Principle and Test Results of Energy-Saving Effect of a Single-Drive Bearingless Motor in Cooling Fan Applications

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This paper presents the energy-saving effect of a single-drive bearingless motor. In the single-drive bearingless motor, only the axial direction is actively positioned. The other radial and tilting directions are passively stabilized by repulsive passive magnetic bearings. Therefore, it has the advantages of low cost, absence of contact, maintenance-free and a long lifetime. In this paper, an additional advantage, an energy-saving effect, is verified. In experiments, the input power is measured with and without mechanical ball bearings. The bearingless motor can reduce the input power because the magnetic suspension power is low compared with the mechanical bearing loss. In addition, it is found that the efficiency can be improved.

Keywords: bearingless motor, single-drive, energy-saving effect, efficiency enhancement

1. Introduction

Bearingless motors have two functions of a rotating machine and a magnetic bearing. Therefore, the advantages are no wear, no lubricant, non-pollution, maintenance-free and long life-time because the rotor shaft is magnetically suspended without mechanical bearings. Thus, the bearingless motors have been studied for industry applications such as centrifugal pumps, contamination-free ventilator assist devices, high purity pharmaceutical mixing devices, compressors, rotating stages and flywheels(1)–(10).

In some cooling fan applications, the maintenance-free and long lifetime are required for operating 24 hours a day in data centers and super computers. Therefore, there are several research and developments to apply the bearingless motor in the fan motors(11)–(17). In addition, it is possible that the bearingless motor has energy-saving effect; the magnetic bearing loss is less than the ball bearing loss. The energy-saving is strongly required in the information devices such as blade servers in the data centers and super computers. Therefore, it is important to clarify the energy-saving effect in experiments. In (14), the magnetic suspension power at only 0 r/min was measured in the one axis-actively positioned magnetic bearing motor. In (15), the sum of input powers for rotating and the magnetic suspension was measured in a no-load test. In (14) and (15), the magnetic suspension power was discussed, however, the energy-saving effect was not verified. Therefore, the magnetic suspension power should be compared with a ball bearing loss.

In (18), the energy-saving effect of the bearingless motor in the fan application has been presented by the authors. The proposed single-drive bearingless motor in (19) has been fabricated to verify the energy-saving effect. In experiments, input powers are measured in the test machines with and without ball bearings. It is found that the magnetic suspension power is low compared with the ball bearing loss when the rotor rotational speed is higher than 3000 r/min. Therefore, it is verified that the bearingless motor has the energy-saving effect. In addition, the bearingless motor can enhance the efficiency.

This paper is an extended version of the previous paper(18). Based on the discussion in the ICEMS2016, the detailed description of the principle of the active axial force generation is included.

2. Basic Concept of Bearingless Motor

2.1 Replacement of Mechanical Bearings with Passive Magnetic Bearings and a Bearingless Motor

Figures 1(a) and 1(b) show a typical motor with ball bearings and a basic structure of the one-axis actively positioned bearingless motor, respectively. Generally, two mechanical ball bearings are installed in the typical motor. In the bearingless motor, the ball bearings are replaced with passive magnetic bearings, made of permanent magnets. In addition, a motor unit is replaced with a bearingless motor unit of one-axis active positioning. Radial and tilting directions are passively stabilized by the passive magnetic bearings. Only axial direction is actively positioned. Therefore, active axial force and torque are generated in the bearingless motor unit.

2.2 Previously Proposed Single-drive Bearingless Motor

Figure 2 shows a concept of previously proposed single-drive bearingless motor by the authors in (19). This is composed of a single-drive bearingless motor and two repulsive passive magnetic bearings. In the center, the stator and the rotor of the bearingless motor are constructed with three axial layers. In the center layer, the rotational torque...
Single-Drive Bearingless Motor in Cooling Fan Applications (Hiroya Sugimoto et al.)

2.3 Basic Principle of Active Axial Force Generation

Figure 3 shows the principle of the active axial force generation. An enlarged $xz$ cross-sectional view of the center part in Fig. 2 is drawn. The active axial force and the torque are generated by the $d$-axis and $q$-axis currents, respectively.

Solid black arrows indicate the magnetized direction of the rotor permanent magnets. Black broken curves show the permanent magnet flux paths. The permanent magnet fluxes pass through the air-gap, the stator teeth, and radially circulate in the stator core. The upper and lower permanent magnet fluxes have $z$-axis direction components in the air-gap because the rotor permanent magnets are installed at unaligned positions with respect to the stator teeth. There are two $d$-axis flux paths, path (I) and (II), indicated with red arrows. The $d$-axis fluxes (I) are radially circulated, thus the active axial force is not generated. The $d$-axis fluxes (II) play an important role to generate the active axial force. Through the center stator core and the stator yoke, the $d$-axis fluxes (II) are circulated and go to the upper and lower stator cores. In the air-gap, the $d$-axis fluxes (II) have $z$-axis direction components. The $d$-axis fluxes (II) are superimposed on the permanent magnet bias fluxes. When the $d$-axis current is positive, the flux densities are increased in the air-gaps 1 and 3. At the same time, the flux densities are weakened in the air-gaps 2 and 4. As a result, a positive axial force is generated. In the case of negative $d$-axis current, a negative axial force is generated.

Figure 4 shows the axial position and rotational speed regulation system with a zero power controller. The active axial force and the rotating torque are proportional to the $d$- and $q$-axis currents, respectively. The current references are generated from the feedback signal of the axial displacement and the rotational speed, respectively. At start-up from touch-down, the error signal between the reference $z^*$ and the measured axial position $z$ is processed by the Proportional-Differential-Integral (PID) controller, and the $d$-axis current reference $i_d^*$ is generated. On the other hand, the rotational angle $\theta_r$ and the rotational speed $\omega$ are calculated from the feedback signals. The rotor rotational angular position is detected by hall sensors. The $q$-axis current reference $i_q^*$ is generated by the PI controller. To compensate the current lag caused by the coil inductance, an additional PI current feedback loops are adopted. The $d$- and $q$-axis voltage commands $v_d^*$ and $v_q^*$ are generated by the PI controllers. These voltage commands are transformed into the three-phase voltage references $v_a^*$, $v_b^*$, and $v_c^*$ with the rotor rotational angular position $\theta_r$. The three-phase voltage source inverter is regulated by these voltage commands. The $u$- and $w$-phase currents $i_u$ and $i_w$ are detected by two current sensors, and the currents are then transformed into $d$- and $q$-axis currents $i_d$ and $i_q$ as the current feedback signals. Therefore, the
Single-Drive Bearingless Motor in Cooling Fan Applications

Hiroya Sugimoto et al.

Axial position and the rotating torque are regulated by one three-phase voltage source inverter, one displacement sensor and hall sensors. After static magnetic suspension is achieved, a zero power control is activated to reduce DC component in the d-axis current. An integral controller is inserted just after the coordinate transformation from \textit{uvw} to \textit{dq}. The d-axis current is integrated in the zero power controller, then, the feedback signal is added to the axial position reference. For example, when integrated d-axis current is positive, the rotor should be moved to positive axial direction to reduce the positive d-axis current. Therefore, the axial position reference is increased. Hence, the axial position is varied to reduce integrated d-axis current. As a result, the DC component in the d-axis current can be reduced. The zero power control is effective to reduce the power consumption of the magnetic suspension.

3. Experiments

In order to verify the energy-saving effect in experiments, two test machines are fabricated. One is with the ball bearings and the other is with the magnetic suspension. The input power in the bearingless motor is compared. In addition, the ball bearing loss is measured to compare with the magnetic suspension power.

3.1 Test Machine Configurations

Figures 5(a) and 5(b) show test machine configurations with the ball bearing and the magnetic bearing, respectively. In Fig. 5(a), two ball bearings are installed at both ends of the rotor shaft. The inner and outer diameters of the bearing are 5 mm and 16 mm, respectively. The axial length of the bearing holder is 5 mm. The motor unit is identical with the single-drive bearingless motor unit in Fig. 5(b). The repulsive passive magnetic bearing is installed in both test machines. In Fig. 5(b), a touchdown bearing is installed above the upper repulsive passive magnetic bearing. The displacement sensor is installed at bottom of the rotor shaft to detect the rotor axial displacement.

Figure 6 shows the fabricated stator. The stator core is made of laminated silicon steel having a thickness of 0.35 mm. One set of three-phase winding in the concentrated winding structure is installed. The number of windings is 90 turns per tooth. A conductor slot fill factor is 0.36. Several hall sensors are installed among tooth tips in the lower stator core to detect the rotor rotational angular position.

Figures 7(a) and 7(b) show a fabricated dummy rotor shaft and an actual rotor shaft, respectively. In Fig. 7(a), the weight of the dummy rotor is identical with the actual one. The outer diameter around center of the shaft is also identical, therefore, the windage loss in the dummy rotor is identical with that in actual one. In Fig. 7(b), three sets of eight-pole permanent magnets are installed at center of the rotor shaft. In addition, two sets of repulsive passive magnetic bearings are installed at both ends of the rotor shaft. The material of all permanent magnets is Nd-Fe-B. The rotor outer diameter is 27.4 mm. The rotor shaft weight is 0.07 kg.

3.2 Measurement of Ball Bearing Loss

Figures 8(a) and 8(b) show an assembled measurement system of the ball bearing loss and the cross-sectional view in 3D-CAD, respectively. The dummy rotor shaft is connected with a DC motor (EC 32, maxson motor) via a torque meter (UTMII-0.05 Nm, 0.05 Nm, 0.05 Nm).
Single-Drive Bearingless Motor in Cooling Fan Applications (Hiroya Sugimoto et al.)

Unipulse Co.). In the experiment, the dummy rotor is driven by the DC motor. The ball bearing loss is calculated by a product of measured torque and the rotor rotational angular speed.

Figure 9 shows the measured bearing loss with respect to the rotor rotational speed with and without the dummy rotor. A mechanical loss in the torque meter is measured without the dummy rotor. Therefore, it is negligible because the loss is much lower compared with the ball bearing loss. Red plots with the dummy rotor indicate the measured bearing loss. In middle speed range from 2000 r/min to 10000 r/min, the bearing loss is approximately proportional to the rotor rotational speed. In high speed range over 10000 r/min, the bearing loss is drastically increased. Therefore, if the magnetic suspension power is low compared with the bearing loss, the bearingless motor will have the energy-saving effect.

3.3 Energy-saving Effect by Single-drive Bearingless Motor

Figures 10(a) and 10(b) show assembled test machines with and without the ball bearing, respectively. Interior structures in Figs. 10(a) and 10(b) are corresponding to Figs. 5(a) and 5(b), respectively. In measurement of input power at no-load, both the torque meter and the DC motor are not connected to the rotor shaft. A power analyzer (WT-1800, Yokogawa Co.) is inserted between the motor winding and the inverter. Then, the input power is measured in the power analyzer. In case of Fig. 10(a), the d-axis current is 0 A. On the other hand, in case of Fig. 10(b), the d-axis current is not 0 A to realize magnetic suspension.

Figure 11 shows the measured input power at no-load. The input power in the bearingless motor is low approximately over 2500 r/min. In particular, the input power is reduced by approximately 50% at 5000 r/min. Therefore, it is found that the bearingless motor has the energy-saving effect at high speed more than 2500 r/min. In addition, approximation curves are included in Fig. 11. These curves with and without the ball bearing are approximated in second- and first-order polynomial equations, respectively. As a result, when the rotor rotational speed is increased, the energy-saving effect is significant.

3.4 Comparison of Input Power with Fan Blade

Figure 12 shows an experimental system with a fan blade. The blade is attached to the top of the rotor shaft. The outer diameter is 110 mm. Similar to the aforementioned method in section C, the input power is measured by the power analyzer.

Figure 13 shows acceleration waveforms of d-axis current $i_d$, q-axis current $i_q$, rotor rotational speed $N$ and axial...
Single-Drive Bearingless Motor in Cooling Fan Applications

Hiroya Sugimoto

Fig. 13. Acceleration waveforms of \(i_d\), \(i_q\), \(N_r\) and \(z\)

Fig. 14. Waveforms of \(i_d\), \(i_q\), U-phase current \(i_u\) and \(z\) at 7200 r/min

Fig. 15. Measured copper loss

Fig. 16. Measured d- and q-axis currents

Fig. 17. Measured input power with fan blade

Fig. 18. Measured output power and efficiency

Before the acceleration, the rotor shaft is already magnetically suspended. When the acceleration is started, q-axis current reaches maximum value. After the rotor rotational speed is increased up to the rated speed of 7200 r/min, q-axis current is converged to 1.1 Arms. While the acceleration, the rotor shaft is slightly vibrated in the tilting direction at resonant frequency of 4500 r/min. However, the rotor can pass through the resonant frequency without touch-down owing to fast acceleration.

Figure 14 shows enlarged waveforms of d-axis current, q-axis current, U-phase current \(i_u\) and axial displacement \(z\) at 7200 r/min. The rotor axial vibration is low enough to the touch-down length, these are \(\pm 0.011\) mm and \(\pm 0.1\) mm, respectively. In the U-phase current, the fundamental component is corresponding to four times of the rotor rotational frequency because the number of pole pairs is four. At 7200 r/min, the U-phase RMS current is 0.7 A.

Figure 15 shows the copper loss with respect to the rotor rotational speed. The three-phase RMS currents are measured in the power analyzer at each rotational speed. Measured winding resistance is 1.84 \(\Omega\) per phase. The copper loss in the bearingless motor is slightly high to generate magnetic suspension force. In the single-drive bearingless motor, d-axis current is necessary in addition to q-axis current.

Figure 16 shows measured d- and q-axis currents. These currents are output by Digital-Analog converters from a Digital-Signal-Processor. The q-axis current is increased with an increase of the rotor rotational speed because the air fluid load of the fan is increased. The d-axis current is also increased, as a result, the phase current is high in the bearingless motor.

Figure 17 shows measured input power with the fan blade. Within 3000 r/min, the input power is competitive. Over 3000 r/min, in the bearingless motor, the input power is reduced because the elimination of the ball bearing loss is effective. The magnetic suspension power is low compared with the ball bearing loss. At 6000 r/min, the input power is reduced by 0.75 W. In the experiment, it is confirmed that the single-drive bearingless motor can reduce the input power because the magnetic suspension power is low compared with the ball bearing loss. In future work, the input power may be reduced further by adjusting gains more precisely in the PID controller and reducing eccentricity in the rotor shaft.

3.5 Output Power and Efficiency

Figure 18 shows measured output power and efficiency. The measured output power is proportional to the cube of the rotational speed because of the air fluid load of the fan. The efficiency is calculated from the output power divided by the input power \(\eta = P_o/P_{in}\). In low speed region within 2500 r/min, the efficiency with the ball bearing is high. However, over 2500 r/min, the
efficiency of the bearingless motor overcomes that with the ball bearing. At 5000 r/min, the efficiency is 5% high in the bearingless motor. The measured maximum efficiency is 84.1% at 7200 r/min at 5000 r/min. In the fan load test, the input power is reduced by around 50% at 5000 r/min. In the fan load test, the input power is also reduced, therefore, the efficiency is improved by 5% at 5000 r/min. As a result, it is verified that the bearingless motor has the energy-saving effect. In future works, the input power will be reduced by adjusting gains more preciously in the PID controller and reducing eccentricity in the rotor shaft. In addition, when the rotor rotational speed is increased, the energy-saving effect may be enhanced because the ball bearing loss is drastically increased. Thus, high rotational speed test will be carried out with a high speed fan with reduced diameter.

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