# Study on the Distribution of the Magnetic Field of Circular and Square Exiting Coils in Electromagnetic Flow Meter

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## Abstract

Exciting coil is an important part of the electromagnetic flow meter, its reasonable design has significant influence on the performance of electromagnetic flow meter. This paper discusses the magnetic field distributions of circular and square exciting coils in electromagnetic flow meter, using Biot-Savart Law and superposition principle, the simulation of magnetic field distribution is done, in the cross section that containing electrodes inside measurement pipe, and two indicators the magnetic induction intensity parallel degree in direction and magnetic induction intensity uniform degree in size is proposed, the analysis and comparison of induced magnetic field generated circular and square exciting coils is done based on above two indicators. This paper provides a reference for the optimal design of exciting coils in electromagnetic flow meter.

***Key words:*** *circular, square, exiting coil, magnetic field distribution, electromagnetic flow meter.*

## 1 Introduction

Electromagnetic flow meter is an instrument measuring the flow volume of conductive liquid by Faraday's law of induction, it is widely used in metallurgy, drainage, chemical and petroleum, food-making, medical, environmental protection, aviation, agriculture irrigation, and so on. It is mainly composed of a sensor and a converter. Electromagnetic flow sensor is installed in fluid transmission process pipe, it converts the flow volume of conductive liquid into induction voltage signal linearly, the converter provides excitation current to the sensor for generating magnetic field, accepts the induction voltage signal, and processes it to standard current or voltage signal.

The magnetic field distribution of electromagnetic flow meter causes the attention of researchers. In 1998, A. Michalski etc established 2D model of electromagnetic flow meter by finite element method [1], studied the optimal design of exciting coil, in order to get the uniform weighting function, making induction voltage signal measured by electrode only related with the mean flow velocity of fluid. In 2002, A. Michalski etc established the 3D hybrid mathematical model of exciting coil of electromagnetic flow meter [2]. XiaoZhang Zhang studied calculation of magnetic field of electromagnetic flow meter with large diameter and multi-electrodes by idealized magnet model [3]. Chen Zhao etc proposed a approximate calculation method for magnetic field distribution of saddle shape exciting coil of electromagnetic flow meter [4]. Through the finite element method [5], Jingzhuo

Wang done numerical simulation and verification of weighting function of electromagnetic flow meter [6]. The measurement principle of the electromagnetic flow meter is based on Faraday's law of induction. As shown in figure 1, while conductivity fluid cut magnetic field line inside magnetic field $\vec{B}$ of the sensor, induced potential E that is proportional to the fluid velocity v is generated at two electrodes, usually it is expressed as following formula [7]:

$$E = kBDV \tag{1}$$

In above formula, $k$ is coefficient of instrument, $D$ is the inner diameter of sensor pipeline.

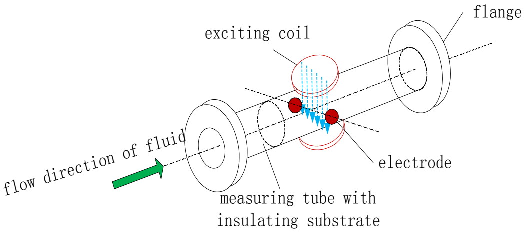


Fig. 1 Measurement principle of electromagnetic flow meter.

The volume flow is determined by the average flow velocity, in a circular pipe the flow volume is as following:

$$Q = \frac{\pi}{4} D^2 V \tag{2}$$

Gained by (1) (2)

$$Q = \frac{\pi D}{4kB} E \tag{3}$$

When the magnetic induction $\vec{B}$ and the inner diameter $D$ of the pipeline are constants, the flow volume $Q$ of fluid is proportional only to induction potential E, and has nothing to do with other physical parameters (such as density, conductivity, etc), that is the significant advantage of electromagnetic flow meter.

Above equations simply illustrate the working principle of electromagnetic flow meter, they are set up only when the following conditions are met: (1) in the infinite range, the magnetic induction B is evenly distributed; (2) the speed of the fluid is as solid conductor, the internal particle speed is the same everywhere, and equals to the average velocity.

According to the required magnetic induction in condition (1), to realize the optimal design of exciting coil of the electromagnetic flow meter, this paper focuses on the analysis of magnetic field distribution for circular and square exciting coils.

## 2 Calculation and simulation of magnetic field distribution of electromagnetic flow meter

### 2.1 Calculation of magnetic field distribution of exciting coil

Basing on Biot-Savart Law, the basic law of magnetic field produced by a current carrying conductor is: Any current element $Id\vec{l}$ produce magnetic induction $d\vec{B}$ at any point P in space is as following:

$$d\vec{B} = \frac{\mu_0}{4\pi} \bullet \frac{Id\vec{l} \times \vec{r}}{r^3} \tag{4}$$

In above formula, $\vec{r}$ is the vector from current element to point $P$, $d\vec{l}$ is the vector of wire element. The total magnetic induction at point $P$ could be got through the integral of the magnetic field generated along the current-carrying conductor.

If $d\vec{B}$ is magnetic field generated by a small section of wire at place $\vec{r}$, above formula could be wrote as:

$$\vec{B} = \frac{\mu_0}{4\pi} \frac{I}{r^3} \begin{vmatrix} \vec{i} & \vec{j} & \vec{k} \\ l_x & l_y & l_z \\ r_x & r_y & r_z \end{vmatrix} = B_x \vec{i} + B_y \vec{j} + B_z \vec{k} \tag{5}$$

To calculate magnetic field generated by $n$ small sections of wire at place $\vec{r}$, it is

$$\sum_{i=1}^{n} \vec{B} = \sum_{i=1}^{n} \frac{\mu_0}{4\pi} \frac{I}{r^3} \begin{vmatrix} \vec{i} & \vec{j} & \vec{k} \\ l_{xi} & l_{yi} & l_{zi} \\ r_x & r_y & r_z \end{vmatrix} = \sum_{i=1}^{n} (B_{xi}\vec{i} + B_{yi}\vec{j} + B_{zi}\vec{k}) \tag{6}$$

Above formula can be applied to calculate the magnetic induction produced by arbitrary shape current at any place. $l_{xi}, l_{yi}, l_{zi}$ mean the components of current element along the axis in rectangular coordinate system. According to formula (6), calculation and simulation of the magnetic field distribution of the exciting coil of electromagnetic flow meter could be done.

## 2.2 Simulation of magnetic field distribution of exciting coil

First of all the coordinate system is established, center axis of measuring pipe for z axis, the connection of geometry centers of two field coils for x axis, the connection of two point electrodes for y axis. In the rectangular coordinate system, calculation and simulation of magnetic field produced by field coil in measurement pipeline's cross section containing electrodes, could be done according to the following steps:

1) In x-y plane, the part between two field coils is meshed, and then coordinate (*x*, *y*, *0*) of each grid point is determined;

2)The current carrying conductor is divided into many small elements, and coordinate (*xc*, *yc*, *zc*) of every small element and coordinate $(l_x, l_y, l_z)$ of every small element vector are determined;

3)Calculating the vector $\vec{r}$ $(r_x, r_y, r_z)$ and corresponding distance *r* from each grid point to small wire elements;

4) Respectively in the x, y direction, calculating the component $B_{xi}$ and $B_{yi}$ of magnetic induction produced at a certain point as following:

$$B_{xi} = \frac{\mu_0}{4\pi}\frac{I}{r^3}(l_{yi}r_z - l_{zi}r_y), \quad B_{yi} = \frac{\mu_0}{4\pi}\frac{I}{r^3}(l_{zi}r_x - l_{xi}r_z);$$

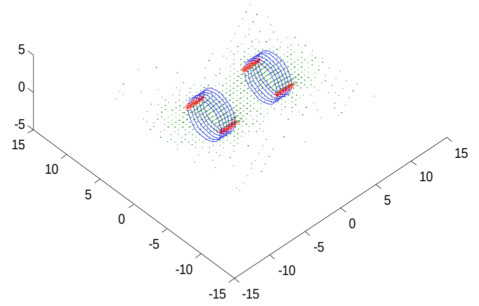
5) Calculating the summation of the magnetic induction at a certain point produced by all the small elements $B_x = \sum_{i=1}^{n} B_{xi}$ , $B_y = \sum_{i=1}^{n} B_{yi}$ ;

6) At each grid point in the given cross section, calculating magnetic induction according to the above steps;

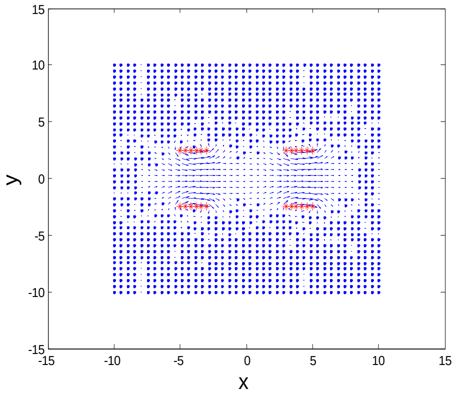
7) Doing simulation, describing the graphics of magnetic strength in given cross section.

In the following content, the part of section between the two field coils is divided into 40 by 40 grids, at each grid point, the simulation of magnetic induction produced respectively by circular and square field coils is done.

When the shape of magnet coil is circle, the radius of magnet coil is 2.5cm, the turn of each field coil is 6, and the thickness of each field coil is 2cm, the distance between two field coils is 6cm, current strength is 10mA in coils. In the cross section of measuring tube containing electrodes, the magnetic field distribution of above circular magnet coils is as shown in figure 2, the red dot mean intersection of field coils and the cross section.



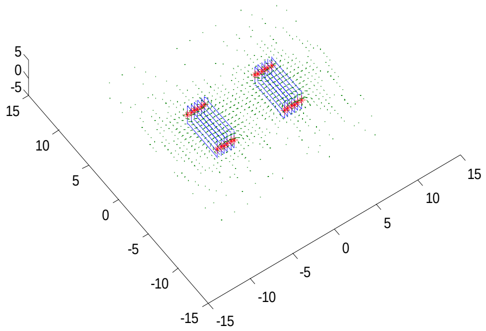
(a) Circular magnet coil



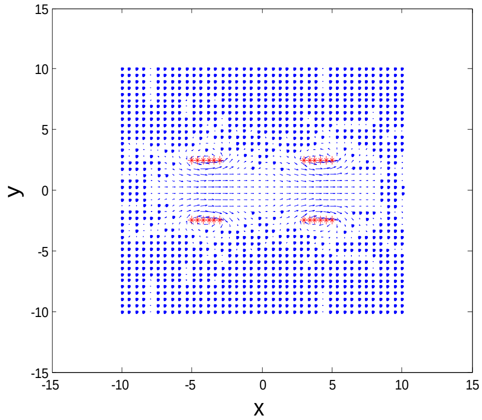
(b) Sectional view of magnetic field distribution

Fig. 2 Magnetic field distribution of circular magnet coil.

When the shape of magnet coil is square, suppose the length of square side is 5cm, the turn of each field coil is 6, and the thickness of each field coil is 2cm, the distance between two field coils is 6cm, current strength is 10mA in coils. In the cross section of measuring tube containing electrodes, the magnetic field distribution of above square magnet coils is as shown in figure 3.



(a) Square magnet coil



(b) Sectional view of magnetic field distribution

Fig. 3 Magnetic field distribution of square magnet coil.

## 3 Magnetic field analysis of field coil

Analysis for the magnetic field distribution of field coil is done in cross section of measuring tube containing electrodes. In the cross section, the vector of produced magnetic induction is: $\vec{B} = cx\cdot\vec{i} + cy\cdot\vec{j}$

### 3.1 Two indicators for analysis

Because the magnetic induction is a vector, so naturally the indicators for analysis and comparison of magnetic field include: uniform degree of strength and parallel degree of direction. In the considered cross section including electrodes, the direction of magnetic induction vector could be represented by the angle $\theta$ between magnetic induction vector and positive direction of x axis as following:

$$\tan\theta = \frac{cx}{cy}, \quad \theta = \arctan\frac{cx}{cy} \tag{7}$$

Describing function for parallel degree of field direction is proposed, supposing that at each grid point, the average of the Angle $\theta_k$ between magnetic induction vector and positive direction of *x* axis is $\theta_0$, then $\theta_0 = \frac{1}{n}\sum_{k=1}^{n}\theta_k$. Defining as follows:

$$RM_1 = MAX(|\frac{\theta_k - \theta_0}{\theta_0}|) \tag{8}$$

$$RD_1 = \sqrt{\frac{1}{n-1}\sum_{k=1}^{n}(\frac{\theta_k - \theta_0}{\theta_0})^2} \tag{9}$$

$RM_1$ reflects the maximum deviation of field direction in the area; $RD_1$ reflects the whole parallel degree of field direction in the region. The smaller value of $RD_1$, the more ideal the whole parallel degree of field direction is.

Vector size of magnetic induction could be represented by length $d$ of vector as following:

$$d = \sqrt{cx^2 + cy^2} \qquad 10)$$

Describing function for uniform degree of field strength is proposed, supposing that at each grid point, the average of the length $d_k$ of magnetic induction vector is $d_0$, then $d_0 = \frac{1}{n}\sum_{k=1}^{n} d_k$. By the same token, defining as follows:

$$RM_2 = MAX(|\frac{d_k - d_0}{d_0}|) \tag{11}$$

$$RD_2 = \sqrt{\frac{1}{n-1}\sum_{k=1}^{n}(\frac{d_k - d_0}{d_0})^2} \tag{12}$$

$RM_2$ reflects the maximum deviation of field strength in the area; $RD_2$ reflects the whole uniform degree of field strength in the region. The smaller value of $RD_2$, the more ideal the whole uniform degree of field strength is.

## 3.2 Magnetic field analysis of circular and square magnet coils

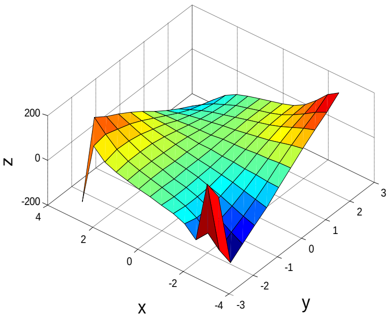
Based on the above indicators, calculation and analysis is done for magnetic field distribution of the circular and square magnet coils described in cross section containing electrodes, and the specific situation is as shown in table 1.

Table 1: Magnetic field distribution of circular and square magnet coils

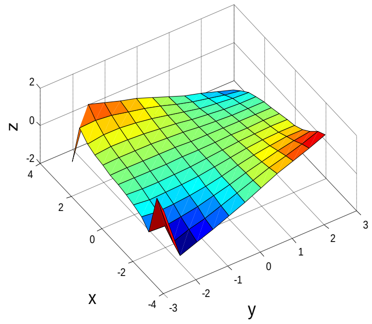
| **Shape of coil** | direction of magnetic induction | | |
|---|---|---|---|
| | $\theta_0$ | $RM_1$ | $RD_1$ |
| circle | 0.0080 | 195.1070 | 68.3793 |
| square | 0.0078 | 198.8714 | 66.3584 |
| **Shape of coil** | strength of magnetic induction | | |
| | $d_0$ | $RM_2$ | $RD_2$ |
| circle | 5.8677e-005 | 1.4594 | 0.5036 |
| square | 6.2802e-005 | 1.7527 | 0.4455 |

It is known from table 1, that for the whole parallel degree in direction of magnetic induction , the square magnet coil is better than circular magnet coil, but the maximum deviation is slightly bigger; for the overall degree of uniformity of field strength, square field coil is better than circular magnet coil, but the maximum deviation is also slightly bigger.

The specific distribution of magnetic induction direction for circular and square magnet coils is respectively as shown in figure 4 and figure 5.

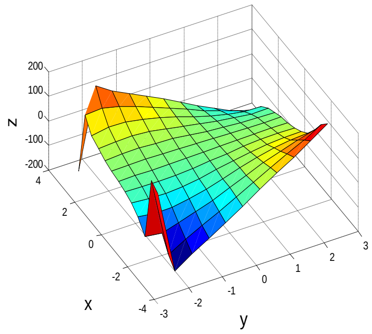


(a) Relative direction of magnetic induction $\frac{\theta_k-\theta_0}{\theta_0}$

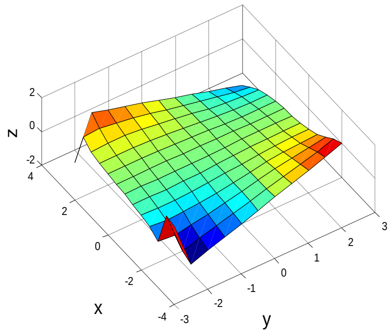


(b) Direction of magnetic induction $\theta_k$

Fig. 4 Distribution of magnetic induction direction of circular magnet coil.



(a) Relative direction of magnetic induction $\frac{\theta_k-\theta_0}{\theta_0}$

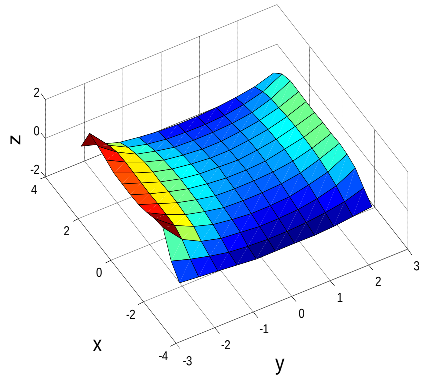


(b) Direction of magnetic induction $\theta_k$

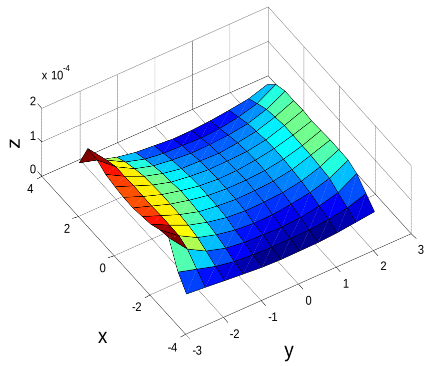
Fig. 5 Distribution of magnetic induction direction of square magnet coil

Contrasting figure 4 and figure 5, it also reflects square field coil is better than circular magnet coil for the whole parallel degree of magnetic induction direction, which is consistent with the results in table 1.

The specific distribution of field strength for circular and square magnet coils is respectively as shown in figure 6 and figure 7.

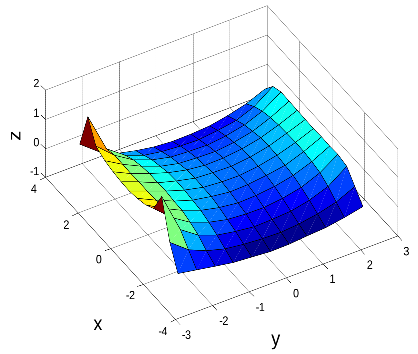


(a) Relative strength of magnetic induction $\frac{d_k - d_0}{d_0}$

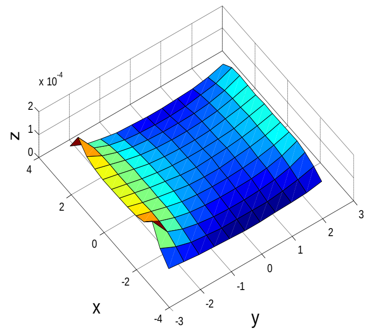


(b) Strength of magnetic induction $d_k$

Fig. 6 Strength distribution of magnetic induction of circular magnet coil



(a) Relative strength of magnetic induction $\frac{d_k - d_0}{d_0}$



(b) Strength of magnetic induction $d_k$

Fig.7 Strength distribution of magnetic induction of square magnet coil.

Contrasting figure 6 and figure 7, it also reflects square field coil is better than circular magnet coil for the overall uniform degree of magnetic induction strength, which is also consistent with the results in table 1.

## 4 Conclusion

In the infinite range, the magnetic induction B is constant and uniform, which is one of the ideal working conditions for the electromagnetic flow meter. In order to realize reasonable design of field coil of electromagnetic flow meter, and improve its performance, in this paper basing on Biot-Savart Law and superposition principle, calculation and simulation for the magnetic field distribution of circular and square magnet coils is done, in the cross section containing electrodes of measuring tube. Two indicators for analysis and comparison of magnetic field distribution are proposed: uniform degree of magnetic induction strength and parallel degree of field direction. Based on above two indicators, the magnetic field distribution of circular and square magnet coils is analyzed, it shows that: square field coil is better than circular magnet coil both for the whole parallel degree of magnetic induction direction and for the overall uniform degree of magnetic induction strength. It could provide certain reference for optimal design of field coil of electromagnetic flow meter.

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