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Analysis and Design of Bearingless Motor with Rectifier Circuit Coil Rotor

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In this paper, a feasibility study for a new type of bearingless motor is carried out by FEM analyses. The feature of the proposed bearingless motor is using a rotor with rectifier circuit coils. The optimum geometrical dimensions of the proposed bearingless motor are determined by comparing the rotor torques at various rotor tooth lengths. The dimension with which the motor has relatively minimum fluctuation and sufficient torque is chosen to build a test machine. In order to realize the radial forces control, a control currents arrangement is proposed. Finite Element Method (FEM) analyses are also used for evaluating the property of the proposed arrangement. The feasibility of the proposed bearingless motor has been verified by the analysis results.

Key Words: Bearingless motor, Rectifier circuit coil, FEM analysis.

1. Introduction

Bearingless motor mechanism has functions of both a magnetic bearing and a motor. It is therefore able to suspend the rotor and generate torque simultaneously. Bearingless motor has not only the advantages of magnetic bearing such as negligible friction loss, no wear, high reliability, low-maintenance, higher speed for extreme environment, and no need of complex lubrication, but also has a shorter shaft comparing with a shaft using both a conventional motor and a magnetic bearing. The critical rotating speed can be increased and its volume can be reduced. Bearingless motors can be used at some special fields such as artificial heart, high speed drives, and generators. Since bearingless motors have so many advantages and special applications, various types of bearingless motors have been developed [1].

From a view of motor types, permanent magnet (PM) bearingless motors are widely developed. Permanent magnet bearingless motors are more effective even with a relatively large air gap. It is helpful to reduce the motor volume using permanent magnet. However, for permanent magnets, there are also some disadvantages, such as demagnetization and limited mechanical strength [2].

Another type of bearingless motor has been proposed in [3]. The feature of the proposed motor is that there is a rectifier circuit in the rotor winding. And the feasibility analysis is carried out by means of simple numerical simulation. The proposed bearingless motor possesses some advantages, *e.g.* no demagnetization, much less rotor reluctance and higher mechanical strength. In this paper, further study results are presented, FEM analyses show that this structure can be put into practice.

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2. Principle of Proposed Bearingless Motor

An illustration of the rectified bearingless motor is shown in Fig.1. It has a four poles rotor and eight poles stator. Details of one set of rotor, stator and coils are illustrated in Fig. 2. In the figure, there are two sets of coils on the stator poles.

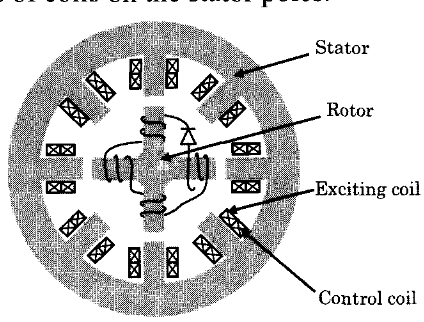

Fig. 1. Illustration of rectified bearingless motor

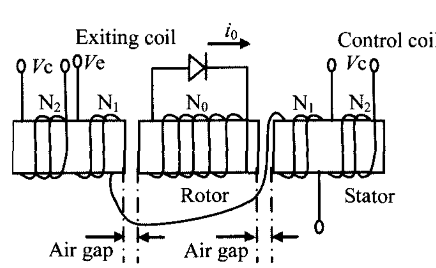

Fig. 2. Schematic of stator and rectified rotor

One set of coils is connected with the opposing stator coil in series. These coils are excited by AC current and called as exciting coils. Another set of coils is called as control coils and control coils are used to control the rotor torque and radial force.

In addition, one set of coils is wound on the rotor poles in series, and a rectifier diode is connected to the rotor winding circuits. When AC current is applied to the exciting coil, DC current will be induced in the rotor windings owing to the existence of the rectifier diode. Therefore, the magnetized rotor will hold a fixed polarity poles. Just like a permanent magnet.

Fig. 3 shows the simulation results of exciting voltage, induced rotor current and rotor flux. It can be seen that when AC current is applied to the exciting coil, DC current is induced in the rotor coil, and the rotor flux almost keeps constant, which validated our assumption.

The experimental results of radial force with respect to control current are given in Fig. 4. It can be seen that the radial force keeps a fixed direction at any control current when the exciting voltage is zero. However, when the exciting voltage is 6 volts, negative forces can be produced. It indicates that the existence of rectified coil makes the rotor hold a fixed polarity and have the characteristic of permanent magnet.

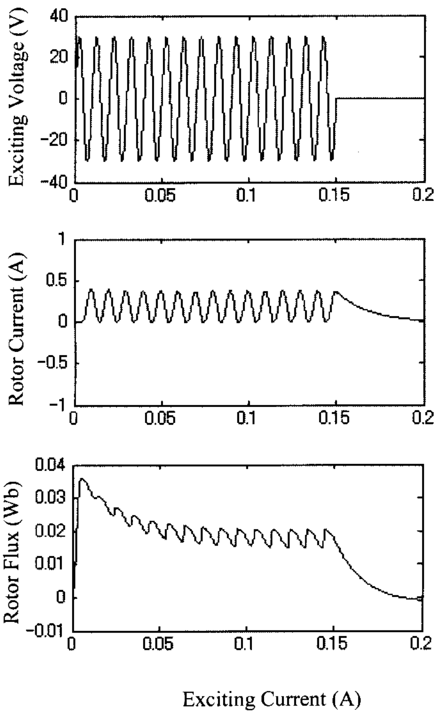

Fig. 3. Function of rectified circuit coil

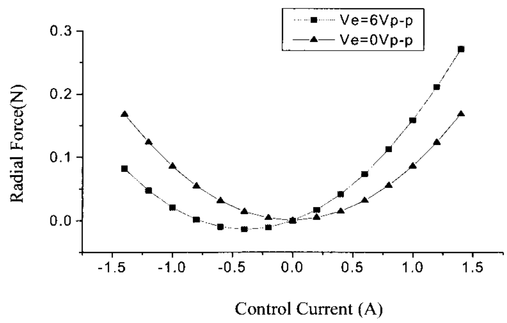

Fig. 4. Experimental results of radial force

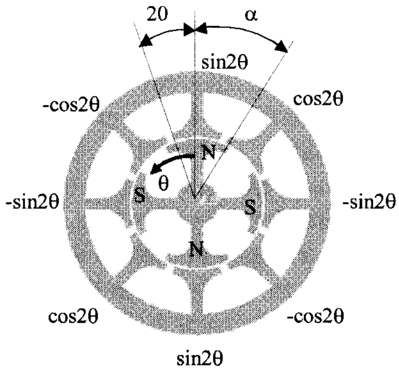

Fig. 5 Shape of rotor and stator and rotation strategy

Moreover, the rotor is made of silicon iron, whose reluctance is much less than that of permanent magnet and the demagnetization will not be caused. Adjusting the magnitude and directions of control current can control the radial force and the rotation torque and the motor can work just like a noncontact PM stepping motor.

3. Prototype Design and Analysis

3.1 Design of rectified bearingless motor

A prototype bearingless motor is designed as shown in Fig. 5. The radius of the rotor is determined as 60 mm. It is decided by easiness of treatment.

Maxwell force acting on the unit area dA of rotor outside surface can be expressed as

$$dF_M = \frac{B_n^{\ 2} dA}{2\mu_0} \tag{1}$$

In which, F_M is the radial force, B_n is the flux density of normal component in air gap, μ_0 is permeability of air.

According to (1), the shape of the stator and the rotor is determined to like an unfolded fan for the necessity of large area where faces each other.

Because induced current must be generated by mutual inductance that depends on the faced area. The angle of the stator tooth has 40 degrees, which is twice to 20 degrees shown in Fig. 5. This value is determined by the consideration for the widest stator tooth. The required angle for the gap to the next tooth is considered as at least 5 degrees. The angle of the rotor is indicated as α. The coils wound on the rotor and stator poles are identical to those shown in Fig. 1.

Since the shape of rectified bearingless motor has been decided, an optimum dimension α of the bearingless motor is desired so that a relatively large radial force and torque can be generated. Based on the assumption that the rotor is located at the geometrical centre of the motor and it is magnetized by uniform induced DC current, a series of FEM analyses have been carried out to determine α.

In order to rotate the rotors, the sine and cosine control current arrangement about the rotation angle is applied as shown in Fig. 5. In the figure, θ is the rotational angle of the rotor which rotates in counter clockwise. The rotor position in Fig. 5 indicates 0 degree. The torques at various angular position have been calculated when θ changes from 15 degrees to 40 degrees with the incremental angle being 5 degrees. These variations of α are corresponding to shorter, equal, and longer than the stator tooth length. Fig. 6 is an example of the flux distribution when θ is 30 degrees. It can be seen that much flux lines flow between the stator and adjacent rotor tooth.

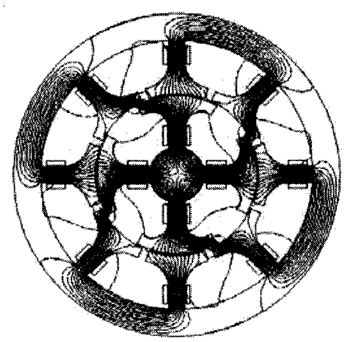

Fig. 6. Schematic of flux distribution at α of 30 degrees

For the symmetry configuration of the rotor and the stator, analyses of the rotor angle from 0 degree to 90 degrees have been examined. The results of torque are shown in Fig. 7. As shown in the figure, when the angle of the rotor tooth increases, the curve of the torque becomes flat. It can be found that a relatively large and smooth torque can be obtained when θ is equal to 30 degree. Thus, the 30 degrees

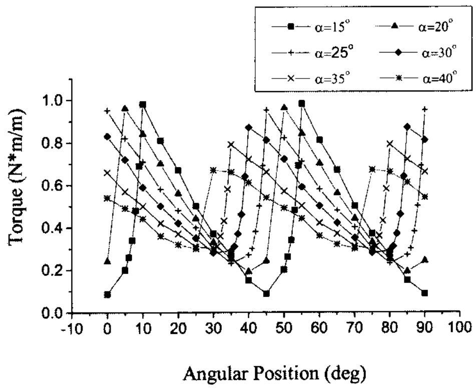

Fig. 7. Torques of various α about rotating angle

of α has been chosen for the prototype bearingless motor. It can also be seen that the torque approaches its maximum when the rotor polar front edge begins to overlap with the stator tooth face about all α.

3.2 Control current arrangement for radial force

In order to verify the validity of the control current arrangement for the radial force control, a series of FEM analyses has been carried out. The control current arrangement is determined as shown in Fig. 8. This arrangement is for the vertical force control (y direction). The radial forces and torques have been calculated about various rotor angular positions.

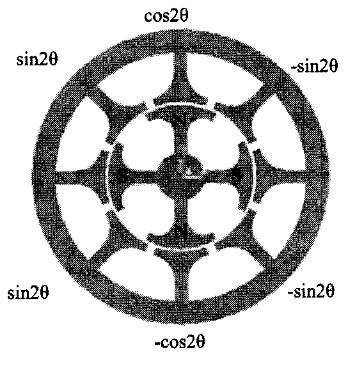

Fig. 8. Control current arrangement for vertical force

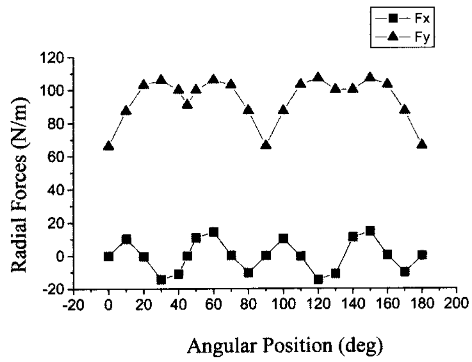

Fig. 9. Radial forces about rotor angular position

The results are shown in Fig. 9 and Fig. 10. From Fig. 9, it can be seen that the specified radial forces are about ten times to lateral forces. As a result, the radial forces can be guaranteed by the control currents shown in Fig. 8. Fig. 10 shows the torques when we applied the currents of the radial force. Torque values are small enough to be neglected comparing with the results shown in Fig. 7. For horizontal force, the identical control current arrangement can be applied.

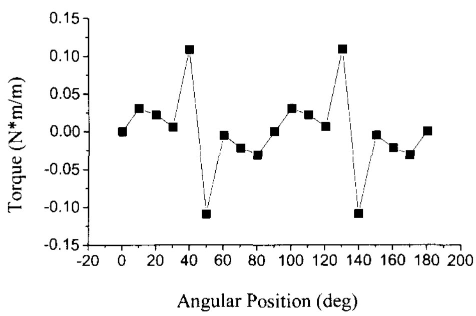

Fig. 10. Torque when control current arrangement for vertical force is applied

The superposition of the control current arrangement illustrated in Fig. 5 and Fig. 8 can be used to realize rotor rotation and vertical radial force control, meanwhile the superposition of the control current arrangements of the torques and horizontal force can be used to control the rotor rotation and horizontal radial force.

3.3 Linearity of input current and radial force

For levitation of a bearingless motor, constant suspension forces are desired. However, the radial forces fluctuate with the rotor angular positions shown in Fig. 9. This problem may be reduced by feedback control. Since feedback control is easy to be applied for a linear system, the linearity of input current and output force has been examined. For the control current arrangement of the vertical direction forces shown in Fig. 8, changing the constant k from 0 to 1 with the incremental value being 0.2, the radial forces in the vertical direction have been calculated.

The results of the forces about the angle are shown in Fig. 11 and the radial forces about the constant k are shown in Fig. 12. From Fig. 12, it can be seen that the radial force and the coefficient k have a proportional relationship. Which verified that a linear feedback control method could be adopted for levitation control.

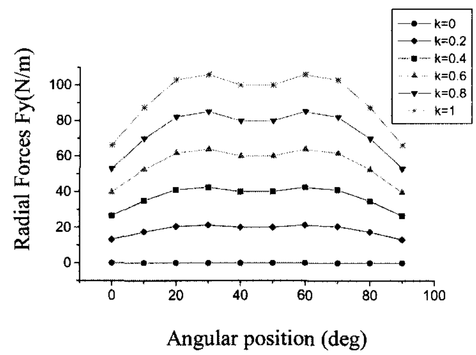

Fig. 11. Radial forces of various constant k about angle

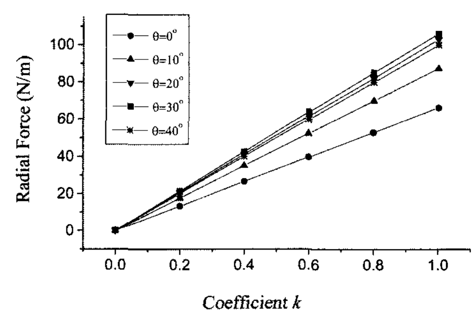

Fig. 12. Radial forces about constant k

4. Conclusion

For making the new type of bearingless motor, the dimensions of the motor has been decided and the feasibility of the designed motor has been investigated by FEM analyses. It has been verified that sufficient torque and radial force can be produced using this dimension. And for feedback control, linearity of the input currents and the output forces has been verified. These results indicate that the proposed bearingless motor with rectifier circuits can be realized.

Acknowledgment

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