A Magnetic Suspension Control Strategy of Bearingless Motors with 2-phase Brushless DC Structure

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***Abstract* – This paper presents a new structure of bearingless motor whose function is applied in a 2-phase brushless DC motor. The proposed structure is illustrated and the principle of suspension force generation and magnetic suspension control strategy are found to suspend the rotor stably without mechanical contact. The rotational torque and suspension force are computed by Finite Element Method (FEM) using a machine model. It is found in the computed results that the mutual interference occurs between the suspension forces in two perpendicular radial axes. The methods to decrease the mutual interference are proposed. The validity proposed control strategy is confirmed through the computed results by FEM.**

***Index Terms* – Bearingless motor, magnetic bearing, brushless DC motor, suspension control strategy, finite element analyses.**

I. Introduction

To solve problems in conventional mechanical or magnetic bearings, the bearingless motor is being actively researched and developed around the world [1][2]. In this type of machine, the functions of the electric motor and magnetic rotor levitation are integrated so that the shaft is shorter and the number of inverters and controllers is less, hence the cost is reduced. The suspension and motor windings are wound together in the stator core so that the air-gap flux density distribution is unbalanced by the addition of the suspension and main motor fluxes; as a result, a suspension force is generated. This concept can be applied to several types of conventional motor, i.e., permanent magnet (PM), induction and switched reluctance, etc [2]. Some prototype machines have been constructed to apply to small chemical liquid pumps [3], canned pumps [4], drivers of data storage medium (CD, DVD) [5], etc. The small liquid pumps are commercially sold in the markets.

It is well known that brushless DC motors are widely applied in drivers in home appliances and information machines such as hard disk and CD drives, etc. Mechanical bearings made from ceramic materials or oil bearings are usually used to support the shaft of brushless DC motors. Because mechanical friction is very low in these bearings. However, maintenance-free, a long life cycle and high speed operation are required in the brushless DC motors. In this paper, the author applies the bearingless drive technique in the general-use brushless DC motors to satisfy the requirements above.

This paper presents a new structure of bearingless motor with 2-phase brushless DC structure. The proposed structure is illustrated and the principle of suspension force generation is found. The magnetic suspension control method is proposed to stably support the rotor without any mechanical contact then the control system configuration is illustrated. The rotational torque and suspension force are computed by FEM using a machine model. It is found that the mutual interference undesirably occurs between the suspension forces in two perpendicular radial axes. The reason why the mutual interference occurs is discussed. The effectiveness of rotor skew and sinusoidal current commands in the suspension windings is confirmed through the computed results by FEM to decrease the mutual interference between the suspension forces, respectively.

II. Bearingless Motor Structure

Fig. 1 shows the cross section of the proposed bearingless motor with 2-phase brushless DC structure. It consists of an inner stator core with 12 slots and an outer rotor with 6 poles. PMs are mounted on the inner surface of the rotor core. The PM poles faced on the rotor core are shown in Fig. 1. Both the motor and suspension windings

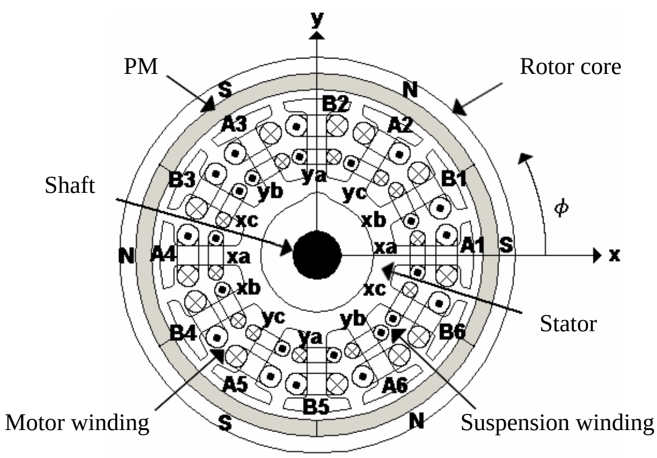
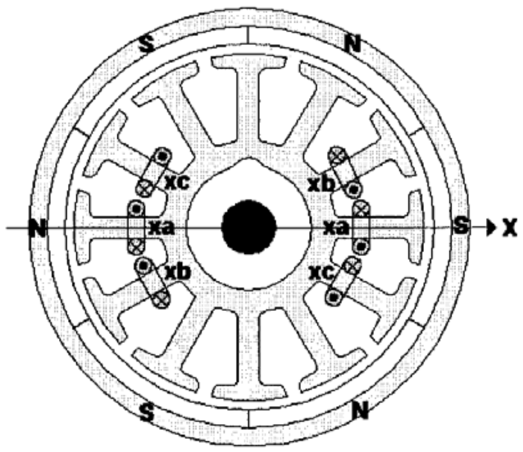
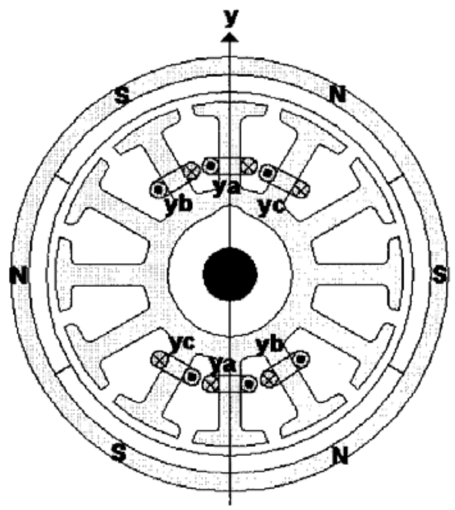


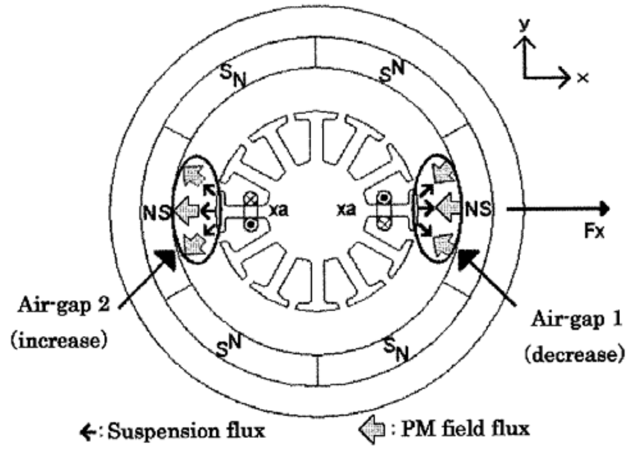
Fig. 1 Cross section of bearingless motor with 2-phase brushless DC structure.



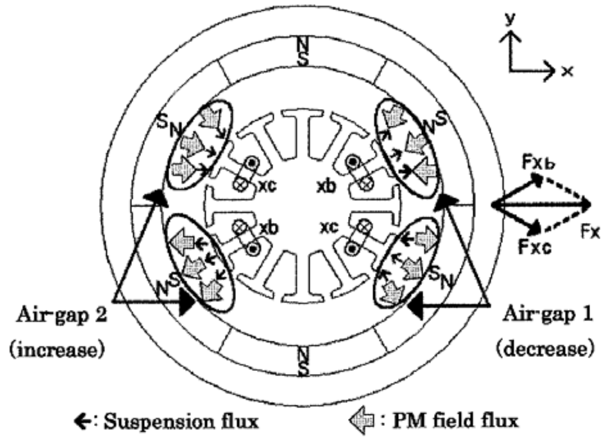
(a) x-windings to generate force in x-direction.



(b) y-windings to generate force in y-direction.
Fig. 2 Suspension winding distribution.



(a) At rotor angular position of 0 [deg].



(b) At rotor angular position of 30 [deg].
Fig. 3 Principle of suspension force generation.

are distributed as short-pitch windings. Six motor windings denoted by A1, A2, A3, A4, A5 and A6 are connected in series (A-phase), and the other six motor windings denoted by B1, B2, B3, B4, B5 and B6 are connected in series (B-phase) so that the motor windings are 2-phase. The motor construction and the motor winding distribution are the same as the conventional brushless DC motors, respectively. The suspension windings are additionally wound in the stator core. The six windings denoted by xa, xb, xc, ya, yb and yc are suspension windings to generate suspension force. Figs. 2 (a) and (b) show the suspension winding arrangement, which are picked up in Fig. 1. Fig. 2 (a) shows the windings xa, xb and xc to generate suspension force in the x-direction and Fig. 2 (b) shows the windings ya, yb and yc to generate suspension force in the y-direction. A suspension winding is wound on each stator tooth as described in Figs. 2 (a) and (b), and two suspension windings, which are wound on two teeth in both sides across the shaft, are connected in series; as a results, it composes a set of the suspension winding such as xa, xb, etc. In the proposed bearingless motor with 2-phase brushless DC structure, the suspension windings are perfectly divided into ones (xa, xb, xc) to contribute in the x-direction force and the others (ya, yb, yc) to contribute in the y-direction force. The air-gap densities are unbalanced by the suspension flux so that the suspension forces generate in radial directions. The arbitrary suspension force can be successfully generated by the resultant force in the x- and y-axes. The principle of suspension force generation is written in detail in next chapter.

III. Principle of Suspension Force Generation and Control Strategy

A. Principle of Suspension Force Generation

In the proposed bearingless motor with 2-phase brushless DC structure, the principle of rotational torque generation is the same as the conventional 2-phase brushless DC motors. Figs. 3 (a) and (b) show the principle of suspension force generation at the rotor angular positions of 0 [deg] and 30 [deg], respectively. The thick

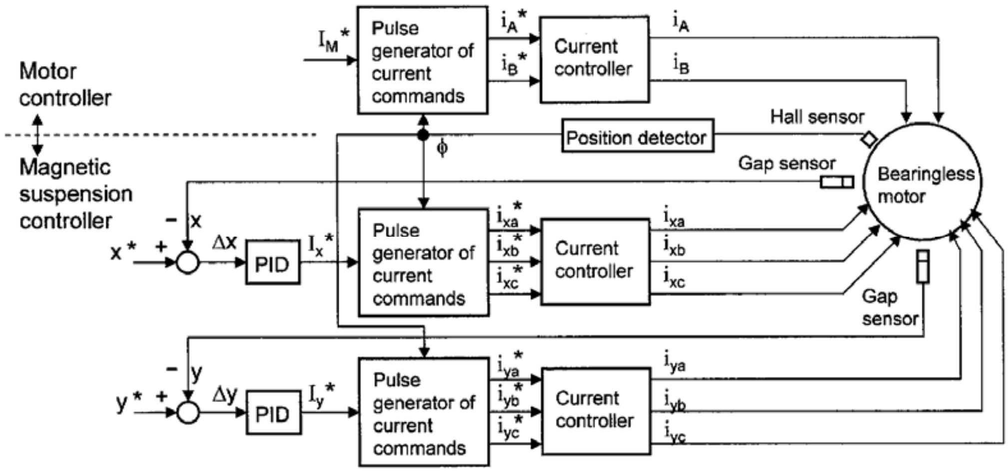


Fig. 4 Control system configuration.

arrows show the field flux of PMs in the air-gaps 1 and 2. At 0 [deg] in Fig. 3 (a), the suspension winding xa is excited then the suspension flux generates in the air-gaps 1 and 2 as described by the thin arrows in Fig. 3 (a) (Mode 1). The flux density is decreased in the air-gap 1, however, it is increased in the air-gap 2. The suspension force F_x generates to positive direction in x-axis by the unbalance of the air-gap flux densities. At 30 [deg] in Fig. 3 (b), the suspension windings xb and xc are excited (Mode 2). The air-gap flux densities are unbalanced by the excitation in the winding xb so that the suspension force F_{xb} generates in the direction as described in Fig. 3 (b). Similarly, the suspension force F_{xc} also generates. Eventually, the resultant force of the F_{xb} and F_{xc} generates in the x-positive direction. The condition when the xa is excited is defined as Mode 1 and the condition when the xb and xc are excited is defined as Mode 2. The excitation of suspension windings is changed depending on the rotor angular position.

However, the resultant force in Mode 2 is larger than the generated force in Mode 1 when the xa is excited as shown in Fig. 3 (a) if the number of winding turns is equal and the exciting current is also equal in the suspension windings. Thus, it is necessary that the number of winding turns of the xb and the xc are set to be less than that of the xa or the exciting currents in the xb and xc are set to be smaller than that in the xa; as a result, the suspension forces are equal in both Mode 1 and Mode 2. The number of winding turns of the xb is equal to that of the xc. The xb and xc are excited and turned off at the same time. The Mode 1 and 2 are repeated every mechanical rotor angular position of 30 [deg] so that the suspension force is constantly generated in x-positive direction. The magnetic suspension control method is shown in detail in next section.

The y-direction force can be also generated by the excitation in the suspension windings ya, yb and yc. Similar to the x-direction windings, it is necessary that the number of turns of the windings yb and yc is less than that in the ya or the exciting currents of the yb and yc are less than that of the ya. In the proposed bearingless motor with brushless DC structure, the suspension windings (xa, xb and xc) are excited when the suspension force generates in the x-direction and the suspension windings (ya, yb and yc) are excited when the suspension force generates in the y-direction thus the role of these windings is independent each other.

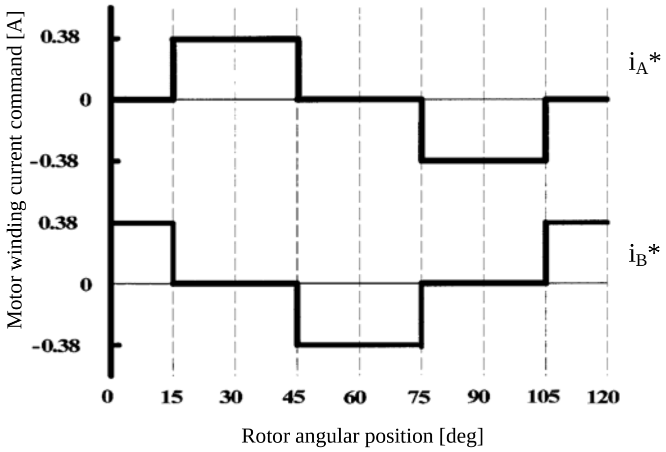
B. Magnetic Suspension Control Strategy

In the proposed bearingless motor with 2-phace brushless DC structure, the excitation of suspension windings is successfully changed in accordance with the rotor angular position such as the excitation of motor windings in the conventional brushless DC motors. It results in the stable rotor suspension without any mechanical contact.

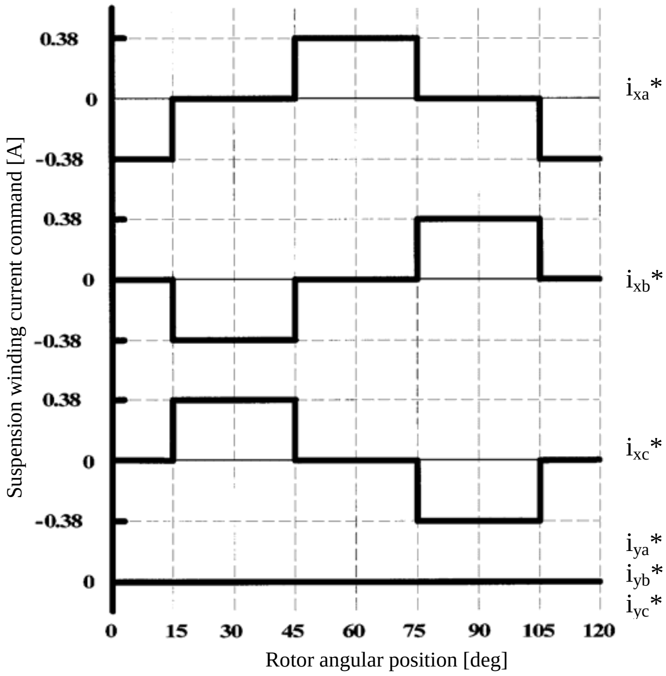
Fig. 4 shows the control system configuration. In the motor controller, the rotor angular position ϕ detected every 30 [deg] (mechanical position) by the hall sensors. By the current command I_M* and the detected angular position ϕ, the current command pattern i_A* and i_B* in the motor A- and B-phase windings are determined. The motor winding currents i_A and i_B are controlled to follow the current commands.

In the rotor suspension controller, the rotor radial positions x and y in two perpendicular axes are detected by the gap sensors. The difference between the detected rotor radial position and position command is amplified by Proportional-Integral-Derivative (PID) Controller in the x- and y-axes, respectively; as a result, the suspension winding current commands I_x* and I_y* are determined. By the current commands and the detected rotor angular position ϕ, the current command pattern in the suspension winding is determined then the suspension winding currents are controlled to follow the commands in the current controller.

Figs. 5 (a) and (b) show the example of waveforms of the current commands in the motor and suspension windings, respectively. The motor current pattern in Fig. 5 (a) is the same as the conventional 2-phase brushless DC motors. Fig. 5 (b) shows the current pattern in the



(a) Motor winding current commands.



(b) Suspension winding current commands.
Fig. 5 Waveforms of current commands.

suspension windings when the suspension force generates in the x-positive direction. The suspension winding currents are rectangular waveforms with the same frequency as the motor winding current. The current commands i_{ya}*, i_{yb}* and i_{yc}* in the suspension windings ya, yb and yc are zero, respectively, when the suspension force generates in the x-direction. It is seen in the winding distribution in Fig. 1 and the current command patterns in Figs. 5 (a) and (b) that both of the motor and suspension windings wound in the same stator tooth are not excited at the same time; for example, during the rotor angular position of 15-30 [deg], the A-phase motor windings A1-A6 are excited, however, the suspension winding xa, which is wound in the stator teeth with the A-phase motor windings A1 and A4, is not excited. It means that the mutual interference between the motor and suspension windings is very small. By the proposed magnetic suspension control method, the motor can be stably suspended without any mechanical contact.

IV. Analyses of Rotational Torque and Suspension Force

The rotational torque and suspension force are computed using a Finite Element (FE) model of the proposed machine. Table I shows the specification of the FE model. The current gains are set to be equal in all of the suspension windings. The number of winding turns of xb and xc is set to be 0.6 times that of the xa and the number of winding turns of yb and yc is also set to be 0.6 times that of the ya considering (1) and (2) below,

(1) The xb and xc are excited in the same term during the motor operation as described in Fig. 5 (b) and the yb and yc are excited in the same term.

(2) The tooth pitch in the stator core, where the xa, xb and xc are wound, is 30 [deg]. The tooth pitch in the stator core, which the ya, yb and yc are wound, is also 30 [deg].

The motor and suspension winding currents are commanded as shown in Figs. 5 (a) and (b) so that the rotational torque generates in the counter-clockwise direction and the suspension force generates in the x-positive direction.

TABLE I
Specification of FE Model

Rotor core	outer diameter	24.6 [mm]
	inner diameter	22.6 [mm]
PM	Nd-Fe-B	
	thickness	1 [mm]
Air-gap length	0.55 [mm]	
Stator core	outer diameter	19.5 [mm]
	stack length	5.1 [mm]
Motor winding	35 [turns] /tooth	
	current rating	0.38 [A]
Suspension winding	30 [turns] /tooth (xa, ya)	
	18 [turns] /tooth (xb, xc, yb, yc)	
	current rating	0.38 [A]

A. *Rotational Torque*

Fig. 6 shows the computed rotational torque by FEM. The horizontal axis is the rotor angular position. It is seen that the torque ripple is large. Thus, it is necessary to make an effort to decrease it.

B. *Suspension Force*

Fig. 7 shows the computed result of suspension force. It is seen that the suspension force is generated in the x-positive direction in accordance with the current command. The x-direction force F_x is about 1 [N] and it is almost equal to the rotor gravity. Thus, it is necessary that the MMF of suspension windings is increased to stably support the rotor. On the other hand, the y-direction force

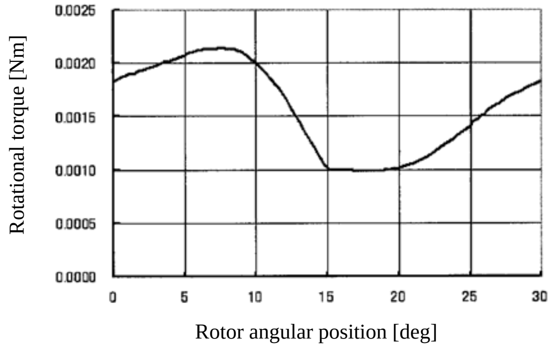


Fig. 6 Rotational torque.

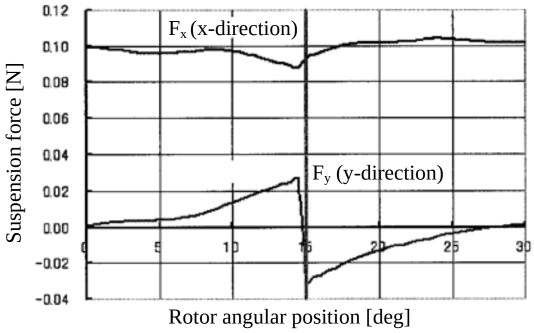
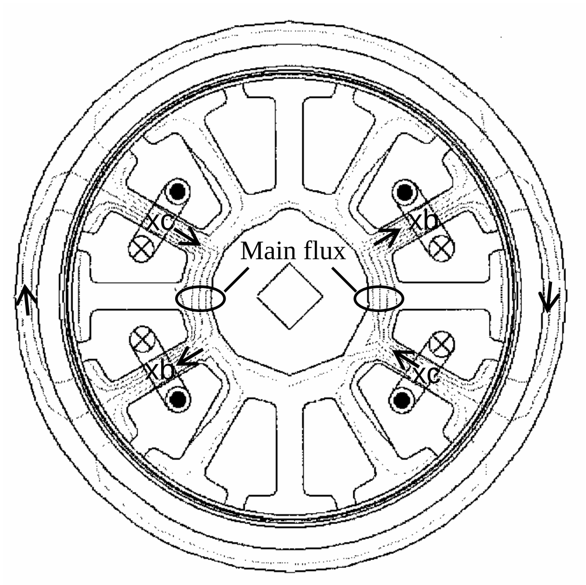


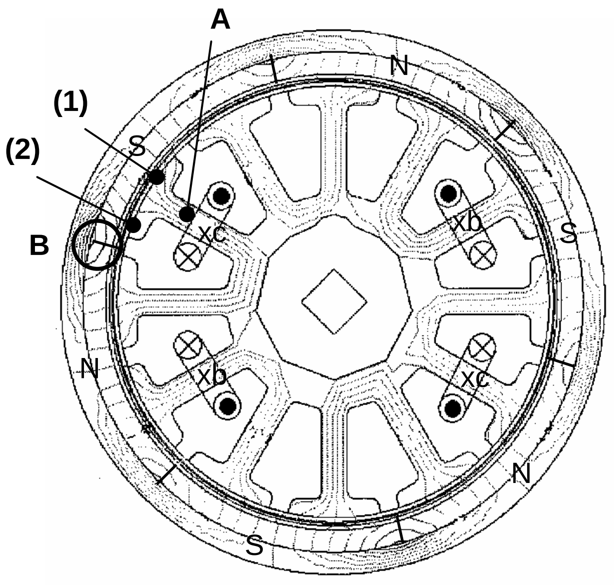
Fig. 7 Suspension forces.

F_y is also generated. The mutual interference occurs in the suspension forces between two perpendicular axes x and y, which causes the unstable rotor levitation. The interference ratio (F_y /F_x) is reached to 32.4% at the rotor angular position of 15 [deg] where the suspension winding excitation is changed from the xa to the set of xb and xc. It is possible that the rotor radial displacement will be large and the rotor suspension will be unstable at this angular position.

The mutual interference is caused by no uniformity of the flux density distribution in the air-gaps faced on the stator teeth where the suspension windings are excited. Figs. 8 (a) and (b) show the flux distribution at the angular position of 15 [deg]. Fig. 8 (a) shows the only suspension flux without the PM field and motor fluxes and Fig. 8 (b) shows the total flux distribution including the PM field and motor fluxes. The N and S show the PM poles faced on the rotor core. It is seen that the air-gap flux distribution on the stator teeth where the excited windings xb and xc wound is almost uniform in Fig. 8 (a), however, it is not uniform in Fig.8 (b). In the air-gap on the surface of the tooth A where the xc is excited, for example, the flux is concentrated in the air-gap area denoted by (1) and the flux density is higher than that in the area (2). It can be seen that no uniformity of flux distribution also occurs in the other air-gaps on the surface of teeth where the suspension windings are excited. Thus, the negative y-direction component in the suspension force is generated at this rotor angular position, however, the suspension force is commanded in the x-positive direction. The reason why the flux



(a) Suspension flux.



(b) PM field, motor and suspension fluxes.
Fig. 8 Flux distribution at the rotor angular position of 15 [deg]

distribution is not uniform in the air-gaps is the pre-magnetization of PMs. The sinusoidal PM pre-magnetization is employed in the computation by FEM. Thus, the leakage fluxes of PMs are generated such as the PMs denoted by the area B; as a result, no uniformity occurs in the air-gap flux distribution. By the y-direction force, the mutual interference occurs in two perpendicular radial axes, which causes the unstable rotor levitation. The next section shows the effective methods to decrease the mutual interference.

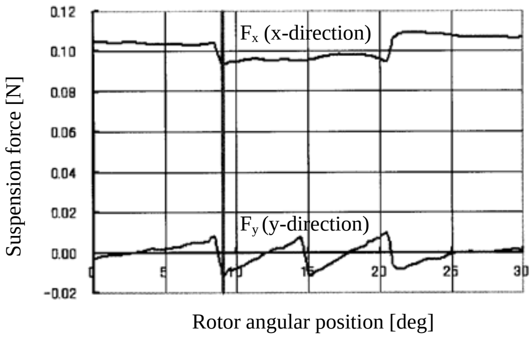


Fig. 9 Suspension forces when the rotor is skewed.

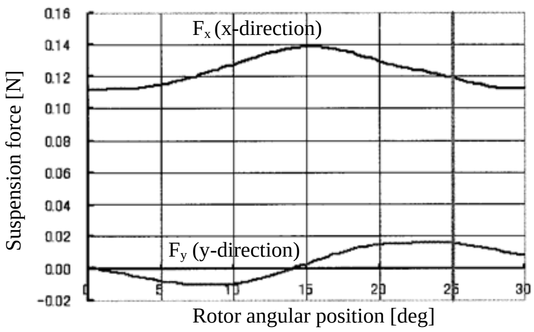


Fig. 10 Suspension forces when the suspension winding current commands are sinusoidal.

C. Effectiveness of Rotor Skew and Sinusoidal Current Commands

The rotor is skewed to eliminate the mutual interference between the suspension forces in the x- and y-axes. Fig. 9 shows the computed results of suspension force when the rotor is skewed. The rotor is divided into three sections in the axial direction. The top section is skewed by 6 [deg] to the rotor rotating direction and the bottom is skewed by 6 [deg] in opposite to the rotor rotating direction. The rotor skew angle is totally 12 [deg] so that the interference ratio (F_y /F_x) is reached to a minimum. In Fig. 9, the y-direction force F_y is smaller than that in the rotor without the skew and the interference ratio is decreased to 11.6%. The effectiveness of rotor skew can be confirmed in the computed result in Fig. 9.

As another method to decrease the mutual interference, the suspension winding current commands are changed from the rectangular to sinusoidal waveforms such as the fundamental components in the rectangular waveforms in Fig. 5 (b). Fig. 10 shows the computed suspension force when the suspension winding current commands are sinusoidal. The interference ratio (F_y /F_x) is less than that of Fig. 7. The maximum ratio is 13% at the rotor angular position 25 [deg]. By the sinusoidal waveforms, there are terms when all of the xa, xb and xc are excited, however, the xa and the set of xb and xc were alternatively excited when the current commands were rectangular as shown in Fig. 5 (b). At the angular position of 15 [deg], for example, the xa as well as the set of xb and xc is excited then the current flows in the xa in the negative direction. In Fig. 8 (b), the x-direction force is generated by the xa excitation, however, the y-direction force is also generated by no uniformity in the air-gap flux distribution on the teeth where the winding xa is wound; as a result, the mutual interference is successfully cancelled by the increased force in the y-axis.

V. CONCLUSION

In this paper, a new bearingless motor with 2-phase brushless DC structure has been proposed. The principle of suspension force generation and magnetic suspension control strategy are found, respectively. The rotational torque and suspension force have been computed by FEM using a machine model. The effectiveness of rotor skew and sinusoidal current commands in the suspension windings is also found to decrease the mutual interference between the suspension force components in two perpendicular axes, respectively. However, it should be considered that the rotor structure and suspension controller are more complex due to the employment of rotor skew and sinusoidal current commands, respectively.

ACKNOWLEDGMENT

The author thankfully acknowledges the work done by Mr. Fukuzawa who was former graduated student at the Tokyo University of Science, Suwa College.

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