Inverse Approach for Determination of the Coils Location during Magnetic Stimulation

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Abstract. An inverse approach using neural networks is extended and applied for determination of coils location during magnetic stimulation. The major constructions of magnetic stimulation coils have been investigated. The electric and magnetic fields are modelled using finite element method and integral equation method. The effects of changing the construction of coils and the frequency to the effect of magnetic stimulation are analysed. The results show that the coils for magnetic stimulation characterize with different focality and magnetic field concentration. The proposed inverse approach using neural networks is very useful for determination the spatial position of the stimulation coils especially when the location of the coil system is required to be changed dynamically.

1. Introduction

Stimulation by magnetic field offers several advantages when compared with stimulation by electric currents produced by contact electrodes. The main advantage is noninvasive, noncontact and painless nature of the stimulation. These features make magnetic stimulation a promising technique for numerous neurophysiological investigations. Magnetic stimulation has been used for both the central and peripheral nervous system [1-5].

In magnetic stimulation, short and very intensive current pulses are supplied to the coil to produce a fast rising strong magnetic field to stimulate nerve fibres in the cerebral cortex or in peripheral nerves. Magnetic stimulation occurs as a result of the current flow and the accompanying electric field induced in the tissue by an externally applied magnetic field. Spatial position and orientation of the coils in order to generate prescribed magnetic and electric field is of main importance to realize reliable and effective magnetic stimulation. The stimulating coil consists of one or more wound and well-insulated copper coils. Determination of coils location in order to generate prescribed magnetic and electric field distribution is a main inverse problem.

In this paper, several types of electromagnetic systems were investigated for stimulation purposes in order to obtain good focality and field concentration. To understand better the ability of these electromagnetic systems to excite peripheral nerves focally, we analyse the magnetic and electric field of these systems. The magnetic and electric field distribution changes according to respective configuration of electromagnetic systems. The aim is to achieve magnetic field focusing and known field distribution based on differently shaped coils and different space positioning among them.

Previously, we developed an approach using Artificial Neural Networks (ANN) for finding a solution of the electromagnetic device design problem. We applied this approach for designing of the gradient coils for MRI [6]. For the purpose of this study we extended that approach for determination of coils location for the synthesis of a given magnetic field distribution. The approach combines two types of ANN and applies a neural network inversion algorithm. The proposed inverse approach using neural networks is very useful for determination the spatial position of the stimulation coils especially when the location of the coil system is required to be changed dynamically.

2. INVERSE PROBLEMS FOR MAGNETIC STIMULATION

2.1. *Basic Principals of Magnetic Stimulation.*

The electric field **E** induced in the tissue during magnetic stimulation is expressed by Faraday's law

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \tag{1}$$

where **B** is the magnetic field produced by coil and given by the Biot-Savart law

$$\mathbf{B} = \frac{\mu_0}{4\pi} I(t) \int_L \frac{\mathbf{dl}(\mathbf{r}') \times (\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3}, \tag{2}$$

where μ_0 is the permeability of free space.

The electric field is expressed by magnetic vector potential **A** and electric potential V as

$$\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t} - \nabla V. \tag{3}$$

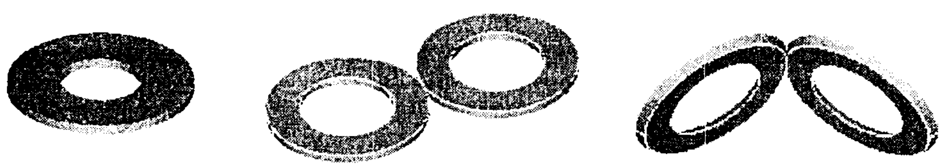
2.2. *Magnetic Stimulation Coils*

The magnetic and electric field distribution in tissue changes according to respective configuration of electromagnetic systems.

Several types of electromagnetic systems were investigated for stimulation purposes in order to obtain good focality and field concentration. To understand better the ability of these electromagnetic systems to excite peripheral nerves focally, we analyse the magnetic and electric fields of these systems.

The stimulating coil consists of one or more wound and well-insulated copper coils.

The different constructions of coils distribution are used in order to realize the requirements of magnetic stimulation. Fig. 1 shows the standard stimulating coils – circular, planar 8-shaped and 8-shaped coils. The coil shown in Fig.1(c) is with cone shape.



(a) Circular coil **(b) Planar 8-shaped coil** **(c) 8-shaped coil**

Figure 1: Magnetic stimulation coils.

2.3. Inverse Approach for Determination of Coil Loccation

Previously, Artificial Neural Networks (ANN) have been utilized for finding a solution of the electromagnetic device design problem [6]. The approach combines two types of ANN and applies a neural network inversion algorithm. This approach is successfully applied for designing of the gradient coils for MRI. For determination of the position of different configuration of coil system in order to synthesize of a given magnetic field distribution we extended that ANN approach.

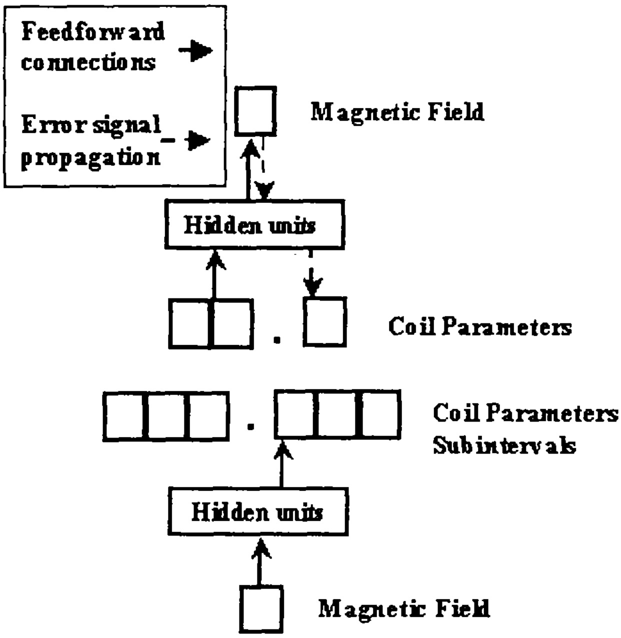
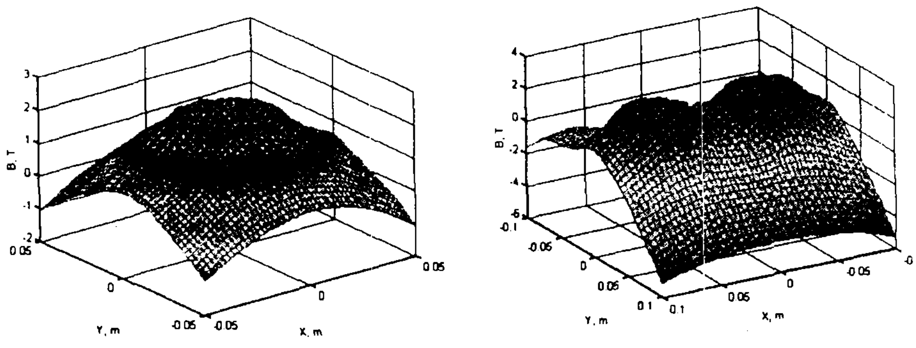


Figure 2: Artificial neural networks approach schema for determination of the coil location

The combined processor produces an analysis of an unknown mapping between a pattern of a given magnetic field distribution and a vector of geometric parameters of coil system. In the core of our approach is an adapted and modified neural network inversion algorithm. It is a gradient descent method to find the input pattern for a particular neural network that generates a specific desired output [12]. Using this algorithm with network trained to map the forward problem we can find a solution or set of solutions for corresponding inverse problem.

Fig. 2 shows the ANN approach schema for determination of the coil location. At first, a multi-layer feed-forward ANN is trained to solve the forward problem for determination of the generated magnetic field from a given particular coil system. After training is completed, the second feed-forward ANN is trained on the simplified inverse problem in order to determine the most appropriate subintervals in the input space to start the inversion in.



(a) Circular coil (b) Planar 8-shaped coil

Figure 3: Magnetic field distribution of (a) circular and (b) planar 8-shaped coil at frequency f=10 Hz

Finally, we start a modified and adapted inversion algorithm with the network trained on the forward problem in order to find the location of particular coil system, which generate the prescribed magnetic field. This approach is very useful when the location of the coil system is required to be changed dynamically. A new coil location can be found starting only the ANN inversion algorithm.

3. APPLICATION

Using ANN approach described above the magnetic stimulation coils were designed and their space locations were determined in order to obtain given magnetic field densities. The sizes of single circular coil are: inner radius r_1=0.022m and outside radius r_2 =0.0435m. The coils are wound of 9 concentric turns of rectangular copper wire (1x5 mm^2). The space angle between coils for 8-shaped stimulation system is $\alpha = 30°$.

To determine the effect of changing the construction of coils we computed and analysed the magnetic and the electric field for circular, planar 8-shaped and 8-shaped coils (Fig. 1) with different sizes and space locations to the tissue. The 3D FEM model and integral equation methods were used [7-11].

In Fig. 3 and Fig. 4 are shown magnetic field distribution of circular coil, planar 8-shaped and 8-shaped coils, respectively.

As shown in Fig. 3 and Fig. 4 the stimulus strength is at its highest close to the coil surface since the magnetic field density falls off with distance from coil.

In the case of circular coils the induced tissue current is zero or near zero on the central axis of the coil and increases to a maximum near the inner radius of the coil. This means that the stimulation will be occur under the winding and not under the coil center. The current direction depends on the used coil side during stimulation. In cortical stimulation as the motor cortex is sensitive when the induced current is flowing from posterior to anterior.

The main advantage of 8-shaped over circular coils is that the induced tissue current is at its maximum directly under its center.

The magnetic field distribution of 8-shape cone coils shows better magnetic coupling. This means that the appropriate choice of the spatial angle allows effective stimulation.

We calculated and analyzed potential distribution at layer with different conductivity using coils with different shape.

In peripheral stimulation, an important activating feature of electric field **E** is thought to be its gradient along the axon, $\partial E / \partial x$.

In Fig. 5 is shown contour maps of X- and Y- component of rotational part of electric field caused by the externally applied magnetic field of the circular coil.

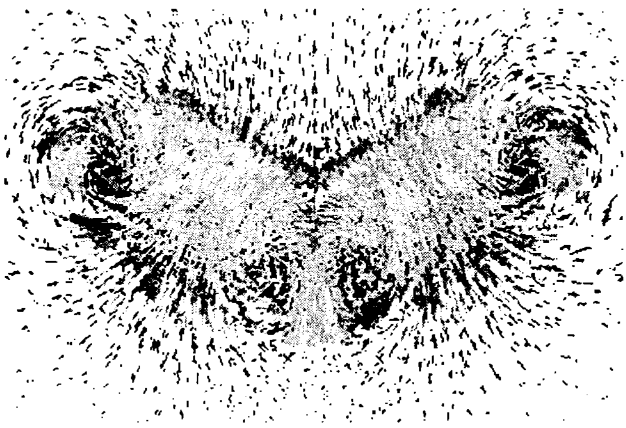
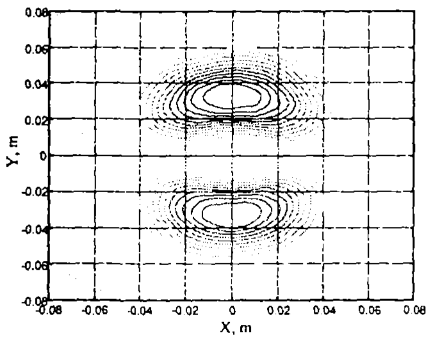
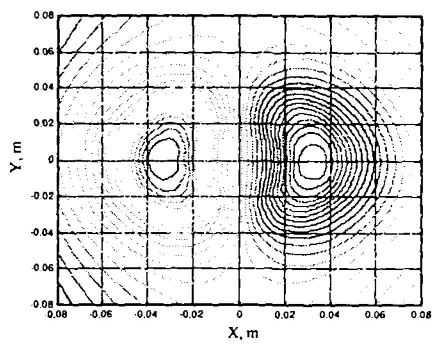


Figure: 4 Magnetic field distribution of 8-shaped coil at frequency f=10 Hz

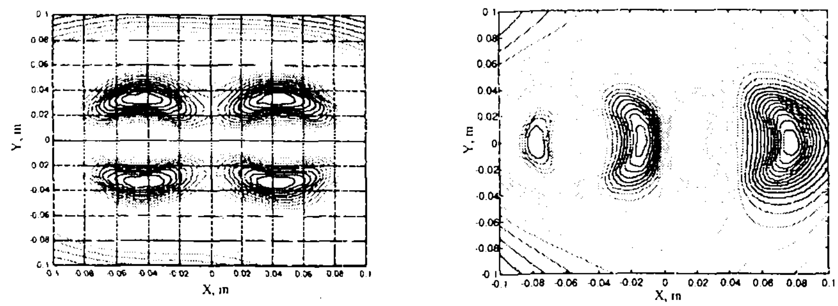


(a) X-component



(b) Y-component

Figure: 5 Contour maps of X-and Y-component of electric field distribution for circular coil



(a) X-component **(b) Y-component**

Figure: 6 Contour maps of X-and Y-component of electric field distribution for 8-shaped coil

Table 1

Coil	h, m	B_{NN}, T	δ , %	h, m	B_{NN}, T	δ , %
Circular	0.0223	0.9999	-0.01	0.0145	1.5019	0.19
Planar 8	0.0407	0.9939	-0.61	0.0202	1.5140	1.40
8-shaped	0.0691	0.9921	-0.79	0.0323	1.5056	0.56

In Fig. 6 ise shown contour maps of X- and Y- component of rotational part of electric field caused by the externally applied magnetic field of the planar 8-shaped coil.

The contour steps in Fig. 5-6 are the same. It allows determining the appropriate stimulation region.

The inverse ANN approach is applied for determination of spatial position of stimulation coils over the tissue in order to synthesis of given magnetic field density. In Table 1 is given the determined location of the stimulation coils under consideration in order to realize the magnetic field density B_d=1; 1.5 and 2 T. The relative errors δ, % show that results obtained using proposed approach characterize with good accuracy. This approach is very useful when the location of the coil system is required to be changed dynamically. A new coil location can be found starting only the ANN inversion algorithm.

4. CONCLUSIONS

This study provides quantitative data on the effects of magnetic stimulation solving forward problem of magnetic and electric field analysis as well as inverse problem for determination of spatial position of the coils. Artificial Neural Network model is utilized.

Computational model of magnetic stimulation has been developed. Numerical methods are used to investigate the electric and magnetic field distribution produced by magnetic stimulation coils.

Significant improvements in the efficacy and device performance are expected as a result of a field analysis using numerical methods as well as a result of precise determination of coils location during magnetic stimulation.

5. ACKNOWLEDGMENTS

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SOFTWARE METHODOLOGY