Non-Contact Radio Frequency Level Sensor Based on Wheeler Cap

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***Abstract*— In this paper, we propose a novel non-contact liquid level sensor based on the Wheeler cap. The sensor utilizes an electrically small antenna operating at 276 MHz enclosed within a metal cap, in conjunction with the liquid container. By analyzing the reflection coefficient at the antenna feed and evaluating the magnitude and frequency of the minimum value, the sensor enables determination of the water level. The experimental results demonstrate the sensor's effectiveness in measuring water levels within the range of 0 to 94 mm, in a water container measuring 109x109x123 mm³. Notably, minimal variations in frequency and magnitude of the minimum reflection coefficient are observed at water levels below 50 mm, while the sensor exhibits improved sensitivity for water levels above 50 mm. The proposed sensor can offer a promising level sensing solution for liquids with extreme temperatures.**

Keywords*— *Wheeler Cap, Electrically Small Antennas, Level Sensor, Folded Spherical Helix Antenna, Internet of Things

I. Introduction

Liquid level sensors are crucial for a variety of applications and industries including medical instruments, oil and gas, agriculture, food and beverage, manufacturing as well as chemical industry. Various types of liquid level sensor are available as commercial products in the market including capacitive, ultrasonic, optical, magnetic float and radar-based level sensors. When selecting a liquid level sensor, several factors come into play, including the maximum volume of liquid to be measured, the desired accuracy of the readings, the required sensing resolution, as well as the ease of installation and maintenance requirements. Contact-based sensors such as capacitive level sensors require integration of sensing electrodes with the liquid container while offering excellent resolution [1]. However, utilizing this type of sensor for large volumes of liquid requires complicated installation and maintenance. For large liquid containers, radar-based level sensors offer ease of installation of the sensor at the tank hatch on the top of a container [2]. Challenges associated with this sensor type are the intricate radar signal processing unit and the necessity for wide-band antennas, resulting in a comparatively higher cost. Magnetic float sensors are commonly used in fuel tanks and industrial process tanks. The magnetic buoyant float of this sensor is designed to directly interface with the liquid, requiring it to withstand extreme temperatures in specific applications [3]. Ultrasonic level sensors are commonly installed on the outer surface of the liquid container [4]. Inexpensive versions are typically employed for basic level detection when the liquid level exceeds or falls below the vertical position of the sensor. However, achieving high-resolution level sensing necessitates sufficient signal power to penetrate both the container's external wall and the liquid. Thus, the cost of this sensor can be relatively high, especially when applying to containers with thick metallic walls.

This paper presents a non-contact liquid level sensor based on the Wheeler cap. The sensor consists of a metal cap enclosing both the liquid container and an electrically small antenna. The dimensions of the cap are designed to avoid the occurrence of resonant cavity modes. In the absence of the metallic cap, the antenna radiates at the operating frequency of 276 MHz. By covering the antenna and liquid container together with a metallic cap, the power injected into the antenna port is effectively prevented from being radiated, leading to the dissipation of a significant portion of the RF energy within the liquid. While the concept of a Wheeler cap-based sensor for determining moisture content in wastepaper was previously introduced in [5], this work focuses on applying a similar concept for liquid level sensing.

II. System Configuration

The proposed RF level sensor incorporates a folded helix antenna from [5] and a metallic cuboid cap. The cap's dimensions measure 206x206x170 mm³, which are sufficiently small to avoid the resonant cavity mode when no liquid sample is present. The plastic liquid container employed in this study has outer dimensions of 109x109x123 mm³, with a material thickness of 1.5 mm. Water with a relative dielectric constant of 78 and a conductivity of 1.59 S/m serves as the liquid under test in the simulation. For simplicity, the simulation disregards material dispersion within the frequency range of interest. The determination of the water level within the container involves measuring the reflection coefficient at the antenna feed port. The system configuration is illustrated in Fig. 1. The sensor was modeled and simulated using CST Microwave Studio. The water level H within the container was varied from 0 to 94 mm.

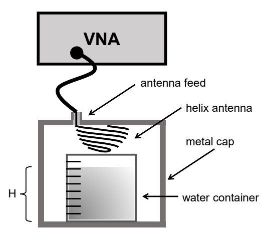


Fig. 1. RF level sensor configuration

III. Simulation and Measurement Results

Fig. 2 shows simulated and measured reflection coefficient of the antenna without the metallic cap. Comparing the simulation with the measurement result, a frequency shift from 310 MHz to 276 MHz is observed. This discrepancy arises from the imperfect fabrication process of the antenna. Due to the complexity of the antenna structure, the fabricated antenna prototype is slightly deformed compared to the CST model. Another reason for the frequency shift is the 3D printed radome used during the measurement to prevent oxidation and mechanical damage of the antenna. However, the change of frequency does not affect functionality of the sensor. Simulation and measurement results of the reflection coefficient with various water levels are shown in Fig. 3. For better visibility, the results with H=0 to 54 mm are shown in Fig. 3 (a) whereas the results with H=64 mm to 94 mm are shown in Fig. 3 (b). It is observed that for higher water levels, a second local minimum arises in addition to the major dip. Possibly, this is caused by the resonant mode in water due to its high relative dielectric constant which leads to a decreased wavelength. Magnitude and frequency of the minimum reflection coefficient are shown in Fig. 4 (a) and (b), respectively. Considering the magnitude of the reflection coefficient, no clear trend can be observed at low water levels up to 50 mm. As the level exceeds this value, the magnitude decreases significantly with increasing water level. Considering frequency of the minimum value, it decreases as the water level increases. At low water levels up to 50 mm, this effect is not very significant but becomes more obvious as

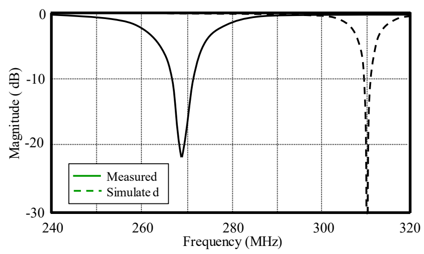
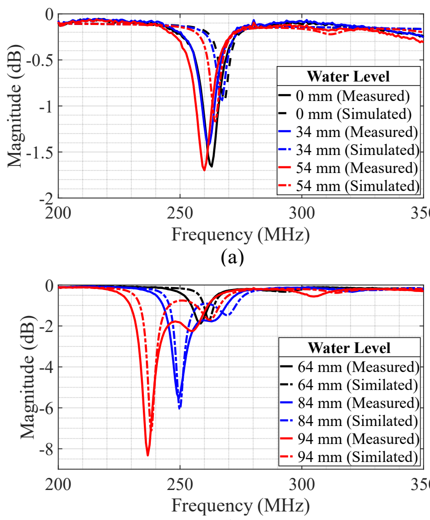
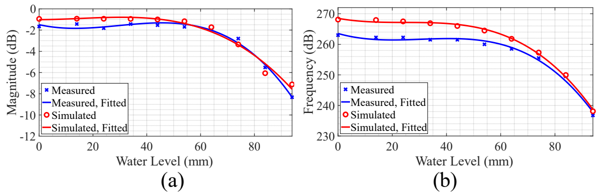


Fig. 2. Simulated and measured reflection coefficient of the antenna without the metal cap.



(a) (b)

Fig. 3. (a) Simulated and measured reflection coefficients of the sensor with H=0 to 54 mm and (b) with with H=64 to 94 mm



(a) (b)

Fig. 4. (a) Magnitude and (b) frequency of the minimum reflection coefficient with various water levels.

the water level reaches 50 mm and higher. To improve the sensitivity, further studies regarding position of the antenna to the liquid container will be investigated in future work.

IV. Conclusion

This paper proposes a non-contact RF level sensor based on the Wheeler cap. The sensor design involves enclosing an electrically small antenna and the liquid container within a metallic cuboid cap to prevent antenna radiation. Consequently, the RF energy supplied to the antenna is partially absorbed by the liquid, which in this case is water. By measuring the reflection coefficient and observing the magnitude and frequency of the minimum, the water level can be determined. Specifically, the magnitude increases and the frequency decreases as the water level rises. The sensor demonstrates better sensitivity at higher water levels compared to lower levels. In future work, further investigation will be conducted to explore the positioning of the liquid in relation to the antenna, with the aim of enhancing sensitivity at lower levels of the liquid.

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