Wireless Power Transfer System for Hyperthermia Therapy

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Abstract

Hyperthermia therapy attracts attension as a low-inversive target treatment for deep-positioned cancer. One of the hyperthermia therapies is hgh-frequency induction heating type by using nano-mgnetic materials and magnetic implants. A tumor with injected magnetic materials is heated by hysteresis loss and eddy-current loss under high frequency magnetic fields with a few handred kHz and a few mT. To generate magnetic fields at the deep position of body, we proposed double pancake type exciting system that consists with two flat coils at both sides of body. This paper discusses a wireless exciting system to generate AC magnetic fields rather than transmit energy to load. The experimantal results proved that a wireless transmission enables us to excite two pancake coils and generate magnetic fields in deep position like series-connected coils.

Keywords: hyperthermia, induction heating, pancake coil, wireless transmission, high frequency magnetic fields

1 INTRODUCTION

Hyperthermia therapy is a low-inversive target treatment that carries out apoptosis or necrosis on cancer tumor[1]. The tumor with injected magnetic materials can be heated by hysteresis loss and eddy-current loss under high frequency magnetic fields with more than 200 kHz×mT[2-4]. There are two types of applicators (exciting coil), solenoidal coil and flat coil to generate magnetic fields for hyperthermia. In the previous coil type, a body is located inside of the exciting coil. The magnitude of magnetic fields is relatively uniform at both surface and deep position of body. But the size of coil and an apparent power capacity become large. On the other hand, the flat coil is located on the surface of body and the structure does not depend on the size of body. However the magnitude of magnetic fields decreases rapidly with increasing the distance from a coil

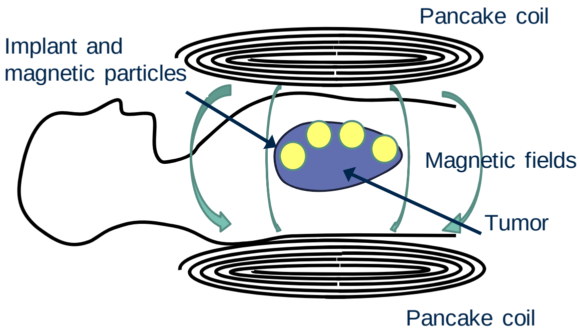
We proposed the double pancake type exciting system with two flat coils sandwiching body. The exciting system does not restrict flexibility of a flat coil and improves the attenuation of magnetic fields far from an exciting coil. But two pancake coils installed separately should be series-connected in the situation where huge current flows. We applied wireless power transfer system to the excitation of double pancake coils, that is, one is the exciting coil and the other is induced coil. Two coils are connected by magnetic couple and without physical connection. We discussed the analysis and characteristics of the system based on the equivalent circuit and examined the magnetic fields inside of both pancake coils for hyperthermia application.

2 DOUBLE PANCAKE TYPE APPLICATOR AND WIRELESS TRANSMISSION

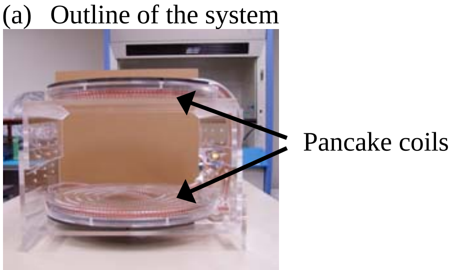
2.1 Applicator System

An applicator is installed outside of body to heat magnetic implant and magnetic particles based on eddy currents and hysteresis losses. We introduce the double pancake exciting system with two flat spiral coils as shown in Figure 1. Two coils sandwiches a body and generates magnetic fields on both upper and lower sides. The distribution becomes flat and smooth near the center of two coils (deep position). Both coils are series-connected to flow current with the same frequency and phase, then the exciting power source needs 2-4 times apparent power as much as a single coil. The connection cable among two coils increases inductance and losses. Furthermore, the arrangement brings a problem to cooling mechanism and installation of patient.

We apply a wireless transmission system to the excitation of double pancake coils[5]. One of pancake coils operates as exciting coil and current is induced on the other coil. Figure 2 show the outline of applicator with double pancake coils by a wireless transmission system. The upper coil with series



(a) Outline of the system



(b) Model

Figure 1. Double pancake type applicator.

capacitor is connected to a high frequency power source directly and the lower pancake coil is connected to a resonance capacitor. Both coils are connected by magnetic coupling. The coupling condition depending upon the distance between two pancake coils remarkably affects the effect of wireless transmission.

2.2 Equivalent Circuit and Parameters

We derive the equivalent circuit in order to analysis the performance of the pancake coils with wireless transmission and estimate the circuit parameters [6]. When an exciting frequency is about some hundred kHz, we neglect the displacement currents and consider only the magnetic coupling between coils. Figure 3(a) shows the equivalent circuit connected with resonance capacitors. The primary side is the exciting part and the secondary side is the induced part. The applicator system has no load but there are losses

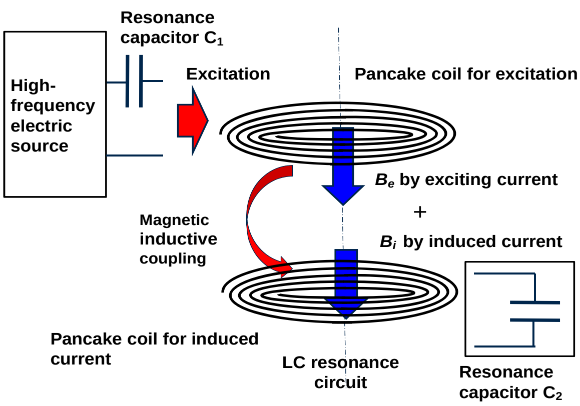
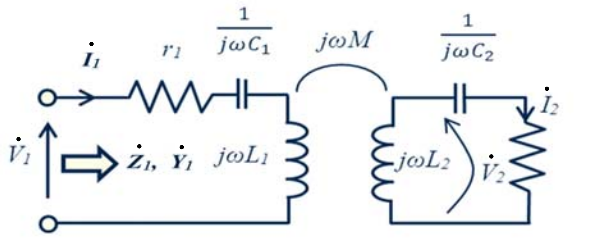
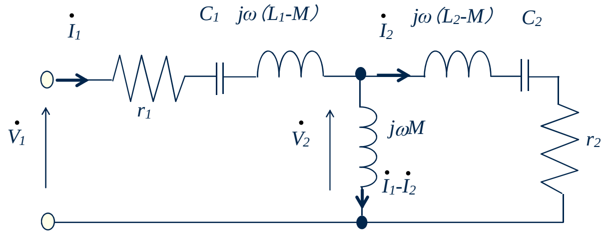


Figure 2. Applicator system with wireless transmission



(a) Equivalent circuit



(b) T-type equivalent circuit

Figure 3. Equivalent circuit of the applicator system.

on coils, capacitors, and connectors. The resistances r_1 and r_2 express all losses on the exciting and induced circuits. Figure 3(b) shows the equivalent circuit for deriving analytical equation. Two series-resonance circuits (L_1-C_1, L_2-C_2) have the same resonance frequency ω_0 expressed as,

$$\omega_0 = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}} \quad . \tag{1}$$

The mutual inductance M is expressed as,

$$M = k\sqrt{L_1 L_2} \quad , \tag{2}$$

where k shows the magnetic coupling factor between two pancake coils. The factor k of the applicator is estimated as

$$0.01 < k < 0.1 \ . \tag{3}$$

The self-inductances L_1, L_2 and the mutual inductance M are derived as a spiral coil is modeled as a flat ring coil as shown in Figure 4. The ring coils are connected in series. The voltage on the pancake coil with a current i is,

$$\begin{aligned} v = \ & d/dt(L_1\, i + m_{21}\, i + m_{31}\, i + m_{41}\, i + m_{51}\, i) \\ & + d/dt(L_2\, i + m_{12}\, i + m_{32}\, i + m_{42}\, i + m_{52}\, i) \\ & + d/dt(L_3\, i + m_{13}\, i + m_{23}\, i + m_{43}\, i + m_{53}\, i) \\ & + d/dt(L_4\, i + m_{14}\, i + m_{24}\, i + m_{34}\, i + m_{54}\, i) \\ & + d/dt(L_5\, i + m_{15}\, i + m_{25}\, i + m_{35}\, i + m_{45}\, i) \\ = \ & L\, di/dt \ , \end{aligned} \tag{4}$$

where L_i is self-inductance of the i-th ring coil and m_{ij} is mutual inductance between the i- and j-th ring coils. Then, the self-inductance L of a pancake coil is,

$$\begin{aligned} L = \ & L_1 + L_2 + L_3 + L_4 + L_5 + 2(m_{21} + m_{31} + m_{41} + m_{51} \\ & + m_{32} + m_{42} + m_{52} + m_{43} + m_{53} + m_{54}), \end{aligned} \tag{5}$$

where $m_{ij} = m_{ji}$. By the same process, the voltage on the i-th ring coil of a pancake coil v_i is induced by another pancake coil with current i_2 is,

$$\begin{aligned} v_i \ & = d/dt(m'_{1i}\, i_2 + m'_{2i}\, i_2 + m'_{3i}\, i_2 + m'_{4i}\, i_2 + m'_{5i}\, i_2) \\ & = (m'_{1i} + m'_{2i} + m'_{3i} + m'_{4i} + m'_{5i})\, di_2/dt = M_i\, di_2/dt \end{aligned} \tag{6}$$

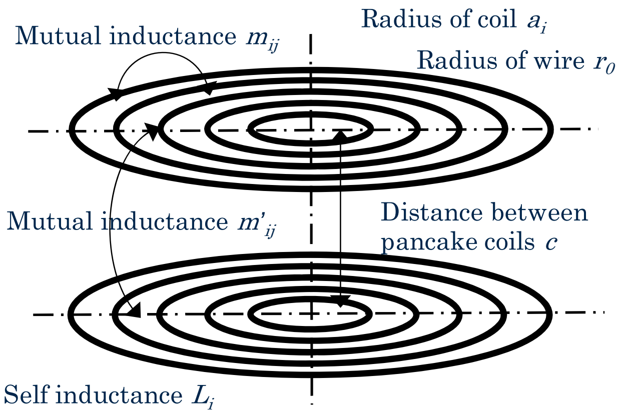


Figure 4. Calculation of self and mutual inductances.

where m'_{ji} is a mutual inductance between the i- and j-th ring coil at each pancake coil, and M_i is a mutual inductance between the i-th ring coil and another pancale coil. Then, the mutual inductance betwen two pancake coils is derived as,

$$M = \Sigma M_i = \Sigma m'_{ii} + \Sigma 2m'_{ij} \ (i>j) \tag{7}$$

A self-inductance of a ring coil and a mutual inductance between two ring coils are given by,

$$\begin{aligned} L_i &= a\left\{\mu_0\left(\ln(\frac{8a}{r_0}) - 2\right) + \frac{\mu_s}{4}\right\} \\ &= a\mu_0\left(\ln(\frac{8a}{r_0}) - 1.75\right) \quad (\because \mu_s = \mu_0) \end{aligned} \tag{8}$$

$$m_{ij} = \mu_o \sqrt{ab}\{(\frac{2}{k} - k)K(k) - \frac{2}{k}E(k)\} \tag{9}$$

where the parameters is shown in Figure 4.

a, b ; radius of ring coil, c ; distance of the pancake coil,
r_0 ; radius of wire, μ_s ; permeability of conductor,
$K(k)$, $E(k)$: the first and secondary elliptical functions,
k : $k^2 = 4ab / \{(a+b)^2 + c^2\}$.

Table 2 shows the comparison of self- and mutual inductances of the pancake coil in Table 2. The pancake coil has only 5 turns coils, then the terminal condition and the variation of the shape affects inductance seriously.

Table 1. Parameters of pancake coils

Unit: mm

Ring coils	No.1	No.2	No.3	No.4	No.5
a_i, b_i	70	90	120	145	170
r_0	5	5	5	5	5
Distance of pancake coil, c		280			

Table 2. Inductances of pancake coils

	Calc.	Exp.
Self-inductance L_1, L_2 (μH)	6.02	6.44 5.89
Mutual inductance M (μH)	0.383	0.407
Coupling factor k	0.064	0.066

The purpose of a hyperthermia system is to generate magnetic fields, then there is no power consumption. Actually the equivalent resistances r_1, r_2 in Figure 3 exist on coils, capacitors, and connections. We estimated Q-values and equivalent resistances by measuring the half band of the resonance characteristics. When the frequency ω_{01} and ω_{02} is on the $1/\sqrt{2}$ of the peak value, the Q-values and equivalent resistances are expressed as,

$$Q = \frac{\omega_0}{\omega_{02} - \omega_{01}} \tag{10}$$

$$r = \frac{\omega_0 L}{Q} \tag{11}$$

Table 3. Q-values and equivalent resistances.

	Exciting side (primary)	Induced side (secondary)
Capacitor C_1,C_2 (μF)	0.29	0.29
Inductance L_1, L_2 (μH)	6.44	5.88
Q-value Q_1 , Q_2	366	471
Resistance r_1 , r_2 (mΩ)	12.9	9.5

2.3 Analysis of Equivalent Circuit

When the phasor theory is applied to the equivalent circuit in Figure 3(b), the primary and secondary currents $\dot{I}_1$, $\dot{I}_2$ and the phases θ_1, $\theta_2$are given by,

$$\dot{I}_1 = \dot{V}_1 / \dot{Z}_1 = \dot{Y}_1 \dot{V}_1 \quad (\dot{Z}_1 = 1/\dot{Y}_1) \tag{12}$$

$$\begin{aligned} \dot{Z}_1 = &\left\{ r_1 + \frac{\omega^2 M^2 r_2}{r_2^2 + \left(\omega L_2 - \frac{1}{\omega C_2}\right)^2} \right\} \\ &+ j\left\{ \left(\omega L_1 - \frac{1}{\omega C_1}\right) - \frac{\omega^2 M^2 \left(\omega L_2 - \frac{1}{\omega C_2}\right)}{r_2^2 + \left(\omega L_2 - \frac{1}{\omega C_2}\right)^2} \right\} \end{aligned} \tag{13}$$

$$\theta_1 = -\tan^{-1}\left(\frac{\mathrm{Im}(Z_1)}{\mathrm{Re}(Z_1)}\right) \tag{14}$$

$$\dot{I}_2 = \frac{j\omega M \left\{ r_2 - j\left(\omega L_2 - \frac{1}{\omega C_2}\right)\right\}}{r_2^2 + \left(\omega L_2 - \frac{1}{\omega C_2}\right)^2} \dot{I}_1 \tag{15}$$

The amplitude ratio of $|I_2/I_1|$ and the phase θ_2 is derived by transforming Eq.(15) ,

$$\left|\frac{I_2}{I_1}\right| = k\left(\frac{\omega}{\omega_0}\right)\sqrt{\frac{L_1}{L_2}} Q_2 \beta \tag{16}$$

$$\theta_2 = \theta_1 + \tan^{-1}\{\frac{1}{Q_2 \alpha \left(\frac{\omega}{\omega_0}\right)}\} \tag{17}$$

where

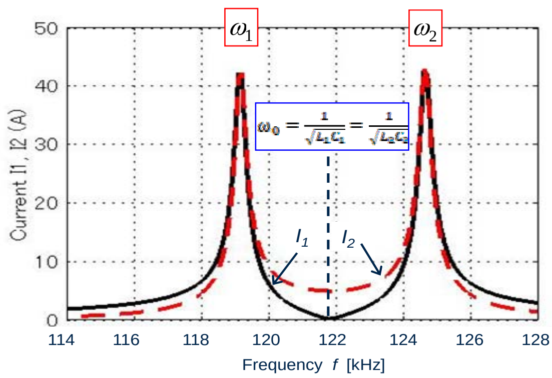
$$\alpha = 1 - \left(\frac{\omega_0}{\omega}\right)^2 \quad (18)$$

$$\beta^2 = \frac{1}{1 + Q_2^2 \alpha^2 \left(\frac{\omega}{\omega_0}\right)^2} \quad (19)$$

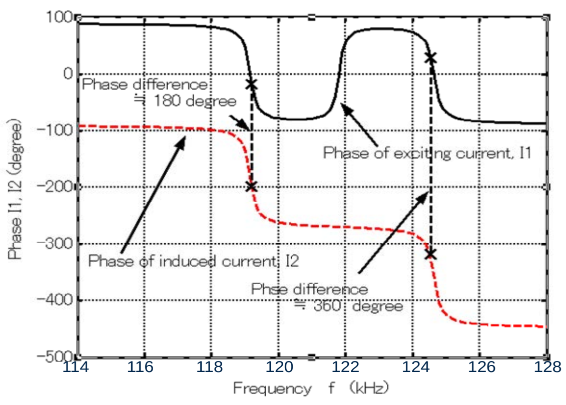
$$Q_2 = \frac{1}{r_2}\sqrt{\frac{L_1}{C_2}} \quad (20)$$

2.4 Characteristics of Model Circuit

According to Eqs. (12)-(17), the frequency characteristics of currents and phase on the exciting and induced circuit are shown in Figure 5. We have two resonance frequencies (ω_1 and ω_2). The resonance frequency of the L-C circuit by Eq. (1) is between these frequencies. The performance depends on the mutual inductance M. Figure 5(b) indicates the phase difference between the exciting and induced currents is approximately π at the frequency ω_1, *and* 2π at ω_2. The currents I_1 and I_2 flow so that the magnetic fields act as addition at ω_1. On the contrary, the magnetic fields induced by two pancake coils are canceled mutually at ω_2.



(a) Exciting and induced currents, I_1, I_2



(b) Phase characteristics, θ_1 and θ_2

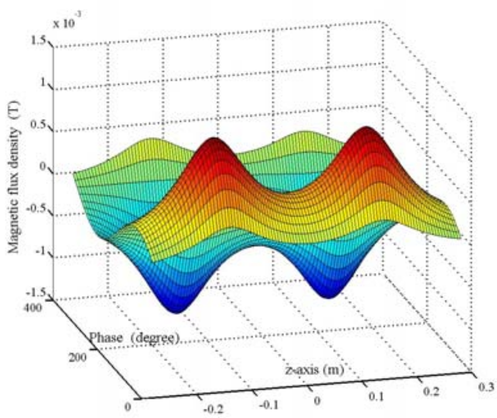
Figure 5. Frequency characteristics of double pancake coil.

2.5 Analysis of Magnetic Fields

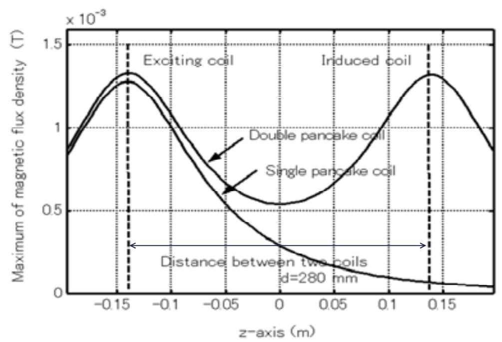
We discuss the magnetic fields generated by two pancake coils. The distribution of the magnetic flux density $B(z,\omega t)$ on z-axis is shown in Figure 6(a) as the frequency is at the lower frequency ω_1. As the phase difference of the currents is approximately π at ω_1, the magnetic fields by two pancake coils generate on an in-phase condition. The fields are simultaneously added at the area of two pancake coils. On the contrary, two peak values of the magnetic fields are shifted by the phase π at the upper frequency ω_2. The maximum of magnetic fields along z-axis is shown in Figure 6(b). For comparison, the distribution generated by the single pancake coil is also drawn. We revealed that the magnetic fields are two times as large as a single pancake coil and the distribution is smooth on the center.

3 EXPERIMENRAL RESULTS ON APPLICATOR

We built up the model of pancake coils as shown in Figure 7. The scale of the testing applicator is almost the same as that for the medical equipment for human body as shown in Table 1. The pancake coil with 5 turns is made from Litz wire with about 6,000 wires of 60 μm diameter. In the experiment, the maximum current is set up to about 100 A_p because there is no compulsory cooling. The upper coil is



(a) Magnetic field density, $B(z, \omega t)$



(b) Maximum of magnetic fields on z-axis

Figure 6. Distribution of magnetic fields on *z*-axis.

exciting side (primary) and the lower coil is induced side (secondary). Each coil has capacitor specified for high frequency operation of some hundred kHz. Small capacitors are connected in parallel to adjust the difference of two resonance frequencies due to the disturbance of inductances and capacitor. An exciting electric source is sinusoidal and the maximum capacity is 75 V_p and 4 A_p. The matching transformer with the turn ratio 20:1 is connected between the source and exciting coil.

Figure 8 shows the frequency characteristics of exciting and induced currents I_1 and I_2 on the experiment setup as shown in Figure 7. We can observe two resonance peaks on both side of the L-C circuit resonance frequency ω_0 (about 113 kHz). It is remarkable point that the exciting and the induced currents have the same value near two resonance points. Even if the current on the secondary coil is induced by the wireless transmission, we could obtain the magnetic fields generated by the excitation of both pancake coils

We measured the distribution of magnetic flux density on the area inside of two pancake coils. The search coil with the a cross section 10 mm^2 is used for measuring the magnetic field B_z on z- and r-axis of the pancake coil. The exciting currents are 25, 50, and 100 A_p and the distance of the pancake coils is 280 mm. Figure 9 shows the distribution of the measured magnetic fields B_z at the frequency of ω_1 in

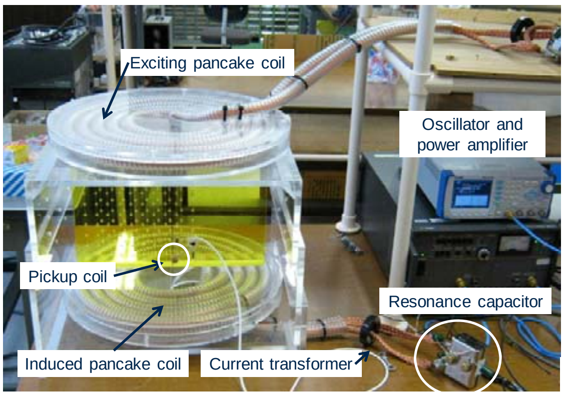


Figure 7. Setup of experiment equipment

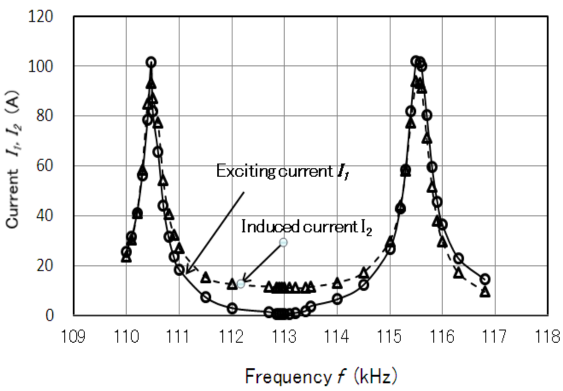
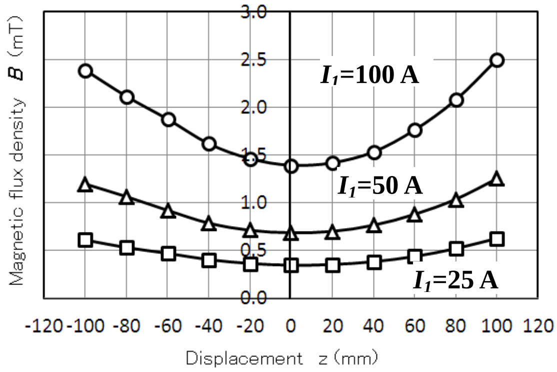
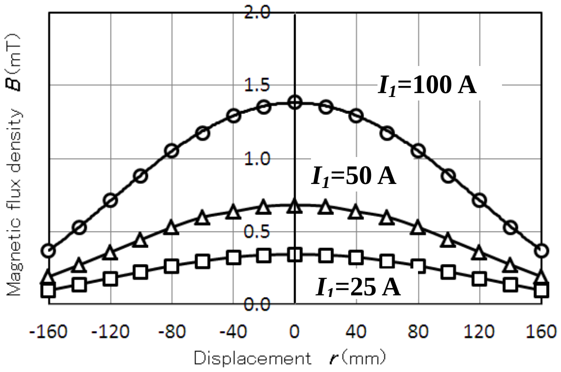


Figure 8. Frequency characteristics of currents I_1 and I_2



(a) Distribution on z-axis



(b) Distribution on r-axis

Figure 9. Distribution of magnetic flux density inside of the applicator at the frequency ω_1.

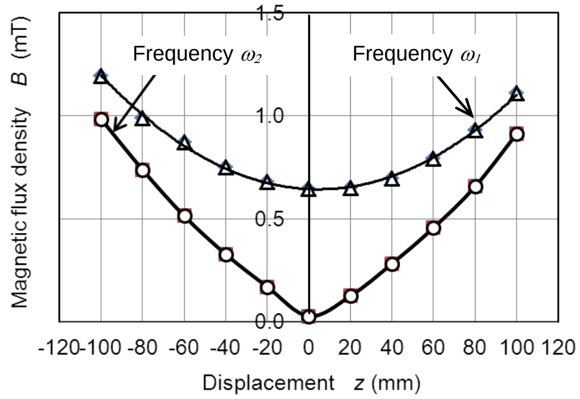


Figure 10. Comparisons of magnetic flux distribution inside of the applicator at the frequencies, ω_1 and ω_2.

Figure 5. The symmetry r-axis distribution clarifies the same value of currents on the exciting and induced pancakes. The magnetic fields on the center of the applicator is about 1.4 mT at the current 100 A. At the rating current, 400 A of the coil with cooling system, we estimate the magnetic fields, 5.6 mT. The product of frequency and magnetic field is about 630 kHz×mT. The important points are that the distribution on the center far from the coil is smooth and the magnitude is only about 0.56 comparing with the position of 100 mm. The smooth distribution of magnetic fields on the center means that it is easy to install heating implants in

order to control and keep a quantity of heat.

Figure 10 shows the difference of magnetic fields at the resonance frequencies, ω_1 and ω_2. The currents at both pancake coils have the same amplitudes as shown in Figure 8. At the low resonance frequency ω_1, the currents at both pancake coils generate the addition of magnetic fields because of the same phase. On the contrary, the currents at both pancake coils generate the subtraction of magnetic fields at the upper resonance frequency ω_2.

4 CONCLUSIONS

The applicator system composed of double pancake coils is discussed to realize hyperthermia treatment at a deep position of body. The wireless transmission system enables us to remove the connection of two exciting coils and to give flexibility of the arrangement of coils. Even if only one pancake coil is excited by the external electric source, the same distribution of magnetic fields by both coils was realized according to the analytical calculation and the experimental result.

5 ACKNOLEDGEMENTS

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Biographies

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Hideo NAGAE was received the BE degree from the Department of Veterinary Medicine, Gifu University in 1969, and acquired the veterinary certificate. He worked at Meito Sangyo Co. Ltd, Nagoya Laboratory from 1969 to 2005, and has researched with Aichi Cancer Center, Kyoto University, National Cancer Center, and others. He has research and developed Resovist®, as MRI contrast agent. From 2005 to 2012, he has been coordinator in Organization of Frontier Science and Innovation, Kanazawa University, and has researched induction heating type hyperthermia system.