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Capacitive Sensor Design

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Abstract: This paper presents a condensed study on a capacitance-based water holdup detection method and the design of a miniature sensor for oil–water two-phase flow. The work is motivated by the need for accurate online monitoring of crude-oil water holdup in highly deviated and horizontal wells, where conventional single-point capacitive sensors suffer from limited structural adaptability and serious stray-capacitance interference. Starting from the physical chain of water holdup, dielectric constant, and capacitance, a probe-type capacitive sensor is developed and integrated with a digitization circuit. The sensor capacitance is converted directly into oscillation frequency by a multivibrator based on a Schmitt inverter, which suppresses the adverse influence of long lead wires and improves the anti-interference capability of the measurement channel. To reduce external wiring, a current-detection conversion circuit is further designed to recover the frequency information from the supply current, thereby enabling power-signal multiplexing. Experimental results obtained at 25 °C over a water-holdup range of 0%–100% show a monotonic frequency response, with particularly good resolution below 50% water holdup. In the low-water-holdup range, the maximum relative error is 3.5% and the maximum absolute error is 2.7%. The proposed sensor therefore provides a compact and practical solution for array-based downhole water holdup measurement.

Keywords: water holdup measurement; capacitance method; probe sensor; frequency conversion

1. INTRODUCTION

Water holdup is a key parameter in crude-oil production, gathering, dehydration, metering, and reservoir evaluation. Accurate online measurement of this variable is essential for judging well condition, estimating production performance, and improving the automation level of oilfield operation. In complex downhole environments, however, the measurement task becomes difficult because oil–water distribution varies with flow pattern, inclination angle, and operating condition.

Among the commonly used measurement routes, electromagnetic, conductance, and capacitance methods each have their own application scope. For low-water-holdup measurement, the capacitance method remains attractive because it is structurally simple, comparatively inexpensive, and highly sensitive to the dielectric contrast between oil and water [1]–[4]. Existing capacitive sensors, however, often exhibit limited adaptability to array deployment and are highly susceptible to stray capacitance introduced by long leads, thermal variation, and harsh wellbore conditions.

To address these problems, this paper focuses on the core technical line. The main contribution is a probe-type capacitive water-holdup sensor with digitization and a current-detection conversion circuit. The former converts capacitance variation directly into frequency, while the latter extracts the same frequency information from the supply current so that power transmission and signal transmission can share the same wiring path.

2. OVERALL STRUCTURE DESIGN

2.1 Measurement Principle

The sensing principle is based on the large dielectric-constant difference between oil and water. Under ordinary conditions, the relative dielectric constant of oil is approximately 2.3, whereas that of water is about 80. When an oil–water mixture enters the electric field of the capacitive sensor, the equivalent dielectric constant of the medium changes with water holdup; the sensor capacitance therefore changes accordingly. In the proposed method, the physical chain can be summarized as water holdup → equivalent dielectric constant → capacitance → oscillation frequency. Once the capacitance-dependent frequency is measured and calibrated, the corresponding water holdup can be obtained.

2.2 System Architecture

The overall system consists of a probe-type capacitive sensing element, a capacitance-to-frequency conversion unit, a current-detection conversion circuit, and an external frequency acquisition and interpretation unit. The sensor and the multivibrator are integrated into a compact digital sensor. When the local water holdup changes, the sensor capacitance changes first; the integrated oscillator then transforms this analog variation into a stable frequency signal at the front end. The supply-current variation produced by the oscillator is subsequently recovered by the external three-stage conversion circuit and reshaped into a square wave with the same frequency.

This architecture is intended for array-based downhole measurement and is therefore governed by several engineering requirements: compact size, compatibility with multi-point deployment, good resolution in the 0%–50% low-water-holdup interval, real-time response, and stable operation in high-temperature and high-pressure environments. By shifting digitization to the sensor front end, the design reduces the influence of parasitic capacitance on channel consistency and measurement accuracy [7].

3. HARDWARE DESIGN

3.1 Probe-Type Capacitive Sensor

After comparing parallel-plate, coaxial, and probe-type capacitive structures, the probe configuration was selected because it better satisfies the requirements of miniaturization and array installation. The proposed sensor is composed of an inner cylindrical electrode, an insulating layer, and an annular outer electrode. In the original design, the outer electrode has a length of 25 mm and an inner diameter of 6 mm; the insulating layer is 20 mm long, with an inner diameter of 3.9 mm and an outer diameter of 6 mm; and the inner electrode is 14 mm long with a diameter of 3.9 mm. The effective detection region is the annular zone between the two electrodes, whose characteristic probe range is about 3 mm.

??.2 Digitization Circuit

To suppress stray-capacitance interference at the source, part of the detection circuit is integrated directly into the sensor. The sensor capacitance Csen, a resistor R, and a Schmitt inverter form a self-excited multivibrator. At power-up, Csen is alternately charged and discharged through R, and the inverter switches state when the capacitor voltage reaches the upper and lower hysteresis thresholds. As a result, a periodic rectangular wave is generated at the output. Because the charging and discharging time is proportional to Csen, the oscillation frequency is inversely related to the sensor capacitance. When water holdup increases, the effective dielectric constant and Csen increase, and the output frequency decreases monotonically.

The selected logic device is the SN74LVC1G14DCK Schmitt inverter, which is suitable for compact integration because of its small package, low supply-voltage requirement, and high-temperature tolerance. More importantly, the conversion from capacitance to frequency transforms a very small and interference-sensitive analog quantity into a robust digital feature, thereby substantially improving measurement stability and channel consistency for array applications.

??.3 Current-Detection Conversion Circuit

If the frequency signal were transmitted in a conventional way, each sensor channel would require separate power, ground, and signal lines, which would significantly increase wiring complexity in an array instrument. To overcome this drawback, the proposed design exploits the periodic current variation naturally drawn by the multivibrator from the power line. A dedicated three-stage circuit is then used to extract and reconstruct the frequency information from this current.

The first stage performs current-to-voltage conversion with an operational amplifier, a sampling resistor, and a feedback capacitor; the second stage applies differential amplification to enhance the useful component and suppress common disturbances; and the third stage reshapes the recovered waveform through a hysteresis comparator to obtain a clean alternating signal with the same frequency as the oscillator output. This scheme achieves power-signal multiplexing, reduces the number of interconnections between the sensor and the detection board, and improves transmission quality and layout compactness.

4. SOFTWARE DESIGN

??.1 Functional Processing Flow

Although the proposed measurement system is hardware-centered, practical deployment still requires a clear functional processing flow. After the circuit produces a frequency-coded output and the external circuit reconstructs the corresponding square wave, the processing layer performs signal sampling, frequency counting, averaging, and conversion into water-holdup information. In this sense, the software design is organized around feature extraction from frequency rather than around direct analog-capacitance computation.

??.2 Calibration and Water-Holdup Inversion

Calibration was carried out at 25 °C using oil–water mixtures with water holdup ranging from 0% to 100% in 10% increments. For each condition, the output frequency was recorded after the mixture was sufficiently stirred and delivered to the sampling chamber. The experimental results show a monotonic decrease in frequency with increasing water holdup. The slope is much larger in the low-water-holdup interval below 50%, indicating better sensitivity and resolution in this range. Based on this monotonic relation, the processing software can establish a lookup table or fitted inversion curve and convert measured frequency values into water-holdup data in real time.

??.3 Signal Validation and Performance Evaluation

Waveform verification demonstrates that the current-detection conversion circuit accurately reproduces the oscillator frequency. In the reported air test, the original multivibrator output frequency was 781.3 kHz, and the reconstructed waveform at the output of the shaping stage exhibited the same frequency. This confirms that the supply-current extraction strategy does not destroy the information content of the original oscillation signal.

The sensor-performance experiment further indicates that the proposed digital sensor is particularly suitable for low-water-holdup measurement. In the interval below 50% water holdup, the maximum relative error is 3.5% and the maximum absolute error is 2.7%. These results show that the condensed design retains the main advantages claimed in the original thesis, namely small error, high resolution in the target interval, and stable measurement performance.

5. CONCLUSION

Starting from the relationship among water holdup, dielectric constant, capacitance, and frequency, the study develops a probe-type capacitive sensor and combines it with a digitization circuit and a current-detection conversion circuit. The resulting architecture addresses two core problems of conventional capacitive water-holdup sensing: susceptibility to stray capacitance and excessive wiring complexity in array deployment.

Experimental results demonstrate that the output frequency varies monotonically with water holdup and that the sensor exhibits good resolution in the low-water-holdup range. With a maximum relative error of 3.5% and a maximum absolute error of 2.7% below 50% water holdup, the proposed design satisfies the expected technical target for low-water-holdup measurement. Future work should further investigate the influence of temperature and salinity on the calibration characteristics so as to improve the environmental adaptability of the sensor.

6. REFERENCES

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