Mathematical modeling

Математическое моделирование

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RESEARCH ARTICLE

Analytical model for the normal component of magnetic induction of a permanent magnets

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Abstract
Objectives. In a measuring system based on the inductive transmission of information from a moving structure to a stationary signal receiver, the signal carrying useful information about the parameters of the moving structure is formed by a magnetic system containing a permanent magnet mounted on the stationary part of the measuring system. The magnetic field of the permanent magnet (MFPM) determines the magnetic flux, and, consequently, the induction current in a conducting coil located on the moving structure. In order to theoretically justify the parameters of the measuring system including the optimization of its components, a simple and easy-to-use analytical model of the useful signal for determining the requirements for the mathematical description of the MFPM is required. The use of known solutions for developing an analytical model of the useful signal of the measuring system is complicated by the need to use inverse trigonometric functions or the results of numerical calculations. The present work sets out to obtain an exact solution to the problem of calculating the MFPM and on this basis to develop a simple, convenient analytical model of the normal component of the magnetic induction vector (NCMIV) of a permanent magnet used to develop an analytical model of the useful signal.
Methods. The equivalent solenoid method was used along with mathematical analysis approaches.
Results. An exact solution for calculating the normal component of the magnetic induction vector of the parallelepiped-shaped permanent magnet was obtained. Based on this, a straightforward and easy-to-use analytical model of the NCMIV was developed, which closely approximates the formula derived for the exact solution.
Conclusions. The developed analytical model of the NCMIV can be used for theoretical development of an analytical model of the useful signal of a measuring system with inductive transmission of information about the parameters of a moving structure to a stationary signal receiver.

Keywords: permanent magnet, magnetic induction, equivalent solenoid, normal component, analytical model

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НАУЧНАЯ СТАТЬЯ

Аналитическая модель нормальной составляющей магнитной индукции постоянного магнита

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Резюме
Цели. В измерительной системе с индукционной передачей информации с перемещающейся конструкции на неподвижный приемник информационный сигнал, несущий информацию о параметрах перемещающейся конструкции, формируется магнитной системой, содержащей постоянный магнит, установленный на неподвижной части измерительной системы. Магнитное поле постоянного магнита (МППМ) определяет магнитный поток, и, следовательно, индукционный ток в другом элементе магнитной системы – проводящем витке, расположенном на перемещающейся конструкции. Для теоретического обоснования параметров измерительной системы, в т.ч. для оптимизации ее составных частей, необходима простая, удобная для применения аналитическая модель информационного сигнала (АМИС), что определяет требования к математическому описанию МППМ. Известные решения задач по расчету МППМ содержат обратные тригонометрические функции или представлены результатами численных расчетов, что затрудняет их использование для разработки АМИС измерительной системы. Целью данной статьи является получение точного решения задачи расчета МППМ и разработка на основании этого точного решения аналитической модели нормальной составляющей вектора магнитной индукции (НСВМИ) постоянного магнита, используемой для разработки АМИС.
Методы. Использовались методы математического анализа и метод эквивалентного соленоида.
Результаты. Получено точное решение задачи расчета НСВМИ МППМ, имеющего форму параллелепипеда, на основании которого получено выражение, аппроксимирующее формулу точного решения, – аналитическая модель НСВМИ.
Выводы. Полученная аналитическая модель НСВМИ может быть использована для теоретической разработки АМИС измерительной системы с индукционной передачей информации о параметрах перемещающейся конструкции на неподвижный приемник сигнала.

Ключевые слова: постоянный магнит, магнитная индукция, эквивалентный соленоид, нормальная составляющая, аналитическая модель

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INTRODUCTION

A radio channel is mostly used to convey information about the parameters of a structure that changes position relative to a stationary signal receiver (consider, for instance, relaying gas pressure readings within a vehicle's tire). In this situation, measurement transducers are mounted on the structure to transform characteristics defining its status into electrical impulses, which are subsequently transmitted to a radio transmitter. A radio signal receiver is mounted on the stationary part, such as the body of the vehicle, close to where the pneumatic tire wheel changes position.

Transmitting information via a radio channel often encounters challenges stemming from limitations imposed on the use of electromagnetic radiation. In a measuring system with inductive transmission of information about the state of a moving structure [1, 2], the useful signal carrying information about the state of the structure is formed by a magnetic system, which is formalized as shown in Fig. 1. A rectangular conducting coil (1) is positioned on the upper edge of a permanent magnet (PM), which is configured as a parallelepiped with a height of H and the base having dimensions a and b. In a plane parallel to the PM upper edge, a structure with a placed-in rectangular coil 2 travels relative to the magnet at velocity V, with the center of coil 2 (point O_2) projected onto the Ox axis in a manner that its projection (point A) traverses along the Ox axis. The distance between the plane and the upper edge of the magnet is equal to d. The electrical resistance of coil 2 is dictated by the design specifications.

When coil 2 travels within the magnetic field of a permanent magnet (MFPM), an induced electric current arises within coil 2. The intensity of this current is influenced by the velocity of coil 2, as well as its internal electrical resistance and the normal component of the magnetic induction vector (NCMIV) of MFPM perpendicular to the plane of coil 2. This induced current in moving coil 2 subsequently produces an alternating magnetic field around coil 1. The electromotive force of coil 1 resulting from the magnetic flux of the alternating magnetic field created by the induced current in moving coil 2 acts as a signal for carrying useful information about the system parameters.

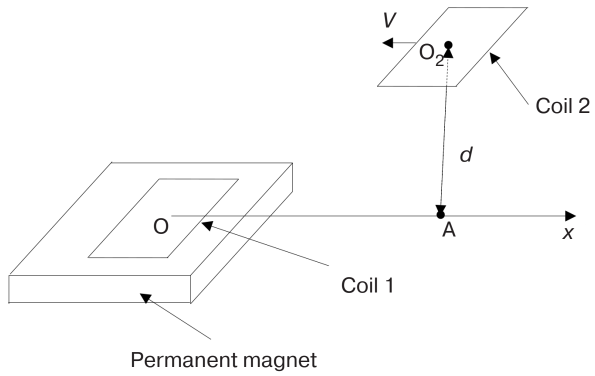

Fig. 1. Schematic of the magnetic system

Various analytical [3–11] and numerical [12–24] techniques have been established for analyzing and calculating the properties of magnetic fields within diverse magnetic systems. The present study employs the equivalent solenoid method to precisely calculate the NCMIV distribution within the MFPM in the plane parallel to the PM upper edge. These findings are then used to create the NCMIV analytical model, which can be used to develop analytical models for magnetic fluxes responsible for generating induced electric currents in conducting coils 1 and 2. The findings regarding the MFPM distribution, as detailed in [11], are expanded upon by additional calculations focusing on the MFPM distribution in the geometric area near permanent magnet.

PROBLEM STATEMENT

Figure 2 depicts the magnetic field produced by a permanent magnet that is uniformly magnetized along the Oz axis. The origin of the coordinate system $Oxyz$ is placed at the magnet base center. Based on Fig. 2, we calculate the normalized MFPM NCMIV, $B_{z\,\mathrm{n}}(x, y, z)$, at point M$(x, y, z)$ located in the specified plane $z \geq H$.

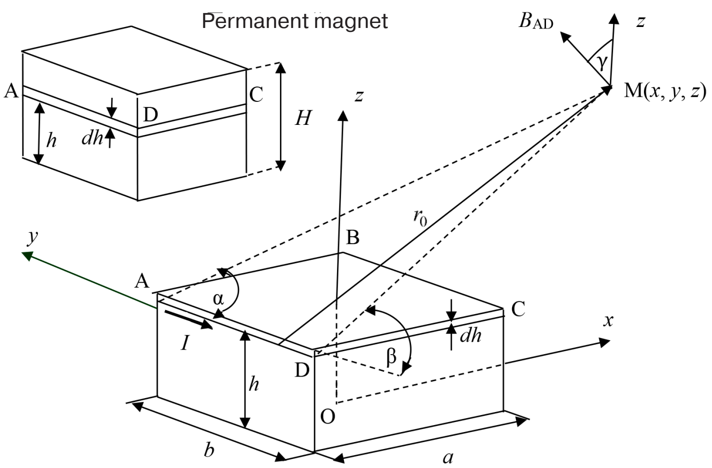

Fig. 2. Geometric layout for calculating MFPM NCMIV

Utilizing the equivalent solenoid approach [3–6], we substitute the permanent magnet with a system of surface electric currents, characterized by a linear density λ, flowing in planes perpendicular to the Oz axis. Then, a surface electric current of strength $I = \lambda dh$ flows along a strip spanning the PM side surface, with a width of dh and situated at a height h above its base. The strip perimeter is defined by the segments AD, DC, CB, and BA, where |AD| = |CB| = b, |DC| = |BA| = a.

The magnetic field strength, $B_{\mathrm{AD}}(x, y, z)$, created by current I flowing through segment AD at point M(x, y, z) is determined by the following equation [3]:

$$B_{\mathrm{AD}}(x, y, z) = \frac{\mu_0}{4\pi} I \frac{\cos\alpha - \cos\beta}{r_0}, \tag{1}$$

where r_0 is the distance from point M(x, y, z) to segment AD.

The magnetic induction vector B_{AD} is directed at an angle γ to the Oz axis.

Based on Fig. 2, the following relationships are derived:

$$-\cos\beta = \frac{y + \frac{b}{2}}{\sqrt{\left(x + \frac{a}{2}\right)^2 + \left(y + \frac{b}{2}\right)^2 + (z-h)^2}}, \tag{2}$$

$$\cos\alpha = \frac{\frac{b}{2} - y}{\sqrt{\left(x + \frac{a}{2}\right)^2 + \left(y - \frac{b}{2}\right)^2 + (z-h)^2}}, \tag{3}$$

$$\cos\gamma = \frac{x + \frac{a}{2}}{\sqrt{\left(x + \frac{a}{2}\right)^2 + (z-h)^2}}. \tag{4}$$

The NCMIV $B_{\mathrm{AD}z}$ generated by the electric current flowing through segment AD is determined by the following equation:

$$B_{\mathrm{AD}z}(x, y, z) = B_{\mathrm{AD}}(x, y, z)\cos\gamma. \tag{5}$$

The NCMIV arising from the electric currents within segments DC, CB, and BA are determined in the same way.

The NCMIV produced by the electric current I flowing through a strip of width dh at a height h above PM is the sum of NCMIVs generated by the currents within segments AD, DC, CB, and BA:

$$B_{hz}(x, y, z) = B_{\mathrm{AD}z}(x, y, z) + B_{\mathrm{DC}z}(x, y, z) + B_{\mathrm{CB}z}(x, y, z) + B_{\mathrm{BA}z}(x, y, z). \tag{6}$$

In the following, the AD, DC, CB, and BA symbols denote the PB side surfaces containing corresponding segments.

Taking into account Eqs. (1)–(6), the formula for calculating the normalized NCMIV of the electric current on the side surface AD is derived as follows:

$$\begin{aligned}\frac{4\pi}{\mu_0\lambda}\int_0^H B_{\mathrm{AD}z}(x,\ y,\ z)dh = &\left(\arcsin\frac{\alpha_{11}z}{\sqrt{(\alpha_{11}^2+\beta_1^2)(\beta_1^2+z^2)}} - \arcsin\frac{\alpha_{11}(z-H)}{\sqrt{(\alpha_{11}^2+\beta_1^2)(\beta_1^2+(z-H)^2)}}\right) + \\ &+\left(\arcsin\frac{\alpha_{12}z}{\sqrt{(\alpha_{12}^2+\beta_1^2)(\beta_1^2+z^2)}} - \arcsin\frac{\alpha_{12}(z-H)}{\sqrt{(\alpha_{12}^2+\beta_1^2)(\beta_1^2+(z-H)^2)}}\right),\end{aligned} \tag{7}$$

where $\alpha_{11} = \frac{b}{2} - y,\ \ \alpha_{12} = \frac{b}{2} + y,\ \ \beta_1 = x + \frac{a}{2}.$

The normalized MFPM NCMIV, $B_{z\,\mathrm{n}}(x, y, z)$, equals the sum of the normalized NCMIVs of all electric currents on the PM side surfaces. Taking into account (7), we obtain the following:

$$B_{z\,\mathrm{n}}(x, y, z) = \sum_{i=1}^{4}\left(\left(\arcsin\frac{\alpha_{i1}z}{\sqrt{(\alpha_{i1}^2+\beta_i^2)(\beta_i^2+z^2)}} - \arcsin\frac{\alpha_{i1}(z-H)}{\sqrt{(\alpha_{i1}^2+\beta_i^2)(\beta_i^2+(z-H)^2)}}\right) + \right.$$
$$\left. + \left(\arcsin\frac{\alpha_{i2}z}{\sqrt{(\alpha_{i2}^2+\beta_i^2)(\beta_i^2+z^2)}} - \arcsin\frac{\alpha_{i2}(z-H)}{\sqrt{(\alpha_{i2}^2+\beta_i^2)(\beta_i^2+(z-H)^2)}}\right)\mathrm{sign}(\beta_i)\right), \quad (8)$$

where $\alpha_{11} = \frac{b}{2} - y$, $\alpha_{12} = \frac{b}{2} + y$, $\beta_1 = x + \frac{a}{2}$ (for AD); $\alpha_{21} = x + \frac{a}{2}$, $\alpha_{22} = \frac{a}{2} - x$, $\beta_2 = y + \frac{b}{2}$ (for DC); $\alpha_{31} = y + \frac{b}{2}$, $\alpha_{32} = \frac{b}{2} - y$, $\beta_3 = \frac{a}{2} - x$ (for CB); $\alpha_{41} = \frac{a}{2} - x$, $\alpha_{42} = \frac{a}{2} + x$, $\beta_4 = \frac{b}{2} - y$ (for BA).

The NCMIV of the electric current on the CB side surface changes sign at $x > \frac{a}{2}$, similar to the NCMIV of the electric current on the BA side surface at $y > \frac{b}{2}$. The change of NCMIV signs is taken into account by the function.

Since the function $B_{z\,\mathrm{n}}(x, y, z)$ is even with respect to both x and y coordinates, determining its distribution within a specified plane only requires evaluating it in one quarter as limited by the inequalities $0 \le x$ and $0 \le y$. To simplify $B_{z\,\mathrm{n}}(x, y, z)$ for further investigations, formula (8) is decomposed into a Taylor series. The analysis indicates that formula (8) can be replaced by the more concise and computationally efficient NCMIV analytical model as follows:

$$B_{z\,\mathrm{n.anal}}(x, y, z) = \begin{cases} B_{z\,\mathrm{n}}(0, 0, z)\left[\left(\frac{y}{y_{\max}}\right)^2 - 1\right]^2\left[\left(\frac{x}{x_{\max}}\right)^2 - 1\right]^2 & \text{at } |x| \le x_{\max},\ |y| \le y_{\max}, \\ 0 & \text{at } |x| > x_{\max},\ |y| > y_{\max}, \end{cases} \quad (9)$$

where $x_{\max}$, $y_{\max}$ are the “dimensions” of the magnetic field in the plane z = const, i.e., the coordinates $x_{\max}$, $y_{\max}$, which depend on the coordinate z, are chosen so that the MFPM NCMIV becomes equal to zero in the region $|x| \ge x_{\max}$, $|y| \ge y_{\max}$ of the plane z = const.

In Fig. 3, the graphs of the dependencies of the normalized MFPM NCMIV, $B_{z\,\mathrm{n}}(x, y, z)$, in the plane z = 13 mm are presented as a function of the x-coordinate at various y-coordinate values, with the following PM parameters: $a = b = 16$ mm, $H = 8$ mm. The values of $B_{z\,\mathrm{n}}(x, y, z)$ are calculated using the exact formula (8) for graphs *1*, *2*, and *3* and formula (9) for graphs *4*, *5*, and *6*.

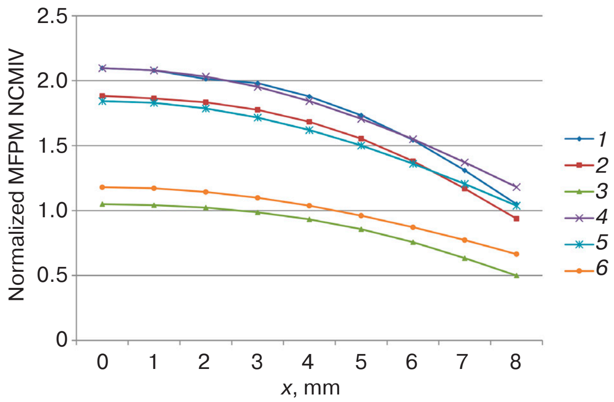

Fig. 3. Graphs of the normalized MFPM NCMIV: *1* is $B_{z\,\mathrm{n}}(x, 0, 13)$, *2* is $B_{z\,\mathrm{n}}(x, 4, 13)$, *3* is $B_{z\,\mathrm{n}}(x, 8, 13)$, *4* is $B_{z\,\mathrm{n.anal}}(x, 0, 13)$, *5* is $B_{z\,\mathrm{n.anal}}(x, 4, 13)$, and *6* is $B_{z\,\mathrm{n.anal}}(x, 8, 13)$

The analysis reveals a significant difference between the calculation results using the exact formula (8) and those using the approximation formula (9) for points in the plane with coordinates $x \ge 6$ mm, $y \ge 6$ mm. The relative error, δ, of the MFPM NCMIV calculations based on the analytical model belongs to the segment $15\% \le \delta \le 33\%$.

For points on the plane with coordinates $x \le 6$ mm, $y \le 6$ mm, the relative error δ is less than 15%. Moreover, for points on the plane limited by the inequality $r \le 4$ mm, where r is the distance between the coordinate system origin and the point on the plane, the relative error is $\delta \le 3.8\%$; for points of the plane limited by the inequality $r \le 2$ mm, the relative error is $\delta \le 2.6\%$.

The parameters of the useful signal of the measuring system, including its amplitude and time-dependent shape over its duration, are determined by the rate of change of magnetic fluxes within coils 1 and 2 when the center of coil 2 is above the center of PM cross-section. Since the magnetic fluxes and the rate of their changes are primarily determined by the central part of the MFPM NCMIV as represented by the points in the plane with coordinates limited by the inequalities $x \leq 6$ mm and $y \leq 6$ mm, the error in calculating the useful signal parameters in this case is minimal.

At high values of the MFPM NCMIV coordinates, the MFPM peripheral part decreases rapidly, while the rate of change of the magnetic fluxes determined by the MFPM peripheral part is less than that determined by the MFPM central part.

Error estimations derived from NCMIV calculations employing the approximation formula (9) reveal the potential of the analytical NCMIV model for creating an analytical model for the useful signal of the measuring system. This analytical model achieves a calculation error for useful signal values not exceeding 15%.

CONCLUSIONS

Based on the results of the research, the following can be deduced:

1. An analytical formula for calculating the NCMIV of the parallelepiped-shaped MFPM, which is oriented perpendicular to a specified plane aligned with the PM end face, has been derived by applying the equivalent solenoid technique.
2. The obtained expression for the NCMIV analytical model enables straightforward calculations of the magnetic fluxes within coils 1 and 2.
3. The feasibility of applying the NCMIV analytical model to theoretically develop an analytical model for the useful signal of the measuring system with inductive signal transmission is confirmed.

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