Sensitivity Study for Improved Magnetic Induction Tomography (MIT) Coil System

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Abstract—The improved magnetic induction tomography (MIT) coil system which consists of the two-arm Archimedean spiral coil (TAASC) as excitation coil and the solenoid as receiver coil has much better performance in coil system sensitivity than the conventional MIT coil system which uses the solenoids as excitation coil and receiver coil. In this paper the theoretical sensitivity property for improved MIT coil system are studied fully. The magnetic fields produced by TAASC and solenoid are derived approximately based on the Biot-Savart law. The relations between the coil system sensitivity and the parameters (amplitude of excitation current, maximum outer radius and number of turns of TAASC, and number of turns and length of solenoid) of coil system are calculated. The results show that the sensitivity for improved MIT coil system is proportional to the number of turns of solenoid and electric current of TAASC, and can be improved with the increase of maximum outer radius of TAASC and radius of solenoid. The sensitivity is decreased as the length of solenoid increasing, and not significantly associated with the number of turns of TAASC.

Keywords—Magnetic induction tomography (MIT), biological tissues, coil system sensitivity, two-arm Archimedean spiral coil (TAASC).

I. INTRODUCTION

Magnetic induction tomography (MIT) is an emerging imaging method to reconstruct the distribution of electrical conductivity within biological tissues. Compared with the earlier electrical impedance tomography (EIT) technique, MIT has a definite advantage of non-contact, and hence is more suitable for medical applications such as the haemorrhagic cerebral stroke or brain oedema diagnosis [1].

The design of coil system is much important for MIT, which can strongly affect the sensitivity of measurement signal [2]–[4]. A typical MIT coil system includes an array of excitation coils and an array of receiver coils. As illustrated in Fig. 1, the excitation coil carrying a harmonic current emits a primary excitation magnetic field \( B_0 \), and then a primary voltage \( V_0 \) is sensed in the receiver coil. With the action of \( B_0 \), the eddy current can be induced due to the electrically conductive object and a secondary magnetic field perturbation \( \Delta B \) is produced, causing a secondary voltage perturbation \( \Delta V \) sensed in the receiver coil. \( \Delta V \) is of our interest, which contains the information about the electrical conductivity \( \sigma \) of object. Unfortunately, because the values of \( \sigma \) for human tissues are usually small, \( \Delta V \) can be very weak in comparison with \( V_0 \), meaning low coil system sensitivity [1], [3].

The solenoid is the commonly used type of excitation coil and receiver coil in MIT coil system [5]–[8]. However, our recent study shows that this conventional MIT coil system has a low sensitivity for measuring the change of \( \sigma \) inside biological tissues compared to the improved MIT coil system with the two-arm Archimedean spiral coil (TAASC) as excitation coil and the solenoid as receiver coil [9]. This paper aims to investigate the sensitivity property for our improved MIT coil system comprehensively. The expressions for \( x, y \) and \( z \) component of the magnetic fields produced by TAASC and solenoid are derived approximately based on the Biot-Savart law, and then the coil system sensitivity is obtained. The maximum coil system sensitivity is tested at different amplitudes of the excitation current, different radiiuses and numbers of turns of the TAASC and the solenoid, and different length of the solenoid via the MATLAB tool.

II. METHODS

A. Model for Improved MIT Coil System

Fig. 2 shows the model for improved MIT coil system. In this model the excitation coil is a two-arm Archimedean spiral coil (TAASC) and the receiver coil is a solenoid. The TAASC is constructed by two opposite Archimedean planar spirals connected at its center. For a TAASC placed in the \( xy \) plane with its center at the origin, the equation in polar coordinate system for it is

\[
\begin{align*}
L_1: r_1 &= \frac{r_0 - \varphi_1}{2\pi} & 0 \leq \varphi_1 &\leq 2\pi \\
L_2: r_2 &= \frac{r_0 - (\varphi_2 - \pi)}{2\pi} & \pi \leq \varphi_2 &\leq (2n + 1)\pi 
\end{align*}
\]

(1)
where $r_0$ and $n$ are the maximum outer radius and the number of turns of TAASC, respectively [9], [10].

\[ B_{lx} = p \left[ \int_{0}^{2\pi} \left( \frac{(\cos \varphi_1 - \varphi_2 \sin \varphi_1)(y - q\varphi_1 \sin \varphi_1)}{((x - q\varphi_1 \cos \varphi_1)^2 + (y - q\varphi_1 \sin \varphi_1)^2 + z^2)^{3/2}} \right)^2 d\varphi_1 + \right. \\
\left. \int_{0}^{2\pi} \frac{(\sin \varphi_1 - \varphi_2 \cos \varphi_1 \sin \varphi_1)}{((x + q\varphi_1 \cos \varphi_1)^2 + (y + q\varphi_1 \sin \varphi_1)^2 + z^2)^{3/2}} d\varphi_2 \right] \\
\]

\[ B_{lx} = p \left[ \int_{0}^{2\pi} \left( \frac{(\cos \varphi_1 - \varphi_2 \sin \varphi_1)(y + q\varphi_1 \sin \varphi_1)}{((x - q\varphi_1 \cos \varphi_1)^2 + (y + q\varphi_1 \sin \varphi_1)^2 + z^2)^{3/2}} \right)^2 d\varphi_1 + \right. \\
\left. \int_{0}^{2\pi} \frac{(\sin \varphi_1 - \varphi_2 \cos \varphi_1 \sin \varphi_1)}{((x + q\varphi_1 \cos \varphi_1)^2 + (y - q\varphi_1 \sin \varphi_1)^2 + z^2)^{3/2}} d\varphi_2 \right] \\
\]

\[ B_{lx} = p \left[ \int_{0}^{2\pi} \left( \frac{(\cos \varphi_1 - \varphi_2 \sin \varphi_1)(y + q\varphi_1 \sin \varphi_1)}{((x + q\varphi_1 \cos \varphi_1)^2 + (y + q\varphi_1 \sin \varphi_1)^2 + z^2)^{3/2}} \right)^2 d\varphi_1 + \right. \\
\left. \int_{0}^{2\pi} \frac{(\sin \varphi_1 - \varphi_2 \cos \varphi_1 \sin \varphi_1)}{((x + q\varphi_1 \cos \varphi_1)^2 + (y + q\varphi_1 \sin \varphi_1)^2 + z^2)^{3/2}} d\varphi_2 \right] \\
\]

where $p = \mu_0 \mu \rho d/4\pi n^2$ and $q = n_0/2n\pi$.

If a solenoid with radius $R$, length $l$, number of turns $N$ and electric current $I_2$ is placed at the position in Fig. 2, the magnetic fields produced by it can be derived similarly based on the Biot-Savart law as

\[ B_{2x} = m \int_{0}^{2\pi} \frac{\cos \theta(Z - t)}{((x - R \cos \theta)^2 + (y - R \sin \theta)^2 + (Z - t)^2)^{3/2}} dt \\
\]

\[ B_{2y} = m \int_{0}^{2\pi} \frac{\sin \theta(Z - t)}{((x - R \cos \theta)^2 + (y - R \sin \theta)^2 + (Z - t)^2)^{3/2}} dt \\
\]

\[ B_{2z} = m \int_{0}^{2\pi} \frac{R \cdot x \cos \theta - y \sin \theta}{((x - R \cos \theta)^2 + (y - R \sin \theta)^2 + (Z - t)^2)^{3/2}} dt \\
\]

where $m = \mu_0 N I_2 / 4\pi l$ and $Z = z - d$.

III. RESULTS

A. Normalized Sensitivity Map for Reference Coil System

The improved MIT coil system which is used as a reference is based on Fig. 2. The values of related parameters for the reference coil system are listed in Table I. The calculation region is in the plane $x = 0$ with $-100 \text{ mm} \leq y \leq 100 \text{ mm}$ and $10 \text{ mm} \leq z \leq 210 \text{ mm}$. Fig. 3 shows the normalized sensitivity map for the reference coil system. The maximum sensitivity appears at the point $x = 0$, $y = 20 \text{ mm}$, $z = 210 \text{ mm}$.  

![Normalized sensitivity map for reference coil system.](image-url)
B. Maximum Sensitivity versus Number of Turns of TAASC and Solenoid

Fig. 4 shows the scaled maximum sensitivity versus the number of turns \( n \) of TAASC and \( N \) of solenoid. The maximum sensitivity is scaled to the maximum sensitivity of reference coil system. The variation range for \( n \) is 1 to 10 and for \( N \) is 5 to 50. In the process of changing \( n \), the maximum sensitivity point is \( x = 0, y = 20 \text{ mm}, z = 210 \text{ mm} \) when \( n = 2 \) to 6 while at the position \( x = 0, y = -20 \text{ mm}, z = 210 \text{ mm} \) when \( n = 7 \) to 10. However, the maximum sensitivity is always at the position \( x = 0, y = 20 \text{ mm}, z = 210 \text{ mm} \) when changing \( N \) in the given range.

![Figure 4. Scaled maximum sensitivity versus number of turns \( n \) (a) of TAASC and \( N \) (b) of solenoid.](image)

C. Maximum Sensitivity versus Maximum Outer Radius of TAASC and Radius of Solenoid

Fig. 5 shows the scaled maximum sensitivity versus the maximum outer radius \( r_0 \) of TAASC and radius \( R \) of solenoid. The maximum sensitivity is scaled to the maximum sensitivity of reference coil system. The change range for \( r_0 \) and \( R \) is both 10 mm to 100 mm. The maximum sensitivity is at the position \( x = 0, y = 20 \text{ mm}, z = 210 \text{ mm} \) when changing \( r_0 \) in the given range. For the parameter \( R \), the maximum sensitivity is obtained at the point with \( x \)-coordinate 0, \( z \)-coordinate 210 mm, and \( y \)-coordinate listed in Table II.

![Figure 5. Scaled maximum sensitivity versus maximum outer radius \( r_0 \) (a) of TAASC and radius \( R \) (b) of solenoid.](image)

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D. Maximum Sensitivity versus Electric Current of TAASC and Length of Solenoid

Fig. 6 shows the scaled maximum sensitivity versus the electric current \( I_1 \) of TAASC and the length \( l \) of solenoid. The maximum sensitivity is scaled to the maximum sensitivity of reference coil system. The change range for \( I_1 \) is 0.2 A to 2 A and for \( l \) is 5 mm to 50 mm. The maximum sensitivity is at the position \( x = 0, y = 20 \text{ mm}, z = 210 \text{ mm} \) when changing \( I_1 \) and \( l \) in the given range.

![Figure 6. Scaled maximum sensitivity versus electric current \( I_1 \) (a) of TAASC and length \( l \) (b) of solenoid.](image)

IV. DISCUSSIONS AND CONCLUSIONS

In the improved MIT coil system, the sensitivity is a quantity related to the position of perturbation. For the reference coil system, its sensitivity map is anti-symmetric about the plane \( y = 0 \) and the maximum value appears at the point \( x = 0, y = 20 \text{ mm}, z = 210 \text{ mm} \) in the calculation region, as shown in Fig. 3.

It can be seen from Fig. 4 that the sensitivity for improved MIT coil system does not specifically relate to the number of turns of TAASC, but is proportional to the number of turns of solenoid. The position of maximum sensitivity is unfixed with the number of turns of TAASC increasing, and yet invariable no matter how the number of turns of solenoid changes.

In Fig. 5, the coil system sensitivity can be improved by increasing the maximum outer radius of TAASC or the radius of solenoid. The position of maximum sensitivity is unaltered with the increase of maximum outer radius of TAASC. However, the \( y \)-coordinate of maximum sensitivity point is variable when the radius of solenoid increases, as shown in Table II.

The coil system sensitivity is proportional to the electric current of solenoid, and decreases as the length of solenoid increases, as shown in Fig. 6. The position of maximum sensitivity is unfixed regardless of the change for electric current of TAASC and length of solenoid.

In conclusion, the sensitivity for improved MIT coil system has its maximum value in the region of interest, and the perturbing object ought to be placed near the maximum sensitivity point. The coil system sensitivity could be improved by increasing the maximum outer radius of TAASC, electrical current of TAASC, number of turns of solenoid and radius of solenoid. For the actual design of improved MIT coil system, all the parameters should be considered synthetically in order to make the coil system sensitivity optimum.
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REFERENCES


