Design and Numerical Simulation of Displacement Sensor Based on Helix Antenna

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Abstract This paper provides a new design of passive wireless displacement sensor. The sensor consists of an external helix antenna and an internal aluminum oxide rod. According to the perturbation theory, there is an approximate linear relationship between the displacement of aluminum oxide rod in the cavity and the resonant frequency of the helix antenna. Due to the structure of the sensor, it can be easily refitted into a maximum displacement sensor. In this paper, numerical analysis and parameter optimization are carried out through High Frequency Structure Simulator (HFSS). The final optimization results show that the sensor has good linearity and sensitivity within the determined range.
Key words passive wireless displacement sensor, helix antenna, RFID

1. Introduction

Displacement sensors have been widely used in structural monitoring [1], industrial control [2], precision optical measurement [3], surveying and mapping [4] and other industries, and have been a hot topic studied by domestic and foreign scholars [5-6]. However, the widely used displacement sensor in the field of structural deformation 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, towering structure, the installing of traditional displacement sensor is often more difficult, and even can't; 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 from 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, the new sensors don't implement passive wireless measurements, just like traditional sensors, so the new sensors may still have certain inconveniences in the complex static structure monitoring.

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. If the size of the antenna is correlated with the displacement of the structure and variations, the resonant frequency of the antenna will have a corresponding drift. Therefore, we can infer the change of the corresponding displacement based on 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. Xiaohua Yi et al. [10] studied the deformation of SMT antenna and proposed a strain gauge based on SMT antenna with high accuracy. Haiyu Huang et al. [11] proposed a helix antenna with an internal cavity filled with liquid. Based on the relationship, they made a corresponding helix antenna liquid level sensor. Moreover, scholars have also studied other sensors, as shown in references [12-15].

The displacement sensor studied in this paper takes the resonant frequency of the antenna as the index of distance measurement, and the relationship between the resonant frequency and the displacement of the helix antenna is deduced theoretically and simulated by HFSS finite element method. In chapter 2, the antenna is analyzed theoretically, and the theory indicates that the height variation of the helix antenna and internal medium is linear in a small range under ideal conditions [11]. In chapter 3, the antenna is designed and optimized by HFSS. In the design, the antenna shows high linearity within a given range after parameter optimization.

2. Methodology

Based on the perturbation theory, for an ideal helix antenna with a large number of turns, the resonant frequency changes can be analyzed by perturbation theory when the interface between the high-dielectric constant (fluid or other nonconductor) and the low-dielectric constant (air or powder) is shifted [17].

Suppose a small shape disturbance ΔV is applied to the resonant medium resonator V_0 at f_0, the obtained resonant frequency f will satisfy [11,16]:

$$\frac{f-f_0}{f_0}=\frac{\int_{\Delta V}(\mu\|\overrightarrow{H_0}\|^2-\epsilon\|\overrightarrow{E_0}\|^2)\,dv}{\int_{V_0}(\mu\|\overrightarrow{H_0}\|^2+\epsilon\|\overrightarrow{E_0}\|^2)\,dv} \qquad (1)$$

Where ε and μ are the relative dielectric constant and magnetic permeability of the nonconductor material loaded in the helical antenna, respectively. In addition, the electromagnetic field in the helical coil is intense and almost constant along the cylindrical direction z, i.e.:

$$\|\overrightarrow{H_0}\|=H(x,y),\|\overrightarrow{E_0}\|=E(x,y) \qquad (2)$$

Then when the height of the nonconductor material shifts from h_0 to h that:

$$\begin{aligned}\frac{f-f_0}{f_0}&=\frac{\int_{\Delta h}\left[\int_S\left(\mu H^2(x,y)-\epsilon\,E^2(x,y)\right)dxdy\right]dz}{\int_{h_0}\left[\int_S\left(\mu H^2(x,y)+\epsilon\,E^2(x,y)\right)dxdy\right]dz}\\&=\frac{\int_{\Delta h}Adz}{\int_{h_0}Bdz}\\&=C\frac{h-h_0}{h_0}\end{aligned} \qquad (3)$$

Equation (3) is effective for small helix antennas with a large number of helical turns, as the distribution of its internal electric and magnetic fields is almost uniform [11,17]. According to the above research, we designed a helical antenna sensor as shown in the figure 1: We placed an aluminum oxide rod with a diameter close to the helical antenna as a contact surface in the interior of the helix antenna to reflect the external displacement.

The conceptual graph of the antenna is shown in figure 2.1 :

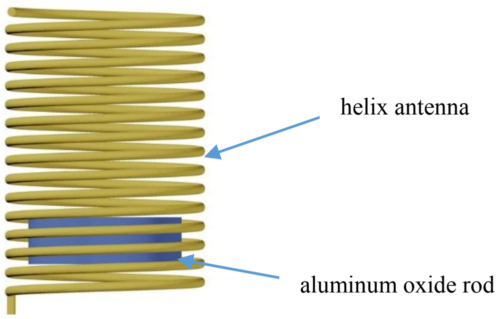

Figure 2.1 Conceptual Graph of The Antenna Sensor

According to the research of Li Chunsheng et al. [18], the axial electric field component and magnetic field component of the end of the helix antenna are weak, so the effect of the aluminum oxide rod can be approximately ignored when it was placed in the end of the antenna. Therefore, when aluminum oxide rod is hoisted at the end of the antenna sensor, we can ignore the end effect of the bar, so its resonant frequency offset approximation also satisfies the equation 3. When the aluminum oxide rod is hoisted to the middle, its influence will gradually weaken, which leads to the stabilization of the resonant frequency.

Based on the above theory, we therefore conclude that the change of the resonant frequency is approximately linear with the movement of the Al_2O_3 bar at the end of the helix antenna.

3. Finite Element Simulation Experiments

In the simulation test step, we used Ansoft High Frequency Simulation Structure (HFSS) which is an electromagnetic simulation software based on the finite element method (FEM) to simulate the radiation characteristics of the helix antenna sensor.

In HFSS software, the cylindrical helix antenna is limited by its radius, number of turns, and spacing between adjacent turns(or pitch Angle). In addition, for the antenna sensor in this paper, the length, radius and position of the internal aluminum oxide rod are also important parameters.

According to the theoretical analysis in the second part of this paper, the closer the circle number of helix antenna is, the closer the internal aluminum oxide rod is to the end, and the better the performance of the sensor. Based on this, we set up the electromagnetic simulation model.

The model we established is shown in figure 3.1:

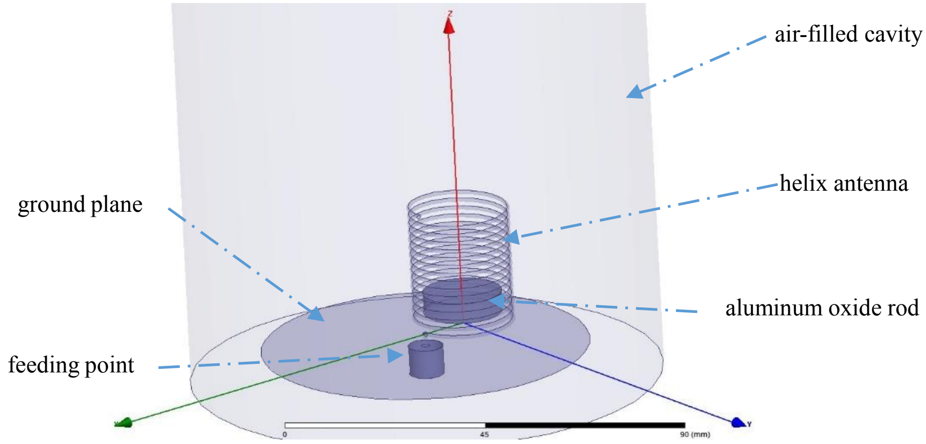

Figure 3.1 Model Composition of The Antenna Sensor in HFSS

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

Table 1 Optimal Parameters of the Antenna Sensor

Parameters for Helix Antenna		Parameters for Aluminum Oxide Rod	
Number of turns	15	Length/mm	5
Radius/mm	11.25	Radius/mm	9
Spacing between adjacent turns/mm	2	Initial height/mm	5
Radius of the line/mm	0.5	material of the rod	Aluminum Oxide
Material of the helix antenna	copper		

The antenna echo loss curve obtained by simulation under this parameter is shown in figure 3.2:

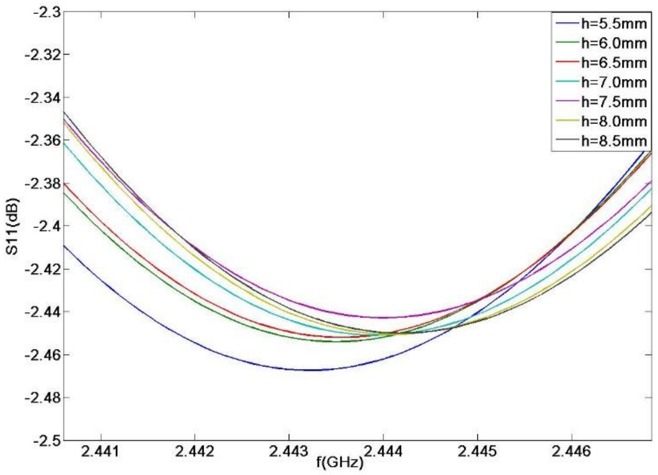

Figure 3.2 Echo Loss curves of The Antenna Sensor in HFSS

Through data processing, the curve of resonant frequency changing with the movement of aluminum oxide rod is obtained, as shown in the following figure:

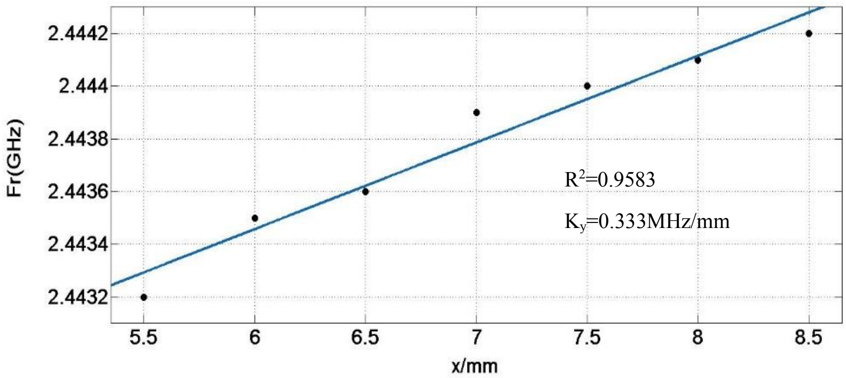

Figure 3.3 Resonance Frequency - Displacement Diagram

The Resonance Frequency Changed with the Increasing of Displacement of the Bar

From this figure, It can be seen that the change of the resonant frequency is approximately linear with the movement of the aluminum oxide rod at the end of the sensor. This is consistent with our hypothesis.

4. Conclusion and Comments

In this paper, we proposed a design of using RFID tag helix 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 or a maximum 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 of the 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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