A Principle and Winding Design of Consequent-Pole Bearingless Motors*

Tomohiro TAKENAGA**, Yutaka KUBOTA**,
Akira CHIBA** and Tadashi FUKAO***

Recently, bearingless motors have been developed to enhance motor drive systems with magnetic suspension. Several types of motors have been proposed as bearingless motors, such as induction, surface mounted permanent magnet, inset permanent magnet, interior permanent magnet, buried permanent magnet, homopolar, hybrid, and switched reluctance bearingless motors. Permanent magnet bearingless motors have been attracting more interests in these years because of the high efficiency. In this paper, a consequent-pole bearingless motor is proposed. A rotor has buried permanent magnets, of which polarities are like. The radial force of a consequent-pole bearingless motor is generated by dc current. Thus, rotational angular position is not needed in a magnetic suspension controller. Radial force variations caused by a rotor rotation are minimized by improving arrangement of stator suspension conductors. A prototype bearingless motor and its controller are built. In experiment, principles of magnetic suspension in the proposed consequent-pole bearingless drive are confirmed.

Key Words: Bearingless Motor, Magnetic Bearing, Magnetic Suspension, Consequent Pole

1. Introduction

Recently, bearingless motors, these are an electro-magnetically integration of a magnetic bearing and a motor, have been developed in several countries. In permanent magnet bearingless motors, various types have been proposed. For example, surface mounted permanent magnet⁽¹⁾⁻⁽³⁾, inset permanent magnet⁽⁴⁾, buried permanent magnet^{(5),(6)}, interior permanent magnet, homopolar⁽⁷⁾, hybrid⁽⁸⁾ and etc. However, the most of these permanent magnet bearingless motors need a rotor rotational angular position in a feedback magnetic suspension controller. If the field rotational position has a significant error, the magnetic suspension loop may not be stable. In homopolar and hybrid motors, a magnetic suspension

controller does not need an exact angular position of magnetic field. These bearingless motors have axial flux flow, thus, suitable for more than 4-axis active magnetic suspension.

In this paper, a new bearingless motor is proposed. The proposed machine is originated from a consequent-pole permanent magnet motor. Radial force is generated by dc current like homopolar and hybrid PM motors, although the axial flux flow does not exist. High reluctance and trade off problems in permanent magnet bearingless motors are avoided. Rather thick permanent magnets are preferred for both torque and radial force generation. There is no trade off in a PM thickness and MMF requirements in suspension windings. In this paper, a previous paper⁽⁹⁾ written in Japanese is briefly summarized and some new FEM and experimental results are included.

2. Principle of Consequent-Pole Motor

Figure 1 shows a cross section of rotor and stator cores of a consequent-pole bearingless motor. Four permanent magnets, indicated by bold lines, are buried in a rotor iron. Polarities of the permanent magnets

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** Department of Electrical Engineering, Faculty of Science and Technology, Tokyo University of Science, 2641 Yamazaki, Noda, Chiba 278-8510, Japan. E-mail: chiba@ee.noda.tus.ac.jp

*** Department of Electrical Engineering, Faculty of Technology, Musashi Institute of Technology, Japan

Fig. 1 A cross section of rotor and stator cores, and rotor permanent magnets

Fig. 2 Flux plots with torque current in motor windings

are unique. The permanent magnets are pre-magnetized in the same radial direction. All permanent magnets are polarized so that the outside and inside are N and S poles, respectively. Bold arrows represent flux flow generated by permanent magnets. The flux goes across the airgap, the stator tooth, the stator yoke, then, neighboring stator tooth, airgap, a rotor iron pole, and then returns to the permanent magnets. Thus, the iron poles between permanent magnets are consequently magnetized as S-pole, because the flux enters in the rotor iron pole. Thus, this motor is called as a consequent-pole motor⁽¹⁰⁾. This motor has totally 8 poles, i.e., four permanent magnet poles and four consequently magnetized iron poles.

Figure 2 shows flux flow with torque current in

Fig. 3 Radial force generation at $\phi_m = 0$ deg

motor windings. Motor winding is arranged as 8-pole 3-phase windings, indicated by $8u$, $8v$, and $8w$. In the figure, a rotor rotational angular position is 0 deg. Rotor rotational angular position ϕ_m is defined in counter clockwise direction. In this situation, torque is generated with zero u -phase current, positive v -phase current, and negative w -phase. In the flux plots, one can see that flux densities of stator teeth are unbalanced in comparison to the Fig. 1, then, torque is generated in counter clockwise direction.

3. Principle of Radial Force Generation

In a consequent-pole bearingless motor, a principle of radial force generation is different from conventional bearingless motors. Figure 3 shows a principle of radial force generation at a rotor rotational angular position $\phi_m = 0$ deg. Suspension conductors N_x and N_y are arranged in 2-pole 2-phase windings. The N_x indicates suspension conductors in order to generate radial force in the x -axis direction. The winding N_y is for the y -direction radial force. Then, eight loops Ψ_m indicated by broken line show representative permanent magnet flux paths. Solid line loops Ψ_x show suspension flux paths generated by positive current in N_x suspension winding. Radial force is generated by an interaction between PM and suspension fluxes. In the airgaps 2 and 8, the flux densities are increased as indicated by "dense". However, in the airgaps 4 and 6, the flux densities are decreased, as indicated by "sparse". Therefore, radial force is generated in the x -axis direction. If negative direction current is supplied in N_x -winding, then, negative radial force is generated. The y -axis radial force is generated by N_y -winding current.

Note that suspension flux paths Ψ_x does not go across the permanent magnets. In the rotor, it goes through rotor iron poles. Thus, magnetic reluctance in the suspension flux loop is low. It is obvious that low MMF is needed in radial force generation.

Figure 4 shows a principle of radial force generation at a rotor rotational angular position $\phi_m = 45$ deg. Corresponding to the rotor position, permanent magnet flux paths Ψ_m are rotated by 45 deg. The suspension fluxes Ψ_x go through rotor iron poles because the reluctance is low. The flux densities in the airgaps 1 and 5 are increased and decreased, respectively. Therefore, radial force is generated in the x -axis direction. Note that the direction of radial force is still despite of a rotor rotation. One may notice that radial force generation is similar to homopolar and hybrid type bearingless motors.

4. Radial Force Variation

Figure 5 shows a FEM analysis model. In the analysis, only the dc current is supplied in N_x -winding. Then, radial force is supposed to be generated in the x -axis direction. Suspension conductors occupy two continuous stator slots with four series winding in one slot. Under this condition, a series of FEM analysis is carried out with a rotor rotation in a step of 5 deg from 0 deg up to 90 deg. A typical FEM analysis model has 40 000 elements and 20 000 nodes in 2-dimensional plain. A commercially available package Opera-2d is employed.

Figures 6(a) and (b) show a result of a series of FEM analysis at 3A in the N_x -winding. Figure 6(a) shows x - and y -axis radial forces F_x and F_y . The horizontal axis is a rotor rotational angular position

ϕ_m . It is seen that F_x is almost constant, however, F_y is not always zero. Ideally, F_y should be zero at any ϕ_m . In the analysis, the F_y is zero only at $\phi_m = 0$ deg, 45 deg and 90 deg.

Figure 6(b) shows the radial force direction ϕ_f . The ϕ_f is given by

$$\phi_f = \tan^{-1} \left(\frac{F_y}{F_x} \right) \quad (1)$$

The largest value of ϕ_f is about 22.8 deg at $\phi_m =$

Fig. 5 FEM analysis model

(a) Radial forces in two-perpendicular axis

(b) Radial force direction

Fig. 6 Result of analysis

Fig. 4 Radial force generation at $\phi_m = 45$ deg

22.5 deg and 67.5 deg. This value of ϕ_f is not very acceptable in stable suspension positioning. In general, dynamic stiffness becomes inferior if ϕ_f is increased. In experimental view, ϕ_f should be less than several degrees.

Figures 7(a), (b) and (c) show flux plots obtained from FEM analysis at $\phi_m=0$ deg, 45 deg and 22.5 deg, respectively. The permanent magnets are assumed to be the air to see flux path exciting N_x -winding. Bold arrows represent flux flow caused by the permanent magnets. Thin arrows represent suspension flux flow.

In Figs. 7(a) and (b), the flux flow is symmetrical with respect to the x -axis. Thus, radial force is generated only in the x -axis direction. In Fig. 7(c), the flux plot of suspension and PM is not symmetrical to the x -axis. The forces F_1 and F_2 are generated at the rotor iron poles. The resulted radial force F is not aligned to the x -axis. Consequently, the resultant force F is inclined with respect to the x -axis.

5. Suspension Conductor Arrangement

Figures 8(a) and (b) show alternative arrangements of stator suspension conductors. In Fig. 8(a), the suspension conductors are distributed in 4 continuous slots. In Fig. 8(b), the suspension conductors are arranged as 3-phase windings. The N_u , N_v and N_w are u -, v - and w -phase windings.

The winding currents i_u , i_v and i_w are determined by the transformation from 2-phase to 3-phase matrix as,

$$\begin{bmatrix} i_u \\ i_v \\ i_w \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_x \\ i_y \end{bmatrix} \quad (2)$$

Suspension conductor arrangements in 2-slot, 4-slot and 3-phase conductor arrangements are hereafter referred as windings A, B and C, respectively.

Figure 9 shows the direction of radial force for three conductor arrangements. The largest value of ϕ_f is 13.0 deg and 3.3 deg in winding B (4 slots) and winding C (3-phase), respectively. Thus, significant reduction in radial force variations is realized by 3-phase winding arrangement. A reason of the improvement can be understood from harmonic analysis in MMF space distribution.

Table 1 shows representative MMF harmonics for winding A, B and C. The third and higher harmonic components are reduced in 3-phase suspension conductors. Therefore, the radial force variations are decreased.

(a) Flux flow at $\phi_m=0$ deg

(b) Flux flow at $\phi_m=45$ deg

(c) Flux flow at $\phi_m=22.5$ deg

Fig. 7 Flux flow at various rotor positions

(a) Suspension conductor arrangement B

(b) Suspension conductor arrangement C

Fig. 8 Suspension conductor arrangements

Fig. 9 Direction of radial force and conductor arrangements

6. Experimental Results

Figure 10 shows a picture of a rotor in a prototype machine. All permanent magnets, polarized as

Table 1 Harmonics included in the suspension winding of A, B and C

	fundamental	third	fifth
A	100%	31.1%	16.0%
B	100%	22.7%	4.3%
C	100%	0%	4.3%

Fig. 10 A rotor of a prototype machine

Fig. 11 A prototype machines

shown in figure, are inserted into a laminated silicon steel stack. There are four permanent magnets, with a thickness of 5 mm and an axial length of 50 mm. Figure 11 shows a prototype machine. The front machine is a consequent-pole bearingless motor, of which shaft is connected to a torque meter. The torque meter is connected to an induction generator.

Figure 12 shows the system configuration of the prototype machine. The upper part shows the magnetic suspension side. The displacements x and y are detected by the displacement sensors. The detected displacement errors are amplified in the PID controllers. Thus, suspension current commands in 2-phase are transformed into 3-phase. The inverter is

Fig. 12 System configuration

Fig. 13 Current reference with respect to ϕ_m

controlled by the 3-phase current commands to supply the suspension winding currents. The lower side shows the electric motor side. The speed is controlled by the PI controller detecting the rotor rotational angular speed with a rotary encoder.

In experiment, a reference value of i_x^* and i_y^* are measured with a rotor rotation in a step of 15 deg from 0 deg up to 360 deg at stand still. The i_x^* and i_y^* are the reference current values in the x - and y -magnetic suspension loops. The values of i_x^* and i_y^* are automatically developed in PID controllers.

Experiments are carried out with and without external 3 kgf radial force applied to a shaft through a spring in the x -axis. Figure 13 shows measured current references at zero and 3 kgf. One can see dc offset in i_x^* at 0 kgf and 3 kgf. The i_y^* plots are not influenced by the external force. In addition, sinusoidal variations are seen with respect to a rotor rotational angular position. These variations are originated from magnetic pull force mainly caused by unalignments of a rotor core, a shaft, and a sensor target ring.

In order to eliminate the influenced of the unalign-

Fig. 14 Difference of current reference with respect to ϕ_m

ment, a difference of current commands at 0 kgf and 3 kgf are plotted in Fig. 14. It is clear that the difference of current reference i_x^* is generated almost at constant value. And i_y^* is almost zero. It is shown that suspension radial force is not very depending on a rotor rotational angular position.

7. Conclusion

A principle and winding design of a consequent-pole bearingless motor are proposed. In the analysis, it is shown that the radial force variations caused by a rotor rotation is minimized by proper conductor arrangement in suspension winding. In experiment, a principle is confirmed. Characteristics under torque generating conditions will be presented in the future study.

References

- (1) Ooshima, M., Miyazawa, S., Chiba, A., Nakamura, F. and Fukao, T., Performance Evaluation and Test Results of a 11 000 r/m, 4 kW Surface-Mounted Permanent Magnet-Type Bearingless Motor, ISMB, August 23-25, (2000), pp. 377-382, ETH Zurich.
- (2) Oguri, K., Watada, M., Torii, S. and Ebihara, D., Design Optimization of Magnetic Bearing Composed of Permanent Magnets for the Bearingless Motor, International Symposium on Magnetic Bearings, August 23-25, (2000), pp. 365-370, ETH Zurich.
- (3) Steele, B. and Stephens, L., A Test Rig for Measuring Force and Torque Production in a Lorenz, Slotless Self Bearing Motor, ISMB, August 23-25, (2000), pp. 407-412, ETH Zurich.
- (4) Inagaki, K., Chiba, A., Rahman, M.A. and Fukao, T., Performance Characteristics of Inset-Type Permanent Magnet Bearingless Motor Drives, PESWM, January 23-27, (2000), Singapore.
- (5) Ooshima, M., Miyazawa, S., Shima, Y., Chiba, A., Nakamura, F. and Fukao, T., Increase in Radial Force of a Bearingless Motor with Buried Permanent Magnet-Type Rotor, Proceedings of the Fourth International Conference on MOVIC,

- Vol. 3 (1998), pp. 1077-1082.
- (6) Fujie, N., Yoshimatsu, R., Chiba, A., Ooshima, M., Rahman, M.A. and Fukao, T., A Decoupling control Method of Buried Permanent Magnet Bearingless Motors Considering Magnetic Saturation, IPEC-Tokyo, (2000), S-10-6, pp. 395-400.
 - (7) Ichikawa, O., Chiba, A. and Fukao, T., Principles and Structures of Homopolar Type Bearingless Motors, IPEC-Tokyo, (2000), pp. 401-406.
 - (8) Kim, S.-J., Shimonishi, T., Kanebako, H. and Okada, Y., Design of a Hybrid-Type Short-Span Self-Bearing Motor, ISMB, August 23-25, (2000), pp. 359-364, ETH Zurich.
 - (9) Kubota, Y., Takenaga, T. and Chiba, A., Consequent-Pole Type Bearingless Motors, IEEJ, SPC-01-102 IEA-01-45, in Ashikaga Oct., (in Japanese), (2001).
 - (10) Hendershot J.R. Jr. and Miller, T.J.E., Design of Brushless Permanent-Magnet Motors, (1994), Oxford Magna Physics.
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