Evaluation of a Bearingless PM Motor with Wide Magnetic Gaps

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Abstract—A new non-contact drive system has been developed employing a consequent-pole type bearingless permanent magnet (PM) motor and a thrust magnetic bearing. This bearingless motor has a wide magnetic gap. The wide magnetic gap may cause a decrease in radial magnetic suspension force because of an increase in magnetic reluctance. A thrust magnetic bearing is installed at the end of the shaft, because strong thrust force exists in centrifugal pump applications. In this paper, the magnetic suspension forces and rotation characteristics of the experimental prototype are evaluated, while the rotor is magnetically suspended. Experimental results are also compared to the calculated ones using the finite element method. It is demonstrated that the developed consequent-pole type bearingless PM motor possesses sufficient magnetic suspension force for non-contact operation.

Index Terms—Bearingless motor, consequent-pole, magnetic bearing, PM motor, centrifugal pump, wide gap.

I. INTRODUCTION

A BEARINGLESS motor combines functions of both non-contact magnetic suspension and torque generation together in a single motor [1]. Magnetic suspension offers the advantage of no wear particles, less maintenance, and high rotational speed as compared to mechanical suspension that causes mechanical friction. In addition, a bearingless motor possesses the advantages of a simple structure, compactness, and cost reduction, in comparison to a conventional tandem structure consisting of magnetic bearings and a motor.

Recently, bearingless motors are practically applied to centrifugal pumps in industries where an infusion of wear particles in pumping medium should be avoided [2]–[5]. In such pumps, protective covers must be attached to both rotor and stator surfaces in order to prevent both medium contamination and material corrosion. These covers should be as thick as possible to enhance mechanical robustness and reliability. It is necessary to design such a motor with wide

magnetic gap between a rotor and a stator. These covers and the medium are not generally made of ferromagnetic material, thus magnetic reluctance is as high as the air. In conventional motors, the gap factor g/r is designed to be from about 0.005 to 0.02, where g and r are the magnetic gap and rotor radius, respectively. The authors consider that the wide gap can be defined as the condition when the gap factor g/r is larger than 0.1.

In bearingless motors [6]–[8] and magnetic bearings [9]–[10] the magnetic gaps are generally designed to be relatively narrow. A wide magnetic gap causes a decrease in magnetic suspension force because of an increase in reluctance. A serious condition occurs at suspension start-up from touched down condition. In this condition strong magnetic attractive force is generated by rotor permanent magnets. Active magnetic force is required to overcome the attractive force to lift a shaft.

A two-axis bearingless centrifugal pump is reported in reference [11]. In this bearingless pump, two radial positions are actively controlled, while the thrust and tilting are passively regulated. This structure provides the advantage of simple and low cost. However, rather large clearance is required for a propeller of the pump. The clearance reduces the overall pump efficiency.

In this paper, a novel 5-axis controlled non-contact bearingless drive system has been developed with wide magnetic gaps. The prototype machine mainly consists of two consequent-pole type permanent magnet (PM) bearingless motor units [6] and a thrust magnetic bearing. The magnetic gaps are much wider than those of conventional bearingless machines. The gap factor is more than 0.13. The aim of this project is the realization of a novel centrifugal pump with bearingless motors. The objective of this paper is the evaluation and the assessment of the magnetic suspension and motor characteristics. The evaluation test is composed of (a) magnetic suspension start-up, (b) static radial force, (c) radial and thrust interference, (d) static thrust force, (e) static torque, and (f) rotation and vibration.

A part of this paper was presented in the Panel Session, sponsored by Motor Sub-Committee in 2008 IEEE-PES General Meeting [12]. Evaluation tests (a) and (b) in the preceding paragraph have been presented. Significant improvements with additional tests (c), (d), (e) and (f) listed in the preceding paragraph are included in this paper.

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Fig. 1. A schematic of a centrifugal pump with bearingless drive.

II. WIDE GAP BEARINGLESS DRIVE SYSTEM

A. Structure of Bearingless Motor Pump

Fig. 1 shows a schematic of the proposed bearingless centrifugal pump and the coordinate definition. The coordinate origin is gravity center of the rotor shaft. x , y and z are translational motion of the rotor. θ_x and θ_y are the tilting motion. Two bearingless motor units are connected in tandem. A thrust magnetic bearing is installed on the right hand side of the shaft. It consists of a thrust disk and two annular coils. On the left hand side, a pump impeller is attached. The bearingless motor can actively regulate both radial (x , y) and tilting (θ_x , θ_y) motions of the rotor. The thrust position (z) is actively controlled by the thrust magnetic bearing. Thus five eddy current displacement sensors are installed. The rotor can be magnetically suspended and rotated without mechanical contact in radial and thrust directions. Pumping medium is sealed with protective covers attached to both the rotor outside surface and the stator inner surface. It should be noted that magnetic gaps are 4-5 mm, much wider than the conventional bearingless machines.

B. Principle of Suspension Force Generation

The bearingless motors in the centrifugal pump are consequent-pole types. Fig. 2 shows a consequent-pole type bearingless PM motor. Radially magnetized PMs are inset between the rotor iron poles. The bias fluxes are generated by PMs so that the iron poles are magnetized as N-poles. The rotor iron between the PMs is consequently magnetized. Therefore, this consequent-pole type bearingless PM rotor has eight poles.

Fig. 2 also shows principles of the radial force generation

when the rotor angle θ_z is 0° . The suspension magnetic flux shown in Fig. 2 is generated by the current in the suspension coil. The airgap flux densities in the right and left directions are increased and decreased, respectively. The flux density at the magnetic gaps are unbalanced because of superposition of the suspension flux on the PM bias fluxes. As a result, suspension force is generated in the positive x -direction.

The negative x -direction force can be generated by providing negative current in suspension winding. The y -direction force can be generated by currents in a suspension winding perpendicular to the excited suspension winding. The total suspension force is generated by a vector sum of the x - and y -direction forces. Even though the rotor is rotated, the same suspension winding current can be provided. The suspension radial force is independent of the rotor rotational angular position [6]. This is one of the advantages of the consequent-pole type bearingless motors. This radial suspension force is proportional to the suspension current.

C. Control System

In the radial directions, centralized position regulations are installed. Fig. 3 shows the control systems in x - and θ_y -directions. The control systems in y - and θ_x -directions are identical. The x_1 and x_2 are output signals from displacement sensors of unit 1 and unit 2, respectively. The x and θ_y are rotor positions in the radial and tilting directions, respectively. The x^* and θ_y^* indicate position references in the control system. The i_x^* and $i_{\theta_y}^*$ are calculated current commands in radial and tilting directions, respectively. The i_{a1}^* and i_{a2}^* are also current commands in the x direction in unit 1 and unit 2, respectively. Control boxes INV and RD indicate abbreviations of the inverter and rotor dynamics, respectively. The input current to the RD block induces suspension force on the rotor. Due to the rotor dynamics, the rotor displaces in the radial direction. The output of the RD block is the radial displacement of the rotor.

Fig. 2. A structure and a principle of suspension force generation in a consequent-pole bearingless PM motor.

Fig. 3. Control system in x - and θ_y - directions.

The sensor outputs are transformed into the movements of the center of the gravity, *i.e.*, parallel and rotational movements. From the sensor outputs (x_1 , x_2), x and θ_y are calculated by following equations:

$$x = \frac{L_{s2}x_1 + L_{s1}x_2}{L_{s1} + L_{s2}} \quad (1)$$

$$\theta_y = \frac{x_1 - x_2}{L_{s1} + L_{s2}} \quad (2)$$

where, L_{s1} and L_{s2} are the distances from the shaft gravity center to each sensor as previously shown in Fig.1. The control boxes (1) and (2) indicate these calculations.

The parallel and rotational movements are compared and these errors are amplified by the proportional-integral-derivative (PID) controllers. As a result, the current commands i_x^* and $i_{\theta_y}^*$ are calculated. From the i_x^* and $i_{\theta_y}^*$, suspension current commands i_{a1}^* and i_{a2}^* are calculated by following equations, as,

$$i_{a1}^* = \frac{2L_{a2}}{L_{a1} + L_{a2}} i_x^* + i_{\theta_y}^* \quad (3)$$

$$i_{a2}^* = \frac{2L_{a1}}{L_{a1} + L_{a2}} i_x^* - i_{\theta_y}^* \quad (4)$$

where, L_{a1} and L_{a2} are the distances from the shaft gravity center to each unit center as previously shown in Fig. 1. The control boxes (3) and (4) indicate these current command calculations. A proportional-integral (PI) loop is constructed so that the suspension currents of i_{a1} and i_{a2} follow the current references of i_{a1}^* and i_{a2}^* , respectively.

In thrust direction, a disk and two coils are installed. The coil of bearingless motor side is u -phase. The other coil is w -phase. Fig. 4 shows the control system in z -direction. This control system is almost the same as the control system in radial directions. The sensor output (z) is compared with the reference z^* and the error is amplified by the PID controller. The current command i_z^* is divided into i_{zu}^* and i_{zw}^* by following equations, as,

$$i_{zu}^* = -(i_{zub} + i_z^*) \quad (5)$$

$$i_{zw}^* = i_{zwb} - i_z^* \quad (6)$$

where, the i_{zub} and i_{zwb} are bias currents of this magnetic bearing. To realize the linear relationships between the suspension force and current, the bias currents are provided in

this magnetic bearing. The control box (5), (6) of Fig. 4 indicates the calculation of the above equations.

D. Target Specification

Table 1 summarizes specification required in bearingless motor system. The target specification is set by the authors' group. A motor torque of 1.9 Nm is needed, which is equal to a motor output of 1.1 kW at a rotational speed of 5,500 r/min.

III. SUSPENSION CHARACTERISTICS

A. Test System

Figure 5 shows a test machine of the 5-axis controlled bearingless motor. An impeller and a pump housing are not installed in the test machine. Table II shows specifications required in the bearingless PM motor. The frame diameter and length are 186 mm and 182 mm, respectively. The length includes the sensor targets, bearingless motors and the thrust magnetic bearing. The rotor diameter is 64 mm. The magnetic gap of 4-5 mm includes protective covers and mechanical gaps. Commercially available eddy current displacement sensors are used in order to detect the radial position of the

TABLE I
DESIGN GOALS OF BEARINGLESS PM MOTOR SYSTEM

Static radial suspension force	100 N
Static thrust suspension force	110 N
Motor output	1.1 kW
Rotational speed	5,500 r/min

Fig. 4. Control system in z -direction.

Fig. 5. A test machine of the developed bearingless PM motor.

TABLE II
SPECIFICATIONS OF BEARINGLESS PM MOTOR

Outer diameter of motor	186 mm
Axial length of motor	182 mm
Motor voltage	200 V
Motor current	8 A

rotor.

The test machine is driven by 200 V three-phase, voltage source IGBT inverters with DC bus voltage of 280 V. A series number of turns for one-phase suspension windings is 155. The motor windings are connected to the PWM inverter. The blocks shown in Fig. 3 and Fig. 4 are realized using a commercial microprocessor. The switching frequency of the inverter is 20 kHz. The microprocessor and its sampling rate for magnetic suspension control are SH7047 (Renesas Technology Corp., Japan) and 300 μ s, respectively. In the following, the experiments are carried out in the air.

B. Radial Start-up

First, radial start-up of the consequent-pole type bearingless PM motor is experimentally investigated. The rotor is actively regulated with a 4-axis (x , y , θ_x , θ_y) active controller. The thrust magnetic bearing is not operated. Fig. 6(a) shows radial and tilting positions at start-up. Fig. 6(b) shows suspension winding current waveforms.

In Fig. 6(a), before the controller is switched on, the rotor is touched down in the negative y -direction because of the gravity. When the suspension controller is switched on, the rotor moves to certain positions. In order to reduce the suspension currents, all position references are adjusted as $x^*=0.2$ mm, $y^*=0.4$ mm, $\theta_x^*=0$ mrad, and $\theta_y^*=3$ mrad. The position references are given so that unbalanced magnetic pull force is mostly balanced with the rotor shaft weight.

In Fig. 6(b), i_{a1} , i_{b1} , i_{a2} and i_{b2} are suspension winding currents of a- and b-phase in the unit 1 and 2, respectively. The steady-state suspension currents are less than 1 A. The current values are intentionally reduced by adjusted reference positions. Figures 6(a) and 6(b) show that this test machine can be magnetically suspended. The performance requirement of radial suspension start-up from power off condition is satisfied.

C. Radial Suspension Force

The static radial force and current characteristics are measured. External forces are applied at both ends of the shaft, then radial suspension force is measured. There are currents on y -direction because of the gravity. Therefore, this experiment is executed in the x -direction.

Fig. 7(a) shows the experimental setup. External forces are applied at both shaft ends of unit 1 and unit 2. The thrust magnetic bearing is switched off and shaft extension is attached to the end of the thrust disk. The center of gravity is not at the center of the shaft due to weight of thrust disk, as shown in Fig. 1. Consequently, if the same external force is

(a) Rotor positions in radial and tilting directions.

(b) Currents in suspension windings of the bearingless motor.

Fig. 6. Waveforms of radial positions and suspension currents of the bearingless PM motor at start-up without an operation of a thrust magnetic bearing.

Fig. 7. Experimental method for measuring radial suspension force of the bearingless PM motor.

Fig. 8. Measured and calculated parallel force of the bearingless PM motor against suspension current when external forces are applied.

applied to both ends, a moment is resulted in the tilting direction. To eliminate such tilting moment, and to apply only parallel external force, the applied forces are adjusted at each shaft end.

The applied forces in this experiment are shown in Fig. 7(b). The applied forces of unit 1 and unit 2 are Force 1 and Force 2, respectively. These forces are adjusted so that there is no moment in θ_y -direction. The sum of the Force 1 and Force 2 is the applied external parallel force F .

Fig. 8 shows the applied external parallel force against the suspension current reference i_x^* generated in the controller. It is noted that parallel suspension force of 100 N is applied. The experimental results are compared to the calculated ones provided by the Finite Element Method (FEM). Commercially available three-dimensional FEM software package (JMAG-Studio, JSOL Corp., Japan) is used. The data points are subjected to least-squares fitting. In Fig. 8, the solid and broken lines indicate the FEM simulation and experimental results, respectively. A suspension force constant is defined as force by current. The measured and calculated suspension force constants are 24.9 N/A and 22.6 N/A, respectively. There is an error of 4.8 %.

In this machine, the rated current of the suspension winding is 4.5 A. With the rated current, the suspension force is 100 N. The performance requirement of static radial suspension force of 100 N is satisfied. The radial levitation current is not zero with zero applied force because the center of the mechanical structure does not coincide with the magnetic center of the bearingless motor.

D. Thrust Start-up

When the rotor is actively regulated with a 4-axis active controller, the passive force exists in thrust direction. Thus, thrust direction is passively stable. However, strong thrust force occurs in pump operation. Hence, the thrust magnetic bearing has been employed in thrust direction.

Fig. 9 shows the thrust and radial positions and currents in response to an impulse force in the thrust direction. The upper waveforms show the thrust displacement z and the currents i_{zu} and i_{zw} of the thrust magnetic bearing. The lower waveforms

Fig. 9. Thrust, radial and tilting positions and currents of thrust magnetic bearing in response to impulse external force in thrust direction.

show the radial displacements and angles.

At $t=0$, the rotor is suspended by the bearingless motor in radial and tilting directions. The thrust motion is stable due to the effect of passive stabilization of bearingless motor. At $t=t_1$, an external impulsive force is applied, and then the rotor has thrust vibration. Although the vibration is gradually converged due to the thrust passive stabilization, the damping effect is not sufficient.

At $t=t_2$, the thrust active control is switched on, then, the vibration is suppressed by active thrust magnetic force. The thrust position is regulated at about 0.6 mm. It is almost magnetic center position of the bearingless motor. The u -phase and w -phase bias current is 1.5 A and 1 A, respectively. The stator structures of the thrust magnetic bearing are different as shown in Fig. 1. Therefore, suspension force constants are different. The difference of suspension force constants causes the difference of the bias current.

In the radial position waveforms before and after $t=t_2$, the vibration amplitude is slightly changed. This change shows the interaction between the thrust and radial suspension. The thrust movement causes a change in the reluctance, because the rotor and stator iron are misaligned.

At $t=t_3$, an external impulsive force is applied, again. The rotor is almost kept in regulated position by the thrust magnetic suspension currents. This figure shows that this machine can start up and tolerate the thrust direction disturbance.

E. Thrust Suspension Force

In this sub-section, static thrust force and current characteristics are measured. In 5-axis actively controlled condition, external thrust force is applied at the shaft end. The direction of the thrust force is in the positive z direction. In the

Fig. 10. Applied axial force against currents of the thrust magnetic bearing in 5-axis magnetic suspension.

pump operation, the positive thrust force should be generated to balance to the pump impeller force. Fig. 10 shows the applied force against the currents of the thrust magnetic bearing. Within the rated current of 4.5 A, this machine can generate 120 N, which is higher than the thrust force requirement of 110 N. This experimental results show that the target thrust suspension force is satisfied.

IV. TORQUE CHARACTERISTICS

In this section, the static torque characteristic is measured. The test machine is mechanically connected to a dc machine through a torque transducer. The rotational angular position is mechanically fixed. The rated current of 8 A is supplied in eight-pole three-phase motor windings. A q-axis current of 13.8 A is supplied to the motor windings. The static torque is then measured with the torque transducer.

Fig. 11 shows the measured and calculated results of the static torque. An average value of the measured torque is 1.87 Nm. There is an error of 1.32 % between the measured and calculated torques. The torque ripple is originated due to cogging torque. However, the ripple may not influence the flow rate of the centrifugal pump.

V. ROTATIONAL CHARACTERISTICS

In this section, rotational characteristics are investigated experimentally. Fig. 12 shows the rotational characteristics of the magnetically suspended shaft. Fig. 12(a) shows the vibration amplitudes against the rotational speed. The measurements are carried out every 300 r/min until 6,000 r/min. The test machine is possible to be driven up to the speed of 6,000 r/min. The maximum peak is observed at a rotational speed of 300 r/min. It may be caused due to the rotor dynamics. The detail about the rotor dynamics is under investigation and will be presented in future works. The maximum vibration amplitude is about $x=0.11$ mm, $y=0.14$ mm, $\theta_x=1.21$ mrad, $\theta_y=1.05$ mrad at 300 r/min, which is less than one third of the touchdown clearance. It is seen that the vibration amplitudes are relatively small compared to movable limitations in the radial and tilting directions.

Figures 12(b) and 12(c) show the radial and tilting positions

Fig. 11. Measured static torque of the bearingless PM motor with the q-axis current of 13.8 A.

(a) Vibration amplitudes of rotor in radial and tilting direction.

(b) Waveforms of rotor positions x and y in radial direction at 6,000 r/min.

(c) Waveforms of rotor positions θ_x and θ_y in tilting direction at 6,000 r/min.

Fig. 12. Rotational characteristics of the bearingless PM motor.

at 6,000 r/min. These figures show the stable rotation at speeds up to 6,000 r/min. The specification of rotation test up to 5,500 r/min is satisfied.

VI. CONCLUSIONS

A new 5-axis actively controlled bearingless drive system is developed for centrifugal pumps. The drive system includes two consequent-pole type bearingless PM motor units and a thrust magnetic bearing. The specified suspension forces of 100 N and 110 N in radial and thrust directions, respectively are successfully met. Moreover, it is shown that the test machine can be driven up to 6,000 r/min with non contact magnetic suspension. The design specifications are experimentally evaluated for stable operation.

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