Analysis of the Effect of Air Gap on the Performance of Self-inductance Displacement Sensor

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***Abstract*—Inductive displacement sensor is one kind of the common sensors widely used in magnetic bearing system. In this paper, the working principle and output characteristics of the self-inductance displacement sensor are analyzed. For magnetic levitation rotor with a shaft diameter of 44.2mm, self-inductance displacement sensors with different air gaps are respectively designed. The magnetic field distribution and output characteristics of the designed sensor are simulated by finite element analysis method. Theoretical analysis and simulation results both show that there is a very good linear relationship between the output voltage and the rotor displacement of differential self-inductive displacement sensor when the displacement of rotor is in the range of -0.4 to 0.4(mm). Simulation results show the sensitivity of the self-inductance sensor is inversely proportional to the equilibrium air gap. With the increasement of air gap , the relative change value of total inductance is decreasing. When the rotor displacement is small relative to the equilibrium air gap, the relative change of total inductance is smaller and it can be considered unchanged. At this time, the amplitude of the current in the coil is basically unchanged when the voltage amplitude of the driving power is unchanged.**

Keywords—Magnetic bearing, Self-inductance displacement sensor, Structural design, FEA simulation

I. INTRODUCTION

Electromagnetic bearing is a new type of high performance bearing. It has the advantages of higher speed, longer life, lower consumption, higher precision and no pollution[1]. According to rotor displacement detected by the displacement sensor, the electromagnetic bearing control system is allowed to change electromagnetic force with real-time and achieve stable suspension of the rotor[2]. Therefore, the performance of the displacement sensor plays an extremely important role for the system of electromagnetic bearing. At present, the most popular choice is eddy current displacement sensor because of the advantages of simple principle, good frequency response characteristics and good real-time performance. However, it is very sensitive to the material type, material uniformity and surface shape tolerance of the material under test[3]. The output signal of eddy current displacement sensor attenuates fast, which is not suitable for long-distance transmission. Compared with eddy current displacement sensor , the inductance displacement sensor[4] has the advantages of higher sensitivity, larger linear measurement range, higher resolution and strong ability of anti-interference, which is good enough to meet the needs of industrial magnetic levitation rotor system displacement detection when the speed is below 1kHz ,in spite that its frequency response characteristics and real-time performance are slightly worse. Therefore, it has been widely concerned and applied.

At present, many scholars had made study for inductive displacement sensors for magnetic bearings [5-9]. In this paper, the structure of self-inductance displacement sensors with different air gaps are designed for a magnetically suspended rotor with a 44.2mm shaft diameter based on the analysis of the working principle. Then, the simulation analysis is done by the finite element method.

II. THE WORKING PRINCIPLE OF SELF-INDUCTANCE DISPLACEMENT SENSOR

In order to reduce the error of non-linearity between the output of the sensor and the air gap and simultaneously increase the sensitivity of the sensor, the differential structure shown in Fig1 is commonly used. The structure includes a movable armature and two iron core coils with the same geometric sizes, materials, and electrical parameters. The two core coils are connected in series and driven by the AC voltage source u_0. The output voltage is $\Delta u = u_1 - u_2$.

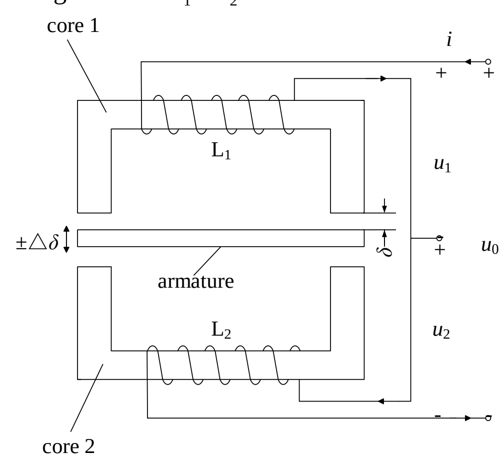

Figure 1. Schematic diagram of differential self-inductance sensor structure

The magnetic field of air gap is considered uniform in the case of small air gap. It is assumed that there is no magnetic leakage, the air gap on both sides is δ, the sectional area of the core magnetic pole is A_0, and the number of turns is N.

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According to the definition of core coil inductance and magnetic circuit ohm's law, when the armature is in the middle of iron core, the inductance of the two core coils are

$$L_0 = \frac{\mu_0 A_0 N^2}{2\delta} \tag{1}$$

When the armature moves $\Delta\delta$ ($\Delta\delta$ >0, the armature moves up; $\Delta\delta$ <0, the armature moves down), inductances of the upper and lower core coil respectively become

$$\begin{cases} L_1 = \dfrac{\mu_0 A_0 N^2}{2(\delta - \Delta\delta)} = \dfrac{L_0}{1 - \dfrac{\Delta\delta}{\delta}} \\ L_2 = \dfrac{\mu_0 A_0 N^2}{2(\delta + \Delta\delta)} = \dfrac{L_0}{1 + \dfrac{\Delta\delta}{\delta}} \end{cases} \tag{2}$$

Then the total inductance of the upper and lower core coil in series is

$$L_T = L_1 + L_2 = \frac{2L_0}{1 - \left(\dfrac{\Delta\delta}{\delta}\right)^2} \tag{3}$$

The relative change of the total inductance is

$$\frac{L_T - 2L_0}{2L_0} = \frac{1}{\left(\dfrac{\delta}{\Delta\delta}\right)^2 - 1} \tag{4}$$

When coil resistance is not considered, the output voltage of the differential self-inductance sensor according to Fig1 is

$$\Delta\dot{U} = \frac{L_1 - L_2}{L_1 + L_2} = \frac{\Delta L}{L_T}\dot{U}_0 \tag{5}$$

Formula (2) is substituted into formula (5), and the output voltage is

$$\Delta\dot{U} = \frac{\Delta\delta}{\delta}\dot{U}_0 \tag{6}$$

Neglecting the equivalent resistance and magnetic flux leakage of the core coil and the movement of armature in a small range, the theoretical analysis shows that the output voltage of the sensor is proportional to the input voltage and air gap changes and is inversely proportional to the equilibrium air gap.

The sensitivity of the self-inductance displacement sensor can be defined as the ratio of output voltage to the amount of changes in air gap. That is,

$$K = \frac{\Delta U}{\Delta\delta} = \frac{U_0}{\delta} \tag{7}$$

It can be seen that the sensitivity of the inductive sensor is only related to the power voltage and the balanced air gap, which is proportional to the power voltage and is inversely proportional to the equilibrium air gap.

III. Structural Design of Self-inductance Displacement Sensor

The initial design requirements of a magnetic suspension rotor system for inductive sensors for a magnetically suspended rotor system with a shaft diameter of 44.2 mm are shown in Table Ⅰ.

TABLE I. Sensor Preliminary Design Requirements

rotor displacement (mm)	-0.4~+0.4	sensitivity (V • mm^{-1})	20
rotor diameter (mm)	44.2	coil current (A)	0.2
rated speed (rpm)	24000	power frequency (kHz)	22

The design of the sensor structure is shown in Fig 2. The coil Y_{p1}, Y_{p2}, Y_{N1} and Y_{N2} are connected in series, and the coil X_{p1}, X_{p2}, X_{N1} and X_{N2} are connected in series. The 8 coils have the same number of turns. The structural parameters of self-inductance displacement sensors with different air gaps are shown in Table Ⅱ.

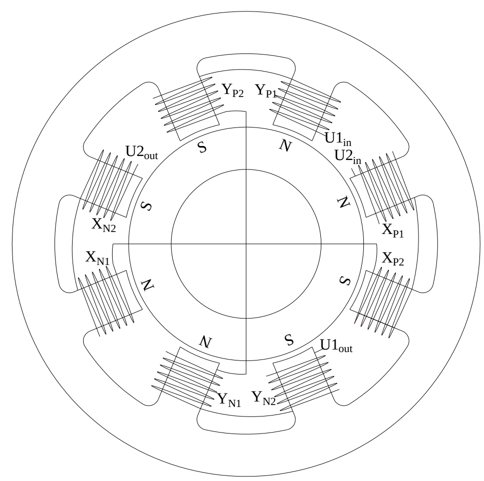

Figure 2. Structure diagram of self-inductance displacement sensor

TABLE II. The Structural Parameters of Self-inductance Displacement Sensors with Different Air Gaps

δ /mm	d /mm	D /mm	D_0 /mm	D_1 /mm	N_p	A_0 /mm^2	U_m /V	N_1
1.6	44.2	47.4	72	88	8	32	78	200
1.2	44.2	46.6	72	88	8	32	78	175
1.0	44.2	46.2	72	88	8	32	78	160
0.8	44.2	45.8	72	88	8	32	78	140
0.6	44.2	45.4	72	88	8	32	78	122

Where, d is outer diameter of rotor, D is the inner diameter of stator, D_0 is the middle diameter of stator, D_1 is the outer diameter of stator, N_p is the number of poles, A_0 is magnetic pole area, U_m is the voltage amplitude of the driving power, N_1 is number turns of per coil。

IV. Simulation Analysis of Self-inductance Displacement Sensor

In order to verify the accuracy of the theoretical analysis and the feasibility of the structural design method, electromagnetic field simulation software is used to simulate the electromagnetic field of the designed inductance sensor. Due to the symmetry of the sensor, the output characteristics are simulated only when the rotor is moved upward.

A. Finite Element Model of Static Magnetic Field of Sensor

Finite element models are established according to Table Ⅱ. Considering the magnetic flux leakage on the periphery of the stator, 5（mm）thick air layer model is established outside the stator[10]. The stator and rotor are stacked by silicon steel sheets of 35W250. The material of the axis is 45# steel. The excitation source uses external circuit excitation of winding as shown in Fig 3. The association of coil and corresponding coil model is achieved by matching the name of the two. The layer boundary conditions of magnetic field lines parallel to the outer edge of the stator air are loaded. Finally, setting the relevant parameters and doing simulation calculation[11].

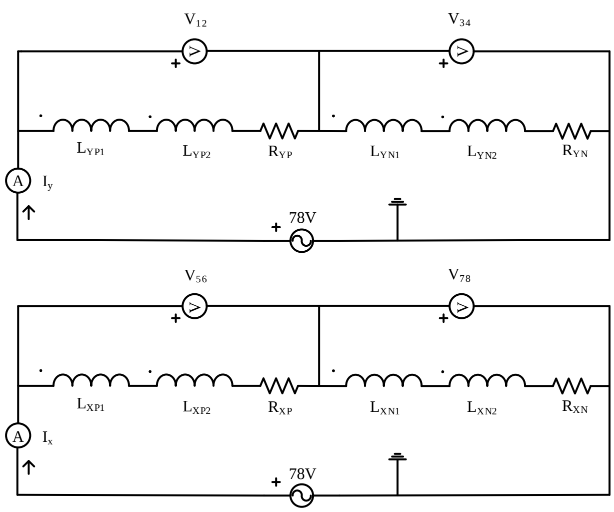

Figure 3. External circuit excitation of coil

B. Simulation Results of Sensor Magnetic Field Distribution Characteristics

The simulated magnetic field distribution of the sensor is shown in Fig 4 and Fig 5 when the air gap is 1mm and the rotor moves up by 0.4mm.

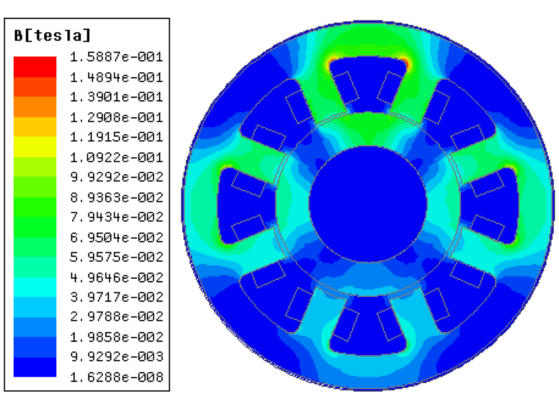

Figure 4. The magnetic field distribution of the sensor when the rotor moves up 0.4mm

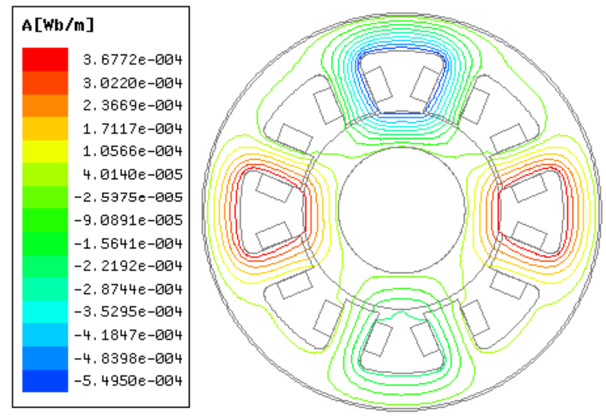

Figure 5. The magnetic lines distribution of the sensor when the rotor moves up 0.4mm

It can be seen that there is almost no magnetic flux leakage and mutual coupling in the probe during the movement of the rotor.

C. Simulation Results of Sensor Output Voltage Variation Characteristic

According to the simulation results, the relationship between the output voltage and the rotor displacement for the self-inductance sensor with different air gaps is shown in Fig 6 .

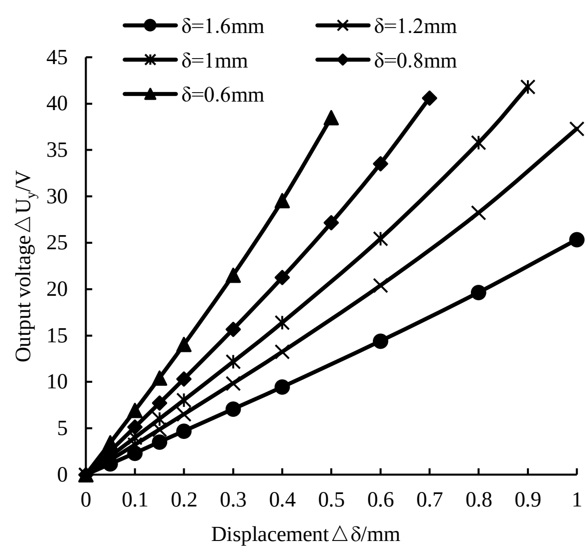

Figure 6. The relationship between the longitudinal output voltage and the rotor displacement

According to Fig 6, there is a good linear relationship between output voltage and the rotor displacement for the sensor of different air gaps. Moreover, the smaller the range of the rotor motion is, the better the linearity is.

D. *Simulation Results of Sensor Coil Inductance Variation Characteristic*

According to the simulation results, the relationship between the variation of total inductance and the rotor displacement for the self-inductance sensor with different air gaps is shown in Fig 7.

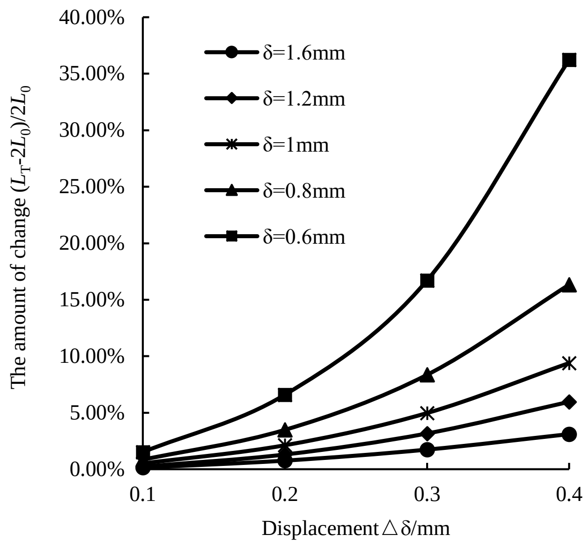

Figure 7. The relationship between the variation of total inductance and the rotor displacement

According to Fig 7, the relative variation of the total inductance for the self-inductance displacement sensors with different air gaps is smaller when the rotor displacement is small. Besides, it is decreasing as the air gap increases.

The magnetic bearing system requires suitable measuring range, higher sensitivity, higher linearity, and stronger anti-interference ability for the displacement sensor. It can be approximately considered that the total inductance remains unchanged when the relative change of the total inductance is less than 10%. At this time, the amplitude of the current in the coil is basically unchanged when the voltage amplitude of the driving power is unchanged. To sum up, the choice of self-inductance displacement sensor with an air gap of 1 mm is superior for a magnetically suspended rotor with a shaft diameter of 44.2 mm.

V. CONCLUSION

The differential self-inductance sensor is analyzed by using the theory of magnetic circuit and electric circuit, and a structural design method of self-inductance displacement sensor for active magnetic bearings is given. In this paper, the structures of self-inductance displacement sensor with different air gaps are designed for a magnetically suspended rotor with a shaft diameter of 44.2 mm. Then, the simulation analysis is done by the finite element method. The following conclusions are obtained:

(a) There is a good linear relationship between the output voltage of the differential self-inductance sensor with different air gaps and the rotor displacement in the range of -0.4~0.4mm;

(b) Differential self-inductance sensor can effectively improve the linearity and sensitivity of the sensor whose sensitivity is proportional to the power voltage and is inversely proportional to the equilibrium air gap between the stator and rotor;

(c) In the case of different air gaps of equilibrium, the relative variation of the total inductance is decreasing as the air gap increases. When the rotor displacement is small relative to the equilibrium air gap, the relative change of total inductance is smaller and it can be considered unchanged. At this time, the amplitude of the current in the coil is basically unchanged when the voltage amplitude of the driving power is unchanged.

The article only analyzes the linearity and sensitivity of the self-inductance displacement sensor. Then, the performance of the sensor will be further researched through static calibration experiment, dynamic calibration experiment and suspension test.

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