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Study on the influence of coil radius on the detection performance of eddy current sensor

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Abstract: Taking the 34th International Young Physicists' Tournament (IYPT) as the starting point, this paper explores the influence of coil parameters on the detection performance (mainly detection distance) of eddy current sensors. On the basis of understanding the working principle of the eddy current sensor, it is concluded that the best range of the inside to outside diameter ratio of the coil is 0<k≤0.7, and the best range of coil section radius is 0.05 mm≤r≤0.15 mm. The smaller the inside to outside diameter ratio of the coil, the larger the inductance value and the farther the detection distance. In addition, due to the simple instrument, convenient operation, small difficulty, and involving theory, simulation and experiment, this experiment provides a novel experimental method for college students' physical experiments, which is helpful to exercise students' hands-on and operational abilities.

Keywords: Eddy current sensor; Detection distance; The inside to outside diameter ratio; Section radius.

1. Introduction

The International Young Physicists' Tournament (IYPT) [1] is one of the most influential physics competitions in the world today[2][3]. The influence of coil radius on eddy current Sensor detection performance we studied originated from the third question of the 34th IYPT: Proximity Sensor. The original topic was to build a simple passive sensor to detect a ferromagnetic object passing through its magnetic field and to study the characteristics of the sensor, such as the sensing range[4].

With the advent of the new technological revolution, sensors are not only playing a vital role in industrial production, but also becoming increasingly visible in daily life. There are many kinds of sensors, different forms, and various detection objects, which can be classified according to the classification methods such as the amount to be checked, physical principles, energy transfer methods, and working principles, and proximity sensors are one of them. As the name suggests, proximity sensor is a general term for sensors that do not need to contact the detection object for detection purposes, including inductive proximity sensors[5][6], capacitive proximity sensors[7], photoelectric contact sensors[8][9] and ultrasonic sensors[10][11]. Eddy current sensor is a kind of inductive proximity sensor, which is widely used in product quality detection[12][13], condition detection[14][15] and motion coupling[16][17][18] for its non-contact, wide bandwidth, high sensitivity, high reliability and adaptability to harsh working environment.

On the basis of fully understanding the working principle of the eddy current sensor, this paper, combined with theoretical calculation and simulation system research, obtained the optimal inside to outside diameter ratio of the eddy current coil $0 < k \leq 0.7$ and the optimal section radius of the coil $0.05\ mm \leq r \leq 0.15\ mm$. Based on our self-built experimental system, we further explore the influence of coil radius parameters on sensor detection performance (detection distance), and prove that the theoretical value is consistent with the actual value. The self-built experimental system has fewer experimental supplies, simple instrument operation, high sensitivity and low power consumption, and can be operated by oneself in the laboratory, which provides an experimental method for college students' physics experiments and exercises students' hands-on operation and operation ability.

2. Working principle of eddy current sensor

To study the detection performance of eddy current sensor, it is necessary to understand its working principle in detail. Figure 1 shows the schematic diagram of the working principle of the eddy current sensor, which is mainly based on the Lenz's law of electromagnetism. When an alternating current is applied to the sensor coil, an alternating magnetic field will be generated around the coil. When the detected object is close to the coil (that is, moving in the alternating magnetic field), according to Lenz's law, the directional movement of free electrons on the surface of the detected object under the force will generate eddy current, which will further generate secondary reverse magnetic field, thus weakening the magnetic field around the coil.

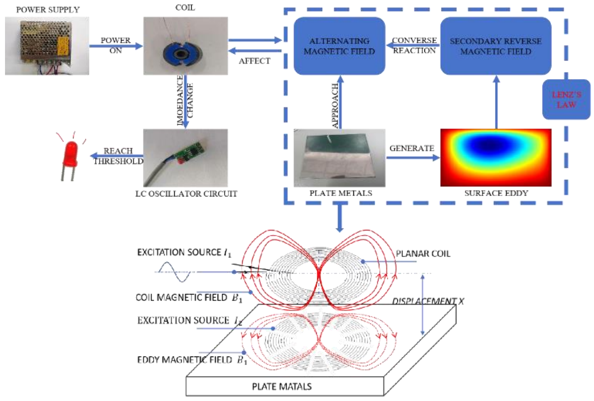

Fig. 1 Schematic diagram of eddy current sensor

This can be seen by the simulated magnetic flux distribution shown in Fig. 2. The magnetic flux density is distributed on the conductor surface, and the longitudinal depth decreases with the increase of coil excitation frequency. The phenomenon of mutual inductance between the detected object and the coil can cause the impedance change of the coil, and the LC oscillation circuit of the sensor will convert the detected impedance change into other detectable circuit signals, such as current signals, so that the indicator light (LED diode) will light up, proving that the relative movement of the detected object.

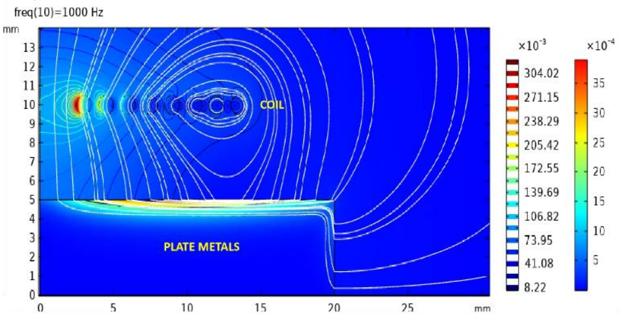

Fig. 2 Magnetic flux distribution on the conductor surface when a ferromagnetic object is near (simulation diagram) [20]

The detected object is generally a ferromagnetic object, and the material is different, the measurement distance is slightly different, but the impact is small. In this process, the displacement signal is converted into electrical signal by the LC oscillation circuit of the sensor, and the movement detection of the ferromagnetic object is realized. In the sensor, the coil is a key component of the sensor's energy transmission. In order to further improve the detection efficiency of the sensor and make the coil inductance achieve the best influence on the detection performance of the eddy current sensor, it is necessary to systematically study the coil geometric parameters (such as the inside to outside diameter ratio of the coil and the coil section radius).

3. Research on geometric parameters of sensor coil

3.1. Theoretical Analysis

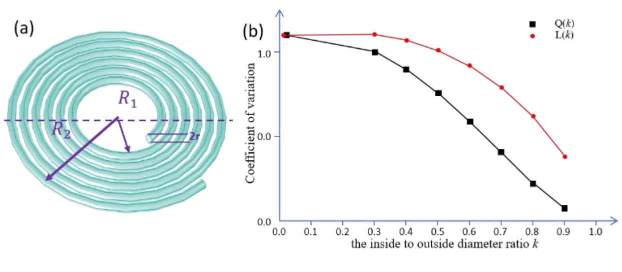

Fig. 3 (a) Schematic diagram of eddy current coil; (b) The variation curve of coil inductance $\boldsymbol{L}$ and quality factor $\boldsymbol{Q}$ with the inside to outside diameter ratio $\boldsymbol{k}$ of the coil c diagram of eddy current sensor

As shown in Fig. 3(a), we define a tightly wound planar circular coil with an inside radius R_1, an outside radius R_2 and a section radius r, whose resistance R can be expressed as:

$$R = \frac{L}{A\sigma} \tag{1}$$

Where L is the length of the coil, A is the section area of the coil, and σ is the conductivity. The corresponding coefficient expression is as follows:

$$L \approx 2\pi\left(\frac{R_1 + R_2}{2}\right) \cdot N \tag{2}$$

$$A = \pi r^2 \tag{3}$$

Where N is the number of turns of the coil.

D_{AVG} is defined as the average radius of a planar circular coil, ρ is the coil filling rate, and its expressions are as follows:

$$D_{AVG} = \frac{R_1 + R_2}{2} \tag{4}$$

$$\rho = \frac{R_2 - R_1}{R_2 + R_1} \tag{5}$$

The expressions of coil inductance L and quality factor Q can be obtained as follows:

$$L = \mu_0 N^2 D_{AVG}\left[\ln\left(\frac{2.46}{\rho}\right) + 0.2\rho^2\right] \tag{6}$$

$$Q = \frac{\omega L}{R} = \pi f \mu_0 N \sigma r^2\left[\ln\left(\frac{2.46}{\rho}\right) + 0.2\rho^2\right] \tag{7}$$

Due to the influence of the inside to outside diameter ratio of the coil on the detection performance, if $k = \frac{R_1}{R_2}$, there is

$$N = \frac{R_2 - R_1}{2r} = \frac{R_2}{2r}(1 - k) \tag{8}$$

$$\rho = \frac{R_2 - R_1}{R_2 + R_1} = \frac{1 - k}{1 + k} \tag{9}$$

By bringing the corresponding parameters into equation (6) and (7), it can be simplified

$$L(k) = \frac{\mu_0 R_2^3}{8r^2}(1 + k)(1 - k)^2 H \tag{10}$$

$$Q(k) = \frac{\pi f \mu_0 \sigma r R_2}{2}(1 - k)H \tag{11}$$

$$H = \left[\ln\frac{2.46(1 + k)}{1 - k} + 0.2\left(\frac{1 - k}{1 + k}\right)^2\right] \tag{12}$$

According to these equations above, the variation curves of inductance $L(k)$ and quality factor $Q(k)$ with the inside to outside diameter ratio k of the coil can be drawn. As shown in Fig. 3(b), with the increase of k value, $L(k)$ first increases and then decreases, while $Q(k)$ continuously decreases. But on the whole, $L(k)$ is positively correlated with $Q(k)$. When $0 < k \leq 0.30$, $L(k)$ and $Q(k)$ have the best value effect. When $k > 0.7$, the $L(k)$ value drops significantly and is not suitable as an optimal reference range. In summary, the best reference range is $0 < k \leq 0.7$.

3.2. Analogue Simulation

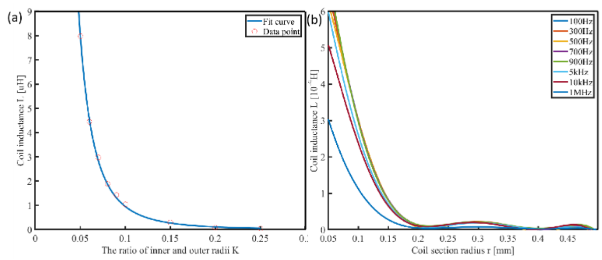

Fig. 4 (a) Simulation diagram of the relationship between the inside to outside diameter ratio $\boldsymbol{k}$ and coil inductance $\boldsymbol{L}$; (b) Simulation diagram of the relationship between coil section radius $\boldsymbol{r}$ and coil inductance $\boldsymbol{L}$ under different coil excitation frequency

In order to further verify the correctness of the theoretical analysis, the COMSOL model is used for simulation. Firstly, the value of the inside to outside diameter ratio k of the coil is studied. With fixed $R_1 = 1.5\,mm$ and $r = 0.2\,mm$, different k values and corresponding inductance L can be obtained by changing R_2. The corresponding results are shown in Fig. 4(a). It can be observed from the figure that the inductance L decays exponentially with k. When $0.05 \le k \le 0.10$, the inductance of the coil decreases rapidly. When $k > 0.10$, the coil inductance changes little. Therefore, the smaller the k value, the better, that is, the larger the coil radius R_2, the better (size limitation). The optimal inside to outside diameter ratio of the coil is $0.05 \le k \le 0.10$, which roughly coincides with our theoretical calculation.

In addition, we also simulate the relationship between coil section radius r and coil inductance L. If $R_1 = 1.5\ mm$ and $R_2 = 25.0\ mm$, $k = 0.06$. By changing coil section radius r, the influence of different coil section radius on coil inductance under different coil excitation frequency is obtained, and the results are shown in Fig. 4(b). It can be found that the larger the section radius r of the coil, the greater the AC resistance will be generated under the AC current of the higher excitation frequency, resulting in the smaller inductance of the coil, then the best section radius of the coil is $0.05\ mm \le r \le 0.15\ mm$.

3.3. Experiment Research

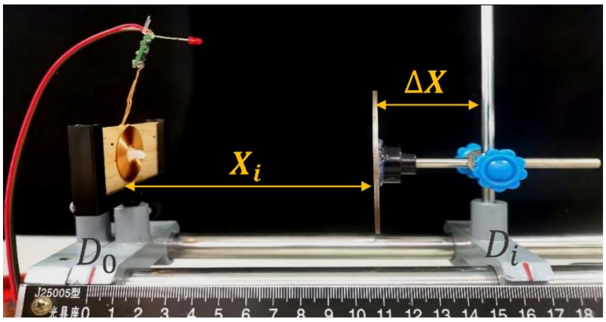

Fig. 5 Schematic diagram of the experimental device

Based on the best ranges obtained by theory and simulation, $0.05 \le k \le 0.10$ and $0.05\ mm \le r \le 0.15\ mm$, experimental exploration was carried out. Due to the limitation of experimental conditions, the section radius $r = 0.20 \pm 0.01\ mm$ was selected, the k value was changed, and the corresponding theoretical inductance value L was calculated according to equation (10). Considering that the inductance value is not easy to measure in practice, the detection distance X_i is selected as the detection object, and its expression is shown as follows:

$$X_i = D_i - D_0 - \Delta X \qquad (12)$$

Where ΔX is the distance between the object to be measured and the vertical axis of the optical base. The specific schematic diagram of the experimental device is shown in Fig. 5. At the same time, experiments are carried out based on the experimental device. In order to ensure the accuracy of the experiment, the average value of multiple measurements is taken, and the corresponding results are shown in Table 1.

Table 1. Experimental data table

$D_0 = 10.0\ mm$, $\Delta X = 31.6mm$

Coil	R_1 (mm)	R_2 (mm)	k	$L(\mu H)$	D_i			$\bar{X}_i$ (mm)
					D_1 (mm)	D_2 (mm)	D_3 (mm)	
1	11.38	15.10	0.75	2.555	46.9	46.7	46.8	5.20
2	11.50	16.18	0.71	4.215	51.8	51.7	51.7	10.13
3	6.10	10.34	0.60	6.411	53.0	53.1	53.1	11.47
4	7.72	13.90	0.56	6.949	55.1	55.0	54.9	13.40

According to the data in the Table 1, the relationship between the average induction distance $\bar{X}_i$ and k and the theoretical inductance value L is plotted and the results are shown in Fig. 6.

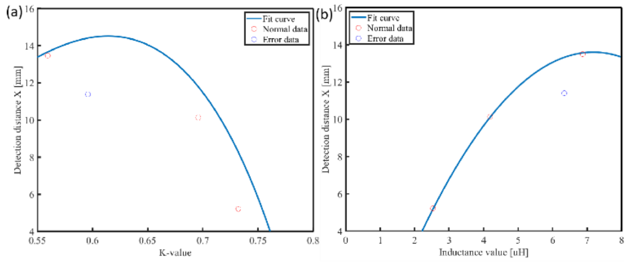

Fig. 6 (a) The relationship between the average detection distance $\bar{X}_i$ and the inside to outside diameter ratio k of the coil; (b) the relationship between the average detection distance $\bar{X}_i$ and the theoretical inductance value L

As can be seen from Fig. 6(a), the induced distance $\bar{X}_i$ firstly increases and then decreases with the increase of the k value (R_2 decreases); Similarly, as can be seen from Fig. 6(b), within the limited range of coil inductance value, the induction distance $\bar{X}_i$ increases with the increase of coil inductance value L; In the error range, the actual value is consistent with the theoretical value, and the relationship between the inductive distance and the inductance value is time increasing function.

Due to the limitation of experimental conditions, the optimal value range in theory and simulation cannot be obtained, which leads to some errors in our results. At the same time, due to the use of self-made coil in the experiment, the tightness of the winding coil is not fixed, the movement lag of the optical base, the contact point of the coil is not good, etc., which makes the error of our experiment relatively large. However, it is precisely because of the few consumables in the experiment, the simple operation of the instrument, high sensitivity, low power consumption, and the ability to operate by themselves in the laboratory, which provides a referential method for college students' physics experiments and exercises students' hands-on operation and operation ability.

4. Conclusion

Starting from the understanding of the working principle of eddy current sensor combined with simulation, this paper defines the value k of the inside to outside diameter ratio as the coil parameter to carry out the parameter optimization experiment of eddy current sensor. The optimal section radius of coil is $0.05mm \le r \le 0.15mm$, and the optimal inside to outside diameter ratio is $0 < k \le 0.7$. The smaller the value of k, the larger the inductance value L, and the farther the detection distance. In the experiment, due to the lack of materials, the range of k value measured is narrow, but the experimental results can be obtained in accordance with the theory. This paper combines theory, simulation and experiment, and the experimental system has fewer consumables, simple instrument operation and low power consumption, which is conducive to training the hands-on operation ability of college students and provides a reference method for college students' physics experiments.

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