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Electromagnetic Analysis of Plane Coils on Eddy Current Sensors

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Abstract: Eddy current testing is an important non-destructive testing method. The eddy current sensor needs to meet the high precision and high resolution requirements, and has a great relationship with the electromagnetic properties of its probe. This paper uses a variety of electromagnetic simulation finite element analysis software, through the establishment of three-dimensional model of the eddy current sensor planar coil for electromagnetic simulation analysis, to obtain its planar magnetic field distribution and different materials under different excitation of the magnetic field penetration. It lays a theoretical foundation for the design of sensors and has practical significance

Keywords: Eddy currents, Plane Coils, Electromagnetic simulation.

1. INTRODUCTION

The eddy current is the “circular current” induced in the body due to a change in the magnetic field. The principle is Faraday's law of electromagnetic induction. As shown in Figure 1.1, when the coil is connected to alternating current, an alternating magnetic field is generated around the coil. The alternating magnetic field will induce an alternating electric field in space, and when the conductor is in the alternating electric field, a toroidal current will be generated in the conductor. The eddy currents form a closed loop in the conductor, and its plane is perpendicular to the direction of the magnetic field. According to Lenz's law, the direction of the magnetic field generated by the eddy current is opposite to the direction of the magnetic field that induces the eddy current[1].

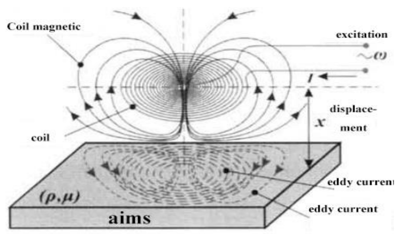

Figure 1.1 Principle of eddy current sensor

In this paper, the electromagnetic coil of the eddy current sensor is analyzed by three-dimensional modeling combined with electromagnetic simulation software "Comsol" and finite element analysis software "Ansoft Maxwell" to obtain the two-dimensional magnetic field distribution and penetration depth simulation results of the planar coil. This helps to optimize the design of eddy current sensor probes.

2. EDDY ELECTROMAGNETIC THEORY

2.1 Eddy current principle

In general, an eddy current displacement sensor consists of a detection coil (probe), a metal conductor (target to be measured), and a sensor signal processing circuit. When a high-frequency coil is connected to high-frequency alternating current, an alternating magnetic field is generated around the coil. According to Faraday's law of electromagnetic induction, the alternating magnetic field generates an induced electromotive force in space. This induced electromotive force generates an induced current in a conductor, which is called a vortex. Induced eddy currents also generate a magnetic field that is opposite to the coil's magnetic field. The interaction of the eddy current magnetic field with the coil magnetic field results in a reduction of the equivalent inductance of the coil. At the same time, as the eddy current in the conductor consumes energy itself, the equivalent resistance of the coil increases. Due to the distance X between the probe and the target to be measured, the electromagnetic properties of the target (resistivity ρ and permeability μ) and the frequency of the alternating current will change the coupling relationship between the conductor and the detection coil[2], so the equivalent of the detection coil Impedance can be written as

$$z_{eff} = f(x, \rho, u, f)$$

When the eddy current sensor is used for displacement measurement, it operates at a certain fixed frequency and the electromagnetic properties of the target conductor to be measured are constant, ie, they are all constants. Therefore, the equivalent impedance of the eddy current sensor can be simplified as follows:

$$Z_{eff} = f(x) = R(x) + j\omega L(x)$$

The above formula $\omega = 2\pi f$is the corner frequency. The detection coil representing the eddy current sensor can be equivalent to a series connection of a resistor and an inductor. This equivalent resistance and inductance change as the distance between the probe and the target to be measured changes. At the same time, parasitic capacitance exists between the two ends of the search coil and the sensor cable. This parasitic capacitance is in parallel with the inductance and resistance. The parasitic capacitance is basically constant for a particular probe. In summary, the eddy current sensor can be equivalent as shown in Figure 2.1

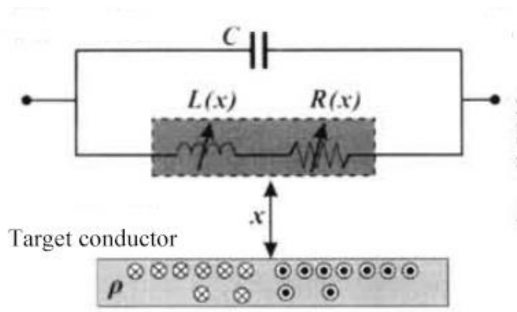

Figure 2.1 Equivalent Circuit of Eddy Current Coil Probe

2.2 Eddy Current Sensor Transformer Model

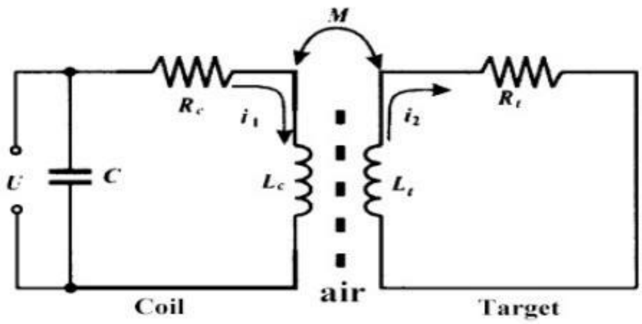

Figure 2.2 Transformer Model of Eddy Current Sensor

The search coil can be seen as an inductor in series with a resistor, applying a transformer primary with a certain frequency of the AC input U. The measured target can be seen as a short circuited secondary consisting of an inductor and a resistor, as shown in Figure 2.2. Available from Kirchhoff's law:

$$\begin{cases} \mathrm{R}_c I_1 + j\omega L_c I_1 - j\omega M I_2 = U \\ R_t I_2 + j\omega L_1 I_2 - j\omega M I_1 = 0 \end{cases}$$

Solve the equation to get:

$$I = \frac{U}{R_c + \frac{\omega^2 M^2}{R_t + (\omega L_t)^2} R_t + j\omega\left[L_c - \frac{\omega^2 M^2}{R_t^2 + (\omega L_t)^2} L_2\right]}$$

Separate the inductor and resistor parts and write the following form:

$$\begin{cases} R = R_c + \frac{\omega^2 M^2}{R_t^2 + (\omega L_t)^2} R_t \\ L = L_c - \frac{\omega^2 M^2}{R_t^2 + (\omega L_t)^2} L_t \end{cases}$$

The above formula $\omega = 2\pi f$ is the corner frequency, M is the mutual inductance between the coil and the measured target, can be written as follows:

$$M = k(x)\sqrt{L_c L_t}\ (0 < k < 1)$$

In the above equation, the coupling coefficient of the primary and secondary transformers is between 0 and 1. The specific expression depends on the structure of the detection coil and the geometric dimensions and electromagnetic characteristics of the measured target.

3. EDDY CURRENT MODEL AND ELECTROMAGNETIC ANALYSIS OF 3 PLANE COILS

3.1 Distribution of planar magnetic field

The eddy current sensor's measured target can be mainly divided into ferromagnetic target and non-ferromagnetic target according to its material electromagnetic characteristics. When the detection coil approaches a non-ferromagnetic target, its working principle is the eddy current effect discussed above. In order to study the magnetic field distribution of planar coils in non-ferromagnetic materials, we have established a three-dimensional model as shown in Figure 3.1 below. Select aluminum material as the target to be measured, select three-layer planar coils, add alternating current at a frequency of 100 kHz, and use comsol software. Electromagnetic simulations were performed and the results are shown in Figure 3.2.

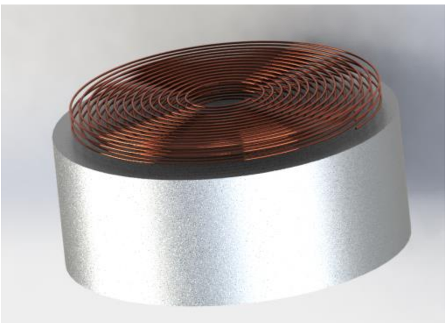

Figure 3.1 3D rendering of a planar coil

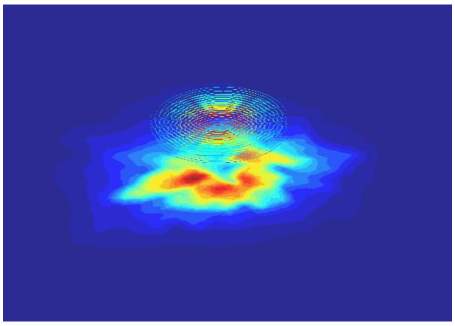

Figure 3.2 Simulation results

From Fig. 3.2, we can see that the eddy current effect energy of the non-ferromagnetic material in the planar coil is distributed between the inner and outer diameters of the coil. The axial position of the coil is not the strongest eddy current. The eddy current drops rapidly when it is larger than the outer diameter of the coil, so the eddy current change caused by the planar coil is concentrated in the area covered by the coil.

3.2 Magnetic field penetration depth analysis

Here we use the two-coil model, using ansoft Maxwell finite element analysis such as that piece to simulate the magnetic field transmission depth of the planar coil on the aluminum material. We used a simplified model of the coil to make the calculation process faster, while ensuring less than 1.2% resistance error and 2.64% inductance error. Coil parameter design is consistent with the coil parameters and excitation frequency in Figure 3.3.

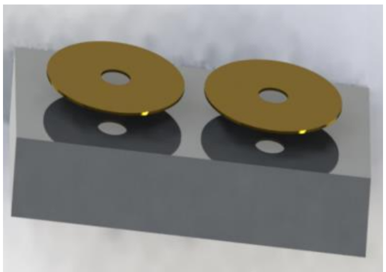

Figure 3.3 Three-dimensional simplified double coil model

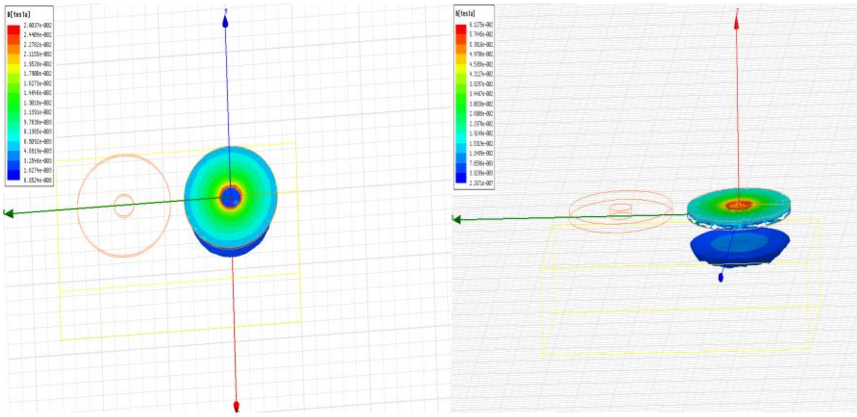

Figure 3.4 Simplify the simulation of the coil

According to the law of electromagnetic induction, the formula for calculating the distribution depth of eddy currents is as follows

$$\delta = \sqrt{\frac{1}{\pi \mu_0 \mu_r \sigma f}}$$

Where μ_0 is the magnetic permeability in vacuum 4 = x10 ~ H/m, μ_r is the relative permeability of the material, σ is the conductivity of the material (sometimes also used resistance = ρ =1/ σ), f is the frequency of the alternating current. The above formula can be simplified into the following formula

$$\delta = \sqrt{\frac{503.3}{\mu_r \sigma f}}$$

Table 1 Three Scheme comparing

material	σ （MS/ m）	μ_r	δ/mm				
			50Hz	10kHz	100kHz	1mHz	10mHz
Cu	59.98	1	9.19	0.65	0.206	0.065	0.0205
Al	37.74	1	11.6	0.819	0.259	0.082	0.0259
SS	4.3032	1	35.4	2.51	0.794	0.251	0.0793
Ti	0.741	1	82.7	5.85	1.85	0.585	0.185
Fe	11.2	4000	0.34	0.024	0.0076	0.0024	0.00076
Ferrite	0.00001	500	3183	225.1	71.18	22.51	7.118

The data in the material table shows that since ferromagnetic conductors are much larger in permeability than non-ferromagnetic conductors, the transmission depth of ferromagnetic conductors is much smaller[3,4]. For example, the transmission depth of pure iron at the power frequency (50 Hz) is only 0.34. Mm. Of course, the transmission depth of a magnetic material such as ferrite, which has a very low conductivity, can be very large, suitable for high-frequency and ultra-high-frequency applications. At frequencies up to 1 GHz, the transmission depth can still reach several cm. For the non-ferromagnetic materials discussed in this paper, the relative permeability is 1, the penetration depth only depends on frequency and conductivity.

4. CONCLUSION

Through the electromagnetic simulation analysis of the eddy current sensor, we obtained that the magnetic field of the planar coil of the eddy current sensor is concentrated in the coil coverage area, and the magnetic field intensity between the inner and outer diameters of the coil is the largest. At the same time, we also analyzed the penetration depth of planar coils under different excitations under different materials, providing theoretical support for the design optimization of eddy current sensors.

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