Design and Numerical Simulation of Displacement Sensor Based on Liquid Antenna

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Abstract—**This paper provides a new design of passive wireless displacement sensor based on liquid antenna. Depending on the electromagnetic theory, there is an approximate linear relationship between the shift of water column height in the cavity and the resonant frequency of the liquid monopole antenna. In this paper, numerical analysis and parameter optimization are performed through High Frequency Structure Simulator (HFSS). The final optimization results show that the sensor has good linearity and sensitivity within the determined range.**

Keywords—passive wireless displacement sensor, liquid antenna, RFID

I. INTRODUCTION

Displacement sensors have been widely used in structural health monitoring[1], industrial control[2], precision optical measurement[3], surveying and mapping[4] and other industries, and have been a hot topic studied by scholars[5-6]. The widely used displacement sensor in the field of structural health monitoring currently is still the traditional displacement sensor, such as the pulling-line displacement sensor and the pulling-bar displacement sensor[7]. These conventional sensors have the advantages of high resolution, good stability, low measurement loss, and measurement accuracy that satisfy the measurement requirements of the structural monitoring industry. Nevertheless, on the one hand, in the large outdoor structure monitoring projects, such as cantilever structure and towering structure, the traditional displacement sensor is often difficult in installing stage; On the other hand, in the static load test of complex structures, traditional displacement sensors and strain gauges would often extend intricate leads to provide energy and transmit data. All in all, it would not only increase the test workload and the probability of error, but also bring difficulties to the faulty handling of the test[7].

In order to overcome the shortcoming of traditional displacement sensor in structural monitoring, many new sensors have been designed and studied with non-contact measurement. Among them, the most representative ones are laser displacement sensors and photogrammetry. The former can perform non-contact measurement of displacement[7], while the latter can additionally achieve larger range measurement[7]. However, on the one hand, the cost of the new sensors is often relatively expensive, with some problems in stability, accuracy and others in practical use. On the other hand, new sensors can not implement passive wireless measurements, just like traditional sensors, so the new sensors may still have certain inconveniences in the complex static structure monitoring stage.

With the rise of interdisciplinary fields, scholars have found that the resonant frequency of antenna sometimes has a functional relationship with some size changes of the antenna. Therefore, we can infer the change of the corresponding displacement from the functional relationship between the resonant frequency drift of the antenna and the change of the corresponding size, so as to achieve the purpose of measuring the structural displacement. In the past decade, the research in antenna-based displacement sensor which uses the resonant frequency offset as the measurement quantity has gradually emerged. Chuang et al.[8-9] studied the functional relationship between resonant frequency and size of the RF cavity and proposed a displacement sensor based on the relationship. Yi X et al.[10] studied the deformation of SMT antenna and proposed a strain gauge based on SMT antenna with high accuracy. Moreover, scholars have also studied other sensors, as shown in references[11-13].

In recent years, with the research upsurge of smart antenna, liquid antenna has gradually entered the sight line of scholars[14-15]. By changing the size, dielectric constant and temperature of the liquid medium, we can easily reconstruct the frequency, direction diagram and bandwidth of the liquid antenna. This is similar to the principle of the antenna sensor, that is, when there is a functional relationship between the resonant frequency drift of the liquid antenna and the size change of the corresponding liquid, the corresponding size change of the liquid antenna can be measured by the drift of frequency of the liquid antenna. Huang H et al.[16] proposed a helix antenna with an internal cavity filled with liquid. Based on the relationship, they made a helix antenna liquid level sensor. Jeongjae Ryu et al.[17] proposed a new liquid volume sensor based on a cylindrical resonator using water as the medium. More scholars have explored some basic forms of liquid antenna[18-19].

The displacement sensor studied in this paper takes the liquid level change of the antenna as the independent variable and the resonance frequency of the antenna as the dependent variable. In chapter 2, the antenna is analyzed theoretically; In chapter 3, the antenna is designed and optimized by HFSS. In this design, the antenna shows high linearity within a given range after parameter optimization. By the way, because of the low cost of fresh water and canning material, the price of the sensor can be quite cheap.

II. METHODOLOGY

The sensor in this paper is composed of polyflon pipe in the middle, polyflon sleeve in coaxial direction, one-way valve at the bottom, platform at the bottom and feeder at the bottom.

A. Take Sea Water as the Liquid

When we use sea water as the liquid, since there is sea water in both inner and outer sleeve, it can be approximately equivalent to a cylindrical condenser. The resonant frequency of the antenna can be calculated by using equivalent capacitance and equivalent inductance[20-23]:

$$f_r = \frac{1}{\sqrt{LC_{post}}} \quad (1)$$

The equivalent capacitance can be calculated by following equation:

$$C_{post} = \frac{2\pi\varepsilon h'}{ln\left(\frac{R_1}{R_2}\right)} \quad (2)$$

Where R_1 and R_2 are the inner and external diameter of the sleeve, ε is the dielectric constant of the polyflon pipe, and h' is the overlap height of the sensor.

In this design, if the initial height of the external sleeve is zero, we can calculate h' by following equation:

$$h' = \frac{\Delta h \pi R_1^2}{\pi R_2^2} = \frac{\Delta h R_1^2}{R_2^2} \quad (3)$$

From below equation, we can get the relation between the resonant frequency and the change of liquid level height:

$$f_r = \frac{1}{\sqrt{LC_{post}}} = \frac{1}{\sqrt{L\frac{2\pi\varepsilon\frac{\Delta h R_1^2}{R_2^2}}{ln\left(\frac{R_1}{R_2}\right)}}} = \frac{1}{\sqrt{k\Delta h}} \quad (4)$$

That is, the relative height of the liquid level is related to the change of resonance frequency. However, since the equivalent capacitance of the antenna is not completely equivalent to the above equation, and the equivalent inductance of the antenna also changes with liquid level height, the resonance frequency of the antenna will have some deviation with the above equation, which needs to be adjusted and verified by specific simulation and test.

B. Take Fresh Water as the Liquid

When fresh water is used as liquid and the water inside the external coaxial sleeve is not considered, since the water is not conductive medium, the liquid sensor can be equivalent to a fresh water monopole antenna.

The wavelength of the liquid antenna is:

$$\lambda = 4h \quad (5)$$

Where h is the height of the water column.

The resonance frequency is:

$$f_r = \frac{c}{\lambda} = \frac{c}{4h} \quad (6)$$

Then when the height of the nonconductor material shifts from h to $h+\Delta h$ that:

$$f_r = \frac{c}{4(h+\Delta h)} = \frac{c(h-\Delta h)}{4(h^2-\Delta h^2)} \quad (7)$$

Therefore, when the change of liquid height is small, the change of resonance frequency is approximately linear.

III. FINITE ELEMENT SIMULATION EXPERIMENTS

In design and simulation step, we choose fresh water as the liquid in this sensor.

The conceptual graph of the antenna is shown in fig. 1：

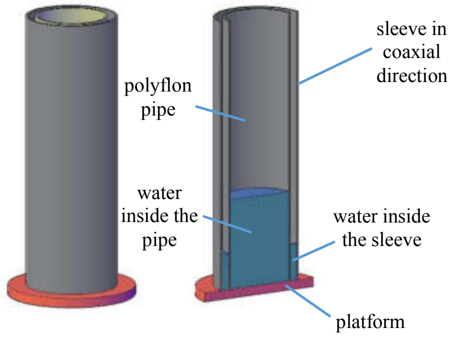

Fig. 1. Conceptual Graph of The Antenna Sensor

For the antenna sensor in this paper, there are some important parameters, such as the Internal and external liquid level, diameter and thickness of the inner and outer sleeve and material of the antenna. In the simulation test step, according to the theoretical analysis in the second part of this paper, we set up the electromagnetic simulation model by Ansoft High Frequency Simulation Structure (HFSS), which is shown in fig. 3:

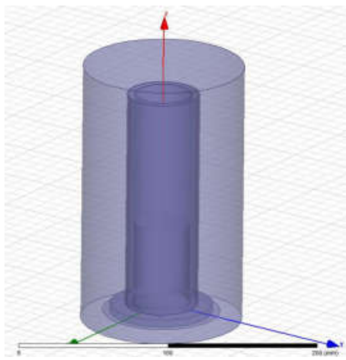

Fig. 2. Model Composition of The Antenna Sensor in HFSS

After plenty of simulation analysis, we get the optimal size of the antenna sensor. Some basic parameters of the sensor are shown in table 1:

TABLE I. OPTIMAL PARAMETERS OF THE ANTENNA SENSOR

Parameters for Liquid Antenna	**Scale**
Inner Radius/mm	19
Total Radius/mm	25
Height/mm	150

The antenna echo loss curve obtained by simulation under this parameter is shown in figure 3:

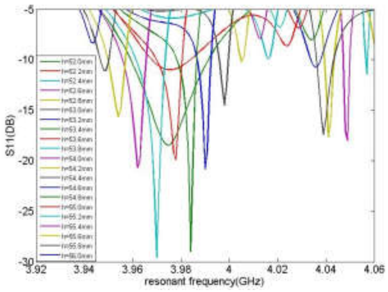

Fig. 3. Echo Loss curves of The Antenna Sensor in HFSS

From this figure, we can see the resonance frequency increased with the increasing of displacement of the bar. Through data processing, the curve of resonant frequency changing with the shift of the height of the water column, as shown in the following figure:

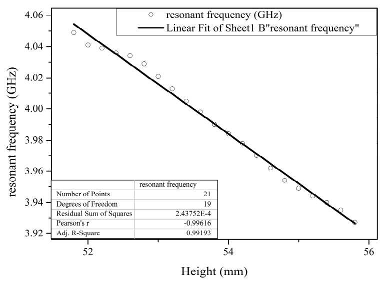

Fig. 4. Echo Loss curves of The Antenna Sensor in HFSS

From this figure, It can be seen that the change of the resonant frequency is approximately linear with the shift of the height of the water column at the medium of the sensor. This is consistent with our hypothesis.

IV. Conclusion and Comments

In this paper, we proposed a design of using RFID tag liquid antenna as a wireless displacement sensor. The final simulation results show that the sensor has better sensitivity and high linearity. Due to the passive wireless characteristics of this kind of sensor, it can be easily used as a displacement sensor in a small range.

Based on the above experimental test and analysis, we plan to carry out the next steps: on the one hand, the finite element simulation of this kind of sensor will be refined, and the precision and the range of measurement of this sensor will be improved through parameter optimization. On the other hand, the model will be made and the actual production and experiment will be carried out to verify the simulation results.

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References

[1] W. Gan, C. Zhang, Y. Dai, et all. Design and Application of the Displacement Sensor Based on Fiber Bragg Grating[J]. Semiconductor Optoelectronics,2012,33(06):795-798(in Chinese).

[2] W. Shao, L. Zhang, S. Li. Development of Noncontact Robotic Measuring and Control System [J]. Machine Tool & Hydraulics,2007(06):157-159+92(in Chinese).

[3] X. Wang, B. Fan, T. Wang, et all. Fusion Overview of Image Sensor and Space Coordinate Measurement Sensor [J]. Bulletin of Surveying and Mapping,2016(S2):22-24+48(in Chinese).

[4] Z. Yun. Smart Photogrammetric and Remote Sensing Image Processing for Optical Very High Resolution Images——Examples from the CRC-AGIP Lab at UNB[J]. Acta Geodaetica et Cartographica Sinica,2018,47(06):722-729(in Chinese).

[5] B. Wang, L. Zhang, P. Wang, et all. Analysis of detection signal for magnetostrictive displacement sensor[J]. Optics and Precision Engineering,2016,24(02):358-364(in Chinese).

[6] Y. Zhang, Y. Tian, X. Fu, et all. Adjustable range draw - wire type fiber Bragg grating displacement sensor [J]. Opto-Electronic Engineering,2017,44(06):626-632(in Chinese).

[7] K. Dai, C. Zhang, M. Yuan, et all. Structural Experimental Technique Course Teaching Innovation-the Application of the Virtual Reality Method in Sensing Technology Teaching[J]. Structural Engineers,2017,33(02):47-53(in Chinese).

[8] D. J. Thomson, D. Card, G.E Bridges. RF cavity passive wireless sensors with time-domain gating-based interrogation for SHM of civil structures[J]. IEEE Sensors Journal, 2009, 9(11): 1430-1438.

[9] J. Chuang, D.J. Thomson, G.E Bridges. Embeddable wireless strain sensor based on resonant RF cavities[J]. Review of Scientific Instruments, 2005, 76(9): 094703.

[10] X. Yi, T. Wu, Y. Wang, et al. Passive wireless smart-skin sensor using RFID-based folded patch antennas[J]. International Journal of Smart and Nano Materials, 2011, 2(1): 22-38.

[11] C. Jiang, L. Xie, S. Wang, et al. Simulation of RFID-based Folded Patched Antenna for Strain Sensing[Z].Jeju, Korea. 2016.

[12] K. Xu, L. Xie, S. Xue, et al. Influence of transverse deformation on resonant frequency of patch antenna[C].2018 IEEE Sensors Applications Symposium (SAS). IEEE, 2018: 1-6.

[13] S. Xue, C. Jiang, L. Xie, et all. A strain sensor based on rectangle patched antenna: simulation and test [J]. Journal of Vibration,Measurement & Diagnosis, 2018, 18(01): 136-142(in Chinese).

[14] S. Wang, Z. Hu, W. Wang, et al. Analysis and design of sea - water monopole Yagi - Uda antenna with pattern reconfigurability[J]. International Journal of RF and Microwave Computer - Aided Engineering, 2018: e21399.

[15] J. Ren, J.Y. Yin. Cylindrical-water-resonator-based ultra-broadband microwave absorber[J]. arXiv preprint arXiv:1805.03245, 2018.

[16] H. Huang, P. Zhao, P.Y. Chen, et al. RFID tag helix antenna sensors for wireless drug dosage monitoring[J]. IEEE J. Transl. Eng. Health Med, 2014, 2(1).

[17] J. Ryu, H. Jeong, Y. Chen, et al. Flexible piezoelectric liquid volume sensor[J]. Sensors and Actuators A: Physical, 2018, 276: 219-225.

[18] G. Li, Y. Huang, G. Gao, et al. A broadband helical saline water liquid antenna for wearable systems[J]. International Journal of Electronics, 2018, 105(4): 645-658.

[19] M. Zou, Z. Shen, J. Pan. Frequency-reconfigurable water antenna of circular polarization[J]. Applied Physics Letters, 2016, 108(1): 014102.

[20] Y. Zhao, Y. Li, B. Pan, et al. RF evanescent-mode cavity resonator for passive wireless sensor applications[J]. Sensors and Actuators A: Physical, 2010, 161(1-2): 322-328.

[21] G. F. Craven, C.K. Mok, The design of evanescent mode waveguide bandpass filters for a prescribed insertion loss characteristic, IEEE Trans. Microwave Theory Tech. 19 (3) (1971) 295–308.

[22] C. K. Mok, Design of evanescent mode waveguide diplexers, IEEE Trans.Microwave Theory Tech. 21 (1) (1973) 43–48.

[23] R. V. Snyder, new application of evanescent mode waveguide to filter design,IEEE Trans. Microwave Theory Tech. 25 (12) (1977) 1013–1021.