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Research on Interstitial Eddy Currents Detection Methods between Two - layer Conductors based on Apparent Conductivity Curve

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Abstract:

In aviation, energy and other fields, the Two-layer Conductors Slabbed Construction has a very wide range of applications, so its reliability is crucial to the operation of the system. However, the traditional testing methods are often limited by complex environment and structural characteristics, but as a nondestructive testing technology, eddy current testing has the advantages of non-contact and high resolution, so it has attracted much attention. As for Two-layer Conductors Slabbed Construction, it is of great theoretical and practical value to accurately detect the internal defects and gaps by analyzing the electromagnetic characteristic changes caused by eddy currents. This study takes the eddy current detection method based on apparent conductivity as the research topic, and explores the theory and method of eddy current detection of two-layer conductors slabbed spacing. First, it describes the physical mechanism of eddy current testing. Then, it analyzes the impedance characteristics of eddy current detection, proposes a two-layer conductors slabbed spacing eddy current detection method, and carries out sweep frequency test of eddy current detection impedance characteristics. On this basis, the analysis of two-layer conductors slabbed spacing eddy current inspection simulation is carried out. Finally, an inversion algorithm of eddy current detection based on orthogonal polynomial is proposed, and its validity is verified by simulation analysis.

Keywords: Two-layer Conductors Slab, Apparent Conductivity, Spacing, Eddy Current Testing

1 Introduction

1.1 Research Background and Significance

In the industrial field, the detection of double-layer metal structure and its thickness has been paid much attention. This kind of structure usually appears in the parts of the aircraft, automobile and other manufacturing industries. Because in the process of processing and forming, they often face problems such as material deformation and stress concentration, resulting in gaps between plates, which directly affect the performance and safety of the product [1]. In the face of this challenge, accurate testing of the thickness of double-layer structures has become crucial, as it is not only about product quality, but also about service life and safety.

In this study, the two-layer conductors slabbed spacing eddy current testing method based on apparent conductivity curves is studied, so that an efficient and accurate eddy current testing technique can be developed for the thickness measurement of double-layer metal structures in industrial applications. The aim of this study is to propose a reliable detection method that can effectively deal with the thickness variation and layer gap problems in double-layer metal structures, so as to improve product quality, production efficiency and safety.

In this study, two-layer conductors slabbed spacing eddy current detection method based on the apparent conductivity curve is studied, which has important theoretical and practical significance.

1.2 Research status at home and abroad

Eddy current method has broad application prospects in aviation, aerospace, automobile, nuclear industry and civil industry because of its unique advantages. At present, eddy current testing technology has obvious advantages when the film thickness of non-conductive insulating materials on non-magnetic substrates is measured by eddy current method, especially when the conductivity of the two media is very different [2]. Eddy current thickness gauge has important applications in many fields such as the oxide film thickness on the surface of aluminum-copper products, the insulating coating thickness on the surface of copper-aluminum alloy and the copper plating thickness of the insulating base material. The use of eddy current testing to measure the thickness of insulating coatings on non-conductive or weakly conductive substrates has been studied for several decades, which has been widely discussed by scholars at home and abroad, and some research results have been obtained.

The current research results mainly focus on the application of eddy current method in the field of coating thickness measurement. Researchers have focused on coating thickness measurement on different matrix materials, including non-magnetic matrix materials, high conductivity matrix materials, and conductor plates [3-5]. Through experimental and theoretical analysis, the measurement accuracy, measurement range and applicability of eddy current method on these materials are explored, which aims to provide a more accurate and reliable coating thickness measurement scheme. However, although some research results have been achieved, there are still some problems in the existing research. There are some theoretical and practical challenges, including eddy current measurement of thin non-ferromagnetic metal thickness and eddy current measurement of conductor plate coating thickness. For example, in the measurement of thin-layer coatings, due to the characteristics of the material and the thin thickness of the coating, the traditional eddy current method may be limited in accuracy and measurement range, resulting in low accuracy of the measurement results. To this end, the two-layer conductors slabbed spacing eddy current detection method based on the apparent conductivity curve has been studied, so as to explore a new eddy current detection method. By utilizing the characteristics of the apparent conductivity curve, a more accurate and reliable eddy current detection scheme for two-layer conductors slabbed spacing is proposed. Through theoretical analysis and experimental research, this method will seek to break through the limitation of traditional eddy current method in thin layer coating thickness measurement, so as to provide a more efficient and accurate solution for coating thickness measurement in industrial production.

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2 Analysis of Forward Problem Solving Coil Impedance

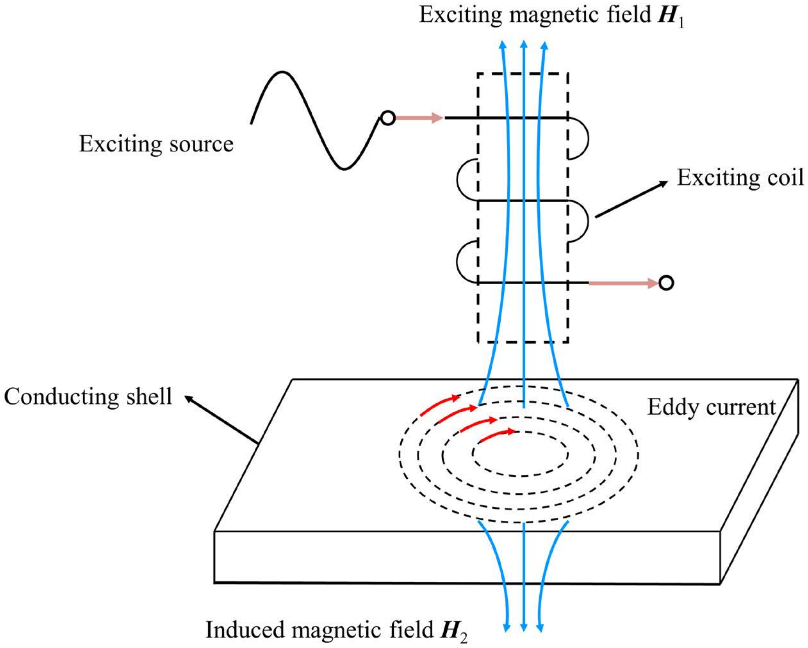

Figure 1 Schematic diagram of the eddy current detection principle

Eddy current testing technology is suitable for the detection of various conductive specimens (including metal materials and non-metallic materials that can sense eddy current). The schematic diagram of the detection principle is shown in Figure 2-1. According to the law of electromagnetic induction, when the conducting specimen approaches the coil with alternating excitation, the induced electromotive force and the corresponding induced current will be generated inside the specimen. The current distribution varies with the surface shape of the specimen and the magnetic field distribution.

2.1 Derivation of the theoretical value of coil impedance

To solve the theoretical value of coil impedance, it is necessary to understand the relationship between various factors and the detected coil impedance, as shown in Figure 2-2.

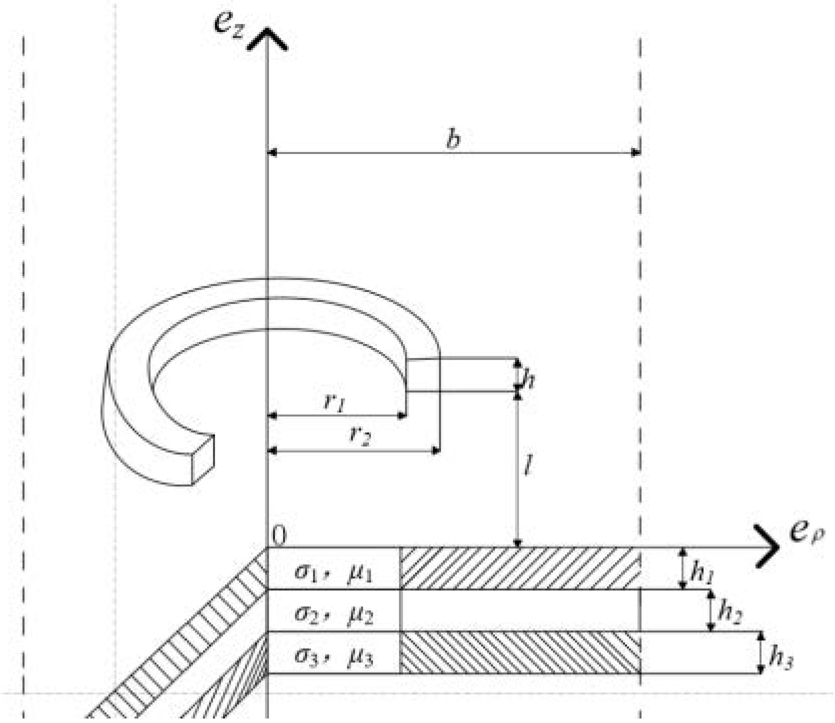

Figure 2 Theoretical model of two-layer conductors slabbed spacing tested by eddy current method

In the case of constant coil parameters, the coil impedance Z is related to the conductivity σ_1 of plate layer 1, the conductivity σ_2 of air gap, the conductivity σ_3 of plate layer 2, the permeability μ_1 of plate layer 1, the permeability μ_2 of air gap, and the permeability μ_3 of plate layer 2. The distance l between the detection probe (coil) and the conductor of the measured part, the height h of the detection probe, the inner radius r_1 of the coil, the outer radius r_2, the geometric factor b (multiple of the inner radius of the coil and the outer radius), and the height h_1 of the plate layer 1, the air gap h_1, and the height h_3 of the plate layer 2. Coil impedance Z and related parameters are expressed by (2-1) :

$$Z = F\left(\sigma_1, \sigma_2, \sigma_3, \mu_1, \mu_2, \mu_3, l, h, r_1, r_2, h_1, h_2, h_3, b\right) \quad (2\text{-}1)$$

As the derivation of the specific formula of coil impedance Z and related parameters is complicated and the calculation is huge, it is necessary to combine the result expression of the analytical solution of coil impedance in the corresponding references and the relevant parameters of the coil (such as the frequency of alternating current f, etc.), and substitute the values of relevant parameters into the analytical solution expression in Matlab software programming to obtain the theoretical value of coil impedance.

Referring to the research on the general series expression of eddy current impedance when the coil is placed above the multilayer board conductor in relevant journals, the series expression of the analytical solution of the coil impedance is obtained as (2-2) formula:

$$\Delta Z = -i2\pi\mu_0 b^5 w \sum_{m=1}^{\infty} L_{Nm} C_m^2 \exp\left(-2x_m l\right) \quad (2\text{-}2)$$

Where C_m is the coil factor, only determined by the coil parameters W, $r1$, $r2$ and, the specific expression is (2-3) formula

$$C_m = \frac{n_{den}\left[1 - \exp\left(-x_m h\right)\right]}{\lambda_m^{7/2} J_0\left(\lambda_m\right)} \int_{x_m r_1}^{x_m r_2} x J_1(x) dx \quad (2\text{-}3)$$

L_{Nm} is the layered plate coefficient, which is a complex function determined by the thickness, electrical conductivity and permeability of each layer, the specific expression is (2-4) formula:

$$L_{Nm} = th\left(\frac{1}{2} ln\left(q_{1m} th\left(\alpha_{1m} h_1 + \cdots + arth\left(q_{N-1,m} th\left(\alpha_{N-1,m} \times h_{N-1} + arth\left(q_{Nm} th\left(\alpha_{Nm} h_N + arthq_{N+1,m}\right)\right)\right)\right)\right)\right)\right) \quad (2\text{-}4)$$

According to the series expression of the analytical solution of the coil impedance (2-2), the program is programmed in Matlab software, and the relevant parameters of the coil parameters (height h, radius r_1 and r_2, number of coils W, etc.) and material properties (electrical conductivity $\sigma_1, \sigma_2, \sigma_3$ and permeability μ_1, μ_2, etc.) are inserted, as shown in Table 2-1. The theoretical value of the coil impedance is obtained when the frequency of the excitation signal is f.

Table 1 Parameters related to the theoretical analytical solution of coil impedance

Real height 1(mm)	Number of coils W(Turn)	Inside radius rl(mm)	Outside radius r2(mm)	Coil height h(mm)
1.2	43	9.95	10.2	7.24
Slab layer 1hl(mm)	Air gap h2(mm)	Slab layer 2h3(mm)	Slab layer 1ol(MS/m)	Air gap o2(MS/m)
2	1.04	3.44	54.55	0
Slab layer 2o3(MS/m)	Slab layer 1μl(H/m	Air gap μ2(H/m)	Slab layer 2μ3(H/m	Geometrical factor b(m)
34.45	1	1	1	1

2.2 Verifying the theoretical value of coil impedance for solving the forward problem

Verifying the theoretical value of coil impedance for solving the positive problem: Compare the theoretical value of coil impedance calculated at 6000Hz with the results of reference journals to see whether the two are consistent. If they are consistent, the programming of Matlab software is correct; otherwise, it is wrong. When the frequency is 6000Hz, the theoretical value of coil impedance obtained by Matlab programming is 0.0477-0.3612i.

The results of the theoretical values of coil impedance referred to in the journal are:

deltaZ $=-2*pi^{*}b^{5}*a0*c$

deltaZ $=n0.0477-0.3612in$

The above two results are consistent, so the theoretical value of coil impedance for the forward problem is correct and reliable.

Next, the frequency is further set as 5000Hz, 6500Hz, 7000Hz, 7500Hz and 8000Hz, and the theoretical value of coil impedance obtained by Matlab programming is compared with the theoretical value of coil impedance solved in this study. The results are shown in Table 2-2.

Table 2 Theoretical values of coil impedance in reference journals and theoretical values of this calculation

Frequency(Hz)	Theoretical values of coil impedance in reference journals	Theoretical value of coil impedance for solving the forward problem
5000	0.0476+-0.3609i	0.0476+-0.3609i
6500	0.0477+-0.3611i	0.0477+-0.3611i
7000	0.0477+-0.3612i	0.0477+-0.3612i
7500Hz	0.0477+-0.3614i	0.0477+-0.3614i
8000Hz	0.0478+-0.3616i	0.0478+-0.3616i

It can be seen that the theoretical value of coil impedance solved by the forward problem is consistent with that of the reference journal.

2.3 Data selection and calculation

There are a total of 36 experimental values of coil impedance, so it is necessary to calculate the theoretical values of coil impedance at the frequencies corresponding to the experimental values. By substituting the frequencies of the 36 experimental values into the solution of the theoretical values of coil impedance, the theoretical values of coil impedance at the experimental frequencies are obtained, as shown in Table 2-3, and the theoretical values of coil impedance are recorded as $\Delta Z(fi)$.

Table 3 Theoretical values of coil impedance (imaginary part)

Frequency(Hz)	Theoretical value (Q)	Frequency(Hz)	Theoretical value(Ω)	Frequency(Hz)	Theoretical value(2)
100	-0.0013	120	-0.0018	140	-0.0025
160	-0.0032	180	-0.0039	200	-0.0047
220	-0.0056	240	-0.0065	260	-0.0074
280	-0.0083	300	-0.0092	400	-0.0142
500	-0.0195	600	-0.0249	700	-0.0305
800	-0.0362	900	-0.0420	1000	-0.0478
1100	-0.0538	1200	-0.0598	1300	-0.0658
1400	-0.0718	1500	-0.0779	1600	-0.0840
1700	-0.0901	1800	-0.0962	1900	-0.1024
2000	-0.1085	2500	-0.1394	3000	-0.1705
3500	-0.2017	4000	-0.2332	4500	-0.2649
5000	-0.2968	5500	-0.3289	6000	-0.3612

3 Calculation and Solution of Apparent Conductivity Curve

Based on the theory of eddy current testing, this chapter analyzes the impedance characteristics of eddy current testing coils, constructs a two-layer conductors slabbed spacing eddy current testing model, carries out the simulation analysis of two-layer conductors slabbed spacing eddy current testing method, and explores the calculation and solution of the apparent conductivity curve, so as to verify the validity of the two-layer conductors slabbed spacing eddy current detection method. The calculation and solution of the apparent conductivity curve are shown in Figure 3-1.

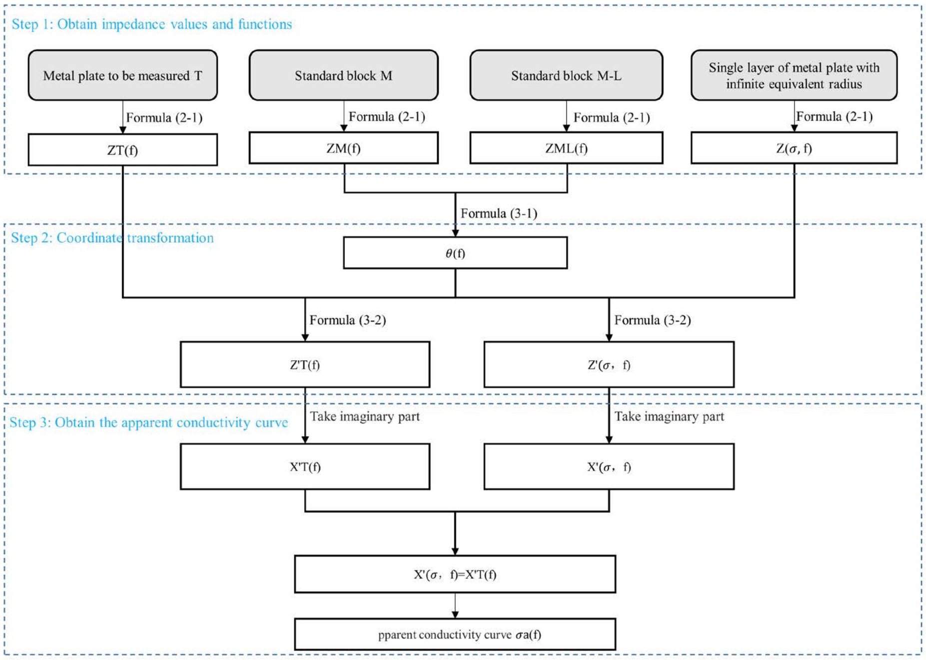

Figure 3 Flowchart for obtaining the apparent conductivity curve

Based on the above, this study constructs an air gap vortex detection model between Slab layers of double-layer conductors, as shown in Figure 3-2.

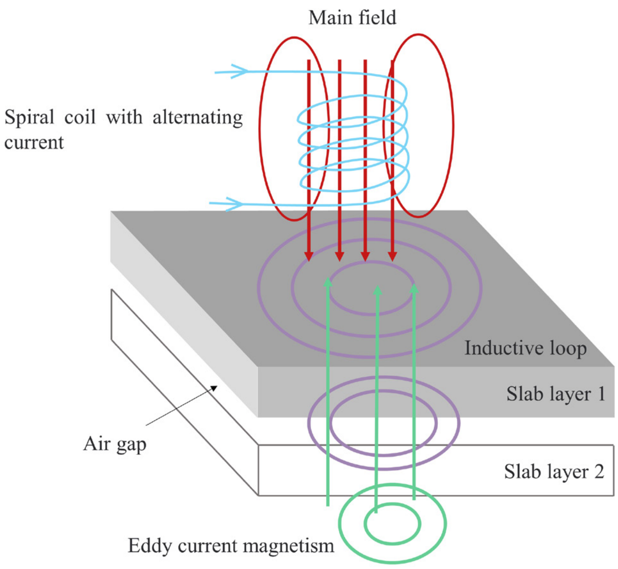

Figure 4 Air gap vortex detection model between Slab layers of a double-layer conductor

As shown in Figure 3-2, eddy current testing technology is widely used to detect defects and evaluate properties of materials, especially in determining the size of the Air gap between conductors. In scenarios involving a double-layer conductor plate, the probe used is usually in the form of a spiral coil, which is placed above the surface of the conductor to be measured. The alternating current in the probe generates a downward dynamic magnetic field that passes through the conductor plate and, according to Lenz's law, it stimulates the formation of induced eddy currents inside the conductor. These induced eddies further generate a magnetic field in the opposite direction of the original field, designed to resist changes in the original field.

4 Inversion Algorithm of Eddy Current Detection based on Apparent Conductivity

According to the two-layer conductors slabbed spacing eddy current detection algorithm mentioned above, this programme proposes an inversion algorithm based on visual conductivity to solve this problem, that is, the visual conductivity is used to retrieve the electrical conductivity of each layer at each excitation frequency within the range of full penetration depth. Then the overall conductivity distribution is obtained through curve fitting [7].

The settings are as follows: the coating base is all aluminum, the coating base is all copper, the coating aluminum base is all copper, the coating copper base is all aluminum, it can been seen that the apparent conductivity of the conductor plate changes with the sweep frequency, as shown in Figure 4-1.

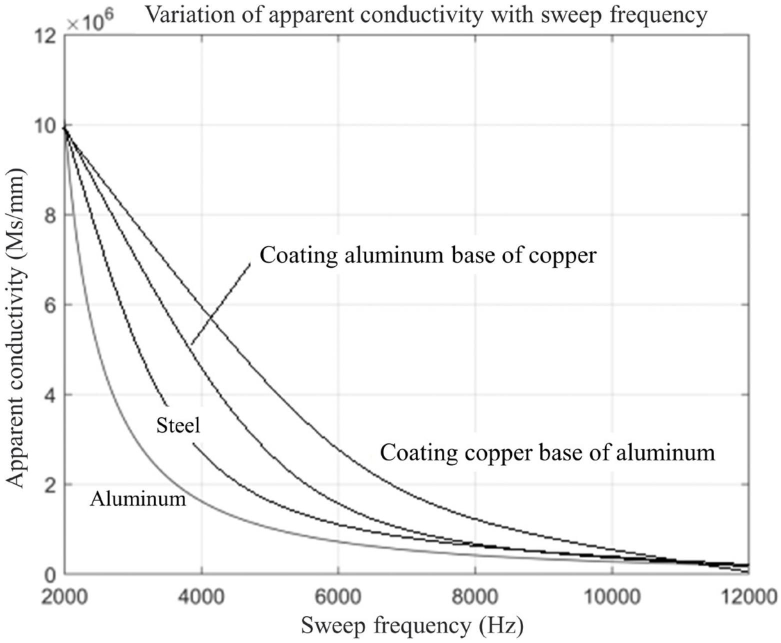

Figure 5 Variation of apparent conductivity of a conductor plate with sweep frequency

It can be seen that the apparent conductivity of the conductor plates with different materials increases first and then decreases with the increase of the sweep frequency. In the low frequency region, the apparent conductivity is low, because at low frequencies, the penetration ability of electromagnetic waves is weak, resulting in insufficient sensitivity to the conductivity measurement of the base layer. As the sweep frequency increases, the apparent conductivity begins to rise, but this is because the penetration of electromagnetic waves increases, making the measurement of the base conductivity more accurate. When the sweep frequency reaches a certain value, the apparent conductivity begins to decline, which is due to the skin effect caused by high frequency electromagnetic waves in the aluminum base, resulting in a decrease in the measured value of the conductivity. Skin effect refers to the tendency of high-frequency current to flow on the surface of the conductor, thereby reducing the effective conductivity of the conductor.

For further analysis, the apparent conductivity of the conductor plate varies with the sweep frequency at different thicknesses (h1 is 0.1mm, 0.2mm, 0.3mm, 0.4mm, 0.5mm, respectively), as shown in Figure 4-2.

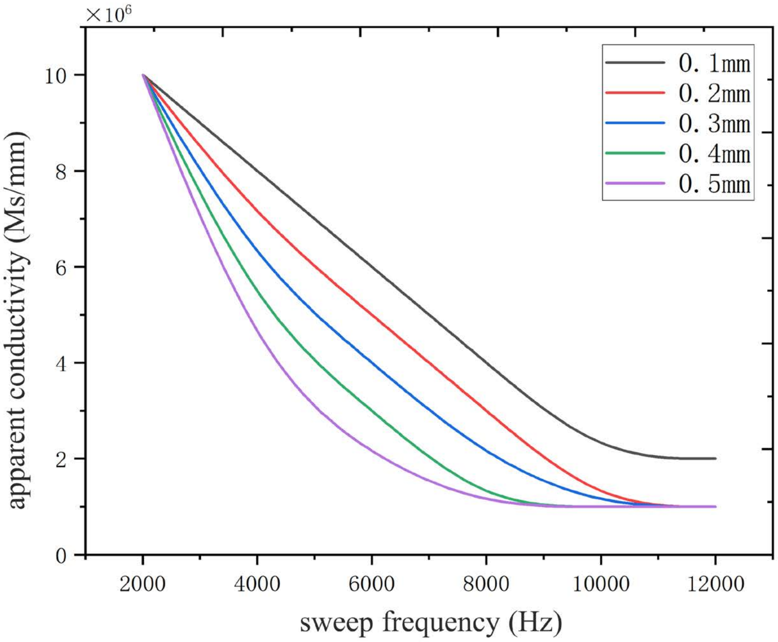

Figure 6 Variation of apparent conductivity of conductor plate with sweep frequency at different thicknesses

As can be seen from Figure 4-2, the apparent conductivity of conductor plates with different thicknesses shows an obvious decreasing trend with the increase of sweep frequency. At low sweep frequency, the apparent conductivity values of all thicknesses are high and similar, indicating that electromagnetic waves can penetrate deeper into the conductor and induce stronger eddy currents in the low frequency region. With the increase of sweep frequency, the skin effect becomes obvious, and the electromagnetic wave mainly induces eddy currents on the conductor surface, resulting in the decrease of apparent conductivity. In the high frequency region, the apparent conductivity of thinner conductors decreases more significantly, while the apparent conductivity of thicker conductors is lower, indicating that the conductivity of thicker conductors decreases faster at high frequencies, and the skin effect is more obvious. This indicates that the response of conductor plates with different thickness to electromagnetic wave gradually weakens with the increase of sweep frequency, and the conductor with larger thickness decreases its apparent conductivity faster, reflecting the relationship between skin depth and conductor thickness and the nonlinear change of conductivity at high frequency.

5 Conclusion

In this study, the theoretical basis and practical application of the two-layer conductors slabbed spacing eddy current testing method are discussed. Based on previous research results, the physical mechanism of eddy-current testing is analyzed in detail, including lifting effect and skin effect, and the theoretical basis of eddy-current testing is established. On this basis, a two-layer conductors slabbed spacing eddy current detection method is designed and implemented, and the feasibility and effectiveness of the method are verified by simulation and experiment. It is found that the two-layer conductors slabbed spacing eddy current testing method can not only measure the thickness of the non-conductive layer and the conductive coating layer material, but also reduce the influence of the lifting

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effect, reduce the calculation amount and improve the detection efficiency, providing a basis for eddy current technology to measure the thickness of the multilayer material.

However, although this study has achieved certain results, there are still some shortcomings and needs to be improved. First, the two-layer conductors slabbed spacing eddy current detection method has not been sufficiently experimentally validated in some specific cases, so its applicability and accuracy need to be further verified. Secondly, the stability and reliability of eddy current detection inversion algorithm based on apparent conductivity still have room to improve in complex situations. The future research direction can further improve the eddy current detection method, improve the detection accuracy and stability, and combine with practical engineering application scenarios for more in-depth research and exploration.

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