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AN INVERSE APPROACH TO OPTIMAL EXCITING COIL DESIGN

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Abstract
In the present paper, the electric current distribution is estimated by the sampled pattern matching (SPM) method with the desirable magnetic field distribution given condition. In order to demonstrate our method, several examples are shown together with experimental results.

1. INTRODUCTION

Conventional designing methodology of the magnetic devices is that the desired magnetic field distribution is iteratively evaluated by solving a governing equation with electric current given condition. On the contrary, in the present paper, the electric current distribution is estimated by the sampled pattern matching (SPM) method with the desirable magnetic field distribution given condition [1,2]. This means that one of the designing strategies is proposed here by means of the inverse analytical approach. Conventional approach to the regular or forward problems yields a unique solution so that iterative approach is essentially required to reach a final goal of the design. On the other side, our inverse approach based on the SPM method provides a unique solution pattern. As the concreate examples, we try to decide the layout of the exciting coils in order to realize the convex, flat and concave magnetic field distributions. Finally, we apply our method to the exciting coil design for an axial type flat induction motor [3].

2. THE OPTIMAL EXCITING COIL DESIGN

2.1 Basic equations

One of the most basic element of the magnetic field sources is a current element, because any shape of coils can be composed by connecting them. A relationship between the magnetic field **H** and current element Idl is given by Biot-Savart's law:

$$\mathbf{H} = \int (\mathbf{I}\times\mathbf{a}_r/4\pi r^2)dl, \tag{1}$$

where $\mathbf{a}_r$ is a unit vector in the direction of r.

Let us consider a problem that the desirable magnetic fields $\mathbf{H}_1$, $\mathbf{H}_2$, $\cdot$,$\mathbf{H}_n$ are caused by the m-th unknown current elements $\mathbf{I}_1$, $\mathbf{I}_2$, $\cdot$, $\mathbf{I}_m$ and we have to evauate the m-th unknown current elements with the condition $n \neq m$. Then by means of (1), it is possible to write a following system equation:

$$\mathbf{U} = \sum_{i=1}^{m} \mathbf{I}_i \mathbf{d}_i , \tag{2}$$

$$\mathbf{U} = [\mathbf{H}_1, \mathbf{H}_2, \cdot, \mathbf{H}_n]^T, \tag{3a}$$

$$\mathbf{d}_i = [\mathbf{n}_i\times\mathbf{a}_{r1i}/4\pi r_{1i}^2, \mathbf{n}_i\times\mathbf{a}_{r2i}/4\pi r_{2i}^2, \cdot, \mathbf{n}_i\times\mathbf{a}_{rni}/4\pi r_{ni}^2]T, \quad i=1,2,\cdot,m, \tag{3b}$$

where $\mathbf{n}_i$ is unit vector in the direction of the current I_i.

2.2 Sampled pattern matching method

<a>Algorism The formal algorithm of our SPM method is as follows.

At first, we calculate a pattern matching figure γ_i using the column vector $\mathbf{d}_i$ of (3b) and given vector $\mathbf{U}$ of (3a), and then find the maximum pattern matching figure, i.e. if a point h takes the maximum of

$$\gamma_i = \mathbf{U}^T \cdot \mathbf{d}_i / [|\mathbf{U}||\mathbf{d}_i|], \quad i=1,2,\cdot,m, \tag{4a}$$

then we call h as a first pilot point and associated vector $\mathbf{d}_h$ is called the first pilot pattern vector.

The second step is carried out by combining the first pattern vector $\mathbf{d}_h$ and remaining pattern vectors in (4b). i.e. we search for the maximum of

$$\gamma_{hj} = \mathbf{U}^T \cdot (\mathbf{d}_h + \mathbf{d}_j) / [|\mathbf{U}||\mathbf{d}_h + \mathbf{d}_j|], \quad j=1,2,\cdot,m;\ j \neq h. \tag{4b}$$

If a point g takes the maximum in (4b), then g is the second pilot point and $\mathbf{d}_g$ is the second pilot pattern vector. Similar processes are continued up to the peak pattern matching figure γ.

<b>Solutions Generally, the number of equations n is not equivalent to the number of unknows m so that it is difficult to obtain a unique solutions I_i, i=1,2,·,m in (2). Obviously, Our SPM argorism of (4a) and (4b) has been based on the following assumptions.

At first, the solution $\mathbf{I}_i$, i=1,2,·,m in (2) takes the value of 1 or 0. This means that the pilot points take the unit value 1 and the other remaining points take the value 0. Secondly, each of the magnitudes $\mathbf{I}_i$, i=1,2,·,m, in (2) could not be evaluated uniquely but is represented by the concentrating ratio of the unit value 1 in space. In the other words, the regions comprising of a large number of unit currents represent a large current flowing region and the regions comprising of a small number of unit currents represent a small current flowing region.

<c>Theoretical background Let us consider a normarized vector $\mathbf{d}_i{}' = \mathbf{d}_i / |\mathbf{d}_i|$ and output vector $\mathbf{\Gamma}_i$, i.e.

$$\begin{array}{lcl} & & \quad 1 \quad 2 \quad 3 \quad \cdot \quad m \\ \mathbf{d}_1{}': \mathbf{\Gamma}_1 & = & [1,\ 0,\ 0,\ \cdot\ ,\ 0]^T, \\ \mathbf{d}_2{}': \mathbf{\Gamma}_2 & = & [0,\ 1,\ 0,\ \cdot\ ,\ 0]^T, \\ \cdots\cdots & & \\ \mathbf{d}_m{}': \mathbf{\Gamma}_m & = & [0,\ 0,\ 0,\ \cdot\ ,\ 1]^T, \end{array}$$

then using these vector, we have

$$W^1 = \sum_{i=1}^{m} \mathbf{\Gamma}_i (\mathbf{d}_i{}')^T. \tag{5}$$

Equation (5) means that the matrix W^1 is one of the neural network matrices (or perceptrons) obtained by the input vector $\mathbf{d}_i{}'$ and supervisor vector $\mathbf{\Gamma}_i$. Thereby, when an input vector to this network is the normarized vector $\mathbf{U}' = \mathbf{U}^T / |\mathbf{U}|$ of (2), the output vector $\mathbf{\Gamma}^1$ becomes

$$\mathbf{\Gamma}^1 = W^1 \cdot \mathbf{U}'. \tag{6}$$

Obviously, the elements of output vector $\mathbf{\Gamma}^1$ are the pattern matching figures γ_i, i=1,2,·,m, in (4a) so that the maximum in these pattern matching figures corresponds to the first pilot point. This means that the threshold value of this neural network is the maximum of output vector $\mathbf{\Gamma}^1$. Thus, the first step of the SPM method is one of the neural network processes. Similarly, when we denote the first pilot point by h, the second step is carried out by means of the normarized vector$(\mathbf{d}_h + \mathbf{d}_i)' = (\mathbf{d}_h + \mathbf{d}_i)/|\mathbf{d}_h + \mathbf{d}_i|$ and supervisor vector $\mathbf{\Gamma}_{hi}$, i.e.

$$
\begin{array}{llllllll}
 & & & 1 & 2 & 3 & \cdot & m\text{-}1 \\
(\mathbf{d}_h+\mathbf{d}_1)': & \Gamma_{h1} & = & [1, & 0, & 0, & \cdot, & 0]^T, \\
(\mathbf{d}_h+\mathbf{d}_2)': & \Gamma_{h2} & = & [0, & 1, & 0, & \cdot, & 0]^T, \\
\cdots\cdots & & & & & & & \\
(\mathbf{d}_h+\mathbf{d}_m)': & \Gamma_{hm} & = & [0, & 0, & 0, & \cdot, & 1]^T.
\end{array}
$$

Using these vectors, we have the second perceptron:

$$W^2 = \sum_{i \neq h}^{m} \Gamma_{hi} (\mathbf{d}_h + \mathbf{d}_i)'^T . \quad (7)$$

Thereby, the second pilot point can be obtained as the maximum of following output vector Γ^2:

$$\Gamma^2 = W^2 \cdot \mathbf{U}'. \quad (8)$$

Thus, it is obvious that the SPM method is one of the neural networks.

2.3 Examples

<a>Convex, flat and concave fields In order to demonstrate our method of designing, we carried out the coil designs giving the convex, flat and concave magnetic field distributions on the cicular cross-sectinal area. Figures 1(a) and 1(b) show the cross-sectional area and its side view including target(coil) as well as field regions , respectively.

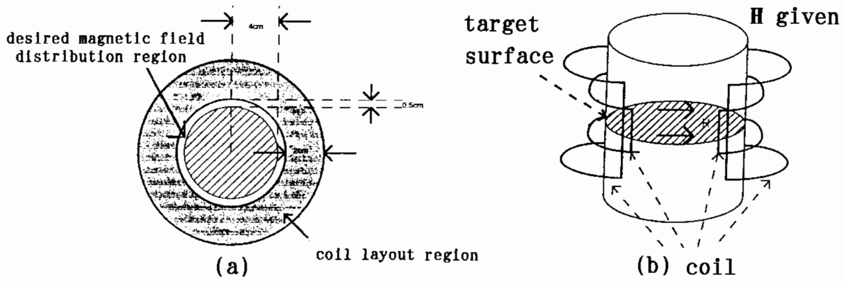
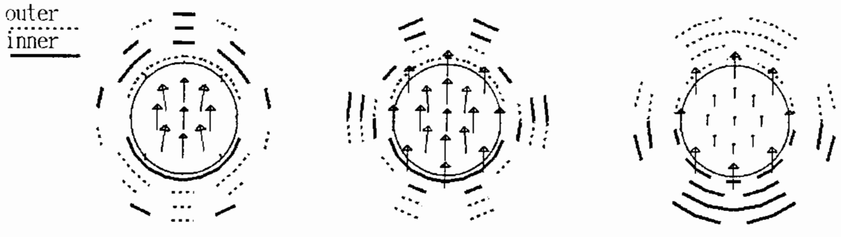


Fig. 1. Convex, flat and concave fields realization problems. (a) Cross-sectional view of target area, and (b) side view of target area. Exciting coils are set on the solid area in (a) and desired fields are realized in the cental circular area.



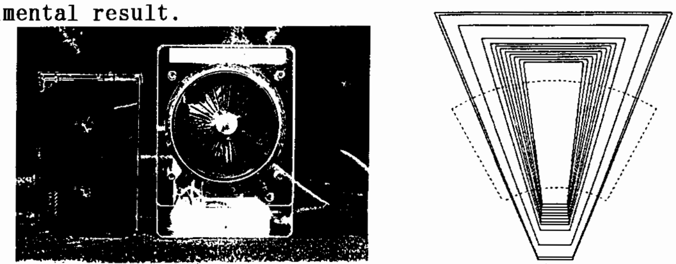
(a)γ=0.9697 (b)γ=0.9979 (c)γ=0.9903

Fig.2 Obtained fields and coil layout. (a) Convex, (b) flat and (c) concave magnetic field distributions. Dotted and solid lines show the exciting coils giving the fields in the directions of outer and inner to the center of circular field region,respectively.

The conditions of designing are as follows: 1)each of the coils has a rectangular shape and is located on the side surface of the cyliderical tube. 2)Symmetrical desirable field is realized by the symmetrical coil layout. 3)Target variables are coil length, width and location. 4)Coil design is carried from the inner to outer regions. 5)plural coils can be located along a same orbital line as long as their positions are not overlapped. 6)SPM processes are continued untill the maximum pattern matching figure γ is obtained.

Figure 2 shows the obtained results togerther with the maximum pattern matching figure γ.

<b>**Exiting coil design for the flat induction motors** In order to realize the sinusoidal magnetic field distributions in the radial as well as tangential directions of the flat induction motor shown in Fig. 3(a), we applied our approach to the stator coil design with similar constraints of the previous examples. The result for one pole is shown in Fig. 3(b). Figure 4 shows the obtained magnetic field distribution together with experimental result.



(a) (b)

Fig. 3. Exciting coil design of the flat induction motor[3]. (a)Picture of a flat induction motor, and (b) designed stator coil.

(a) (b)

Fig. 4. Magnetic field distributions produced by the stator exciting coil. (a) Computed, and (b) experimented magnetic fields.

3. CONCLUSION

As shown above, we have succeeded in realizing the desirable magnetic field distribution by an inverse analytical approach. One of the best merits of this new approach is that a fairly good result can be expected even if no iteration is carried out. Thus, it has been suggested that the inverse analytical approach makes it possible to design the electromagnetic devices in a highly efficient manner.

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