects, the disclosure relates to analysis of fluids using surface waves.

BACKGROUND OF THE DISCLOSURE

[0002] Fluid evaluation techniques are well known. Broadly speaking, analysis of fluids may provide valuable data indicative of formation and wellbore parameters. Many fluids, such as formation fluids, production fluids, and drilling fluids, contain a large number of components with a complex composition.

[0003] The complex composition of such fluids may be sensitive to changes in the environment, e.g., pressure changes, temperature changes, contamination, etc. Thus, retrieval of a sample may cause unwanted separation or precipitation within the fluid. Additionally, some components of the fluid may change state (gas to liquid, or liquid to solid) when removed to surface conditions. If precipitation or separation occurs, it may not be possible to restore the original composition of the fluid.

SUMMARY OF THE DISCLOSURE

[0004] In aspects, this disclosure generally relates to analysis of fluids. More specifically, this disclosure relates to analysis of fluids using a device configured to respond to a dissipation of surface waves.

[0005] One embodiment according to the present disclosure includes an apparatus for estimating a parameter of interest of a fluid downhole, comprising: a first transducer responsive to a dissipation of at least one surface wave in the fluid and configured to generate an electrical signal indicative of the parameter of interest.

[0006] Another embodiment according to the present disclosure includes a method of estimating a parameter of interest in a fluid downhole, comprising: estimating the parameter of interest using an electrical signal indicative of a dissipation of at least one surface wave in the fluid, the electrical signal being generated using a first transducer.

[0007] Examples of certain features of the disclosure have been summarized rather broadly in order that the detailed description thereof that follows may be better understood and in order that the contributions they represent to the art may be appreciated.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] For a detailed understanding of the present disclosure, reference should be made to the following detailed description of the embodiments, taken in conjunction with the accompanying drawings, in which like elements have been given like numerals, wherein:

Fig. 1 shows a schematic of a fluid analysis module deployed in a borehole along a wireline according to one embodiment of the present disclosure;

Fig. 2 shows a schematic of a fluid analysis module according to one embodiment of the present disclosure;

Fig. 3 shows a schematic of a fluid analysis module according to another embodiment of the present disclosure;

Fig. 4 shows a schematic of a fluid analysis module according to another embodiment of the present disclosure;

Fig. 5 shows a schematic of a fluid analysis module according to another embodiment of the present disclosure; and

Fig. 6 shows a flow chart of a method for analyzing a fluid using a fluid analysis module according to one embodiment of the present disclosure.

DETAILED DESCRIPTION

[0009] This disclosure generally relates to analysis of fluids. In one aspect, this disclosure relates to analysis of fluids using a transducer responsive to a dissipation of at least one surface wave and configured to generate an electric signal indicative of the dissipation. Herein, the term “surface wave” relates to a mechanical wave that propagates along the interface between differing media.

[0010] A surface wave may be introduced to a fluid by a transmitter. The resulting vibrations may begin to dissipate due to resistance to motion due to the fluid. Herein, the term “dissipation” relates to damping, reduction, or attenuation of the amplitude or energy of a wave. The time and manner of the dissipation may be related to properties of the fluid, such as, but not limited to, viscosity, density, and viscosity-density product. A receiver may be configured to generate a signal in response to the dissipation of the surface waves in the fluid. The transmitter and receiver may be separate devices or a single device may be configured to operate as transmitter and receiver. The surface wave transmitted into the fluid may be, but is not limited to, a square pulse or a sinusoid (continuous or stored in memory). The modification of the signal in amplitude, frequency, or phase may be used individually or together to estimate the viscosity and density of the fluid using suitable analytical and empirical models known to those of skill in the art. In embodiments where the same transducer may be used as both transmitter and receiver, the transmitter may be switched off during a period for the reflected signal from a metal-liquid interface.

[0011] Different configurations of transmitters may be used for different types of surface waves. A lamb wave transmitter may include a wedge configured to couple lamb waves with a body in contact with the fluid. Herein, the term “couple” relates to channeling the energy from a transducer to a structure from which surface waves may propagate. In some embodiments, the wedge may be configured to reduce undesired wave components. A love wave transmitter may use a transducer directed to generate a wave in a thin layer surrounding, at least in part, a solid body in communication with the fluid. The solid body may include a crystal, such as, but not limited to, one of: i) an XY-cut quartz crystal, ii) an ST-quartz crystal, and iii) a Y-rotated quartz crystal. The thin layer may include a metal configured to act as a waveguide for love waves. In some embodiments, the love wave transmitter may include a solid body of lithium tantalite with a thin layer that includes silica. Finally, a Rayleigh wave sensor may include a surface acoustic crystal disposed in the fluid. Transducers that may be used to generate lamb, love, and Rayleigh waves, may also be used to generate flexural plate waves and skimming bulk waves. Several non-limiting embodiments of an apparatus configured to use the proposed technique are described below.

[0012] Referring initially to **FIG. 1**, there is schematically represented a cross-section of a subterranean formation **10** in which is drilled a borehole **12**. Suspended within the borehole **12** at the bottom end of a carrier **14**, such as a wireline, is a downhole assembly **100**. In some embodiments, the carrier **14** may be rigid, such as a coiled tube, casing, liners, drill pipe, etc. In other embodiments, the carrier **14** may be non-rigid, such as wirelines, wireline sondes, slickline sondes, e-lines, drop tools, self-propelled tractors, etc. The term "carrier" as used herein means any device, device component, combination of devices, media and/or member that may be used to convey, house, support, or otherwise facilitate the use of another device, device component, combination of devices, media and/or member. The carrier **14** is often carried over a pulley **18** supported by a derrick **20**. Wireline deployment and retrieval is performed by a powered winch carried by a service truck **22**, for example. A control panel **24** interconnected to the downhole assembly **100** through the carrier **14** by conventional means controls transmission of electrical power, data/command signals, and also provides control over operation of the components in the downhole assembly **100**. The data may be transmitted in analog or digital form. Downhole assembly **100** may include a fluid analysis module **112**. Downhole assembly **100** may also include a sampling device **110**. Herein, the downhole assembly **100** may be used in a drilling system (not shown) as well as a wireline. While a wireline conveyance system has been shown, it should be understood that embodiments of the present disclosure may be utilized in connection with tools conveyed via rigid carriers (e.g., jointed tubular or coiled tubing) as well as non-rigid carriers (e.g., wireline, slickline, e-line, etc.). Some embodiments of the present disclosure may be deployed along with Logging While Drilling/Measurement While Drilling tools. In some embodiments, downhole assembly **100** may be configured for installation in a borehole **12**.

[0013] **FIG. 2** shows an exemplary embodiment for a fluid analysis module **112** for testing one or more fluids. Fluid analysis module **112** may include an actuator **210** configured to generate waves in a body **230**. The body **230** may include, at least in part, one of: i) a metal, ii) a ceramic, and iii) a composite material. The actuator **210** may generate waves using techniques known to those of skill in the art. The actuator **210** may include one or more of: i) a piezoelectric crystal, ii) a fine point contact transducer, iii) an air-coupled ultrasonic transducer, iv) a laser wave generator, and v) a wedge transducer. The actuator **210** may be in contact with a wedge **220** configured to couple lamb waves to body **230**. The wedge may have an angle **225** selected to enhance the coupling of lamb waves to the body. The angle **225** may be selected to adjust the degree of coupling of the lamb waves using techniques known to those of skill in the art. The body **230** may be positioned within a housing **250** such that part of the body **230** may be in contact with the fluid **240** for analysis. In some embodiments, body **230** may include multiple sub-bodies (not shown) such that at least one sub-body is in contact with fluid **240**, at least one sub-body is in contact with wedge **220**, and each of the multiple sub-bodies is in physical communication with at least one other sub-body.

[0014] After a lamb wave is introduced to the fluid **240**, the dissipation of the lamb wave may be detected by a transducer. The actuator **210** may be configured to serve as the transducer and thus receive the dissipating vibrations from the lamb waves in the fluid **240**. In some embodiments, a separate transducer (not shown) may be placed in communication with the lamb waves in the fluid **240** to generate an electrical signal in response to the dissipating waves.

The use of a separate transducer may enable wave generation and dissipation measurement to take place simultaneously. In some embodiments, the actuator **210** may be used to both transmit the surface waves and measure the dissipation of the surface waves, separately. When using the actuator **210** to transmit and receive, the actuator **210** may use a duty cycle where the transmission aspect of actuator **210** is active to transmit and inactive to receive. In some embodiments, fluid analysis module **112** may include multiple transducers disposed to estimate the dissipation of surface waves at several points along housing **250**. The transducers may be configured to transmit, receive, or transmit/receive. The estimates from multiple locations may compensate for variations in dissipation estimates due to differences in environmental conditions along housing **250**. The environmental conditions may include, but are not limited to, one or more of: i) temperature and ii) pressure. In some embodiments, one or more of flexural plate waves and skimming bulk waves may be substituted for lamb waves.

[0015] **FIG. 3** shows another embodiment for the fluid analysis module **112**. In this embodiment, fluid analysis module **112** may include an electromagnetic transducer (eMAT) **320** configured to generate an alternating magnetic field. The eMAT **320** may include a permanent magnet **340** and coil **310**. The module **112** may include a metallic plate **330** positioned in wave communication with fluid **240** under investigation. The metallic plate **330** may be configured to generate lamb waves and/or love waves when exposed to the magnetic field from magnetic field source **320**. In some embodiments, the magnetic field source **320** may include an electromagnet coil. In some embodiments, the eMAT **320** may include one or more of: i) a permanent magnet, ii) an array of permanent magnets, iii) a DC electromagnet, and iv) a pulsed current electromagnet.

[0016] After a lamb/love wave is introduced to the fluid **240**, the dissipation of the wave may be detected by vibrations of the fluid causing vibrations in metallic plate **330**. The dissipation of the waves may be estimated from an electrical signal generated by the magnetic field interaction between the metallic plate and the magnetic field source **320**. In some embodiments, a separate transducer (not shown) may be in communication with the fluid **240** to estimate the dissipation of the surface waves in the fluid **240**. The use of a separate transducer may enable wave generation and dissipation measurement to take place simultaneously. In some embodiments, the magnetic field source **320** may be used to both transmit the surface waves and measure the dissipation of the surface waves, separately. When using the magnetic field source **320** to transmit and receive, the magnetic field source **320** may use a duty cycle where the transmission aspect of magnetic field source **320** is active to transmit and inactive to receive. In some embodiments, one or more of flexural plate waves and skimming bulk waves may be substituted for lamb/love waves.

[0017] **FIG. 4** shows another embodiment for the fluid analysis module **112**. This embodiment may be configured to generate a Rayleigh wave using a surface acoustic wave (SAW) crystal **410** as a transducer. In some embodiments, the SAW crystal **410** may include an interdigitated transducer **450** configured to excite a surface wave in a crystal **460**. The fluid analysis module **112** may include a SAW crystal **410** disposed within the fluid **240**. The SAW crystal **410** may be disposed in a holder **420** to insulate the SAW crystal **410** from the housing **250**. The SAW crystal **410** may further have patterns on its surface which can be used to perform additional measurements of density of the fluid.

[0018] The crystal **460** may include a piezoelectric crystal that may be configured to generate a Rayleigh wave, such as by being cut along a specific plane of the piezoelectric crystal. Techniques for cutting crystals to generate different types of waves are known to those of skill in the art. The crystal **460** may include, but is not limited to, one or more of: quartz, langasite, $GaPO_4$, and lithium niobiate. The interdigitated transducer **450** may be configured to convert acoustic waves into electric signals and vice versa.

[0019] After the Rayleigh wave is introduced to the fluid **240**, the dissipation of the wave may be detected by vibrations of the fluid causing vibrations in SAW crystal **410**. The dissipation of the waves may be estimated from an electrical signal generated due to the vibrations in the SAW crystal **410**. In some embodiments, a sound speed sensor **430** may be configured to estimate the speed of sound in the fluid **240** and/or compressibility of the fluid **240**. The sound speed sensor **430** may be separated from the fluid by a metallic plate **440**. The sound speed sensor **430** may include an ultrasonic transducer. In some embodiments, a separate transducer (not shown) may be in communication with the fluid **240** to estimate the dissipation of the surface waves in the fluid **240**. The use of a separate transducer may enable wave generation and dissipation measurement to take place simultaneously. In some embodiments, the SAW crystal **410** may be used to both transmit the surface waves and measure the dissipation of the surface waves, separately. When using the SAW crystal **410** to transmit and receive, the SAW crystal **410** may use a duty cycle where the transmission aspect of SAW crystal **410** is active to transmit and inactive to receive. In some embodiments, one or more of flexural plate waves and skimming bulk waves may be substituted for Rayleigh waves.

[0020] One example of a SAW crystal **410** is a shear-horizontal SAW crystal, wherein the crystal may be configured to generate surface waves with a shear-horizontal propagation. The shear-horizontal SAW crystal may be configured to concentrate wave energy on the surface in contact with lower attenuation than a bulk acoustic wave sensor.

[0021] **FIG. 5** shows another embodiment for the fluid analysis module **112**. This embodiment may be configured to generate a Rayleigh wave using a SAW crystal **510**. The fluid analysis module **112** may include a SAW crystal **510** in contact with the fluid **240**. The SAW crystal **510** may also be in contact with a compensator **520**. The compensator **520** may be configured to reduce a pressure difference between the fluid side **530** of the SAW crystal **510** and the compensated side **540** of the SAW crystal **510**. The use of pressure compensator **520** may reduce the thickness of SAW crystal **510** used in high pressure fluids, since the differential pressure across the SAW crystal **510** may be maintained within a range which is not detrimental to the SAW crystal **510**. The compensator **520** may be disposed in housing **250**. In some embodiments, the compensator **520** may include a pressurized fluid. In other embodiments, the compensator **520** may include a mechanical compensation device, such as, but not limited to, a piston or a mechanical spring.

[0022] After the Rayleigh wave is introduced to the fluid **240**, the dissipation of the wave may be detected by vibrations of the fluid causing vibrations in SAW crystal **510**. The dissipation of the waves may be estimated from an electrical signal generated due to the vibrations in the SAW crystal **510**. In some embodiments, a separate transducer (not shown) may be in communication with the fluid **240** to estimate the dissipation of the surface waves in the fluid **240**. The use of a separate transducer may enable wave generation and dissipation measurement to take place simultaneously. In some embodiments, the SAW crystal **510** may be used to both transmit the surface waves and measure the dissipation of the surface waves, separately. When using the SAW crystal **510** to transmit and receive, the SAW crystal **510** may use a duty cycle where the transmission aspect of SAW crystal **510** is active to transmit and inactive to receive. In some embodiments, one or more of flexural plate waves and skimming bulk waves may be substituted for Rayleigh waves.

[0023] **FIG. 6** shows a flow chart of a method **600** for estimating fluid properties in the fluid **240** using embodiments of the fluid analysis module **112**. In step **610**, a surface wave may be introduced to the fluid **240**. In step **620**, an electrical signal may be generated by a transducer in module **112** in response to the dissipation of the surface wave in the fluid **240**. The transducer responsive to the dissipation of the surface waves may be the actuator **210**, coil **310**, SAW crystal **410**, SAW crystal **510**, or a separate transducer (not shown). In step **630**, at least one fluid property may be estimated using the electrical signal. The at least one fluid property may include, but is not limited to, at least one of: i) viscosity, ii) density, and iii) density-viscosity product. In some embodiments, step **630** may include using information from an additional sensor, such as a sound speed sensor.

[0024] While the present teachings have been discussed in the context of hydrocarbon producing wells, it should be understood that the present teachings may be applied to geothermal wells, groundwater wells, subsea analysis, etc. Also, the present teachings may be applied to downhole installations for wellbore fluid monitoring and surface-based fluid recovery and analysis.

[0025] While the foregoing disclosure is directed to the one mode embodiments of the disclosure, various modifications will be apparent to those skilled in the art. It is intended that all variations be embraced by the foregoing disclosure.

CLAIMS

We claim:

1. An apparatus for estimating a parameter of interest of a fluid downhole, comprising:

   a first transducer responsive to a dissipation of at least one surface wave in the fluid and configured to generate an electrical signal indicative of the parameter of interest.

2. The apparatus of claim 1, the first transducer being disposed downhole and in communication with the fluid.

3. The apparatus of claim 1, wherein the first transducer is configured to generate the at least one surface wave in the fluid.

4. The apparatus of claim 1, further comprising:

   a second transducer configured to generate the at least one surface wave in the fluid.

5. The apparatus of claim 4, wherein the generation of the electrical signal and the generation of the at least one surface wave take place simultaneously.

6. The apparatus of claim 1, wherein the at least one surface wave includes at least one of: i) a Lamb wave, ii) a Love wave, iii) a Rayleigh wave, iv) a flexural plate wave, and v) a skimming bulk wave.

7. The apparatus of claim 1, wherein the parameter of interest includes at least one of: i) a density of the fluid, ii) a viscosity of the fluid, and iii) a density-viscosity product of the fluid.

8. The apparatus of claim 1, wherein the first transducer includes:

   an element configured to generate an alternating magnetic field when energized; and a plate disposed between the element and the fluid and configured to generate the at least one surface wave when exposed to the alternating magnetic field.

9. The apparatus of claim 8, wherein the plate is, at least in part, metallic.

10. The apparatus of claim 8, wherein the element includes at least one of: a permanent magnet and an electromagnet coil.

11. The apparatus of claim 1, wherein the first transducer includes:

a piezoelectric crystal; and

a wedge configured to couple lamb waves to a body in communication with the fluid.

12. The apparatus of claim 1, wherein the first transducer includes a surface acoustic wave crystal.

13. The apparatus of claim 12, further comprising:

a second transducer in communication with the fluid.

14. The apparatus of claim 12, further comprising:

a compensator configured to reduce a physical stress from the fluid on the first transducer.

15. The apparatus of claim 14, wherein the compensator includes at least one of: i) a pressurized fluid, ii) a piston, and iii) a mechanical spring.

16. A method of estimating a parameter of interest in a fluid downhole, comprising:

estimating the parameter of interest using an electrical signal indicative of a dissipation of at least one surface wave in the fluid, the electrical signal being generated using a first transducer.

17. The method of claim 16, the first transducer being disposed downhole and in communication with the fluid.

18. The method of claim 16, further comprising:

    generating the at least one surface wave in the fluid.

19. The method of claim 18, wherein the at least one surface wave is generated using one of: the first transducer and a second transducer.

20. The method of claim 16, wherein the first transducer includes:

    an element configured to generate an alternating magnetic field when energized; and

    a plate disposed between the element and the fluid and configured to generate the at least one surface wave when exposed to the alternating magnetic field.

21. The method of claim 16, wherein the estimation of the parameter of interest includes using at least one of: a sound speed in the fluid and a compressibility of the fluid.

22. The method of claim 16, wherein the first transducer includes a surface acoustic wave crystal; and

    further comprising reducing a physical stress from the fluid on the surface acoustic wave crystal.

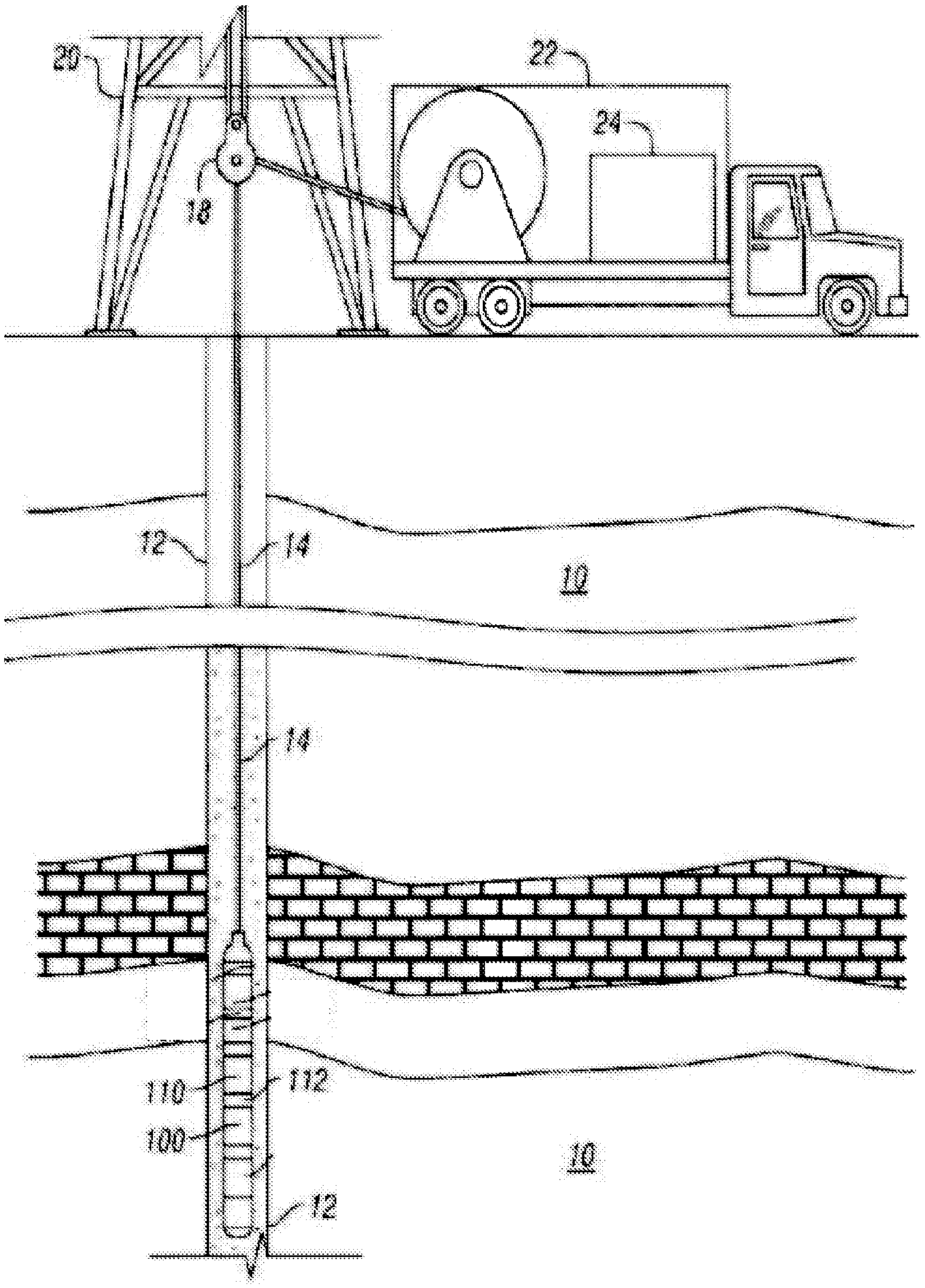

FIG. 1

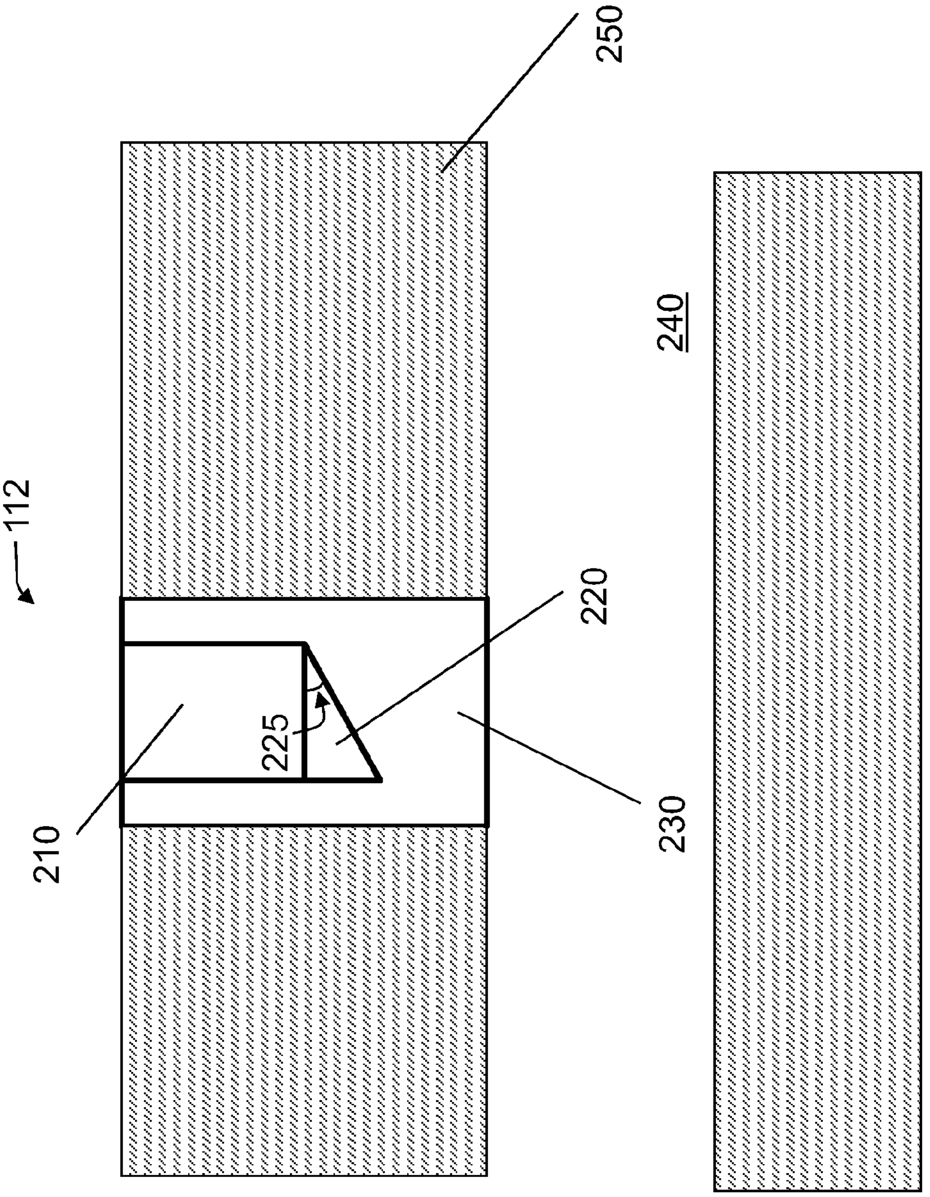

FIG. 2

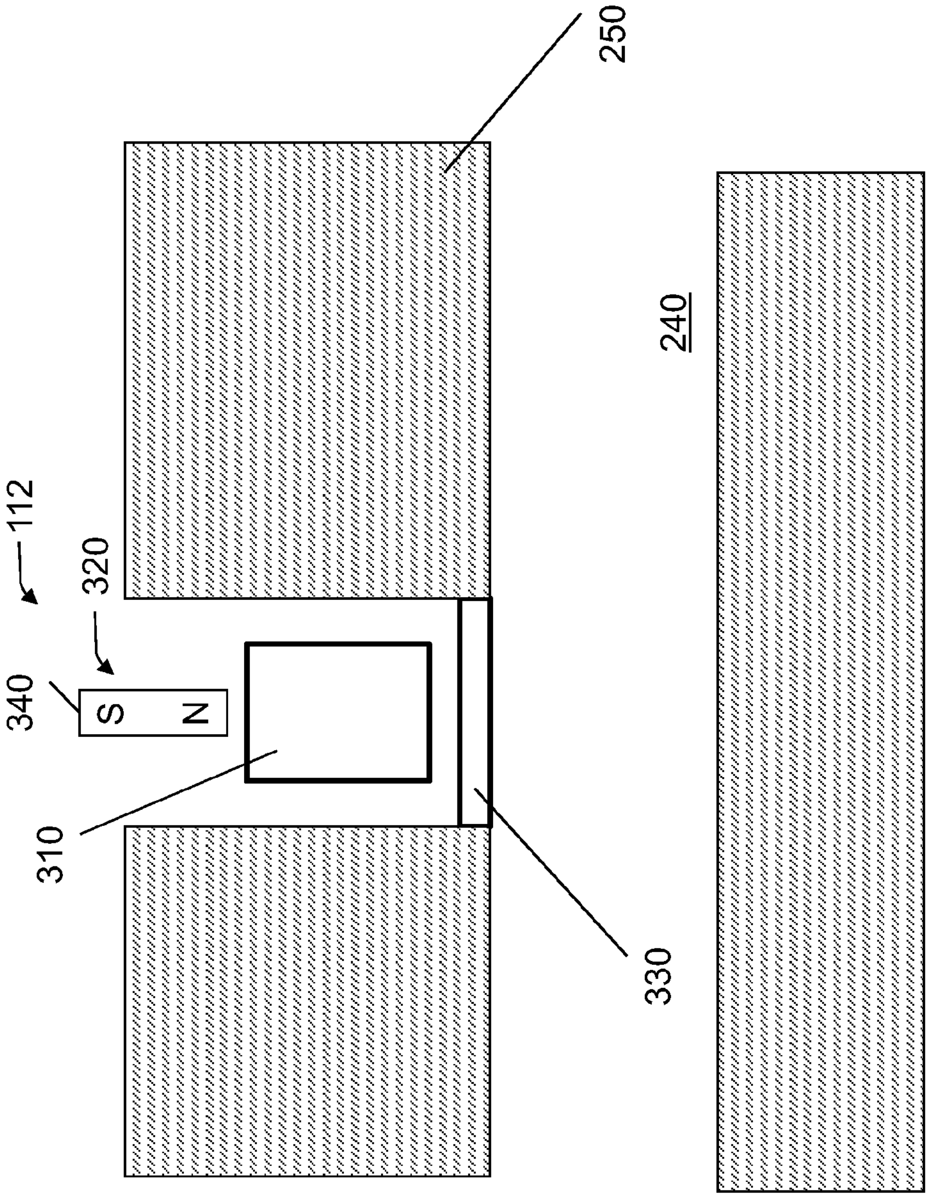

FIG. 3

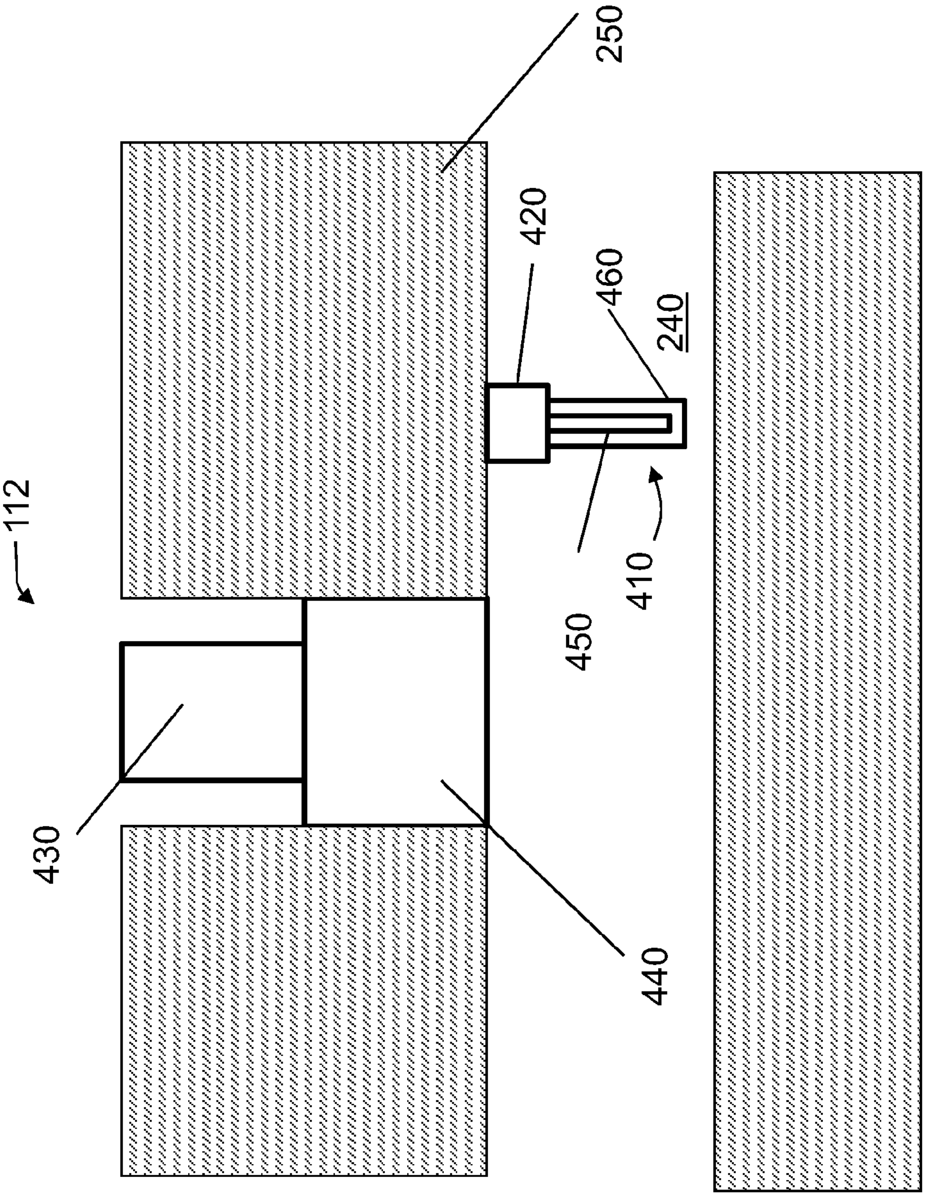

FIG. 4

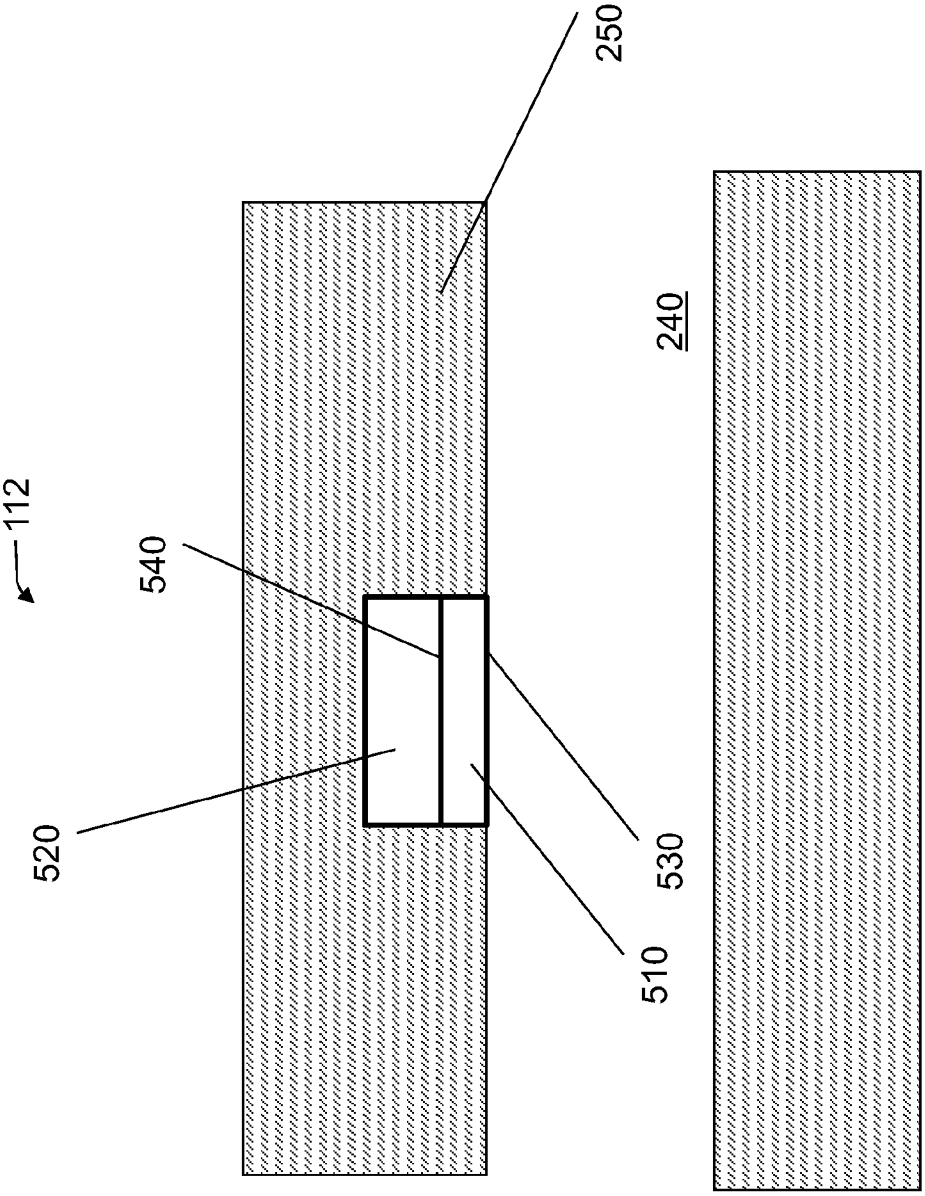

FIG. 5

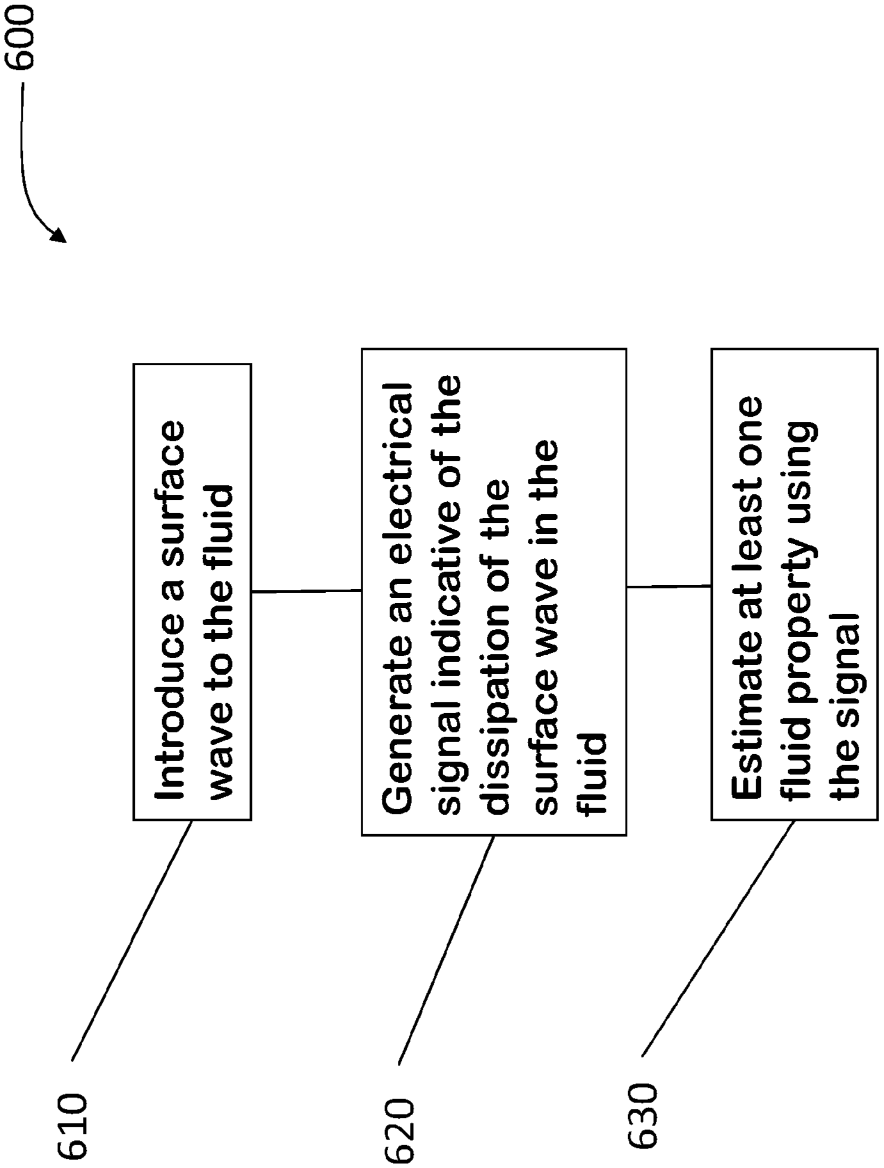
600
Introduce a surface wave to the fluid
Generate an electrical signal indicative of the dissipation of the surface wave in the fluid
Estimate at least one fluid property using the signal
610
620
630

FIG. 6