Influence of Eddy Current in Permanent Magnet Rotor on Suspension Forces and Experimental Verification in Bearingless Motors with Divided Winding

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Abstract

This paper focuses on the influence of eddy current in the permanent magnet (PM) rotor on the suspension force in the bearingless motors with the divided stator winding. In the PM synchronous bearingless motors, the eddy current flows in the PM on the rotor at high speed drives, especially on its surface of PMs. As a result, the uncontrollable electromagnetic force is generated and interferes on the originally commanded suspension force. It makes the rotor levitation unstable and in the worst case, it is seriously concerned that the rotor stabilization unfortunately is not kept. The interference component is mainly Lorentz Forces generated in the PMs by the eddy current. The bearingless motor with 2-pole motor and 4-pole suspension windings (2t4s Belm) and the bearingless motor with 4-pole motor and 2-pole suspension windings (4t2s Belm) have been targeted and compared between the electromagnetic forces in both Belms by the authors. The eddy current in the PMs and the Lorentz Force have been computed by Finite Element Method (FEM) using a simulation software. The difference between 2t4s and 4t2s Belms in the electromagnetic forces, eddy current and Lorentz Force has been found using the FE models and discussed it in detailed. The reason why the rotor levitation is unstable in the 4t2s Belm model has been analytically derived by the simulation. In this paper, it is experimentally verified by a prototype machine of 4t2s Belm.

Keywords: *Magnetic bearing, Bearingless motor, Permanent magnet synchronous motor, High speed drive, Eddy current*

1. Introduction

In the Belms, the functions of electric motor and magnetic bearing are successfully integrated. Therefore, they have the remarkable advantageous features such as maintenance-free, long life-cycle and the drives in the special circumstance as in vacuum, high or low temperature can be performed. A lot of structures and rotor suspension control strategies have been proposed and the papers related to their technique have been published [1]. The Belms can be grouped into two by the winding configuration. One is the divided winding type, in which the suspension winding is independently wound in the stator core as well as the motor winding. Another is the combined winding type, in which only one kind of winding is wound in the stator core and both the torque and suspension force are generated by the excitation of its winding [2]. In this paper, the Belms with divided winding are focused. It is noted that the suspension winding with (n±2) pole is necessarily wound on the stator core for the motors with n pole [3]. As a result, the electromagnetic force can be properly generated in any radial direction and the rotor is stably levitated. In this kind of PM synchronous Belms, the difference between the angular speeds of revolving magnetic fields by PM on the rotor and MMF of the suspension winding is significantly caused. Because the pole number of suspension winding is different from that of motor winding. The eddy current in the rotor PMs is generated due to the difference between the angular speeds in accordance with the same principle as induction motors [4]-[6]. The current is induced in the PMs, especially on the surface of them by the eddy current. It results in the Lorentz Force generation and the interference on the originally commanded suspension force is caused. It is seriously concerned that the suspension force is not followed to its command and the rotor levitation is unfortunately unstable. Especially, the induced current is more as the rotational speed is up. Therefore, the rotor stabilization has to be paid attention in the high speed range.

The authors have focused on the 2t4s and 4t2s Belms and compared between the electromagnetic forces in both Belms by FE analyzed results using the above two models. In the 2t4s Belm, as a result, the influence of the eddy current on suspension force is not so much. In the 4t2s Belm, however, the electromagnetic force is much varied with the eddy current, especially in the high speed region. Therefore the rotor levitation is not stabilized. The reason why they are caused has been analytically made clear based on the FE analyzed results using a simulation software [5][6]. In next step, the experimental verification is necessary, in this paper, firstly the influence of eddy current on the electromagnetic force is experimentally verified by a prototype machine of 4t2s Belm. It is confirmed which it agrees with the simulation result or not.

2. Revolving Magnetic Field in Belm

The authors have theoretically derived the relationship between the suspension force and suspension winding current in the 2t4s and 4t2s Belms, respectively [1][6]. The theoretical equations of motor and suspension winding currents have been derived based on the relationship. As a result, the angular speeds of revolving magnetic fields produced by MMF of suspension winding for 2t4s and 4t2s Belms are shown in Table 1. In the 2t4s Belm, the angular speed of revolving magnetic field by MMF of the suspension winding is a half of that of the main revolving motor magnetic field and the minus means that it is slower than the angular speed of main motor revolving motor magnetic field. In the 4t2s Belm, on the other hand, the angular speed of revolving magnetic field by MMF of the suspension winding is twice of that of the motor. Therefore it is possible that the larger eddy current in the PM is generated in 4t2s Belm, especially in high speed region.

Table 1 Angular speed of revolving magnetic field produced by MMF of suspension winding. (*2t4s and 4t2s Belms*)

Model	*2t4s Belm*	*4t2s Belm*
Pole number of suspension winding	4	2
Mechanical angular speed of motor	ω	ω
Angular speed of suspension winding current	ω	2 ω
Angular speed of revolving magnetic field produced by MMF suspension winding	-(1/2)ω	2 ω

3. Simulation result of suspension forces

The authors have verified by the simulation using the FEM software (JMAG, Ver.21.2, 2D, JSOL CORPORATION) that the current is induced in the rotor PMs and the suspension force is influenced by the induced current in the high speed range. Figure 1 shows the cross section and winding arrangement of 2t4sBelm and 4t2sBelm FE models and Table 2 shows the specification of FE models.

Firstly, the induced current density distribution in the rotor PMs (0-360 deg) in the axial direction for the 2t4s and 4t2s Belm FE models have been computed, respectively. Figure 2 shows the analyzed result of current density in PM in axial direction. The rotational speed is set at 12,000 r/min and the motor winding current is set to 0.5 A considering the inertia of rotor shaft at no load condition. The suspension force is commanded to x-positive direction. It is the waveforms of current density at the moment of 360 degree rotor angular position. It is found in the computed results that the frequency of current density of 4t2s Belm is a half of that in the 2t4s Belm. It is dependent on the number of poles of suspension winding. However, the peak value of current density in 4t2s Belm is a few times that of 2t4s Belm. Because the angular speed of revolving magnetic field produced by MMF of suspension winding is faster by 2 times than the rotor rotational speed as shown in Table 1. On the other hand, it is a half of the rotor rotational speed in the 2t4s Belm.

Next, Figure 3 shows the computed results of electromagnetic force in the 2t4s and 4t2s Belm FE models. The authors can compute the electromagnetic force in both conditions, in which the eddy current is considered or not on the employed simulation software. In each model, the electromagnetic force is computed under both of conditions without and with the eddy current. The suspension force is commanded in the x-positive direction in both models and the electromagnetic force is computed in x- and y-axis directions, respectively. Similar to Figure 2, the rotational speed is set at 12,000 r/min and the motor winding current is set to 0.5 A considering the inertia of rotor shaft at no load condition. In the 2t4s Belm of Figure 3 (a), the electromagnetic force is not influenced by the eddy current and approximately agrees with the suspension force command even if the eddy current is considered. In the 4t2s Belm of Figure 3 (b), on the other hand, when the eddy current is not considered, the electromagnetic force is generated approximately in accordance with the command. However, the electromagnetic force is generated also in y-direction under the consideration of eddy current, i.e., the mutual interference occurs between the x- and y-direction forces. In addition, also the x-direction force is varied with the eddy current. It is concluded in the result of Figure 3 that in the 4t2s Belm, the larger current is induced by the eddy current due to high frequency revolving suspension magnetic field and it much influences on the electromagnetic force generation.

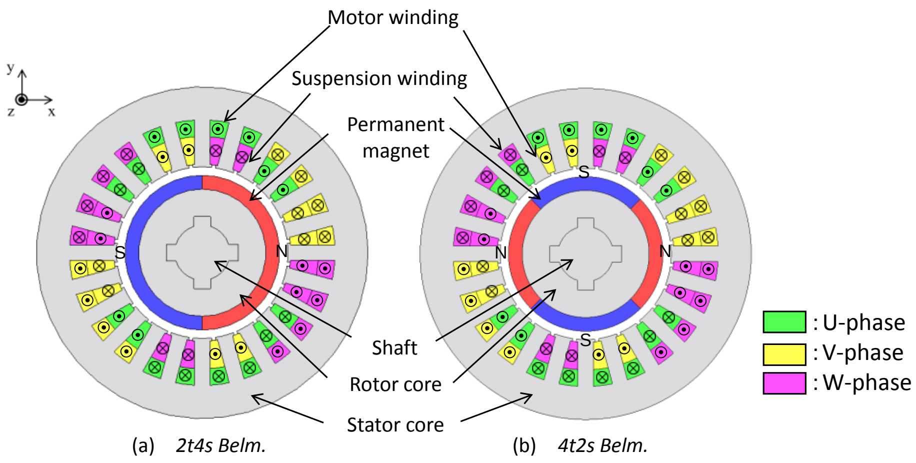


Figure 1 Cross section and winding arrangement of 2t4s and 4t2s Belm models.

Table 2 Specification of FE models. (2t4s and 4t2s Belms)

Stator core outer diameter		120 mm
Rotor core outer diameter		46 mm
PM thickness		5.0 mm
Airgap length		3.0 mm
Axial length		110 mm
Winding turns in series / slot	Motor	4
	Suspension	6
Rated current	Motor	13.6 A
	Suspension	9.42 A

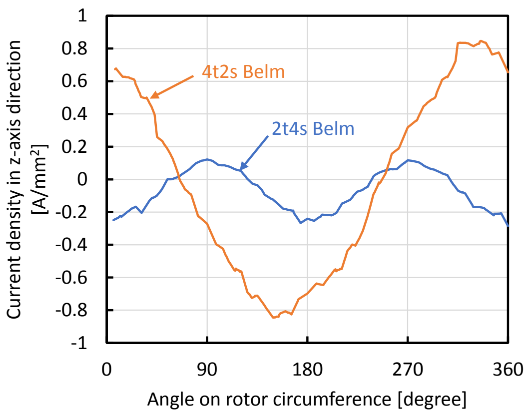


Figure 2 Analyzed result of current density in PM in axial direction at rotor angular position of 360 degree.

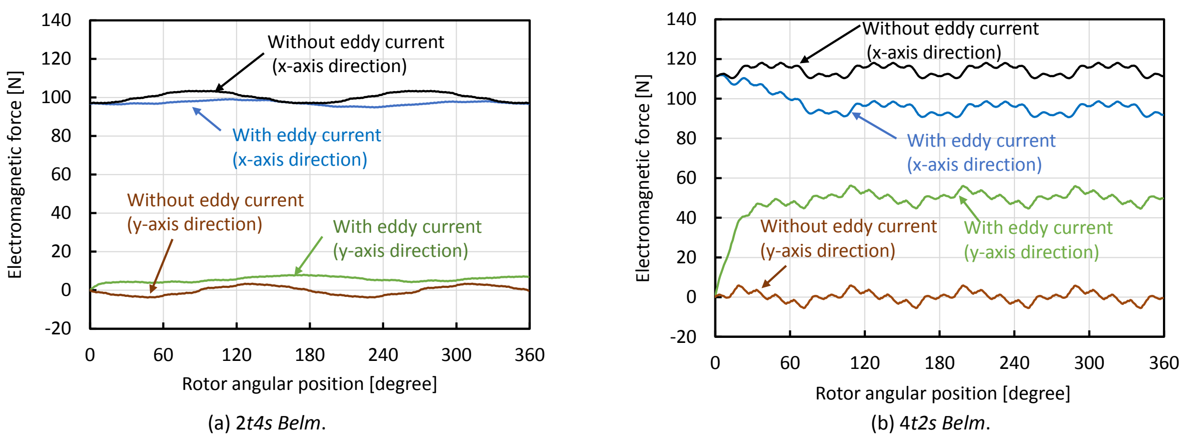


Figure 3 Analyzed results of electromagnetic force in x- and y- axis directions.

4. Experimental verification

4.1 Prototype machine

In order to verify the large variation of electromagnetic force caused by the eddy current and the mutual interference between the electromagnetic forces in x- and y-axes in the 4t2s Belm, a prototype surface-mounted PM synchronous type Belm is built. Figure 4 shows the structure and size of the prototype machine. It is a lateral type. The right side of the shaft is supported by a self-aligning ball bearing. In the Belm, the rotor radial position is actively controlled in two perpendicular radial axes. The touchdown bearing is equipped with the left side of shaft. The clearance of touchdown bearing is 100 μm. The rotor shaft is magnetically suspended without mechanical contact during the normal operation. It is touched down on the touchdown bearing only at standstill or emergency. The rotary encoder is equipped in the end of shaft right side.

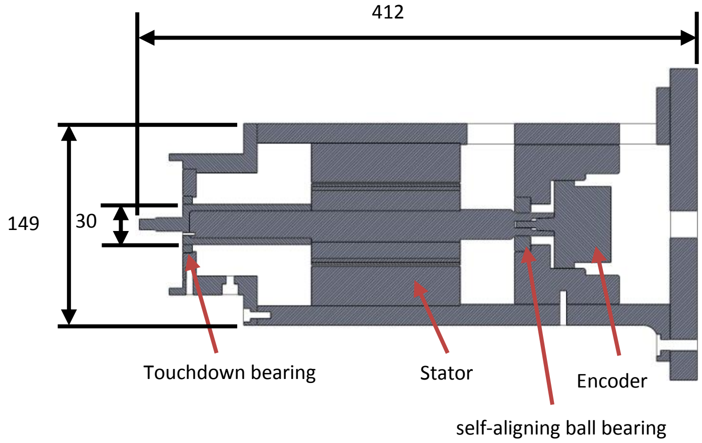


Figure 4 Prototype machine.

4.2 Interference component

When the experiment is carried out using the prototype machine shown in Figure 4, the prototype machine is arranged in lateral so that the vertical direction is aligned in x-axis and the below direction in vertical agrees in x-positive direction considering the experimental setup and the environment around it.

The electromagnetic force is computed once again because the direction of suspension force command is changed to the negative direction in x-axis. Figure 5 shows the computed x- and y-axis components of electromagnetic forces when the rotational speed is set at 12,000 r/min and the motor winding current is set to 0.5 A. The suspension force is commanded to x-negative direction. It can be seen in Figure 5 that similar to Figure 3, the electromagnetic forces are significantly varied by the influence of eddy current. The difference between the electromagnetic forces without and with the consideration of eddy current is caused. It is done in both x- and y-axis directions as shown in Figures 5 (a) and (b), respectively. The difference is defined as the interference component of electromagnetic force, in which the electromagnetic force without consideration of eddy current is subtracted from that with consideration of eddy current. It can be seen in Figures 5 (a) and (b) that the interference component is dc at steady state in both axes.

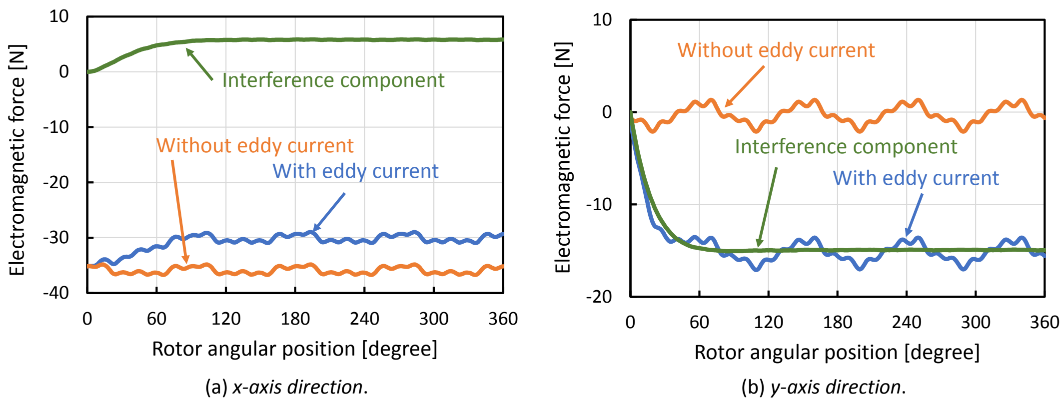


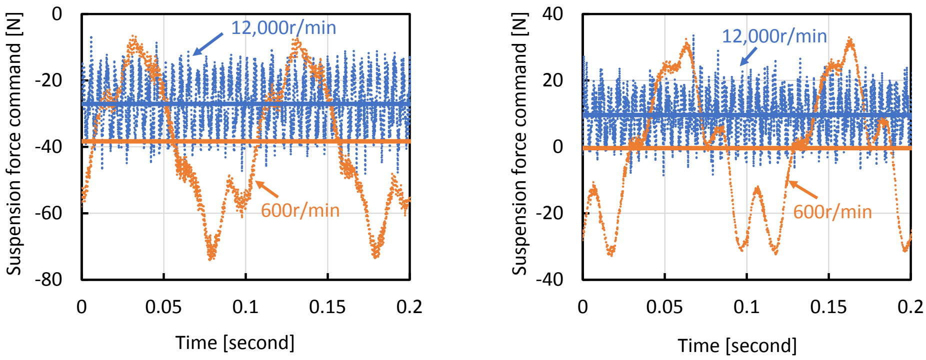
Figure 5 Interference component of electromagnetic force in x- and y- axis directions.

4.3 Experimental test result

The electromagnetic force is generated so that it is followed to the suspension force command in normal operation of Belm. Therefore the generated electromagnetic force can be easily estimated by the command. To experimentally verify the influence of eddy current on the electromagnetic force and observe the interference component of electromagnetic force, the suspension force command in x- and y-axes in the magnetic suspension controller is measured in the magnetic suspension controller of the prototype machine, respectively. The position of prototype machine is set as mentioned in Sections 4.1 and 4.2. Therefore, as the gravity force is applied on the rotor shaft in x-positive direction, the suspension force is commanded to x-negative direction. Namely the experimental condition agrees with the simulation one shown in Figure 5 with respect to the force direction. Figure 6 shows the waveforms of suspension force command in x- and y-axes at the rotational speeds of 600 r/min and 12,000 r/min, respectively. It has been confirmed by the FE analysis that the eddy current does not influence on the electromagnetic force in the low speed region. Therefore the waveform of suspension force command at 600 r/min is also observed and compared with that at 12,000 r/min. In each waveform of Figures 6 (a) and (b), the ac component is caused by the rotor fluctuation due to the mechanical unbalance. As mentioned in Section 4.2, the interference component by eddy current is dc. Therefore the dc component of each waveform in Figures 6 (a) and (b) is derived and also described in these figures. It can be seen that there is a difference between the dc components of suspension force command at 600 r/min and 12,000 r/min. It is found also in the experiment that the electromagnetic force is influenced by the eddy current. The interference component is derived by subtracting the dc component of suspension force command at 600 r/min from that at 12,000 r/min. In the case of x-direction force in Figure 6 (a), the subtraction of the dc component of suspension force command at 600 r/min from that at 12,000 r/min is positive. It is estimated from this experimental test result that the interference component by eddy current is actually generated in x-negative direction. It is the same as that in y-axis direction as shown in Figure 6 (b).

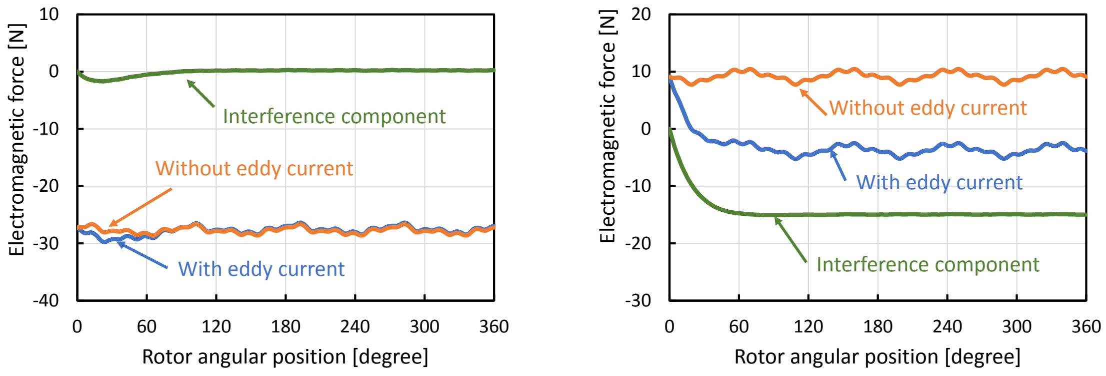
Compared with the simulation results of electromagnetic force shown in Figures 5 (a) and (b), the estimated electromagnetic force from the experiment is obviously different in both the magnitude and direction as shown in Figures 6 (a) and (b). Therefore the electromagnetic force at the rotational speed of 12,000 r/min is simulated again so that the suspension force command agrees with one measured by the experiment in Figures 6 (a) and (b). The suspension winding current command is set in the FEA simulation software so that the same electromagnetic forces as Figures 6 (a) and (b) are generated. Figure 7 shows the simulation result of electromagnetic force when the suspension force is commanded to agree with one in the experiment shown in Figure 6. The rotational speed is set at 12,000 r/min. The interference component by the eddy current on the electromagnetic force is found in the y-axis direction of Figure 7 (b). In the x-axis direction of Figure 7 (a), however, the electromagnetic force with the consideration of eddy current almost agrees with one without consideration of eddy current. It seems that there is no interference component in the x-axis direction. It is accidentally caused depending on the magnitude and direction of suspension force command and the interference component by the eddy current. Actually the electromagnetic force is interfered by the eddy current.

The interference components estimated by the experiment and simulated by FEM are summarized in Table 3. The estimated interference component is calculated from the measured suspension force command by the experiment as shown in Figures 6 (a) and (b). It is defined as the subtraction of the dc component of suspension force command at 600 r/min from that at 12,000 r/min. It is noted that the direction of actual electromagnetic force is estimated in opposite of the force command. On the other hand, the simulated interference component is derived by the results shown in Figures 7 (a) and (b). The estimated interference component by the experiment does not agree with the simulated one. Because this discrepancy between the experiment and simulation results is caused by the error of eddy current in PMs. It is because the eddy current is dependent on the manufacture tolerance of the prototype machine and the employed PM characteristics.



(a) *x-axis direction.* (b) *y-axis direction.*

Figure 6 Suspension force commands at 600 r/min and 12,000 r/min.



(a) *x-axis direction.* (b) *y-axis direction.*

Figure 7 Simulation result of electromagnetic force when the suspension force is commanded so as to agree with the experimental ones at 12,000 r/min.

Table 3 Interference components of electromagnetic force by eddy current

Axis	x	y
Force commands at 600 r/min [N]	-38.36	-0.3721
Force commands at 12,000 r/min [N]	-27.05	9.594
Estimated interference component [N]	-11.30	-9.966
Interference component by FEA [N]	0.2252	-14.94

5. Conclusion

In the Belm with 4-pole motor and 2-pole suspension windings, the magnitude and direction of electromagnetic force is varied with the eddy current in the PM, which is caused by the difference between the angular speed of revolving magnetic field by MMF of PM on the rotor and that by MMF of suspension winding. It is remarkable especially in the high speed region. In this paper, it is verified by the experiment test using the prototype machine as well as the FE analyzed result using the simulation software. The reason why the difference between the interference components of electromagnetic force derived by the experiment and simulation is caused should be solved in the next stage. In addition, a prototype Belm with 2-pole motor and 4-pole suspension windings will be built and it will be verified that the influence of eddy current on the electromagnetic force is less than that in the 4t2s Belm.

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