Characteristic Measurement of the Wide-Gap Bearingless Motor

Bearingless motor, Magnetic levitation, Vibration suppression, Efficiency

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Abstract

As suggested by the very word, a bearingless motor has no bearings. The motor shaft is levitated by magnetic force. Like an ordinary magnetic bearing, the motor shaft is free from contacts. Since there is no friction, a bearingless motor requires no lubricants and maintenance is easy. As an original bearingless feature, the magnetic levitation force is dependent on the overall motor shaft surface. Because of this effect, a wide-gap between the rotor and the stator can be obtained. In order to commercialize motor with a wide-gap structure, we have verified the characteristics and efficiencies of shaft suspension with a prototype. The results show that the shaft suspension is stable and its required power has a small effect on efficiency.

1. Preface

Unlike ordinary magnetic suspension, a bearingless motor(1)(2) has an active magnetic bearing to support the rotor. Since windings of the radial direction force are wound together into the stator of motor in terms of the windings of the angular direction force, the space of coils at each end of the motor is reduced. Since a wide air gap surface could be utilized between the stator and the opposed rotor, it requires little magnetic flux density to support the shaft and a sufficient levitation force can be obtained even through the air gap extension.

In past research experiments, however, investigation was mainly focused on bearingless motors rated in a wattage class of many hundreds of watts. In considering the future industrial application, it is necessary to verify shaft suspension performance, stability, efficiency, etc. for several kW class motors.

Given the above, we produced a prototype with a rated capacity of 5.5kW and maximum rotation speed of 8000min^{-1} while verifying the performance characteristics. This paper introduces the result of characteristic measurements for the prototype and the vibration reduction control to realize stable magnetic shaft suspension.

2. Prototype of Bearingless Motor

2.1 Construction

Table 1 shows prototype specification of the bearingless motor. The stator has 36 slots for 2-pole windings. There are two types of windings, one is a 2-pole motor winding and another is a 4-pole magnetic suspension winding, that are inserted in the same slot. Since the overall air gap surface of the motor is used also for the generation of levitation force, the magnetic flux density for shaft suspension can be low and the air gap length can be longer. Considering an application using this feature, the gap length of the prototype was designed as 3.6mm(3)(4) and the magnetic suspension force was set at 300N that is about 3 times the mass of the rotor.

Table 1 Major Specification for Prototype

One of the features of the prototype bearingless motor is that it has wide the air gap length of 3.6mm between the stator and the rotor. Even with this air gap length, an output of 300N of levitation force can be generated.

Rated capacity	5.5kW
Max. rotation speed	8000min^{-1}
No. of slots	36
Motor windings	2-pole distributed winding
Magnetic suspension windings	4-pole concentric winding
Stator outer diameter	ϕ220mm
Air gap length	3.6mm
Levitation force	300N

Fig. 1 shows schematically the configuration of the prototype. To control shaft tilt, a stator is axially split into two sections, each having stator windings. Two windings are controlled independently with two suspension structures. For each stator, different inverters feed the power to motor windings to generate torque and to support windings to produce the shaft levitation. Therefore, this motor is driven by a total of four inverters.

In regard to sensors, gap sensors for shaft position detection are installed at both ends of the motor and a rotary encoder for rotation angle is installed at one end of the motor. To assure mechanical support in

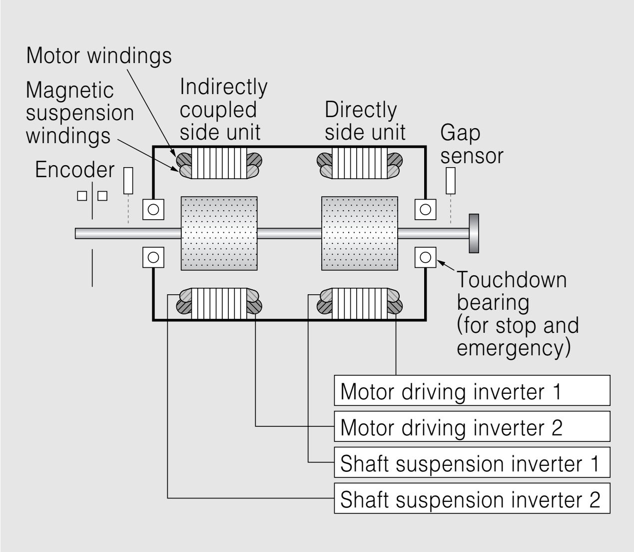

Fig. 1 Configuration of Prototype Bearingless Motor Individual
Two stators are incorporated in this motor. Windings are independently controlled to suspend the motor shaft at two points.

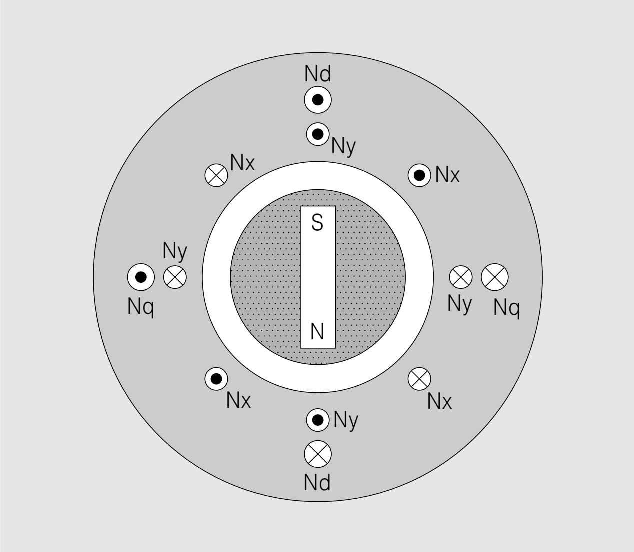

Fig. 2 General Cross-Section of Prototype Bearingless Motor
Motor windings Nd, Nq and suspension windings Nx, Ny are allocated in the stator.

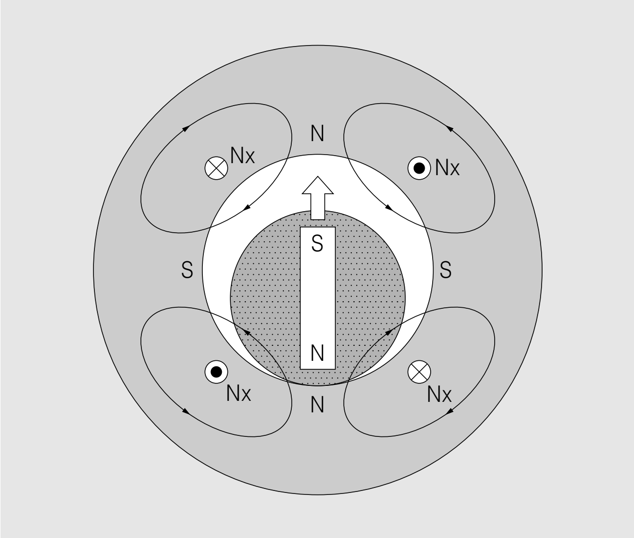

Fig. 3 Levitation Mechanism for Bearingless Motor
To levitate the motor shaft in this condition, current is flown through windings Nx. As a result, a magnetic field is produced and an upward levitation force is generated in the rotor core.

emergency cases such as operation stop and a power outage, a magnetic spindle “touchdown” bearing (“touchdown bearing” hereafter) with an air gap length of 0.5mm is added.

For control of thrust direction, the motor shaft is directly coupled with the load machine with mechanical bearings. Control mechanisms are omitted because the shaft position of the motor unit is put under restraint by the attractive force between the stator and the rotor and no contact occurs between the frame and the touchdown bearing even without control.

2.2 Principle of Levitation

In a bearingless motor, magnetic fields are generated by flowing currents through magnetic suspension windings so that the shaft is sustained by the attractive and repulsive forces exerted on the rotor core. Fig. 2 shows a cross-section of the stator and the rotor. In the stator, two types of windings are allocated, the motor windings Nd and Nq and the magnetic suspension windings Nx and Ny. A two-pole permanent magnet is embedded in the rotor.

We would like to explain how the bearingless motor suspends the shaft. As shown in Fig. 3, it is assumed that the upper section of the two-pole permanent magnet allocated in the rotor is a south pole. If a current is led through the magnetic suspension winding Nx in this state, four magnetic poles are formed in the state that north pole is at the upper and lower parts of the stator and south pole is at the right and left of the stator. An attractive force by north and south poles is generated at the upper section of the rotor and a repulsive force by two north poles at the lower section. As a result, an upward force is exerted on the rotor, which is eventually lifted up. Actually, however, the motor is rotated and the direction and position of the rotor change all the time. The current to be carried in the magnetic suspension winding is controlled(3) based on the revolving angle of the rotor detected by the encoder. In addition, feedback control by gap sensor is carried out to lock the motor shaft in the predetermined position.

2.3 Vibration Reduction Control

Compared with mechanical bearings, the levitation force of the shaft suspension system is smaller, the rigidity is lower, and there can be a delay in detection or current control in the shaft suspension control system. This will cause a large vibration. Fig. 4 shows the shaft vibration generation mechanism. Fig. 4 indicates that there is imbalance in the shaft because the center of gravity point (Point A) of the motor shaft

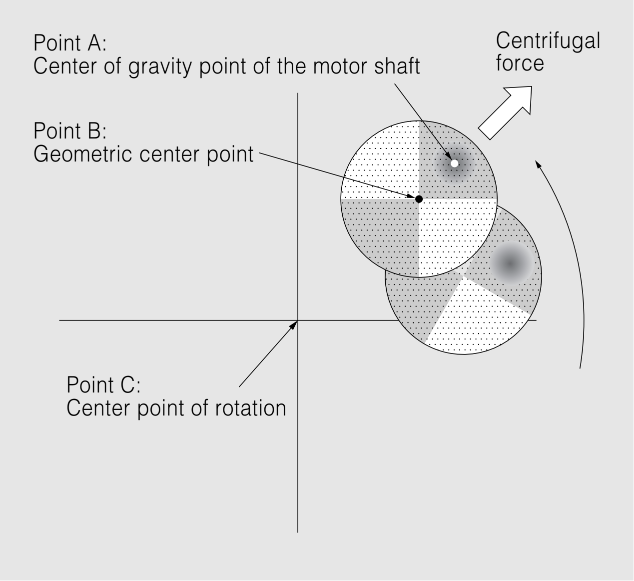

Fig. 4 Shaft Vibration Generation Mechanism
If the center of gravity point (Point A) of the motor shaft is different from the geometric center point (Point B), a centrifugal force is generated as a result of revolutions. The motor shaft is then separated from the center point of rotation (Point C) and large vibration is generated.

including the rotor is different from the geometric center point (Point B). If such a shaft is made to rotate around the geometric center point (Point B), this point (Point B) is separated from the point rotation (Point C) due to the effect of centrifugal force, resulting in generation of large vibration. Since imbalance in the motor shaft can also be generated from coupling with the load machine, it is necessary to permit some imbalance. For this reason, the motor unit has been balanced, but testing has been carried out without adjusting imbalance including encoder and load.

For measures against shaft vibration, two types of vibration reduction control are available as itemized below. Both methods were used for the test.

(1) Control Method 1: Control to rotate the shaft around the geometric center (Fig. 5)

(2) Control Method 2: Control the rotation of the shaft around the center of gravity point (Fig. 6)

In Control Method 1, a levitation force with the same intensity of the centrifugal force, but in an opposite direction, is applied by control to the unbalanced motor shaft to cancel the centrifugal force. By this control, the motor shaft is pulled back to the center point of rotation so that the geometric center point (Point B) can coincide with the center point of rotation (Point C). For Control Method 1, the motor frame will react with this control force. Therefore, it is necessary to make the motor mounts firm. If this rigidity is not sufficient, the motor itself will begin to vibrate.

Control Method 2 is a method of control to prevent the generation of centrifugal force itself by making the center of gravity point (Point A) of the motor shaft coincided with the center point of rotation (Point C) to allow the displacement of the air gap sensor. Unlike Control Method 1, the air gap length is effectively utilized and we could reduce the transmission of vibrations to the motor frame while shaft vibration still remains.

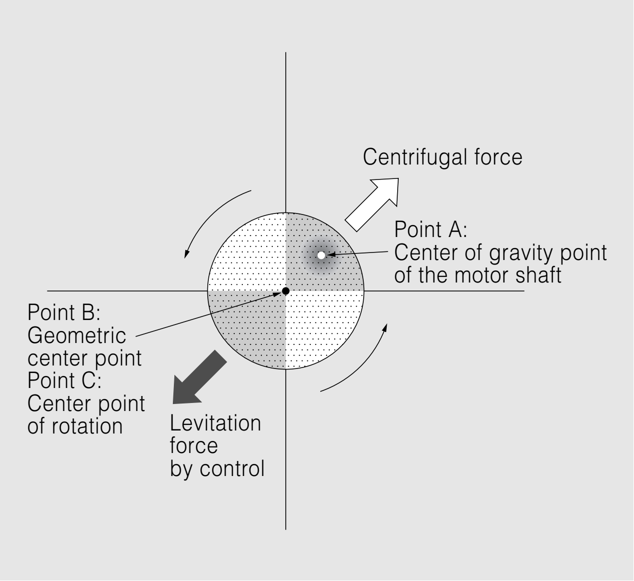

Fig. 5 Control Method 1: Control to Rotate the Shaft around the Geometric Center Point
A levitation force having the same intensity of the centrifugal force, but in opposite direction, is applied by control to the motor shaft to cancel the centrifugal force. Through this treatment, the geometric center point (Point B) of the motor shaft can coincide with the center point of rotation (Point C).

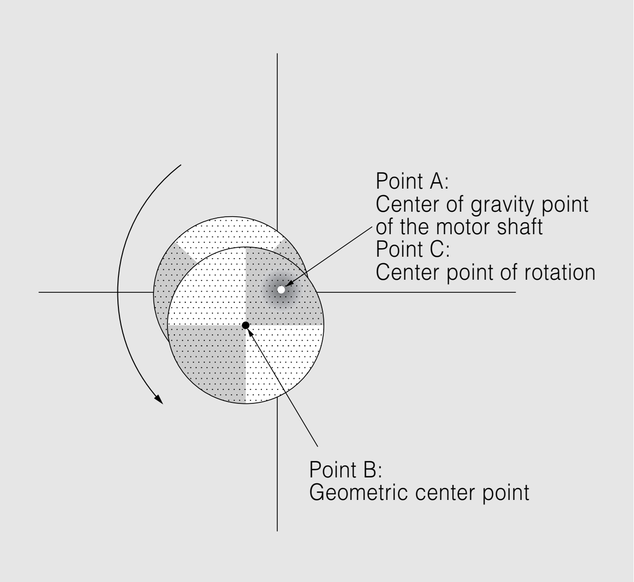

Fig. 6 Control Method 2: Control to Rotate the Shaft around the Center of Gravity Point
By this method of control, the center of gravity point (Point A) of the motor shaft is made to coincide with the center point of rotation (Point C). In this principle, no centrifugal force is generated and no reaction is received. Therefore, the motor frame will hardly generate vibration.

3. Result of Motor Efficiency Measurements and Characteristics of Vibration Reduction Control

Using the bearingless motor prototype, we measured shaft vibration characteristics and shaft suspension power in response to motor rotation speed under various vibration reduction controls to compare other control methods. In addition, the load test was carried out and we produced the efficiency map from the test result.

3.1 Shaft Displacement Characteristics with Vibration Reduction Control

First, we measured the vibration for a single unit of bearingless motor and there was a shaft displacement increase phenomenon, possibly due to resonance. The maximum displacement appeared at 5000min^{-1}. Fig. 7 shows a trajectory waveform observed at that time. It indicates that the maximum shaft displacement amounts to 110μm. This value is substantially large compared with a motor shaft displacement of 10μm to be observed in ordinary mechanical suspension. In Fig. 7, the vibration is particularly strong on the indirectly coupled side in a motor shaft. This is considered to be due to the effect of imbalance of the encoder mounted on indirectly coupled side of the load. However, even though there is somewhat an imbalance in the shaft, the shaft vibration is sufficiently small compared with an air gap length of 0.5mm on the touch-down bearing. In practical terms, a shaft suspension without any contact has been created.

Fig. 8 shows the result of application of control method 1 to vibration reduction control. Shaft displacement becomes to a maximum of 20μm, but is finally reduced to as low as 18% on indirectly coupled side of load where the imbalance effect is significant in comparison with no vibration reduction control. This value is still bigger than the shaft displacement of the mechanical bearing, but we think the improvement is possible by applying a learning control, etc. because the vibration is periodic.

Fig. 9 shows a state of the shaft vibration when Control Method 2 of the vibration reduction control was applied. Shaft displacement becomes to a maximum of 40μm. Compared with the case when no vibration reduction control is carried out, shaft displacement can be reduced 36%. As far as our manual inspection, we could confirm that vibration in the motor frame was decreased. If our research goes to the feedback control of motor frame vibration, there is a possibility that we could further realize frame vibration reduction.

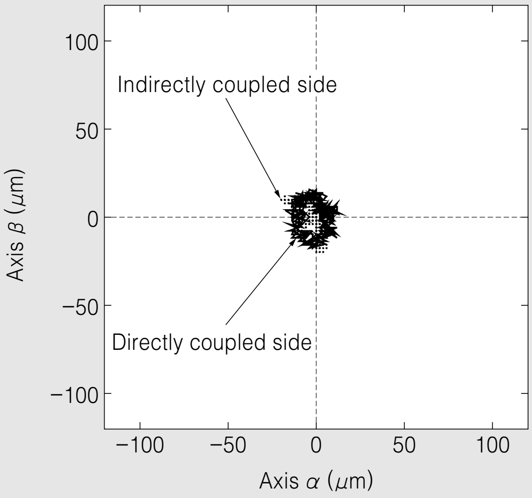

Fig. 8 Trajectory Waveform of Motor Shaft Vibration (Control Method 1)

When the Control Method 1 is applied, vibration in the motor shaft becomes small and radius of shaft displacement can be controlled within 20μm.

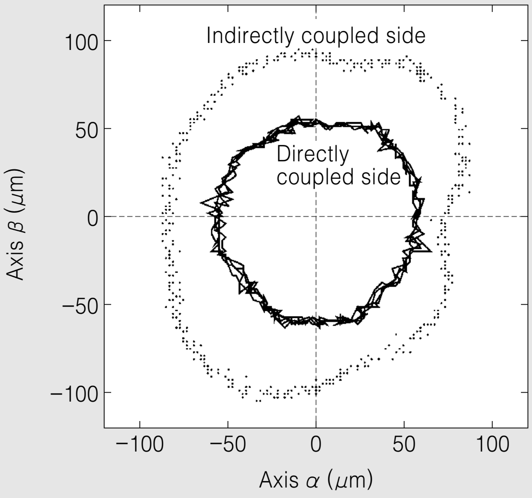

Fig. 7 Trajectory Waveform of Motor Shaft Vibration (without control)

Vibration in the motor shaft becomes great without control. Radius of shaft displacement becomes as high as 110μm.

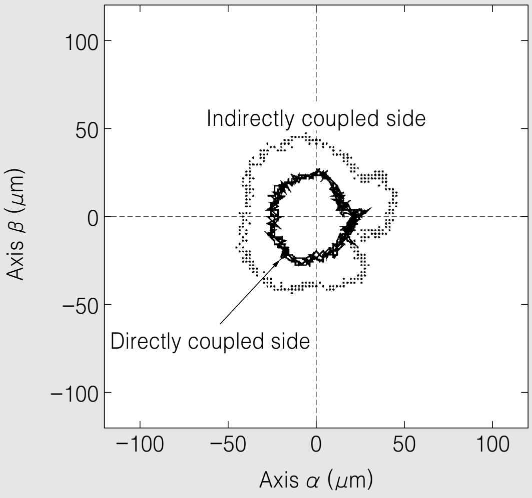

Fig. 9 Trajectory Waveform of Motor Shaft Vibration (Control Method 2)

In Control Method 2, vibration in the motor shaft remains to exist. Radius of shaft displacement amounts to as high as 40μm.

3.2 Magnetic Suspension Operating Power

The power for shaft suspension is an essential factor. Two power meters were connected to each magnetic suspension winding at the motor input section to measure the shaft suspension power for the motor unit changing the vibration reduction control methods or rotation speed.

Fig. 10 shows the magnetic suspension operating power in case no vibration reduction control is in place. The rotation speed that shaft displacement became biggest was 5000min^{-1}, but the centrifugal force produced the maximum shaft suspension at 7000min^{-1}. Because centrifugal force increases in proportion to the square of rotating speed, the speed of the maximum suspension power is faster than that of the maximum shaft displacement. And the total of power value for the shaft suspension at this speed became 185W (equivalent to 3.4% of motor rating). In case the motor shaft is simply maintained at a constant position, it could not do the mechanical work. Ideally, the active power needed for shaft suspension is zero. This means, most of the 185W power is consumed as copper and iron losses.

Fig. 11 shows the case when vibration reduction control of Control Method 1 is applied. Maximum magnetic suspension operating power is 45W and it is reduced to 0.8% of motor rating. In Control Method 1, the shaft displacement lowers and this causes the distance to decrease between the center point of rotation of the motor shaft and the center of gravity point. This further reduces the centrifugal force in proportion, thus reducing the effective current carried through the magnetic suspension windings. All in all, this can be the reason for the reduction of copper and iron losses.

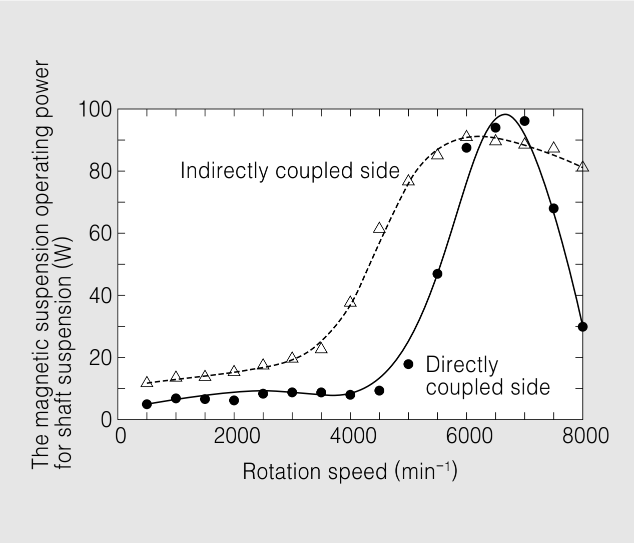

Fig. 10 Measurement Result of Magnetic Suspension Operating Power (without control)

The magnetic suspension operating power becomes a maximum at a rotation speed of 7000min^{-1}. The total power is 185W at the maximum (3.4% of motor rating).

Fig. 12 shows the result of application of control by Control Method 2. Maximum magnetic suspension operating power is further reduced to 23W (0.4% of motor rating). Since control is carried out to prevent generation of centrifugal force in Control Method 2, magnetic suspension operating power is further reduced and kept almost constant at all speeds.

3.3 Efficiency

Total efficiency of the motor is determined by the measurement of all input power of the four windings including the magnetic suspension operating power and torque by meter, and also calculation of shaft output based on the rotation speed by the encoder.

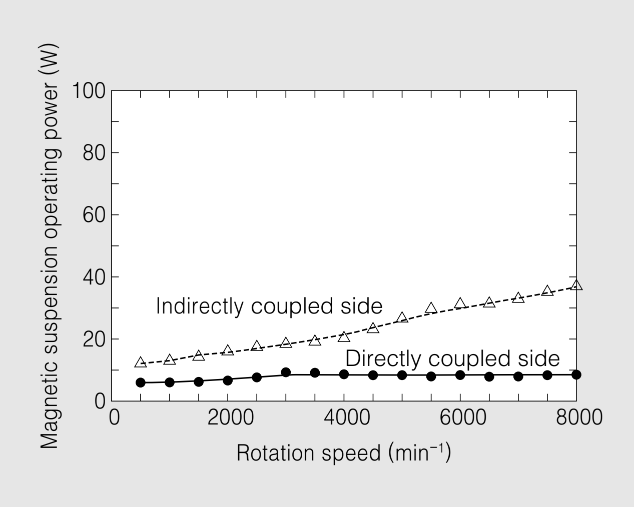

Fig. 11 Measurement Result of Magnetic Suspension Operating Power (Control Method 1)

The magnetic suspension operating power slowly increases with an increase in rotation speed. However, the power can be controlled within 45W at the maximum (0.8% of motor rating).

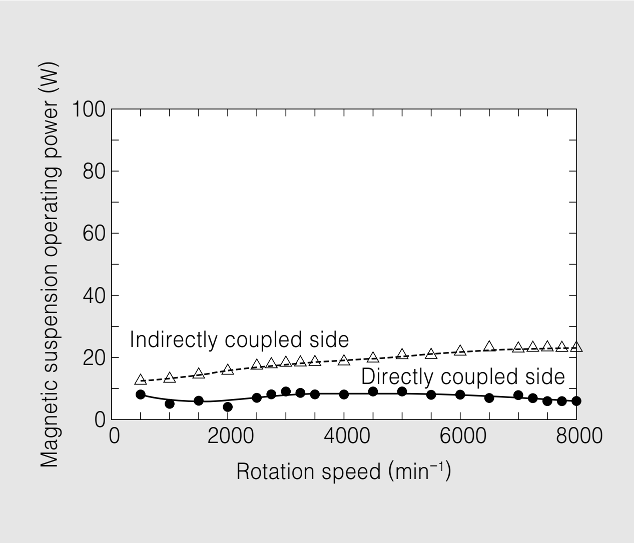

Fig. 12 Measurement Result of Magnetic Suspension Operating Power (Control Method 2)

The magnetic suspension operating power is kept almost constant with the rotation speed. The total power is 23W at the maximum (0.4% of motor rating). This figure is lower than that of the Control Method 1.

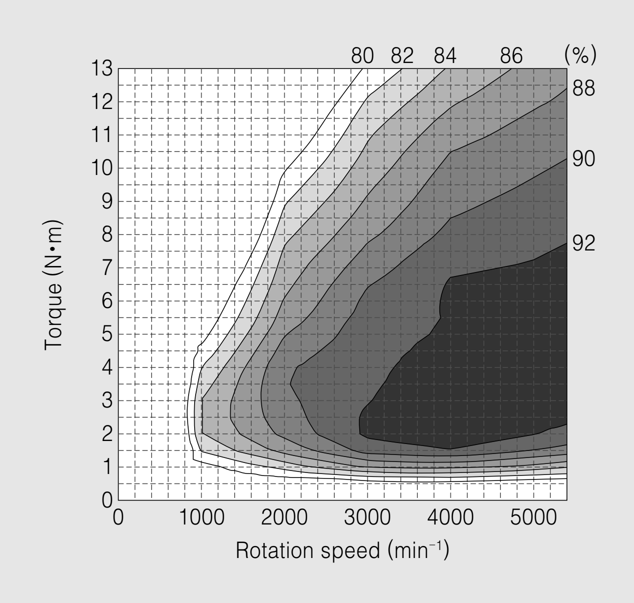

Fig. 13 Efficiency Map of the Prototype Bearingless Motor

This is the total efficiency including the factor of magnetic suspension operating power. It becomes 90.8% under the rated conditions of torque 9.5N・m and rotation speed 5400min^{-1}. This is almost the same level as that of Meiden standard PM motors.

Fig. 13 shows the efficiency map with the horizontal axis for rotation speed and vertical axis for load torque. In this case, the upper limit of the rotation speed is set at 5400min^{-1} because of limitation from the load machine. For vibration reduction control, Control Method 1 was used because it offers the high reduction effect of motor shaft displacement. For the rated torque of 9.5N・m, we measured the load torque up to 13N・m. It results in an efficiency value of 90.8% under the rated conditions. This efficiency is almost equal to our standard PM motors (90.0%) with the same rating. Accordingly, we verified that there is no significant reduction of efficiencies in case we change the design to a bearingless motor. Maximum efficiency becomes 93.9%. If vibration reduction control of Control Method 2 is applied, we could expect an efficiency increase of about 0.4% more.

4. Postscript

This time we made a prototype of 5.5kW bearingless motor and verified its performance and characteristics. The result indicates that stable operation of shaft suspension was realized by using a wide air gap 3.6mm structure. In addition, two types of vibration reduction control were developed and we verified that the amplitude of shaft vibration could be reduced from 110μm to 20μm. Since this vibration shows a periodical feature, we view that improvement is possible with the use of learning control. These vibration reduction control systems are also effective in reducing the power for shaft suspension. Since the mechanical structure is different, it is difficult to make comparison simply with a PM motor, but efficiency is almost equal to that of ordinary PM motor. As such, we consider that reduction of efficiency by adopting bearingless design is minimal. In the future, we would like to promote our development to a further high rotation speed in applied technology innovations or the addition of the learning functions for vibration reduction control.

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