Ultra-low-power sensor for 3-phase water cut applications

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Abstract—Precise measurement of the water fraction in oil is of critical importance in the oil industry. Currently, cost-effective, reliable and compact downhole measurement technologies capable of full range three phase measurements are not available. This paper presents an ultra-low-power, low cost, wireless and non-corrosive resonance sensor based on magnetoelastic technology that has been implemented by an amorphous ribbon and electromagnetic interrogation. The proposed technology enables distinguishing all three gas, water and oil phases with amplitude changes of 75% and 99% and resonant frequency shifts of 0.46 % and 3.88 %, respectively, compared to the gas phase. The response of the sensor enables characterizing the water-cut range from 10% - 90%. The addition of a Teflon anti-corrosion layer enables sensor deployment for extended periods of time in harsh environments.

Index Terms— Magnetoelastic, amorphous material, water-cut, magnetostriction, downhole, low-power, non-corrosive

I. INTRODUCTION

Efficient well performance in the oil and gas industry is optimized using various sensors that monitor production parameters including multiphase flow rates and contactless water fraction of produced hydrocarbons, also known as water-cut (WC). Technical advances in electronics, low-power sensors and wireless communications have enabled a paradigm shift in wireless monitoring and control for a wide range of applications in the oil and gas industry. The abundance of remote and hazardous locations in the industry has fueled a growing demand for remote sensor applications [1]. Measurements downhole present both challenges and opportunities. The challenge is that the design of the metering hardware must withstand the harsh conditions, where hydrostatic pressure and temperature can reach 30,000 PSI and more than 230 °C, respectively. Downhole measurement does, however, mean that the gas phase may not be present in the mixture, due to the high pressure; thereby, potentially simplifying the system design [2].

Real-time monitoring through inline WC sensors allows for efficient reservoir management and production allocation [3]. WC sensors currently available are either costly, heavy, intrusive, severely sensitive to water salinity or incapable of covering the full WC range [3]. Inline detection of water fraction in oil can be done by sensing the differences in viscosity, effective electric permittivity [4], or IR/gamma-ray absorption characteristics of oil/water mixtures [5]. Electrical sensors based on capacitive measurements or radio frequency resonator measurements (s-parameters) are two different approaches that can be used to analyze the water-in-oil content of emulsions; both measure the impedance of the emulsion [6]. A commercially available WC sensor, like the sensor produced by Delta-C (DC-1510 Series), is based on the capacitance measurement of the oil/water (O/W) mixture, which can cover a limited WC range. Even though this approach offers high accuracy,

it is not applicable nor reliable for WC measurements above 50%, due to a short circuit effect between the capacitor electrodes after inversion [7].

Another common method for measuring the phase fraction is to transmit gamma rays through the production mixture and analyze the energy attenuation [5]. As radioactive materials are required to produce gamma rays, gaining regulatory permits for this sensor type as well as the handling and later disposal of the radioactive materials strongly affects the employment of this technology. The use of X-rays for phase fraction measurements presents similar complications [8]. A WC sensor developed by Saudi Aramco [2] is based on the difference in densities of oil and water, which affects the acoustic speeds of sound traveling through it. This method has the advantages of being nonintrusive to allow full bore access. Although it works in the 0% - 100% water-cut range, flow loop reference measurements show an error of 5%, exceeding the accuracy required for production and reservoir management uses [2].

In this paper, we propose a low-cost magnetoelastic ribbon-based method for WC measurements that can provide real-time information about water-in-oil as well as gas concentrations remotely. Such magnetoelastic sensors have been utilized for various sensing applications before [9]. Our approach consists of a magnetoelastic sensor ribbon in combination with an interrogation module for electromagnetic excitation and detection. The sensor is scalable in size and, consequently, resonating frequency, meaning it can be altered for a specific bore diameter or emulsion compositions, while avoiding frequency noise that may be present or providing multi-sensor encoded readout. The proposed sensor requires very little power, due to the low biasing field required to excite a signal from the sensor ribbon, which can be provided by an additional magnetized biasing ribbon. With a thickness of 28 µm the sensor ribbon is of very low mass and greatly affected by slight changes in surface damping caused by viscosity changes in the surrounding medium, making it adequately sensitive for WC measurements.

The relative change in resonant frequency can be calculated by [10]:

$$\Delta f = \frac{\sqrt{\pi f_0}}{2\pi \rho_s d} \sqrt{\eta \rho_l} . \quad (1)$$

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Equation 1 considers f_o , the resonant frequency of the ribbon in vacuum, ρ_s and d the density and thickness of the ribbon, respectively, and η and ρ_l the effective dynamic viscosity and density of the surrounding medium, respectively. The frequency shift is proportional to the square root of the medium's viscosity and density product. In this case, prior knowledge of the medium density is required for measuring the viscosity. However, it should be noted that for many fluids the density remains essentially constant, while viscosity rapidly changes [10].

The effective viscosity of the WC emulsions was estimated using different emulsion viscosity models, which is difficult to accurately predict for an oil/water emulsion, and various theories exist, namely Einstein [11], Taylor [12], Yaron & Gal-Or [13] and the Dougherty-Krieger model [14]. A combination of these prediction models is used to validate the experimental data in this work. The magnetoelastic sensor concept was further evaluated by investigating the decay of the magnetic material properties and performance reduction caused by exposure to O/W and high salinity mixtures, and the effects of non-corrosive coatings were studied.

II. METHODOLOGY

An Impedance Analyzer (Agilent 4294A) was used to characterize the impedance and phase of the vibrating ribbons with a 4TP 1M adaptor. Images of the amorphous ribbon and the non-corrosive coating layer were captured using a scanning electron microscope (Nova NanoSEM 630, FEI). The magnetic characteristics were measured with a Vibrating Sample Magnetometer (3900 Series MicroMag™, PMC).

Figure 1: (a) Schematic showing the experimental setup with the ribbon immersed in oil/water. (b) A typical frequency response measured with the impedance analyzer.

An oil/water emulsion was produced and used as an analogue for crude oil mixtures present in downhole conditions. Two different strategies were studied for making the oil-water emulsions used for the experiments. In the first one, the required amount of oil and water were mixed along with 10% surfactant (Tween 20). The mixture was then dispersed by utilizing an Eppendorf shaker at 1500 rpm for 3 hours. When studied under the microscope, large islands of the disperse phase were observed indicating a low degree of emulsification (Figure 2a). As expected, this mixture was unstable and separated into oil and water, when left standing for a few minutes. In the second approach, the oil, water and Tween 20 mixture was subjected to agitation at 20 kHz using a probe tip

sonicator (Sonics® Vibra-Cell VCX 500) for 3 hours. The dispersed phase in the resultant emulsion was reduced to extremely fine dimensions (Figure 2b), resulting in a long-lasting emulsion.

Figure 2: Optical microscopy images showing a) the unstable oil/water emulsion dispersed using an Eppendorf Shaker - presented to allow for comparison with b) the stable emulsion dispersed with the Vibra-Cell sonicator at 20 kHz and used in the test.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The sensor consists of two metallic ribbons, namely, an amorphous sensor ribbon and a magnetic biasing ribbon with dimensions $36 \times 6 \times 0.028 \text{ mm}^3$ and $30 \times 6 \times 0.05 \text{ mm}^3$, respectively. The ribbons are encased in a poly-ethylene housing containing the oil/water mixture. The amorphous ribbon samples used in this work are made from an iron-based alloy (Sensormatic, Ultra-Strip®). The saturation magnetization of this material is 1.61 Tesla. The ribbons were interrogated with an inductive coil (resonant frequency of 904 kHz) and an AC current source with frequencies between 50 kHz and 62 kHz, covering the relevant range that included the resonance peak (Given by manufacturer as 58 kHz). The biasing ribbon, made from iron and nickel and hung from the PET housing, magnetizes the amorphous ribbon, thereby reducing the required excitation field strength and increasing the impedance response. The impedance measured in the interrogation coil is affected by the magnetic susceptibility of the core materials. These include the magnetic ribbons and the water/oil emulsion. The impedance of the interrogation coil is given as $Z = R + jX_L$, where the reactance $X_L = \omega L$, and the inductance L of the coil can be written as:

$$L = \frac{N^2 \mu(f, \eta) A}{l} \quad (2)$$

Here, N represents the amount of turns in the coil (350), l the length (12.6 m) and A the cross-sectional area of the inductor (6 mm^2). Furthermore, the permeability of the core material, μ , is influenced by the water/oil liquid volume inside the sensor and the permeability of the ribbons. The change in core material permeability induced by changing the liquid from pure water to pure crude is significantly smaller than the fluctuations measured in the sensor material and is therefore ignored. The permeability of the amorphous ribbon is a function of frequency f and the surrounding medium's viscosity η through magnetostriction. Magnetoelastic vibrations in a magnetoelastic sensor occur, when the applied magnetic field is time varying in nature, causing the field-generated strain to vary with time; thus, producing a longitudinal elastic wave [15]. These vibrations, in turn, generate a secondary magnetic field that can be detected. The measured shift in frequency/amplitude of the coil's impedance is caused by a change in the material surrounding the amorphous ribbon.

A. Water cut response

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The resonant frequency of the amorphous ribbon is determined by the effective damping force induced by the viscosity of the surrounding medium. Therefore, amorphous ribbons in mediums of varying viscosity possess a significantly different characteristic frequency response. The impedance of the interrogation coil with the amorphous and bias ribbons was measured for air, water and oil.

Figure 3: The frequency response of the sensor measured in air, water and oil as impedance amplitude plotted over frequency. The peaks are found at 58.601 kHz, 57.61 kHz and 54.24 kHz, for air, water and oil, respectively.

The results in Figure 3 show a reduction in resonant frequency and vibration amplitude from exposure in air to water of 0.99 kHz and 1.93 k Ω , respectively. Further reductions with exposure to oil were measured at 3.37 kHz and 0.4 k Ω from the measured peaks in water. With a measurement voltage of 10 mV the power consumption was 40 nW in air. When immersed in the water/oil emulsion this value ranges from 160 nW to 500 nW (Find overview of commercial sensors in Table 1S of the Supplementary Material).

The WC response of the sensor was further evaluated by immersing the sensor in different WC emulsions and measuring the resonant frequency shift of the interrogation coil's impedance. Stable oil/water emulsions were created with 10% volumetric surfactant (Tween 20). Different amorphous ribbons were used with every WC emulsion, thereby ensuring that there were no liquids present on the surface of the amorphous ribbon before immersing it in the WC emulsion. Each amorphous ribbon was characterized in air, where-after the frequency and impedance shifts were normalized to the frequency shift caused by 100% water.

Figure 4: The experimentally obtained frequency shift of the interrogation coil's impedance response measured with the sensor immersed in different water cut (WC) emulsions.

Figure 5: Experimental measurements compared with theoretical predictions of the Taylor, Yaron & Gal-Or and Dougherty-Krieger

models 90% - 30% WC. The frequency reduction is normalized to the reduction from unloaded to loaded sensor at 100 % WC.

The results presented in Figure 4 show a decrease in resonant frequency (relative to an undamped sensor) with a decrease in emulsion WC. This is supported by the theoretical predictions made using Equation 1 and the considered viscosity models, as shown in figure 5. Here, however, the frequency shifts are plotted as far as 30% WC, due to phase inversion that occurs at high volume fractions of the dispersed phase [16]. At this point all theoretical models lose their validity. At lower volume fractions the dispersed particles are assumed to be near spherical, and the viscosity can be determined as a function of temperature and volume fraction. At higher volume fractions, however, this can no longer be assumed as hydrodynamic interaction between the droplets becomes significant and the effective viscosity drastically increases [16]. The experimental results fall between the prediction models that were considered. This indicates that the sensor possesses a sensitivity to a reduction or increase of the density/viscosity product. The Yaron & Gal-Or formula shows the closest correlation with the experimental results, due to its consideration of the effects of surfactant addition. The sensitivity is approximated as 27 Hz/% by fitting a linear function within the 90 – 10% WC range.

Regarding the derivation of emulsion viscosity, a method has been described by Herrmann *et al.* [17] that separates the density/viscosity product. This is achieved with dual liquid-loaded sensors with different surface roughness. Furthermore, any measured frequency shift smaller than the measured shift for 90% WC is indicative of air/gas surrounding the sensor.

B. Non-corrosive coating

Since the sensor needs to be capable of operating in harsh conditions (brine salinity ranging from thousands to 260,000 ppm [18]), the magnetic characteristics and performance of the sensor were investigated under various conditions over the period of twenty days. The magnetic properties of a 4 mm x 2 mm amorphous ribbon were characterized using a Vibrating Sample Magnetometer (VSM). The ribbon was secured to the sample holder using silicon grease and the sample holder was vibrated with an amplitude of 1 mm and a frequency of 83 Hz, while sweeping the applied magnetic field from -15 kOe to 15 kOe. The amorphous ribbon is soft magnetic with very low remnant magnetization and coercive field, without hysteresis and a high susceptibility at the origin (inset of Figure 6a).

Figure 6: a) Saturation magnetization of amorphous ribbon without protective coating in water at each day, with the inset showing the normalized magnetization profile of the ribbon at day zero. b) Resonant frequency of amorphous ribbon without protective coating.

Figure 7: Scanning electron microscope images showing the amorphous ribbon's cross-section a) without the protective Teflon layer and b) with the Teflon layer.

Figure 6a shows that the saturation magnetization of the amorphous ribbon decreased quickly by 67%, when the ribbon was immersed in water, due to corrosion. To overcome this limitation different coatings were applied to the sensors, i.e. Teflon (Teflon® AF, Dupont), Parylene C (PDS 2010, Parylene Deposition System). Teflon provided the most effective solution, acting as an anti-corrosion layer and offering chemical resistance and low moisture absorption [19]. An analysis of the Parylene C performance as a non-corrosive coating can be found in the supplementary information. The Teflon was applied to the sensor ribbons by dip coating, which is a simple, low-cost and waste-free coating process. By immersing the ribbons into Teflon solution and withdrawing them at a constant speed, a two-sided Teflon coating of $\sim 2.5 \mu\text{m}$ thickness has been deposited on the sensor surface (Figure 7b).

Figure 8: a) Saturation magnetization and b) resonant frequency of the magnetic ribbon before and after coating with Teflon and during 20 days in air, water and oil.

With this coating, the saturation magnetization of the sensors remained stable in air, water and oil for the entire test duration, which was twenty days (Figure 8a), enabling reliable sensor deployment. The resonant frequency dropped by $\sim 3\%$ (Figure 8b) after coating the sensor ribbons with Teflon. This is due to the mass loading the Teflon causes to the vibrating body. This value is near the theoretical value of 2.13% [see supplementary material]. With the coating applied, the sensors' resonant frequencies remain constant in all three media for an extended period of time.

IV. CONCLUSION

In conclusion, we have developed a low power and low-cost magnetoelastic sensor for WC measurements. The sensor response allows distinguishing the three phases air, water and oil either by the amplitude or resonant frequency changes of an interrogating coil. Amplitude changes of 75% and 99% have been observed for loaded sensors in water and oil, respectively, compared to unloaded sensors in air. The corresponding frequency changes were 0.46% and 3.88%.

The sensor enables water fraction quantification for crude oil for 10 – 90% W/C with a sensitivity of 27 Hz/%. We have also shown that the sensor can operate in the harsh environmental conditions found in downhole applications by the addition of a non-corrosive, $2.5 \mu\text{m}$ thick Teflon layer that prevents the decay of the magnetic characteristics and ensures long-lasting performance of the sensor. The wireless capability and low power requirements of these sensors mean that they are ideal for application in the challenging downhole environment.

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