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Novel Thin Heating Coil Structure with Reduced Copper Loss for High Frequency Induction Cookers

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***Abstract*—Litz wire has been widely utilized for heating coils of high frequency induction cookers. However, these coils often suffer from large winding height due to low space factor of Litz wire. Certainly, rectangular wire may reduce the winding height of the coil owing to its high space factor. However, the rectangular wire tends to suffer from large copper loss caused by the skin effect and the proximity effect. In the conventional coil structure of the rectangular wire, these effects cause concentrated AC current distribution, which leads to excessive copper loss. This paper addresses this issue by proposing a novel heating coil structure of the rectangular wire that can homogenize the AC current distribution. This paper also presents the simulation results that successfully verified the effectiveness of the proposed structure.**

***Index Terms*—ac resistance, induction heating, proximity effect, rectangular wire.**

I. Introduction

Induction cookers are a widespread home appliance that offers safe heating without flame. In addition to the safety, induction cookers are beneficial in their low maintenance feature because of the simple mechanical construction. Owing to these attractive features, induction cookers are widely applied to domestic grills and portable grills.

Like other electrical equipment, induction cookers are commonly required for miniaturization. For this purpose, many of recent induction cookers drive their heating coils at a high frequency. High frequency operation can achieve effective heating even under limited current rating of the inverter, which provides the AC current to the heating coil. As a result, the inverter can be miniaturized by the high frequency operation.

However, the high frequency operation tends to cause concentrated AC current distribution due to the skin effect [1] and the proximity effect [2]–[6]. As a result, large amount of the copper loss may be generated in the heating coil, deteriorating the heating efficiency or causing thermal destruction of the heating coil. In order to address this issue, Litz wire is commonly employed for the heating coils [7]–[9].

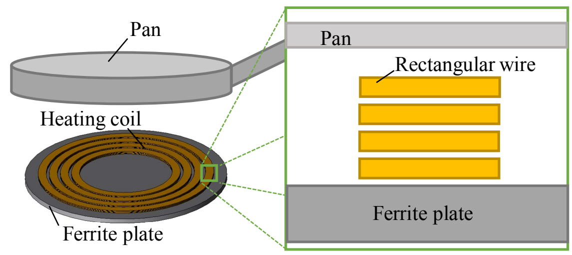
As widely known, Litz wire is effective in homogenization of the AC current distribution by suppressing the skin effect and the proximity effect. However, the heating coils of Litz wire tend to have large winding height because of the comparatively low space factor of Litz wire. Therefore, Litz wire may increase the volume of the induction cookers, hindering the miniaturization effect by the high frequency operation.

Certainly, heating coils of the rectangular wire may reduce the winding height, because this wire generally has larger space factor than Litz wire. However, the rectangular wire are generally susceptible to the skin effect and the proximity effect, causing significant copper loss in the high frequency operation. Therefore, the heating coils of the rectangular wire tend to suffer from large copper loss.

The purpose of this paper is to propose a novel thin heating coil structure with reduced copper loss. The proposed structure utilizes the rectangular wire for reducing the winding height. Furthermore, the proposed structure employs a particular magnetic structure to suppress the skin effect as well as the proximity effect. As a result, the AC current can be distributed uniformly inside the rectangular wire, thus reducing the copper loss compared with the normal heating coil structure made of the rectangular wire shown in Fig. 1. (Hereafter, we refer to this structure as the conventional heating coil structure.)

This paper derives the proposed structure based on analysis of the AC current distribution in the conventional heating coil structure. Appropriateness of the analysis as well as the basic principles of the proposed structure was evaluated by simulation.

Following discussion consists of four sections. Section II analyzes the AC current distribution in the conventional heating coil structure. Based on this analysis, section III derives and proposes the proposed heating coil structure. Section IV presents simulation



(a) Overview (b) Cross-sectional view

Fig. 1. Conventional heating coil structure.

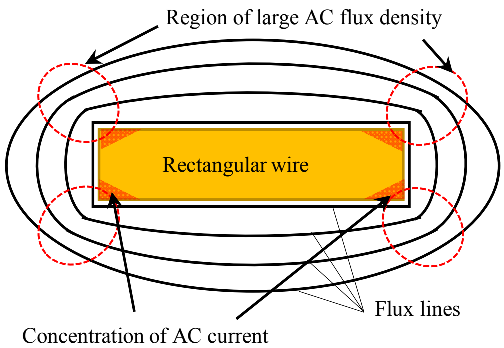


Fig. 2. AC flux and current distribution in a rectangular wire.

results of the AC current distribution to evaluate the copper loss reduction by the proposed structure. Finally, section V presents conclusions.

II. Analysis of Conventional Heating Coil of Rectangular Wire

The purpose of this section is to analyze the AC current distribution in the conventional heating coil structure with the rectangular wire shown in Fig. 1. However, we first analyze the electromagnetic field distribution and the resultant AC current distribution of a single rectangular wire, before discussing the conventional heating coil structure.

A. Current Distribution in a Rectangular Wire

Wires for heating coils generally consist of the metal with extremely high conductivity, such as the copper. Therefore, the voltage difference is extremely small inside the wire. Noting that penetrating AC flux into the wire must induces the voltage difference according to Faraday's law, we can find that the AC flux does not hardly penetrate through the actual wire. Consequently, most of the AC flux induced by the heating coil turns around the wire, as illustrated in Fig. 2.

According to the electromagnetism of the linear media, curving flux lines must cause inhomogeneity of the magnetic flux density [10][11]. The inner side of the curving flux lines must have larger flux density than the outer side because the inner side provides the shorter flux path than the outer side. This inhomogeneity is known to be proportional to the curvature [11].

As discussed above, most of the AC flux turns around the wire. Therefore, their flux lines have large curvature particularly at the edge of the wire cross-section. As a result, large AC magnetic flux density occurs near the wire edge. This large AC flux density causes the intense AC magnetic field because the surface of the wire edge is covered with low permeability material, i.e. the air.

According to the electromagnetism, the surface AC current per unit length is equal to the surface AC magnetic field, if the wire is far thicker than the skin depth. (Detailed demonstration is presented in the appendix.) As a result, the large AC magnetic field at the wire edge causes concentration of the AC current near the wire edge. This inhomogeneity in the AC current distribution results in large copper loss.

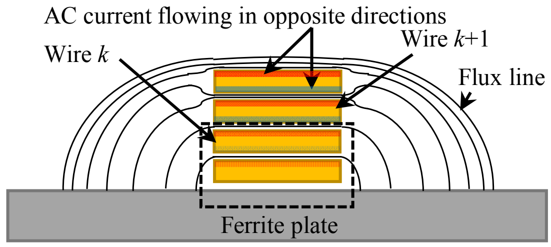


Fig. 3. AC flux and current distribution of the conventional structure.

B. Current Distribution in the Conventional Structure

In the conventional structure, the heating coil is placed on a ferrite plate to avoid electromagnetic interference between the coil and the inverter, which is generally placed beneath the ferrite plate. Then, the pan to be heated is placed on the top of the heating coil. The heating coil is formed as the edgewise coils of the rectangular wire. We assume that the wire is far greater than twice the skin depth in order to ensure sufficient wire cross-sectional area for the AC current.

Similarly as in the previous subsection, the AC current tends to be concentrated at the wire edge in the conventional structure because the flux lines curve steeply at the wire edge. This also causes increase in the copper loss. However, another type of inhomogeneity in the AC current distribution can occur in the conventional structure, which can further increase the copper loss. Below, we discuss this inhomogeneity.

We apply Ampere's law along the dotted line shown in Fig. 3. For convenience, we assume that the width of the wire of the heating coil is far larger than the winding height, because we want to discuss thin heating coil for induction cookers. In addition, we neglect the magnetic field in the ferrite plate because the ferrite plate has far larger permeability than the air. Under these assumptions, we can approximate the average AC magnetic field H_{top_k} along the top surface of the wire k as

$$H_{\mathrm{top}\_k} = \frac{k}{W} i_{\mathrm{ac}} . \tag{1}$$

where k is the index of the wire counted from the bottom, W is the width of the winding, and i_{ac} is the AC current flowing in the wire.

As presented in the appendix, the AC current per unit length of the surface is equal to the surface AC magnetic field. Therefore, the total AC current i_{top_k} flowing at the top surface of the wire k is

$$i_{\mathrm{top}\_k} = W H_{\mathrm{top}\_k} = k i_{\mathrm{ac}} . \tag{2}$$

Note that the bottom surface of the wire k+1 also shares the same surface magnetic field with the top surface of wire k. Therefore, the total AC current i_{bottom_k+1} flowing at the bottom surface of the wire k+1 is

$$i_{\mathrm{bottom}\_k+1} = -k i_{\mathrm{ac}} . \tag{3}$$

This result is consistent with the fact that the total AC current in the whole wire is always i_{ac}, because we have $i_{top\_k}+i_{bottom\_k}=i_{ac}$ regardless to k. However, (2) and (3) indicates that the intense AC current flows in the opposite directions between the top and bottom surfaces of the wire, particularly in the wire with large k. Therefore, intense copper loss can be generated in the wire near the top of the winding.

The above discussion neglected the local inhomogeneity of the surface AC current because (2) and (3) contain only the total AC current on the top and bottom surfaces of the wire. However, the concentration of the AC current at the wire edge also occurs in the conventional structure. As a result, the conventional structure tends to suffer from large copper loss due to two types of inhomogeneity in the AC current inhomogeneities:

1. Concentration of the AC current at the wire edge,
2. Induction of the AC current in the opposite directions between the top and bottom surfaces of the wire, particularly near the top of the winding.

The proposed structure is intended to solve these two difficulties. The next section presents derivation of the proposed heating coil structure.

III. Proposed Heating Coil Structure

A. Overview

Figure 4 shows the proposed heating coil structure. Similarly as in Fig. 1, the heating coil is also placed on a ferrite plate; and, the heating coil is also formed as the edgewise coil of the rectangular wire. However, the coil of the proposed structure is made of a far thinner rectangular wire than the conventional structure. The thickness of the wire is approximately equal to the skin depth. Therefore, the proposed structure can reduce the winding height even compared with the conventional structure. In addition, the soft magnetic material is filled between the horizontally adjacent turns to form walls standing from the ferrite plate.

B. Basic Principles of Proposed Structure

The proposed structure can suppress the aforementioned two inhomogeneities in the AC current distribution. The reason is discussed below.

First, we discuss suppression of the former inhomogeneity. In the proposed structure, the space between the horizontally adjacent turns is designed to have far larger permeability than the space between the vertically adjacent turns as shown in Fig. 5. Therefore, the flux path turning around the wire (marked by the dotted box.) passes through the magnetic material except for the straight path formed by the space between the vertically adjacent turns. Because the flux line does not curve in the straight path between the opposing walls of the soft-magnetic material, no concentration of the flux density occurs on the top and bottom surfaces of the wire. As a result, the uniform magnetic field can be achieved

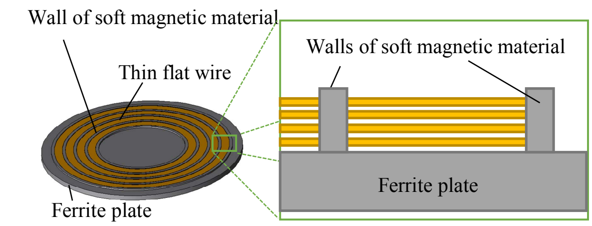


Fig. 4. Proposed heating coil structure.

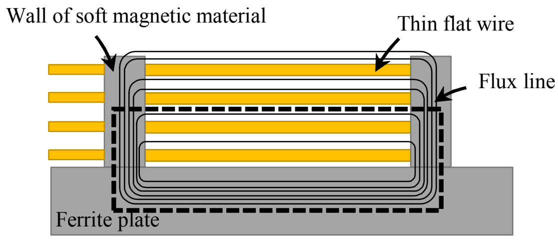


Fig. 5. AC flux and current distribution in the proposed structure.

on the top and bottom surface.

Certainly, the flux lines must curve in the wall to turn around the wire. As a result, the flux concentration can occur in the wall. However, because of large permeability of the wall, this does not lead to intense magnetic field at the wire edge. As a result, the magnetic field is distributed uniformly on the surface of the wire without the intense magnetic field at the wire edge.

According to the appendix, the AC current is distributed to be proportional to the average magnetic field between the top and bottom surfaces in a thin rectangular wire. Therefore, the AC current is distributed uniformly in the horizontal direction. Consequently, the proposed structure can solve the former inhomogeneity.

Some previous studies also utilized this type of mechanism for reducing the copper loss. For example, [12] utilized the soft-magnetic cap on the edge of the bus bar to reduce the copper loss of the bus bar.

Next, we discuss the latter inhomogeneity. The wire of the proposed structure is approximately as thin as the skin depth. In this case, the opposite current at the top and bottom surfaces of the wire are cancelled each other to achieve the uniform AC current distribution inside the wire in the depth direction. (Detailed demonstration is presented in the appendix.) As a result, intense AC current induction is suppressed at the top and bottom surfaces of the wire, thus solving the latter inhomogeneity.

To summarize, the proposed structure can reduce the winding height owing to its thin rectangular wire. In addition, the proposed structure can suppress the aforementioned two inhomogeneities in the AC current distribution, which can cause the large copper loss in the conventional structure. Therefore, the proposed structure can be expected to show reduction in the copper loss compared with the conventional structure.

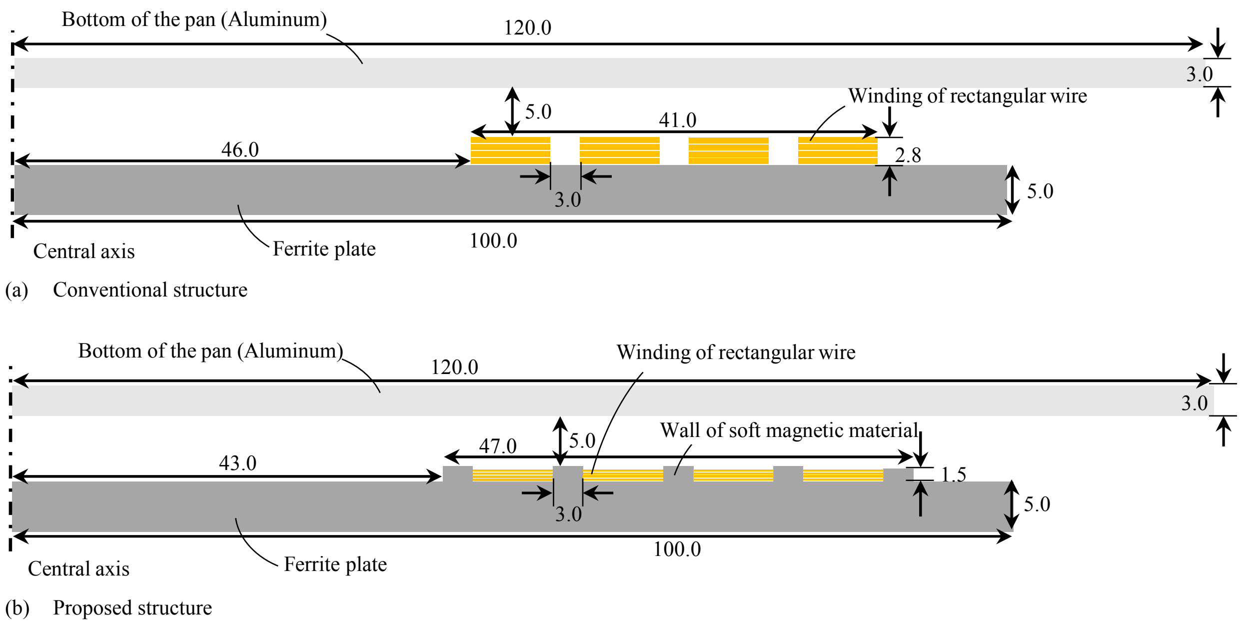


Fig. 6. The axis-symmetry model for simulation.

TABLE I
SPECIFICATIONS OF THE SIMULATION

	Conventional structure	Proposed structure
AC current	80kHz, 30Arms	
Number of turns [T]	16	16
Wire thickness [mm]	0.6	0.2
Coil thickness [mm]	2.8	1.5
Permeability of the core [H/m]	2300	2300
Permeability of the wall of soft magnetic material [H/m]		50

TABLE II
SIMULATION RESULT OF THE COPPER LOSS

	Conventional structure	Proposed structure
Copper loss [W]	379	106
AC resistance [Ω]	0.421	0.118

IV. SIMULATION

Simulation was carried out to verify the basic principles of the proposed heating coil structure. In this simulation, the AC current distribution, as well as the AC copper loss, is compared between the proposed and conventional heating coil structures. In order to simplify the simulation, we constructed these heating coil structures as axis-symmetry models shown in Fig. 6.

Table I shows the specifications of the simulation. The number of turns of the heating coils are set at 16 in both of the models. However, the wire thickness is set at 0.2mm in the proposed structure, whereas 0.6mm in the conventional structure. As a result, the proposed structure reduced the winding height by 46% of the conventional structure. (The winding height includes the wall of the soft-magnetic material.) The relative permeability of the ferrite plate below the heating coil is set at 2300. In addition, the relative permeability of the walls of the soft magnetic material in the proposed structure is set at 50. The heating coils are driven at 80kHz with the AC current of 30Arms.

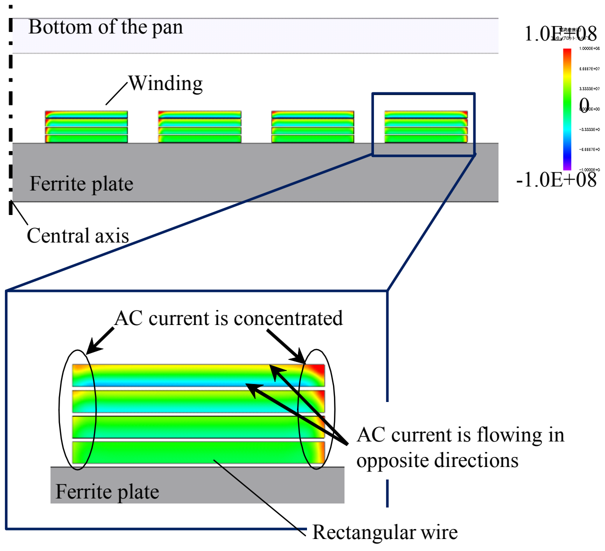
Figure 7 shows the results of the AC current distribution. As expected from the theory, the intense AC current is concentrated at the wire edge in the conventional structure. In addition, the opposite current is found to flow particularly in the wire near the top of the winding in the conventional structure. On the other hand, the AC current is distributed almost uniformly in the proposed structure, which is also consistent with the analysis results.

Table II shows the total copper loss generated in the heating coils. The result indicates that the proposed structure can suppress the copper loss into 1/3 approximately in spite of the reduced winding height.

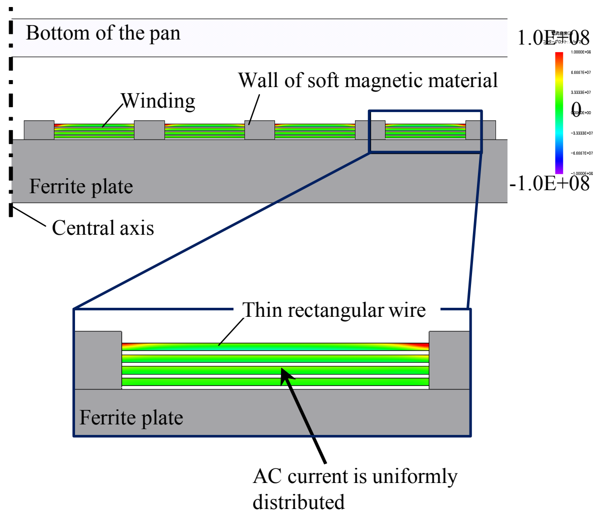
V. CONCLUSIONS

The induction cookers commonly utilizes the Litz wire for their heating coils. However, the low space factor of the Litz wire leads to large winding height, hindering miniaturization of the induction cookers. Contrarily, the heating coils of the rectangular wire is attractive for possible reduction of the winding height. However, the rectangular wire is susceptible to the skin effect and the proximity effect, causing large copper loss.

In order to provide a thin heating coil with reduced copper loss, this paper proposed a novel heating coil structure based on extremely thin rectangular wire with the thickness equal to the skin depth approximately. In addition, soft-magnetic material is filled between the horizontally adjacent turns. The proposed heating coil structure can homogenize the AC current distribution in the wire, resulting in suppression of the copper loss. Furthermore, the proposed structure can further reduce



(a) Conventional structure



(b) Proposed structure

Fig. 7. Simulation results of AC current distribution.

the winding height even compared with the conventional heating coils with the rectangular wire.

Simulation was carried out to verify homogenization of the AC current distribution and resultant reduction in the copper loss. The result revealed almost uniform distribution of the AC current in the proposed structure, whereas the conventional structure showed intense concentration of the AC current at the wire edge as well as induction of opposite AC current between the top and bottom surfaces of the wires near the top of the winding. As a result, the proposed structure reduced the copper loss into 1/3 approximately. These results suggest that the proposed structure is promising for the heating coils of the induction cookers.

APPENDIX

This appendix demonstrates that the surface AC current per unit length is equal to the surface AC magnetic field, if the wire is far thicker than the skin

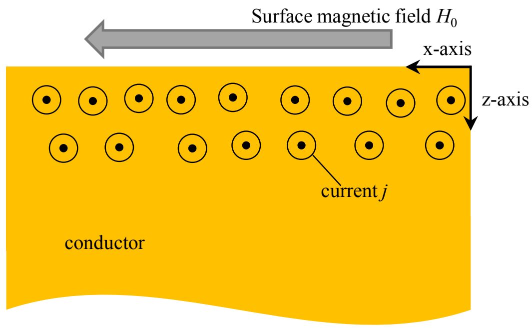


Fig. 8. Definition of the condition.

depth. In addition, this appendix investigates the AC current distribution in a thin rectangular wire with the thickness equal or less than the skin depth.

First, we investigate the AC current distribution in the rectangular wire with the thickness far larger than the skin depth. For convenience, we assume the uniform surface magnetic field along the wire surface. In this case, we can approximate that the wire has infinitely large depth, because most of the AC current is distributed only at the surface of the wire due to the skin effect. We take the x-axis and the z-axis in the directions of the surface AC magnetic field and the depth, respectively, as shown in Fig. 8. In addition, we take the y-axis in perpendicular to the x-axis and the z-axis.

For convenience, we assume constant permeability μ inside the wire. In addition, we neglect the displacement current. Then, the following relations can be obtained inside the wire according to Maxwell's equations:

$$\nabla \times \mathbf{E} + \mu \frac{d\mathbf{H}}{dt} = 0, \quad \nabla \times \mathbf{H} = \mathbf{i} \quad \nabla \cdot \mathbf{H} = 0. \tag{4}$$

where **E**, **H**, and **i** are the electric field, the magnetic field, and the current vector, respectively. We assume the ohmic relation between **E** and **i** as **E**=ρ**i**, where ρ is the resistivity of the material of the wire. Because this problem is uniform in the x and y directions, the partial derivative in these directions must vanish. Hence, we have

$$\nabla \times (\nabla \times \mathbf{H}) = \nabla(\nabla \cdot \mathbf{H}) - \Delta \mathbf{H} = -\frac{\mu}{\rho}\frac{d\mathbf{H}}{dt}.$$
$$\therefore \Delta \mathbf{H} = \frac{d^2}{dz^2}\mathbf{H} = \frac{\mu}{\rho}\frac{d\mathbf{H}}{dt}. \tag{5}$$

According to (5), we can find that the magnetic field in the y and z directions must vanish because zero field in the y and z directions suffices (5) as well as the boundary condition at the surface. As a result, we have

$$\frac{d^2 H_x}{dz^2} = \frac{\mu}{\rho}\frac{dH_x}{dt}, \tag{6}$$

where H_x is the magnetic field in the x direction.

Now, we solve (6) under the surface AC magnetic field H_0 given as

$$H_0 = H_{0\_amp} \exp(j\omega t), \tag{7}$$

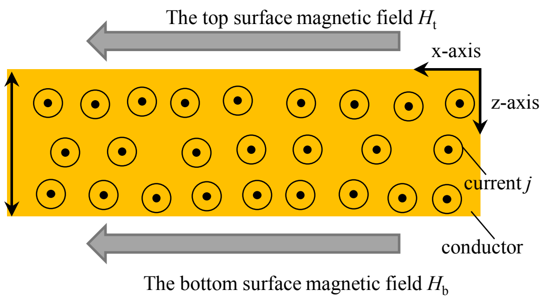


Fig. 9. Definition of the condition under the approximation.

where H_{0_amp} and ω are the amplitude and the angular velocity. Noting that the AC current must flow in the y direction because of the relation **i**=∇×**H**, we obtain the solution as follows:

$$H_x = H_0 \exp\left(-\frac{1+j}{\delta}z\right), \quad i_y = -\frac{1+j}{\delta}H_0 \exp\left(-\frac{1+j}{\delta}z\right), \tag{8}$$

where i_y is the AC current in the y direction and δ is the skin depth defined as

$$\delta = \sqrt{2\rho/\omega\mu}. \tag{9}$$

The total surface current I per unit length of the surface can be obtained by integrating i_y in the z direction:

$$I = \int_0^\infty i_y dz = H_0. \tag{10}$$

This result indicates that the total surface current per unit length equals to the AC surface magnetic field.

Next, we investigate the AC current distribution in a thin wire with the thickness d as presented in Fig. 9. We again assume the uniform surface magnetic field given as

$$H_t = H_{t\_amp}\exp(j\omega t), \quad H_b = H_{b\_amp}\exp(j\omega t), \tag{11}$$

where H_t and H_{t_amp} are the magnetic field at the top surface and its amplitude, respectively; H_b and H_{b_amp} are the magnetic field at the bottom surface and its amplitude, respectively.

Then, the solution of (6) is obtained as

$$H_x = \frac{\exp(j\omega t)}{\sinh\{(1+j)\eta\}}\left[H_{b\_amp}\sinh\{(1+j)\zeta\} + H_{t\_amp}\sinh\{(1+j)(\eta-\zeta)\}\right], \tag{12}$$

$$i_y = \frac{\exp(j\omega t)}{d} f(\eta)\left[H_{b\_amp}\cosh\{(1+j)\zeta\} - H_{t\_amp}\cosh\{(1+j)(\eta-\zeta)\}\right], \tag{13}$$

where η, ζ, and f(η) are defined as

$$\eta = \frac{d}{\delta}, \quad \zeta = \frac{z}{\delta}, \quad f(\eta) = \frac{(1+j)\eta}{\sinh\{(1+j)\eta\}}. \tag{14}$$

The absolute value of f(η) is almost unity within an error of 3%, if 0<η<1. In addition, the absolute value of cosh{(1+j)ζ} and cosh{(1+j)(η− ζ)} are also close to unity within an error of 30%, if 0<η<1 and 0<ζ<η. Therefore, the AC current is distributed almost uniformly in the depth direction in a thin wire with the thickness equal or less than the skin depth.

If we roughly approximate f(η), cosh{(1+j)ζ}, and cosh{(1+j)(η− ζ)} as unity, the AC current in the wire is proportional to the difference of the surface magnetic field between the top and bottom surfaces. Therefore, the AC current is distributed uniformly in the horizontal direction if the magnetic field is uniform along the top and bottom surfaces.

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