Analysis of magnetic characteristics of a brushless DC motor taking into account the distribution of magnetization

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ANALYSIS OF MAGNETIC CHARACTERISTICS OF A BRUSHLESS DC MOTOR TAKING INTO ACCOUNT THE DISTRIBUTION OF MAGNETIZATION

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ABSTRACT

Magnetic characteristics of a brushless d.c. motor have been analyzed taking into account the magnetization distribution in the rotor magnet. The magnetization is calculated taking into account the magnetizing process of a magnet. This paper describes a method for calculating the magnetization in the magnet, and the effects of the pattern of magnetization distribution and the shape of the coil on torque ripples. The calculated results are in good agreement with the results measured. Because of the flux distribution and the torque characteristics can be calculated, the optimum design of the brushless d.c. motor will be possible without a trial manufacture.

1. INTRODUCTION

In order to miniaturize a brushless d.c. motor and to decrease its torque ripple, it is necessary to know accurately the flux distribution in the motor. The magnetization distribution in the rotor magnet, however, was unknown, because the analysis of 3D magnetic field in a magnetizer for the rotor magnet was difficult. Therefore, the precise analysis of magnetic field could not be anticipated. Moreover, the shape of the coil of the motor is generally three-dimensional, and interlinkage flux of the coil varies with the rotation of the rotor magnet. Therefore, it was difficult to predict the torque ripple, which is a function of the rotor position.

Several methods have been reported for the analysis of similar types of motors. In scalar potential method[2], it is difficult to analyze magnetic field produced by an exciting coil of the magnetizer, because the scalar potential cannot be defined in the current region. On the other hand, in the integral equation method[3], the calculation becomes very much complicated. Therefore, the FEM using magnetic vector potentials is used to analyze the magnetic fields of the magnetizer and the motor, because the magnetic field produced by an exciting coil can be analyzed using the magnetic vector potential. Then, a new method for calculating magnetization distribution in the rotor magnet is developed by modifying the conventional finite element method, which represents magnetic fields by Fourier series[4]. The magnetization distribution in the rotor magnet is calculated taking into account the magnetizing process of magnets. The torque characteristics can be estimated from the 3D flux distribution, which is calculated using the magnetization.

In this paper, the new method is explained, and the effects of the pattern of magnetization distribution and the shape of the coil on torque ripples are described. The validity of the analysis is clarified by comparing calculated results with measured ones.

2. BRUSHLESS DC MOTOR AND MAGNETIZER

Figure 1 shows the analyzed brushless d.c. motor for a 3.5-inch floppy disc drive. The motor has six coils and is driven by a three-phase switching circuit.

Figure 2 shows the cross section of the rotor. The rotor magnet is magnetized by a magnetizer shown in Fig.2. Figure 2(c) denotes the cross section on the line $\theta=0$ in Fig.2(b). The magnetizing coil is made of copper. The pole pieces and the yoke are made of soft iron. The peak value of the impulse current $I_0$ is 6000 A.

The effects of three kinds of patterns of magnetization distribution denoted in Fig.3 on the torque ripples are investigated. The central angle $\theta$ of the coil shown in Fig.1(a) is varied from $24^\circ$ to $36^\circ$ in order to analyze the effects of the shape of the coil on the torque ripple. Coil width $W$, shown in Fig.1(a), is varied with angle $\theta$ in order to obtain a maximum torque in a limited space. Table 1 shows the relationships among coil width $W$, the number of turns $N$ per coil and angle $\theta$ of the coil.

3. METHOD OF ANALYSIS

Magnetic fields with permanent magnets can be represented by the following Poisson's equation:

$$\nabla \times (\nabla \times A) = J + \nabla \times \rho \nabla \times M$$

(1)

where $\nabla$, $J$ and $M$ are the vector potential, the current density and the magnetization. $\nabla$ and $\rho \nabla$ are the reluctivities of iron and air respectively.

As the magnetic field in the brushless d.c. motor varies periodically in the $\theta$-direction, $\nabla$, $J$ and $M$ can be represented by Fourier series as follows:

$$A_\theta = \frac{1}{2} \left[ A_{\theta,1} \cos \theta + A_{\theta,2} \cos 2\theta + \cdots + A_{\theta,n} \cos n\theta \right] + B_{\theta,1} \sin \theta + B_{\theta,2} \sin 2\theta + \cdots + B_{\theta,n} \sin n\theta$$

$$J_\theta = \frac{1}{2} \left[ J_{\theta,1} \cos \theta + J_{\theta,2} \cos 2\theta + \cdots + J_{\theta,n} \cos n\theta \right] + B_{J,1} \sin \theta + B_{J,2} \sin 2\theta + \cdots + B_{J,n} \sin n\theta$$

$$M_\theta = \frac{1}{2} \left[ M_{\theta,1} \cos \theta + M_{\theta,2} \cos 2\theta + \cdots + M_{\theta,n} \cos n\theta \right] + B_{M,1} \sin \theta + B_{M,2} \sin 2\theta + \cdots + B_{M,n} \sin n\theta$$

where $A_{\theta,n}$, $B_{\theta,n}$, $J_{\theta,n}$, $B_{J,n}$, $M_{\theta,n}$ and $B_{M,n}$ are the Fourier coefficients of $A_\theta$, $B_{\theta,n}$, $J_\theta$, $B_{J,n}$, $M_\theta$, and $B_{M,n}$ respectively.
The magnetic field, which varies periodically in the $\theta$-direction, can be calculated from Eqs. (3) and (4) by treating $A_{m}$ and $A_{0n}$ as unknown values. If the magnetic characteristics of iron are represented by Eq. (5), the pole piece can be treated as a magnet.

$$B = \frac{H}{\nu_0 + M}$$

where $H$ is magnetic field intensity.

In the hatched part of Fig. 2(c), the pole piece and the magnetizing coil are set alternately in the $\theta$-direction. Therefore, it can be assumed that flux density $B$ and magnetization $M$ in the pole piece can be represented by a square wave, as shown in Fig. 4. Although the value of magnetization $M$ in the pole piece is unknown, the calculation is made possible by introducing the iteration technique.

From the 3D flux distribution data obtained, variation of torque with rotor position was calculated taking into account the complicated structure of the coil of the motor. The torque of the motor is calculated by dividing a coil into small parts and multiplying flux density, the current, the coil length and the radius in each part.

Magnetization $M$ in the magnet is determined taking into account the magnetizing process of the magnet.[5]

### 4. RESULTS AND DISCUSSIONS

Figure 5 shows the magnetization distribution at point $Q$ denoted in Fig. 1(b).

| Table 1 Relationship among central angle $\alpha$, number of turns $N$ and coil width $W$. |
|---------------------------------|-----|-----|
| Central angle $\alpha$ (deg.)  | 24  | 30  | 36  |
| Number of turns $N$ (turn)     | 610 | 490 | 290 |
| Coil width $W$ (mm)            | 6.0 | 4.8 | 2.8 |

Figure 6 shows the calculated and measured flux densities $B_r$, $B_\theta$ and $B_z$ at point $P$ denoted in Fig. 1(b). The flux density is measured by a Hall sensor. In
In this case, the stator yoke shown in Fig.1(b) is removed in order to perform the experiment in an easy manner. Because the rotor magnet is magnetized in 10 poles, north and south poles oppose each other with respect to the z-axis as shown in Fig.2(b). Accordingly, there exists z-directional component $B_r$, Fig. 7 shows the torques. The torque is measured using a strain gauge. The calculated results agree well with the results measured.

Figure 8 shows the effects of the pattern of magnetization distribution denoted in Fig. 3 on the flux distributions and torque characteristics. The torque becomes a maximum value in the case of the square-wave magnetization, because the flux produced by the magnet reaches a maximum.

Let us define a torque ripple rate $\varepsilon$ by

$$\varepsilon = \frac{\text{maximum torque} - \text{minimum torque}}{\text{average torque}} \times 100(\%)$$

(6)

![Fig.6 Flux distributions at a point P (a=30°).](image)

![Fig.7 Torque characteristics.](image)

(a) flux distributions at a point P

(b) torque characteristics

![Fig.8 Effects of the pattern of magnetization distribution(calculated,a=30°).](image)

The values of $\varepsilon$ are 14.3(%), 14.0(%) and 14.1(%), for square-, trapezoidal- and cosine-wave magnetizations, respectively. The pattern of magnetization distribution does not affect torque ripple significantly. Therefore, it can be said that square-wave magnetization is the most suitable for a brushless d.c. motor.

Figure 9 shows the effects of the central angle $a$ on the torque characteristics. In this case, the magnet has square-wave magnetization. The values of $\varepsilon$ are 15.0(%), 14.3(%) and 16.5(%) when $a$ is 24°, 30° and 36°, respectively. The torque with the maximum amplitude and minimum ripple can be obtained when the angle $a$ is 30°.

![Fig.9 Effects of the shape of coil (square wave magnetization).](image)

5. CONCLUSIONS

A precise simulation of torque characteristics of a brushless d.c. motor has become possible by taking into account the magnetization distribution in the rotor magnet. As the effect of the pattern of magnetization distribution and the shape of the coil on flux distributions and torque ripples can be calculated without repeating a trial manufacture, the optimum design of the motor will be possible.

As the coil shape is a function of the central angle, number of turns and coil width, it is not easy to differenciate various reasons for torque ripples. The paper which discusses such reasons will be reported later.

It is hoped that our method will clarify the detailed behaviour of fluxes and torques of other motors such as core-less motors, linear motors, etc. This method also gives useful suggestions for the optimum design of brushless d.c. motors.

REFERENCES


