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Skin Effect in Eddy Current Testing with Bobbin Coil and Encircling Coil

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Abstract—Eddy current testing (ECT) is known as an effective technology for inspecting surface and near surface defects in metallic components. It is well known that the amplitude of eddy current (EC) density decreases with increasing depth, which is referred to as skin effect. Skin depth is an important parameter that quantifies the speed of attenuation of EC in the depth direction and is closely related to the capability of ECT for detecting deeply hidden defects. It is found that the traditional formula for calculating skin depth derived under the assumption of uniform plane field excitation is not applicable to the cases of ECT with coils. The skin effect in component with flat surface excited by pancake coil has been investigated by the authors. The skin effect in conductive tube tested by bobbin coil and that in conductive bar tested by encircling coil are more complex. The paper studies the skin effect in these two cases. Finite element analysis shows that the attenuation of EC is not only due to the ohmic loss, but also influenced by the diffusion effects, the aggregation effect, and the combined cancellation/diffusion effect of EC. The skin depth of EC associated with bobbin coil is always smaller than that associated with uniform plane field excitation, whereas the skin depth of EC associated with encircling coil can be greater than that associated with uniform plane field excitation under certain conditions.

1. INTRODUCTION

Eddy current testing (ECT) is widely used in industry for detecting defects in metallic components and ensuring structural safety [1–5]. The technology has many advantages such as single-side testing, being noncontact, and being easy to realize automatic examination. It is well known that the amplitude of EC density is maximum on conductor surface and decreases exponentially with increasing penetrating depth. This phenomenon is called skin effect and is illustrated in Fig. 1. In the figure, the thickness of circular line represents the amplitude of EC density. Due to the skin effect, the capability of ECT for detecting buried defects is limited. To assess the speed of EC attenuation, the normalized EC density is computed by dividing the amplitude of EC density at any depth by the value on conductor surface. Then the speed of EC attenuation is defined as the reduction of normalized EC density per unit depth and is independent of the intensity of the excitation current. The depth at which the normalized EC density equals 1/e (36.7%) is referred to as skin depth. It is essential to have a prior knowledge of skin depth for designing excitation coil and selecting working frequency.

Given excitation frequency f, permeability μ, and conductivity σ, skin depth is typically calculated as

$$\delta_s = \frac{1}{\sqrt{\pi f \mu \sigma}} \tag{1}$$

The value obtained by Eq. (1) is referred to as standard skin depth. It is derived under the assumption that the test sample has infinite thickness and flat surface and the excitation is a uniform plane field [6].

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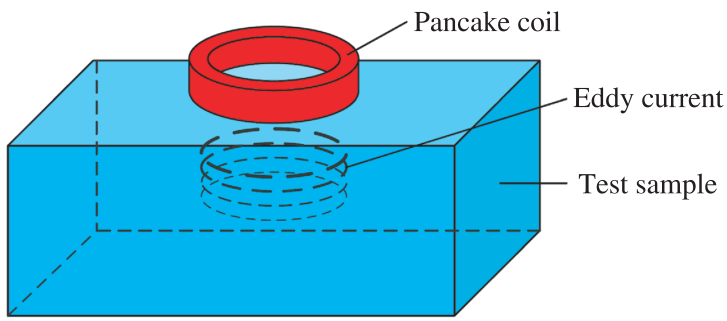


Figure 1. Illustration of skin effect in ECT with pancake coil.

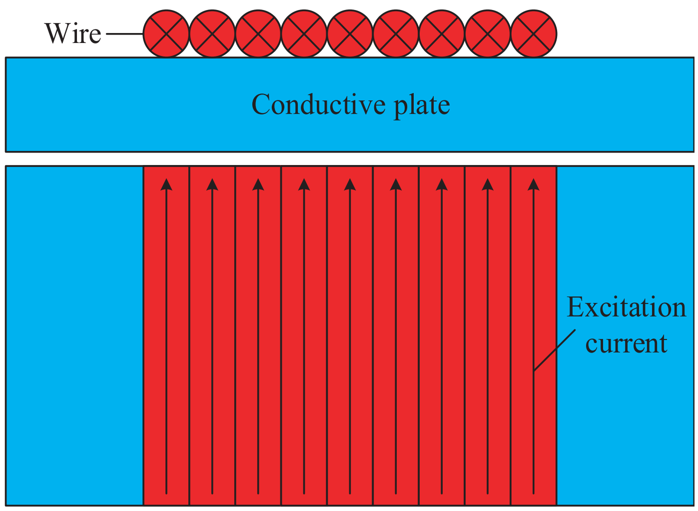


Figure 2. Illustration of uniform plane field excitation.

The source generating uniform plane field can be considered as consisting of numerous parallel straight wires having alternating currents with the same amplitude and phase, as illustrated in Fig. 2.

It has been noticed that the true skin depth is smaller than the standard skin depth if the excitation source is a pancake coil as shown in Fig. 1 [6–8]. When testing conductive plate of infinite thickness, the true skin depth depends on the coil parameters [9]. In order to detect deeply hidden defect, the coil parameters must be properly selected to reduce the discrepancy between the true skin depth and the standard skin depth, which can be done by finite element analysis (FEA) [10]. Two reasons of the discrepancy have been analyzed: one is that the variation of EC density in the radial direction becomes more gentle with increasing depth, which is named the diffusion effect; the other is that the ECs induced by symmetric current elements of the coil under the current elements cancel each other and the level of cancellation becomes greater with increasing depth, which is referred to as the combined cancellation/diffusion effect [11].

The skin effect is much more complex if the excitation source is bobbin coil or encircling coil. Bobbin coil and encircling coil are widely used in the inspection of workpiece of cylindrical shape [12–18], as illustrated in Fig. 3. Literature on the skin effect associated with these two types of coils is not found. The paper attempts to reveal the laws and the underlying physics of the attenuation of ECs under the excitations of bobbin coil and encircling coil, and obtain the relations between skin depths and the geometrical parameters of the coils. To this end, it is necessary to acquire the EC densities at various depths in the conductor, which is not possible to be experimentally measured from outside of the conductor. The paper utilizes the FEA software AxisymMag developed in lab for solving axisymmetric magnetic field problems to compute EC densities. The software has been verified by comparing computation results with analytical solutions in [11].

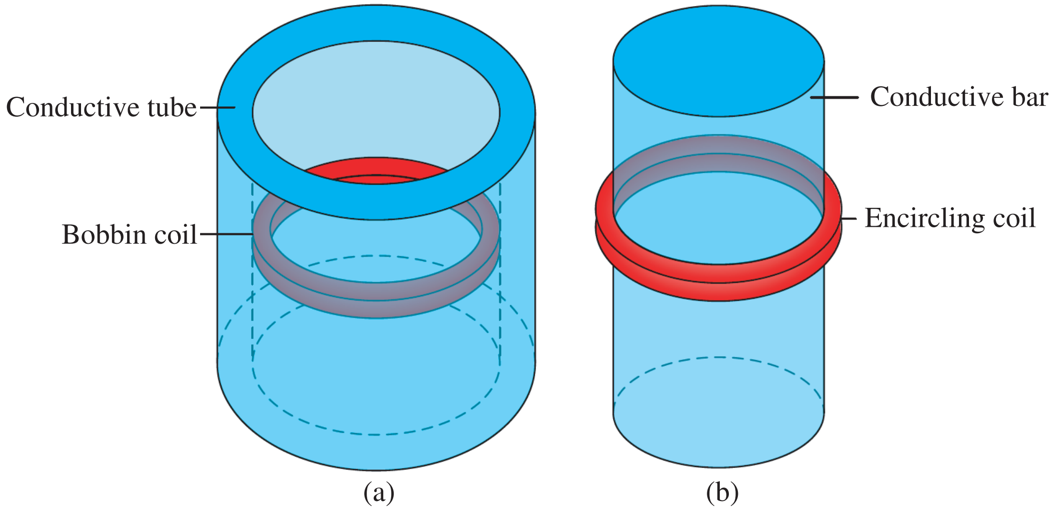


Figure 3. Illustration of ECT with bobbin coil and ECT with encircling coil. (a) ECT with bobbin coil. (b) ECT with encircling coil.

Section 2 analyzes the factors influencing the attenuation speed of EC. Section 3 describes the setup of simulations for studying the skin effects in ECT with bobbin coil and ECT with encircling coil. Section 4 presents the skin effect associated with bobbin coil, including comparing the attenuation speed of EC under the excitation of bobbin coil with those under the excitation of uniform plane field and pancake coil, followed by a parametric study. Section 5 addresses the skin effect associated with encircling coil in the same manner. Conclusive remarks are given in Section 6.

2. THE FACTORS INFLUENCING THE ATTENUATION SPEED OF EC

In this paper, we assume that the conductive plate tested by pancake coil is thick enough such that the EC on the surface opposite to the coil is very small. Similarly, when testing conductive tube using bobbin coil, the thickness of the tube's wall is assumed to be big enough such that the EC on the outside surface of the tube can be neglected. When testing conductive bar with encircling coil, the diameter of the bar is assumed to be sufficiently large such that the ECs induced by symmetric current elements of the encircling coil do not influence each other.

The standard skin depth given by Eq. (1) is derived under the assumption that the excitation is a uniform plane field. In that case, EC attenuates in the penetrating direction only because conductor is lossy material. In ECT, however, the magnetic fields generated by coils are not uniform plane fields [6–9]. Therefore, the attenuation of ECs under the excitations of pancake coil, bobbin coil, and encircling coil must be different from that associated with uniform plane field. The factors affecting the attenuation of EC besides the ohmic loss are analyzed in the following subsections.

2.1. The Diffusion Effects and the Aggregation Effect

Figure 4 shows the EC densities along the radial direction at two different depths induced by a current element of pancake coil. At each depth, EC focuses in the region beneath the current element and decays towards both sides. It is rather remarkable that the decay of EC in the radial direction becomes slower with increasing depth, which means the EC energy is not only losing but also spreading out. This phenomenon is referred to as the diffusion effect of EC [11]. The diffusion effect makes the EC excited by pancake coil attenuates faster in the depth direction.

The diffusion effect also exists in the ECT with bobbin coil and the ECT with encircling coil. In these cases, EC decays along the axial direction and the EC energy is both losing and spreading out with increasing depth, as illustrated in Fig. 5. This fact speeds up the attenuation speeds of ECs under the excitations of bobbin coil and encircling coil.

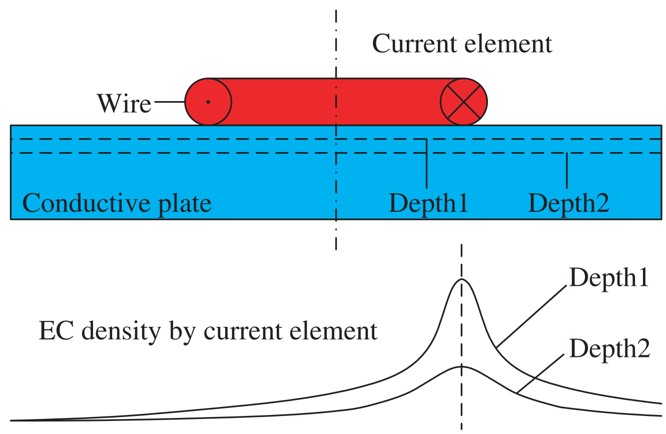


Figure 4. Illustration of the diffusion effect associated with pancake coil.

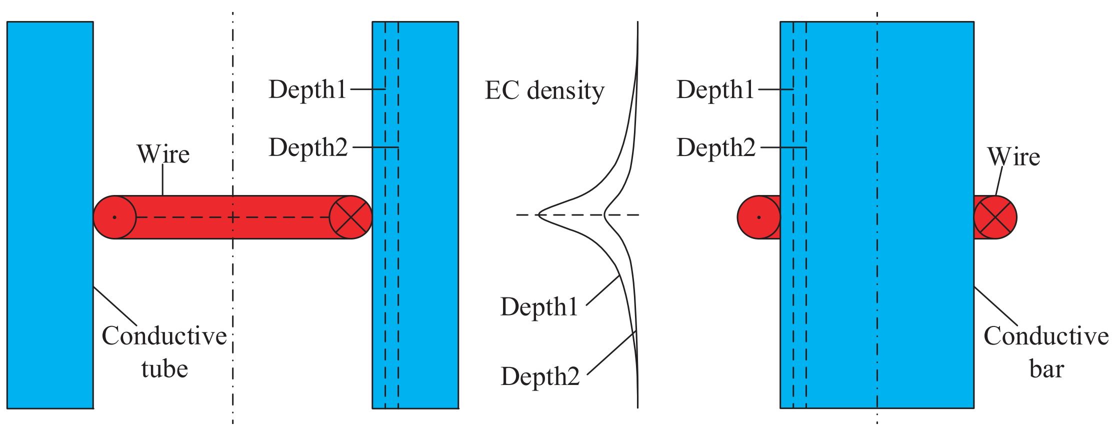


Figure 5. Illustration of the diffusion effect associated with bobbin coil and encircling coil relating to current element.

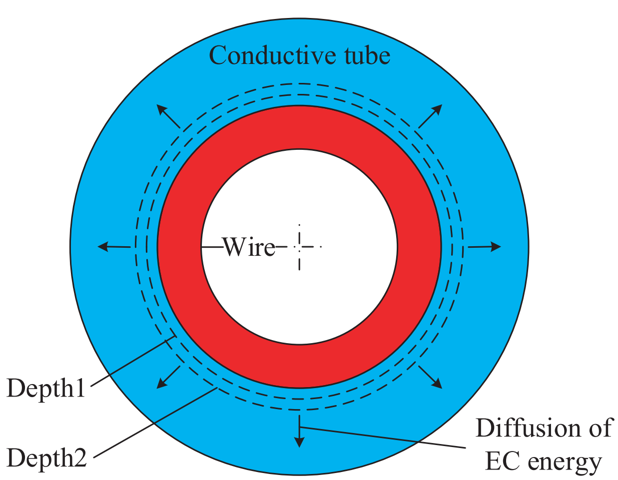


Figure 6. Illustration of the diffusion effect relating to current loop associated with bobbin coil.

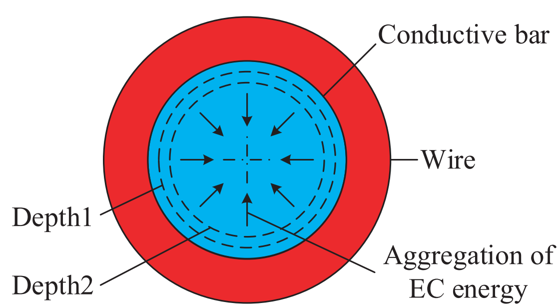


Figure 7. Illustration of the aggregation effect associated with encircling coil.

The diffusion effect discussed above is related to current element. In the effect, the EC density reduces along the direction that is normal to current element and parallel to conductor surface and the speed of reduction becomes slower with increasing depth. There is another diffusion effect that is related to current loop. Fig. 6 illustrates the diffusion of EC energy relating to current loop in conductive tube tested by bobbin coil. Two circular paths coaxial with the tube and the coil are drawn in the figure. Obviously, the circular path with larger depth is longer than that with smaller depth. Therefore, the EC energy on unit circumferential length becomes smaller with increasing depth even if the ohmic loss is not taken into account, which increases the attenuation speed of EC.

Figure 7 illustrates the aggregation of EC energy in conductive bar tested by encircling coil. Two circular paths coaxial with the bar and the coil are also shown. The circular path with larger depth is shorter than that with smaller depth. Consequently, the EC energy on unit circumferential length becomes larger with increasing depth if the ohmic loss is not considered. This fact attempts to decrease the attenuation speed of EC.

2.2. The Cancelation Effect

Figure 8 shows the distribution of EC densities along the radial direction at a certain depth in a conductive plate induced by two current elements of a pancake coil. Current element A and Current element B have symmetric positions about the axis of the coil and the EC densities generated by the current elements are denoted as EC_{A} and EC_{B}, respectively. At any position on the radial line under the current elements, EC_{A} and EC_{B} are in opposite directions; thereupon, EC_{B} reduces the amplitude of EC density under Current element A and EC_{A} reduces the amplitude of EC density under Current element B. This phenomenon is referred to as the cancellation effect [11].

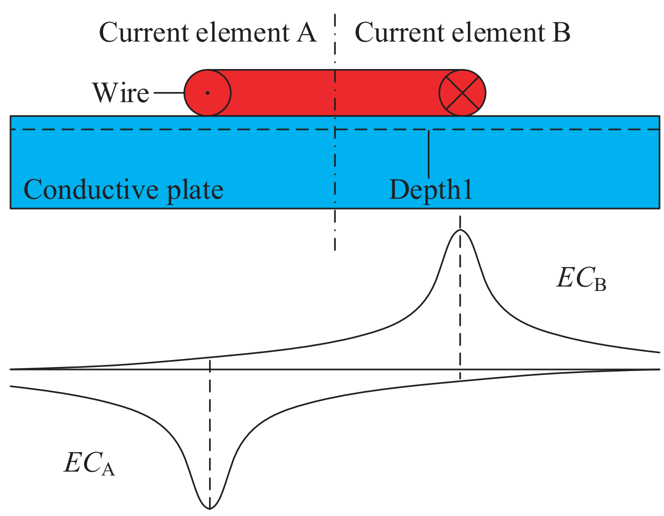


Figure 8. Illustration of the cancelation effect associated with pancake coil.

The cancelation effect also exists in conductive tube tested by bobbin coil. At any position on the radial line connecting Current elements A and B, EC_{A} and EC_{B} are in opposite directions so that EC_{A} and EC_{B} cancel each other, as illustrated in Fig. 9(a). Thus, the amplitude of EC density is reduced.

In conductive bar whose diameter is large enough, the ECs induced by symmetric current elements of the encircling coil do not influence each other due to the shielding effect of conductive bar, as illustrated in Fig. 9(b). Therefore, the cancellation effect does not exist in this scenario.

The cancelation effect decreases the amplitude of EC density in each depth. Nonetheless, without comparing the degrees of cancelations of ECs at different depths, it cannot come to the conclusion that the cancelation effect makes the attenuation speed of EC faster or slower.

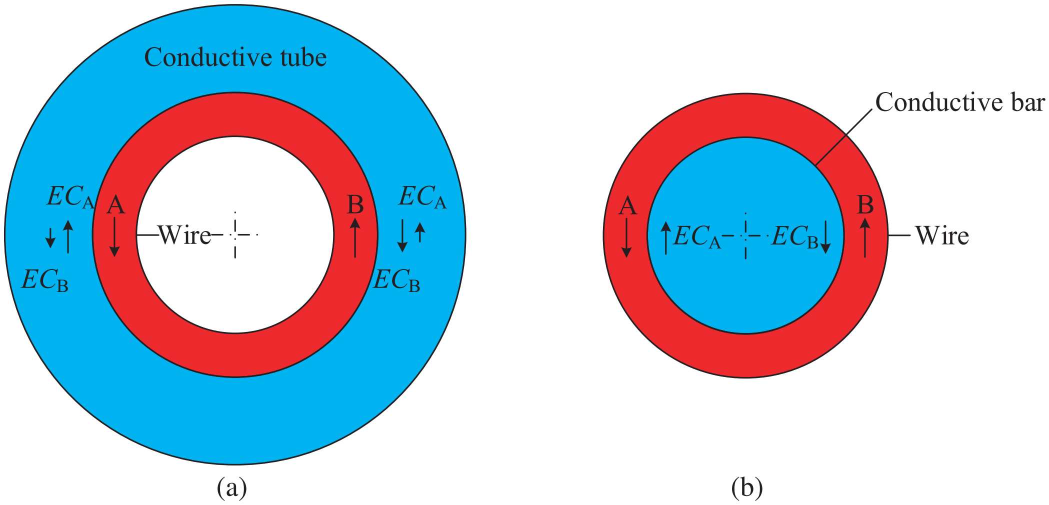


Figure 9. Illustration of the cancelation effect associated with bobbin coil and encircling coil. (a) Bobbin coil. (b) Encircling coil.

2.3. The Combined Cancellation/Diffusion Effect

The degrees of cancelations of ECs at various depths are affected by the diffusion effect. With increasing depth in conductive plate under Current element A of pancake coil (cf. Fig. 8), without considering the ohmic loss, the amplitude of EC_A decreases and the amplitude of EC_B increases, owing to the diffusion effect relating to current element. Correspondingly, the cancelation of EC becomes more serious at larger depth. Therefore, the attenuation speed of EC under the excitation of pancake coil becomes faster as a result of the combined cancellation/diffusion effect [11].

At points in conductive tube beside Current element A of bobbin coil (cf. Fig. 9(a)), without considering the loss attenuation of EC, both the diffusion effect relating to current element and the diffusion effect relating to current loop make the amplitude of EC_A decrease with increasing depth. Meanwhile, as current element B is far away from the points, the magnetic field at the points generated by current element B is akin to uniform plane field; therefore, EC_B is almost independent of depth if the loss attenuation is not taken into account. Correspondingly, the cancelation of EC becomes more serious at larger depth. Therefore, the combined cancellation/diffusion effect accelerates the attenuation speed of EC under the excitation of bobbin coil.

In conductive bar inside encircling coil, since there is no cancelation effect, the combined cancellation/diffusion effect does not exist.

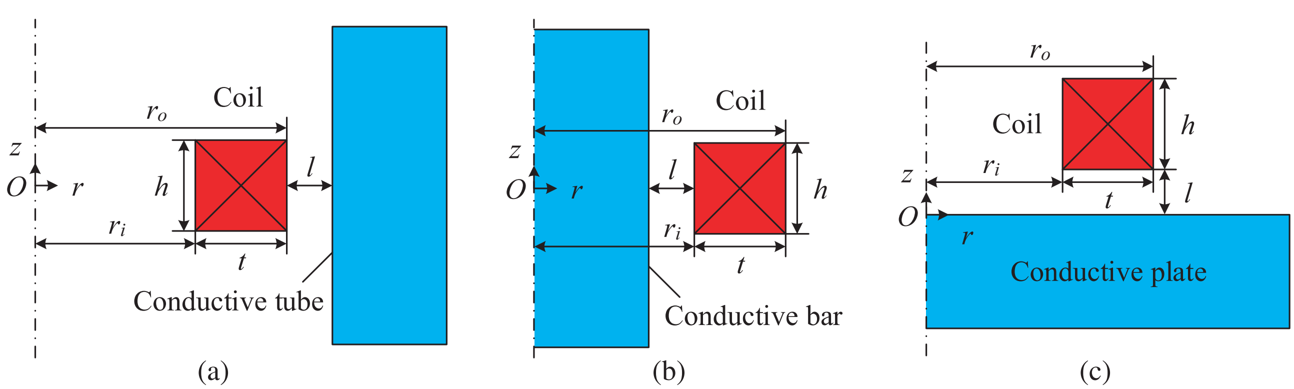


Figure 10. Geometrical models of ECT with different types of coils. (a) Bobbin coil. (b) Encircling coil. (c) Pancake coil.

3. SETUP OF SIMULATIONS

This section describes the setup of simulations for computing the attenuation speeds of EC in conductive tube tested by bobbin coil and conductive bar tested by encircling coil as well as that in conductive plate tested by pancake coil.

Figure 10 shows the geometrical models of ECT with three types of coils, in which h, r_i, r_o, and t stand for the height (length), inner radius, outer radius, and thickness of coil, respectively, and l is the lift-off. The parameters of the coils for comparing the attenuation speeds of EC are tabulated in Table 1. The excitation frequency is set at 10 kHz for each case. The conductive materials being tested have the same conductivity of 2.3×10^7 S/m and the same relative permeability of 1. The inner radius of the tube is 7 mm. The outer radius of the bar is 5 mm. As claimed in Section 2, thickness of the tube's wall, diameter of the bar, and thickness of the plate are sufficiently large.

Table 1. Parameters of coils for comparing the attenuation speeds of EC.

Parameters	Bobbin coil	Encircling coil	Pancake coil
h (mm)	2	2	2
r_i (mm)	5	5	5
r_o (mm)	7	7	7
t (mm)	2	2	2
l (mm)	0	0	0

4. THE SKIN EFFECT OF BOBBIN COIL

4.1. Attenuation of EC

This subsection analyzes the laws of attenuation of EC in the testing of conductive tube using bobbin coil and compares the attenuation speed of EC with that in conductive plate excited by uniform plane field and that in conductive plate tested by pancake coil. The parameters of the coils are shown in Table 1.

Figure 11 shows the normalized EC density as function of depth under the excitation of bobbin coil. For comparison, the normalized EC densities in conductive plates under the excitations of uniform plane field and pancake coil are also presented. The value of 1/e is also shown as a horizontal line. The

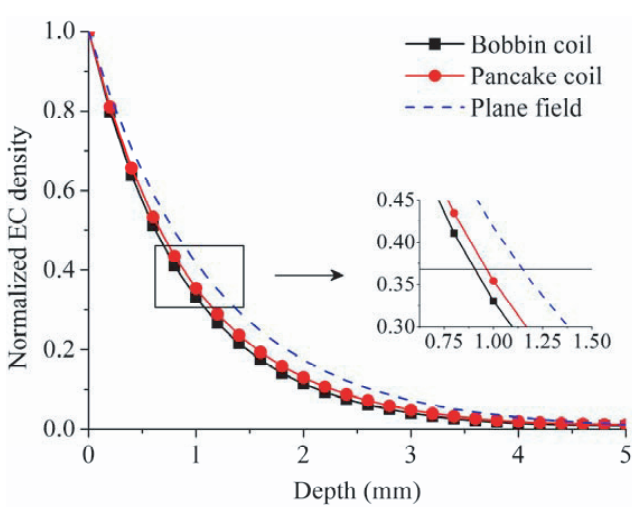


Figure 11. Attenuation of ECs associated with bobbin coil, uniform plane field, and pancake coil.

attenuation speed of EC associated with pancake coil is faster than that associated with uniform plane field excitation, which is the result of the diffusion effect and the combined cancellation/diffusion effect and has been analyzed in [11]. It is the attenuation of EC associated with bobbin coil that is of interest in this subsection. In the following, we compare the attenuation speed of EC under the excitation of bobbin coil with those under the excitation of uniform plane field and pancake coil.

The attenuation speed of EC under the excitation of bobbin coil is always faster than that associated with uniform plane field excitation, as the diffusion effect relating to current element, the diffusion effect relating to current loop, and the combined cancellation/diffusion effect increase the attenuation speed of EC associated with bobbin coil.

To compare the attenuation speeds of ECs between ECT with bobbin coil and ECT with pancake coil, the following factors are considered: (1) as presented in Subsection 2.1, the diffusion of EC is only related to current element in the testing with pancake coil, whereas the diffusion effects both relating to current element and current loop exist in the testing with bobbin coil; (2) as presented in Subsection 2.3, the combined cancellation/diffusion effect of EC exists in both cases. Which case has faster attenuation speed of EC depends on the levels of the diffusion effects and the levels of the combined cancellation/diffusion effect in both cases, which may be related to the parameters of the coils and the excitation frequency. With the parameters shown in Table 1, the attenuation speed of EC under the excitation of bobbin coil is faster than that associated with pancake coil.

4.2. Parametric Study

To further investigate the behavior of the attenuation of EC associated with bobbin coil, this subsection studies the effects of the geometrical parameters of bobbin coil on the attenuation speed of EC in conductive tube. When studying the effect of a certain parameter of the coil, the values of the other parameters are fixed at the critical values shown in Table 1. Fig. 12 illustrates the coils with different

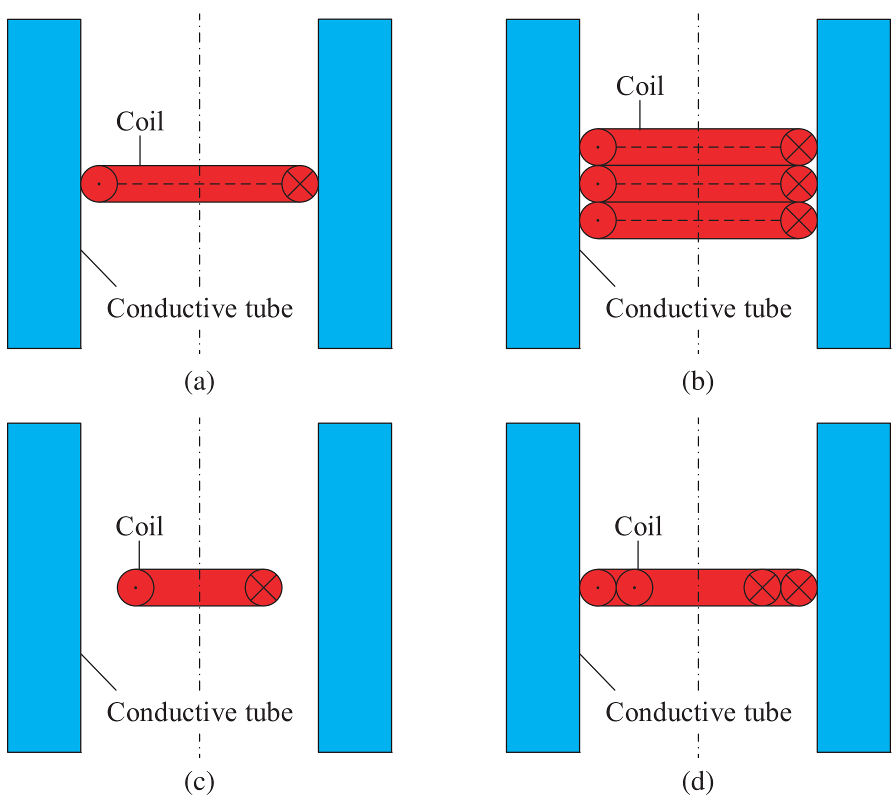
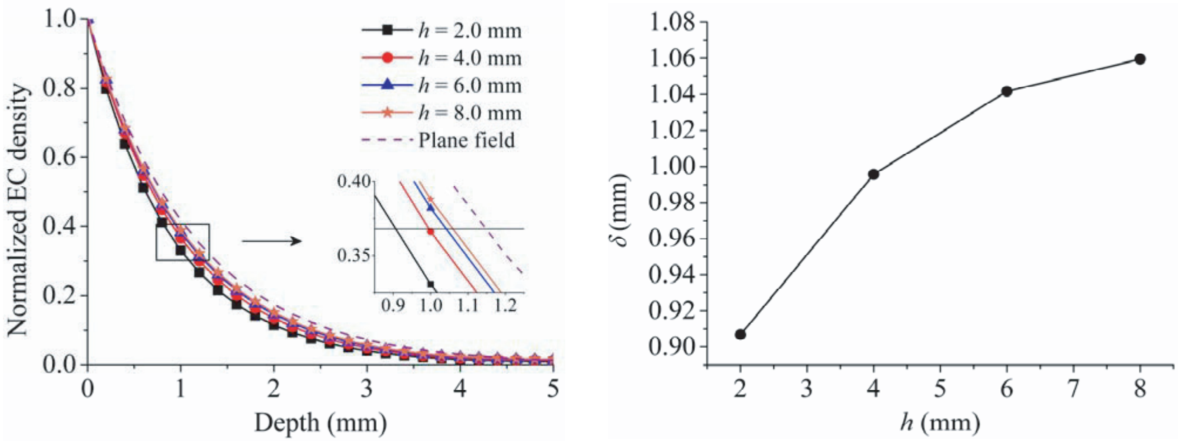
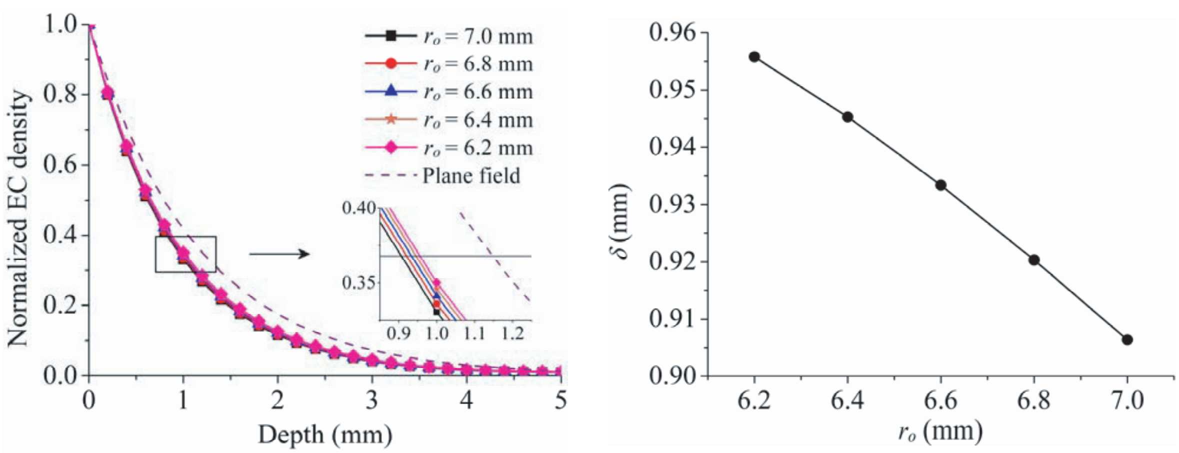


Figure 12. Geometrical models of ECT using bobbin coils with different sizes. (a) Critical size. (b) Larger height. (c) Smaller outer radius. (d) Larger thickness.



(a) (b)

Figure 13. Attenuation of ECs associated with bobbin coils with different heights. (a) Attenuation of ECs. (b) Relation between the skin depth and the height of the coil.



(a) (b)

Figure 14. Attenuation of ECs associated with bobbin coils with different outer radii. (a) Attenuation of ECs. (b) Relation between the skin depth and the outer radius of the coil.

sizes.

Figure 13(a) shows the attenuation of ECs associated with bobbin coils with different heights. Fig. 13(b) shows the relation between the skin depth and the height of the coil. It is seen that when increasing the height of the coil, the attenuation speed of EC slows down and the skin depth increases and approaches to the standard skin depth. Comparing Figs. 12(a) and (b) is helpful for understanding the phenomenon. When the height of bobbin coil is larger, the magnetic field near the conductor surface becomes more similar to a uniform plane field, which results in less diffusion and slower attenuation of EC.

Figure 14(a) shows the attenuation of ECs associated with bobbin coils with different outer radii. Fig. 14(b) shows the relation between the skin depth and the outer radius of the coil. It is seen that the attenuation speed of EC slows down with decreasing the outer radius of the coil. Comparing Figs. 12(a) and (c) is helpful for understanding this fact. Changing the outer radius while fixing the thickness of the coil, not only the size of the coil but also the lift-off is changed. When the outer radius of the coil is decreased, the coil is away from the conductor surface, which makes the magnetic field near the conductor surface more similar to a uniform plane field. Therefore, there is less diffusion of EC in the conductor and the attenuation speed of EC is slower.

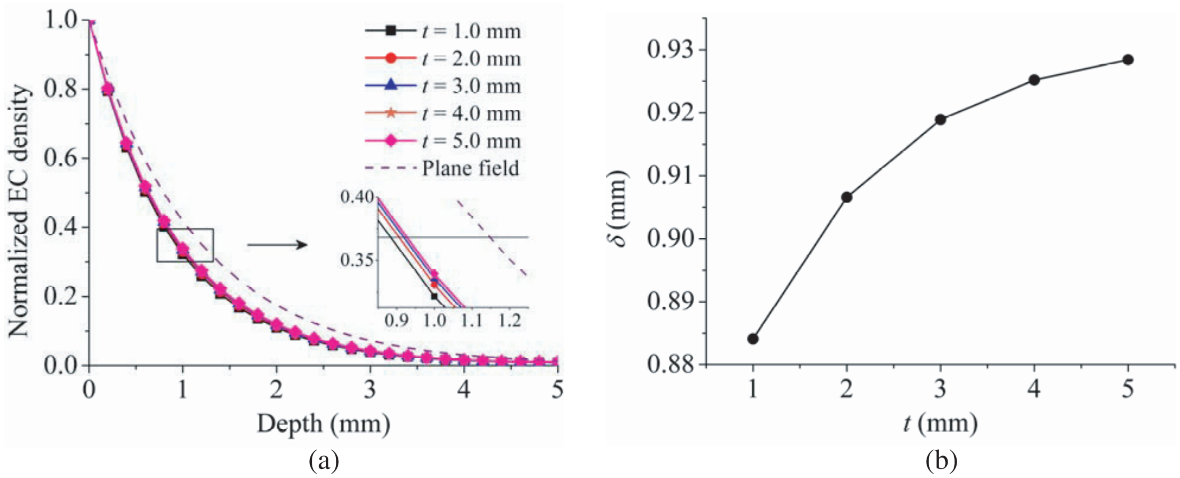


Figure 15. Attenuation of ECs associated with bobbin coils with different thicknesses. (a) Attenuation of ECs. (b) Relation between the skin depth and the thickness of the coil.

Figure 15(a) shows the attenuation of ECs associated with bobbin coils with different thicknesses. Fig. 15(b) shows the relation between the skin depth and the thickness of the coil. It is seen that the attenuation speed of EC slows down with increasing the thickness of the coil. Comparing Figs. 12(a) and (d) is helpful for understanding the phenomenon. When changing the thickness, the outer radius of the coil is not changed. The bobbin coil with large thickness can be considered as two coils connected in series in which one coil has smaller outer radius than the other and the EC is mostly contributed by the coil with larger outer radius. Thus, increasing the thickness of the coil is equivalent to marginally decreasing the outer radius of the coil. Consequently, the attenuation speed of EC slows down with increasing the thickness of the coil.

5. THE SKIN EFFECT OF ENCIRCLING COIL

5.1. Attenuation of EC

This subsection analyzes the laws of attenuation of EC in the testing of conductive bar using encircling coil and compares the attenuation speed of EC with that associated with uniform plane field excitation and that in conductive plate tested by pancake coil. The parameters of the coils are shown in Table 1.

Figure 16 shows the normalized EC density as function of depth under the excitation of encircling coil. For comparison, the normalized EC densities in conductive plate under the excitations of uniform plane field and pancake coil are also presented.

To compare the attenuation speeds of ECs between ECT with encircling coil and ECT with uniform plane field excitation, the following factors are considered: (1) as presented in Subsection 2.1, in conductive bar tested by encircling coil, the diffusion of EC relating to current element makes the attenuation speed of EC faster than that associated with uniform plane field excitation; (2) the aggregation effect, also presented in Subsection 2.1, slows down the attenuation speed of EC; (3) the combined cancellation/diffusion effect does not exist in both cases. Whether the attenuation speed of EC associated with encircling coil is faster or slower than that associated with uniform plane field excitation depends on the level of the diffusion effect relating to current element and the level of the aggregation effect. With the parameters shown in Table 1, the diffusion effect is dominant and the attenuation speed of EC under the excitation of encircling coil is faster.

To compare the attenuation speeds of ECs between ECT with encircling coil and ECT with pancake coil, the following factors are considered: (1) the diffusion effect relating to current element exists in both cases and has the effect of increasing the attenuation speed of EC; (2) the aggregation effect slowing down the attenuation speed of EC exists in the testing with encircling coil; (3) unlike testing conductive plate with pancake coil, the combined cancellation/diffusion effect does not exist in testing

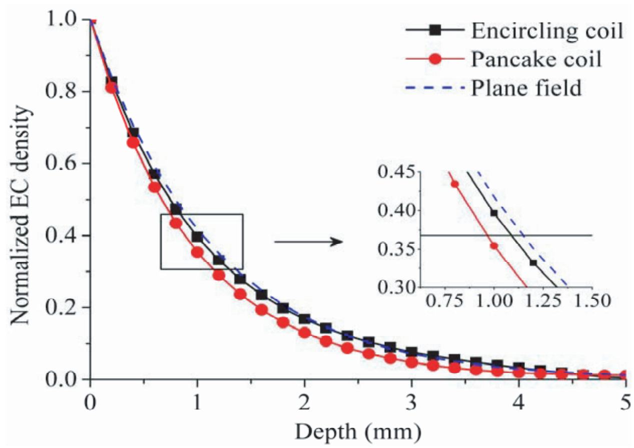


Figure 16. Attenuation of ECs associated encircling coil, uniform plane field, and pancake coil.

conductive bar with encircling coil. Unless the diffusion effect relating to current element associated with encircling coil is very strong, the attenuation speed of EC under the excitation of encircling coil is slower than that of EC excited by pancake coil.

5.2. Parametric Study

To further investigate the behavior of the attenuation of EC in the testing of conductive bar with encircling coil, this subsection studies the effects of the geometrical parameters of encircling coil on the attenuation speed of ECT. When studying the effect of a certain parameter of the coil, the values of the other parameters are fixed at the critical values shown in Table 1. Fig. 17 illustrates the coils with different sizes.

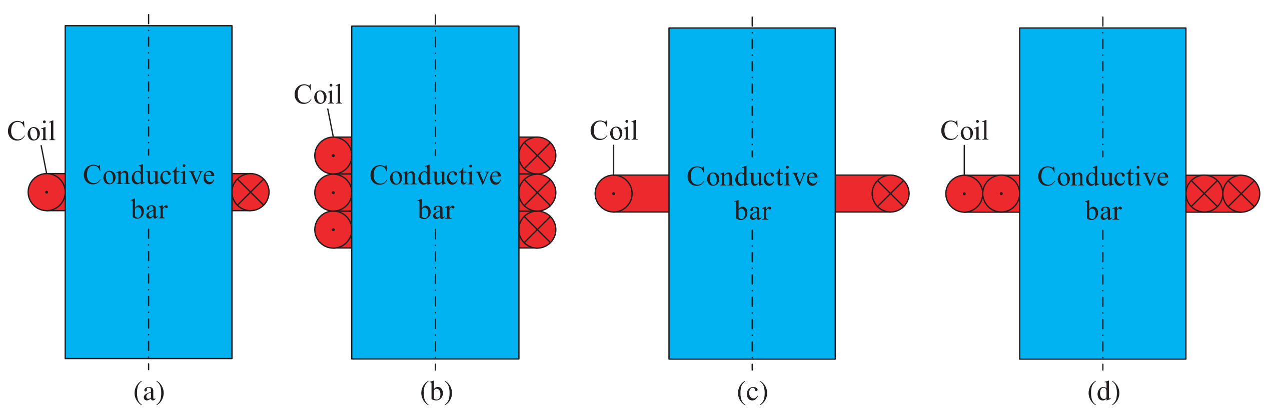
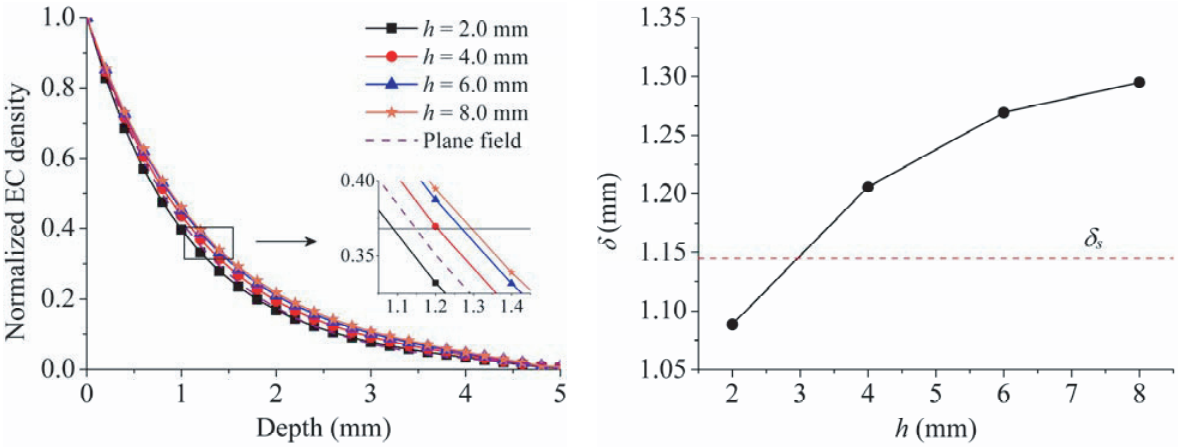


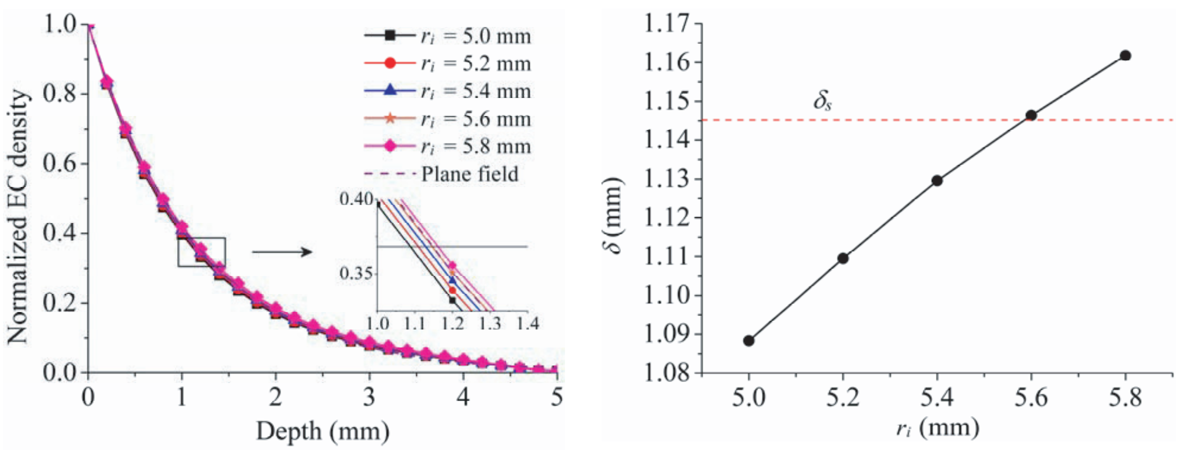
Figure 17. Geometrical models of ECT using encircling coils with different sizes. (a) Critical size. (b) Larger height. (c) Larger inner radius. (d) Larger thickness.

Figure 18(a) shows the attenuation of ECs associated with encircling coils with different heights. Fig. 18(b) shows the relation between the skin depth and the height of the coil. The line of the standard skin depth is also shown. Obviously, the attenuation speed of EC slows down with increasing the height of the coil. Especially, when the height of the coil is larger than 3 mm, the skin depth is larger than that associated with uniform plane field excitation. Comparing Figs. 17(a) and (b) is helpful for understanding the phenomenon. When the height of the coil is larger, the magnetic field near the conductor surface becomes more similar to a uniform plane field, which results in less diffusion and slower attenuation speed of EC. When the height of the coil is larger than a certain value, the influence



(a) (b)

Figure 18. Attenuation of ECs associated with encircling coils with different heights. (a) Attenuation of ECs. (b) Relation between the skin depth and the height of the coil.



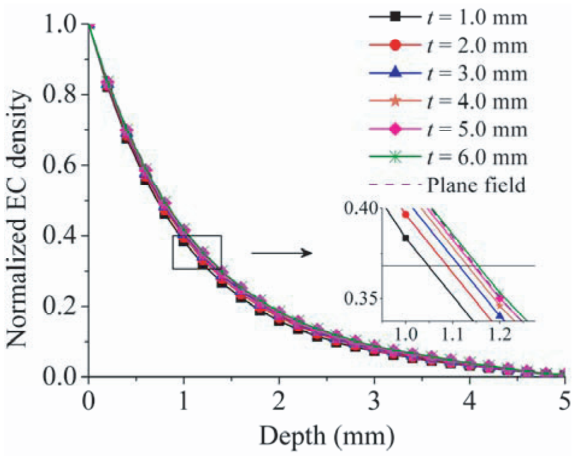
(a) (b)

Figure 19. Attenuation of ECs associated with encircling coils with different inner radii. (a) Attenuation of ECs. (b) Relation between the skin depth and the inner radius of the coil.

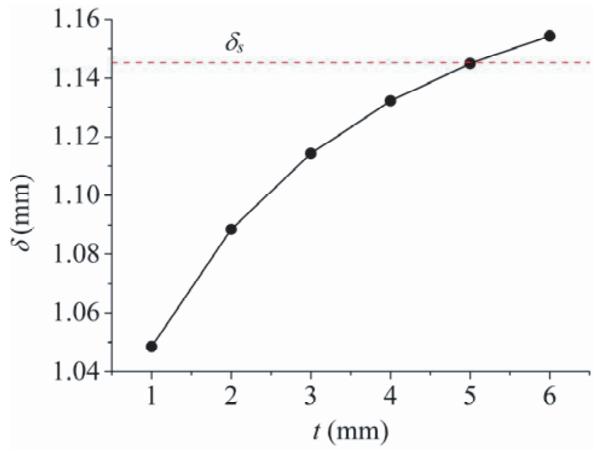
of the diffusion effect relating to current element on the attenuation speed of EC is smaller than that of the aggregation effect. In this case, the skin depth is larger than the standard skin depth.

Figure 19(a) shows the attenuation of ECs associated with encircling coils with different inner radii. Fig. 19(b) shows the relation between the skin depth and the inner radius of the coil. The attenuation speed of EC slows down with increasing the inner radius of the coil. Especially, when the inner radius of the coil is larger than 5.6 mm, the skin depth is larger than that associated with uniform plane field excitation. Comparing Figs. 17(a) and (c) is helpful for understanding this fact. Changing the inner radius while remaining the thickness unchanged, not only the size of the coil but also the lift-off is changed. When the inner radius of encircling coil is increased, the coil becomes far away from the conductor surface, which makes the magnetic field near the conductor surface more similar to a uniform plane field. Therefore, there is less diffusion of EC in the conductor. When the inner radius of the coil is larger than a certain value, the influence of the diffusion effect relating to current element on the attenuation speed of EC is less than that of the aggregation effect. In this case, the skin depth is larger than the standard skin depth.

Figure 20(a) shows the attenuation of ECs associated with encircling coils with different thicknesses.



(a)



(b)

Figure 20. Attenuation of ECs associated with encircling coils with different thicknesses. (a) Attenuation of ECs. (b) Relation between the skin depth and the thickness of the coil.

Fig. 20(b) shows the relation between the skin depth and the thickness of the coil. The attenuation speed of EC slows down with increasing the thickness of the coil. Comparing Figs. 17(a) and (d) is good for understanding the phenomenon. When changing the thickness, the inner radius of the coil is fixed. The encircling coil with large thickness can be considered as two coils connected in series in which one coil has larger inner radius than the other and the EC is mostly contributed by the coil with smaller inner radius. Thus, increasing the thickness of the coil is equivalent to marginally increasing the inner radius of the coil. Consequently, the attenuation speed of EC slows down with increasing the thickness of the coil. As expected, the skin depth is larger than the standard skin depth if the thickness of the coil is sufficiently large.

6. CONCLUSIONS

It is the first time to discuss the skin effect in conductive tube tested by bobbin coil and the skin effect in conductive bar tested by encircling coil. The factors influencing the attenuation speed of EC include: (1) the diffusion effect relating to current element; (2) the diffusion effect relating to current loop; (3) the aggregation effect; (4) the combined cancellation/diffusion effect. Among the factors, the diffusion effects and the combined cancellation/diffusion effect increase the attenuation speed of EC, whereas the aggregation effect decreases the attenuation speed of EC.

In the testing of conductive tube using bobbin coil, the diffusion effects and the combined cancellation/diffusion effect make the attenuation speed of EC always faster than that associated with uniform plane field excitation. Parametric study shows that the attenuation speed of EC slows down with increasing the height or thickness of the coil, or decreasing the outer radius of the coil.

In the testing of conductive bar using encircling coil, the diffusion effect relating to current element and the combined cancellation/diffusion effect increase the attenuation speed of EC, whereas the aggregation effect decreases the attenuation speed of EC. Parametric study shows that the attenuation speed of EC slows down with increasing the height, inner radius, or thickness of the coil. Under certain conditions, the skin depth can be larger than the standard skin depth.

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