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Impact of inclination of teeth for bearingless motor with non-contact power supply

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Abstract
A new type of bearingless motor has been developed. The feature of this bearingless motor is no use of permanent magnets. The rotor is magnetized by a current of a non-contact power supply, which consists of a bridge rectifier circuit and coils. Levitation is achieved through attractive forces generated by inclinations on the edges of the rotor and the stator. In the previous study, levitation of a prototype system could not be achieved. It was posited that the inclination of edges decreases restitutive force, which is used to control the tilting motion of the rotor. In this paper, the impact of the inclination of the edges on the decrease of restitutive force was investigated and confirmed by 3D-FEM analysis. Additionally, levitation of the prototype system was investigated by simulating the displacement of the rotor with both linear and non-linear rotor models. Finally, the control principle was changed according to findings of this study and the controllable range of the rotor was calculated.

Keywords : Bearingless Motor, Magnetic Bearing, Contactless feed, Electromagnetic Rotor, No Permanent Magnet, Electromagnet

1. Introduction

Research on bearingless motors has been conducted to develop motors and magnetic bearings (Chiba and Fukao, 2001; The Magnetic Levitation Technical Committee of The Institute of Electrical Engineers of Japan ed., 1993). Most bearingless motors use permanent magnets on their rotors (Asama, 2013; Onuma, et al., 2012), but permanent magnets have issues of decreased magnetic force due to heat. As a solution, researchers are developing bearingless motors which do not use permanent magnets (Tachibana, 2014; Morimitsu, 2015). The rotor of these motors have coils which are magnetized by a non-contact power supply.

The rotor and stator edges of the bearingless motor prototype used in this study have an inclination (teeth inclination) to generate the levitation force. It is suspected that the restitutive force is decreased by the teeth inclination, consequently, preventing levitation of the rotor. In this paper, the impact of the teeth inclination and float controllability of the rotor of the prototype system were investigated.

First, the prototype system used in this research is described in detail. Second, FEM analysis, which is used to investigate the impact of the teeth inclination, is described. Third, the improvement of the control principle with linear control simulation is described. Finally, non-linear control simulation, which is used to investigate the controllable range of the rotor, is described.

2. Prototype system

2.1. Control principle

The rotor receives electric power from electromagnetic induction, and rotor coils for levitation and rotation are magnetized in one direction by diode bridge. The levitation is achieved by generating a pulling force on the rotor coils by the stator coils, as shown in fig. 1. In the horizontal-axis, the rotor displacement is

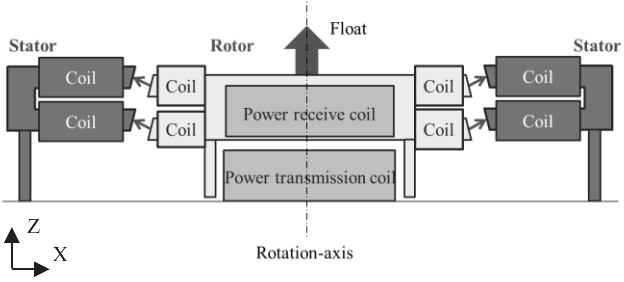

Fig. 1 Side view of the prototype system.

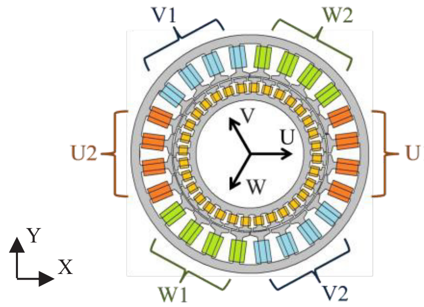

Fig. 2 Principle of radial suspension force generation.

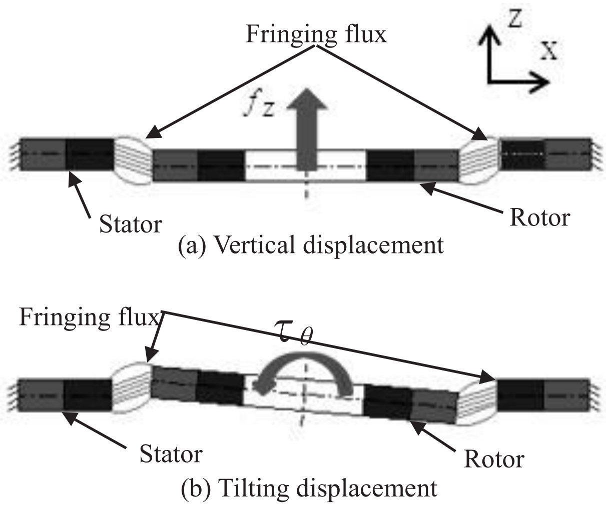

Fig. 3 Principle of axial and tilting restitutive force generation .

actively controlled by controlling the current of the stator coils for levitation, as shown in fig. 2. Tilting displacement and vertical displacement of the rotor are passively controlled, as shown in fig. 3. The inclination of the sartor and rotor teeth edges increases the lifting force produced by the coils. The rotation of the rotor is controlled by sequentially adjusting the current of stator coils for rotation.

2.2. Specifications of the prototype

The specifications of the prototype bearingless motor are shown in table 1. The levitation and rotation coils were winded in parallel on one tooth of the stator. The winding orientation for the non-contact power supply coils was a spider winding and the winding numbers of these coils were 60 turns. Litz type 7 strand wires were used for the coils for the non-contact power supply. The current of the rotor was 1.2A and the efficiency of the power supply was kept over 90% by using a resonance circuit.

Table 1 Specifications of the prototype bearingless motor.

Parameter	Rotor	Stator
Material	SS 400	SS 400
Teeth number	32×2	24×2
Winding number of coil	100	100＋100
Mass	772 g	-
Outside diameter	142 mm	220 mm
Inside diameter	100 mm	144 mm
Suction force coefficient	2.56 Nmm	
Bias current	1.2 A	
Air gap	1 mm	
Teeth inclination	7.6°	

2.3. Problem point

No levitation of the rotor was achieved in the previous studies. The reason for failed levitation is considered to be due to a decrease of the restitutive forces caused by teeth inclination, as shown in Fig.4.

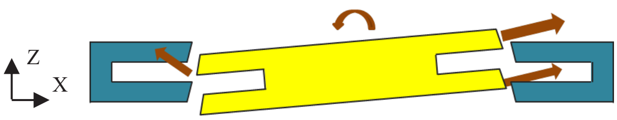

Fig. 4 When the rotor tilts, generation of the restitutive force is decreased due to teeth inclination.

3. FEM analysis

3.1 Purpose

FEM analysis can find out the relationship between the teeth inclinations and the rotor tilt, more easily than experiment in many cases. This data is useful to find out the controllability of the rotor and how development is valid.

3.2 Methodology

The prototype system is cylindrically symmetric, so an XZ-plane model is sufficient to be used as the model for analysis, as shown in fig. 5. Details of the analysis are shown in Table 2. The generated force and torque were calculated for different setup parameters, such as the applied current of the stator coils or the displacement of the rotor along X-axis. In addition, this analysis was

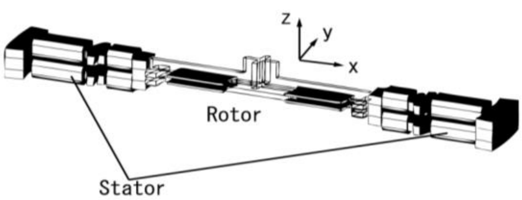

Fig. 5 The rotor model for analysis.

conducted for different teeth inclination angles.

Table 2 Analysis method.

Analysis software	J-MAG
Analysis method	3D FEM
Mesh size	0.2 mm

3.3 Result

Figure 6 shows the relation between torque generated on the rotor and the angle of tilt along the Y axis for different teeth inclination angles. The restitutive force is directly proportional to the torque generated in response to the tilting displacement. According to these results, the generated restitutive force is reversely proportional to the teeth inclination angle.

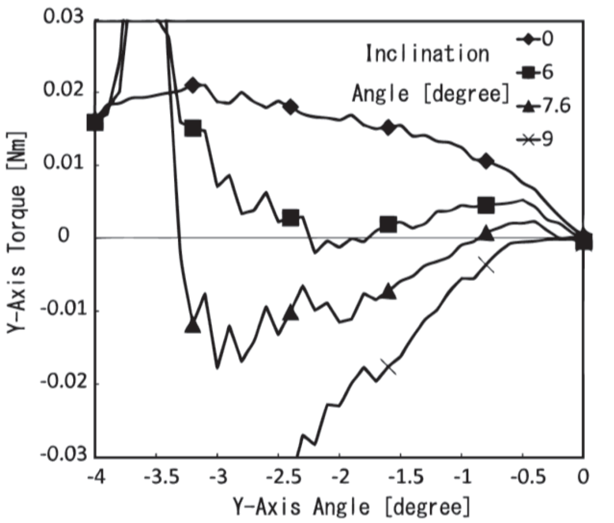

Fig. 6 Relationship between the torque generated on the rotor and the tilt angle for different teeth inclinations.

Figure 7 shows the relation between force generated on the rotor for the levitation and the angle of tilt along the Y axis for different teeth inclination angles. The

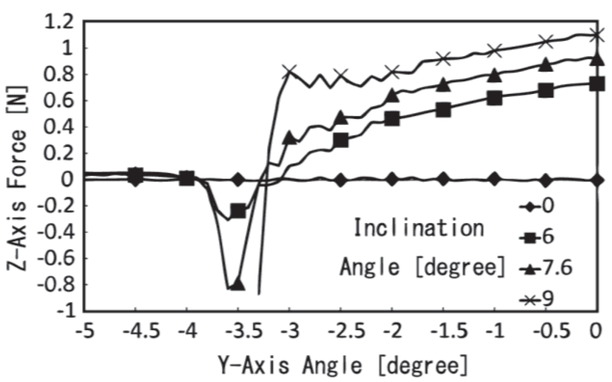

Fig. 7 Relations between Z-axis force generated on the rotor and the tilt angle around Y-axis of the rotor for different teeth inclinations.

force generated for levitation was found to be directly proportional to the teeth inclination angle.

Figure 8 shows the relation between torque generated by the rotor and the current of the stator coil, which is winded in the positive side of the X-axis. The analysis result shows that increasing the current of the lower coil will, in turn, will increase the torque generated by the rotor.

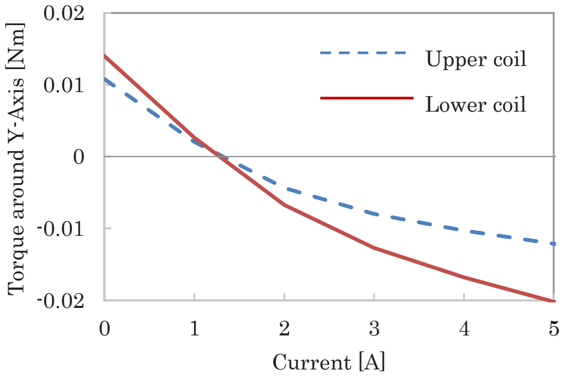

Fig. 8 Relation between torque generated on the rotor and the current of a stator coil which is winded in positive side of X-Axis.

3.4 Discussion

The result of the analysis indicates that the controllability of levitation is decreased by the increasing of the teeth inclination. The result shown in fig. 8 suggests that the tilting of the rotor is controllable by adjusting the current of the upper and lower coils of the stator. It was also determined that the generated force is sufficient for levitation of the rotor.

4. Linear control simulation

4.1 Purpose

Linear control simulations were conducted to investigate the controllability of the rotor, and to improve the prototype system. The state equation of the rotor was obtained by linearizing the FEM analysis results, and was used for the linear simulations. The simulation was performed with the commercial software, Matlab. Initial condition response of the state-space models were used for the controls simulation.

4.2 Conventional system

In a conventional system, state equation of the rotor was calculated as shown in eq. (1)-(5), obtained from results of FEM analysis. In equations (4) and (5) **O** indicates zero matrices and **I** indicates identity matrix. An example of the linear simulation result is shown in Fig. 9. The simulation was unable to achieve convergence for the tilting displacement.

$$\boldsymbol{x} = \begin{bmatrix} x & y & z & \theta_y & \theta_x & \dot{x} & \dot{y} & \dot{z} & \dot{\theta}_y & \dot{\theta}_x \end{bmatrix}^T \quad (1)$$

$$\boldsymbol{u} = \begin{bmatrix} i_{U1} & i_{V1} & i_{W1} & i_{U2} & i_{V2} & i_{W2} \end{bmatrix}^T \quad (2)$$

$$\dot{\boldsymbol{x}} = \mathrm{A}\boldsymbol{x} + \mathrm{B}\boldsymbol{u} \quad (3)$$

$$\mathbf{A} = \left[\begin{array}{c|c} \mathbf{O} & \mathbf{I} \\ \hline \begin{matrix} 21281 & 0 & 0 & -166 & 0 \\ 0 & 21281 & 0 & 0 & 166 \\ 0 & 0 & -346 & 0 & 0 \\ -193 & 0 & 0 & -0.6 & 0 \\ 0 & 193 & 0 & 0 & -0.6 \end{matrix} & \mathbf{O} \end{array}\right] \quad (4)$$

$$\mathrm{B} = \left[\begin{array}{cccccc} & & \mathrm{O} & & & \\ \hline 9.73 & -4.86 & -4.86 & -9.73 & 4.86 & 4.86 \\ 0 & 8.43 & -8.43 & 0 & -8.43 & 8.43 \\ 1.23 & 1.23 & 1.23 & 1.23 & 1.23 & 1.23 \\ -0.08 & 0.04 & 0.04 & 0.08 & -0.04 & -0.04 \\ 0 & 0.08 & -0.08 & 0 & -0.08 & 0.08 \end{array}\right] \quad (5)$$

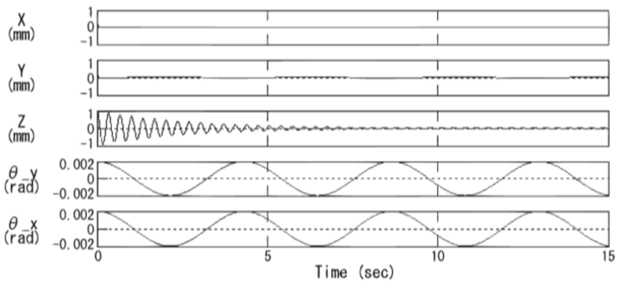

Fig. 9 A result of the linear control simulation in conventional system.

4.3 Improved system

To eliminate the tilt displacement of the rotor, the principle of the control was changed, as shown in Fig. 10. Previously, the current of only one side of the coils of the UVW-axis was controlled. In the new control method, however, the current of the upper and the lower coils were controlled separately. The horizontal position of the rotor is controlled along UVW-axis (fig. 10a) while the tilt displacement is controlled by adjusting the current of upper and lower coils separately fig. 10c). Levitation of the stator is controlled by controlling the current of the stator coils X (fig. 10b). The controller for this system is shown in fig. 11. All three, vertical, horizontal, and tilting displacements were controlled by a PID controller.

In the improved system, vector $\boldsymbol{u}$ and matrix **B** of eq. (3) were calculated, as shown in eq. (6), (7). A result of

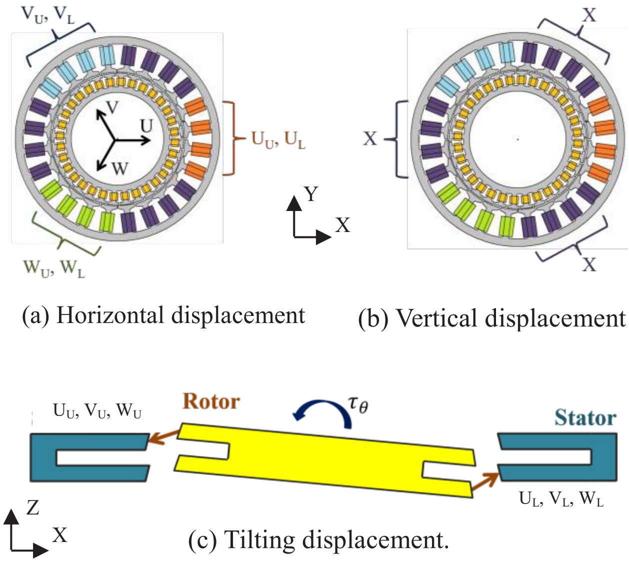

Fig. 10 Principle of suspension force generation.

the linear simulations is shown in Fig. 12. Convergence of the tilt displacement was achieved with the improved control system.

$$\boldsymbol{u} = \begin{bmatrix} \mathrm{i}_{UU} & \mathrm{i}_{VU} & \mathrm{i}_{WU} & \mathrm{i}_{UL} & \mathrm{i}_{VL} & \mathrm{i}_{WL} & \mathrm{i}_{X} \end{bmatrix}^{\mathrm{T}} \quad (6)$$

$$\mathbf{B} = \left[\begin{array}{ccccccc} & & & \mathbf{O} & & & \\ \hline 4.91 & -2.46 & -2.46 & 4.91 & -2.46 & -2.46 & 0 \\ 0 & 4.26 & -4.26 & 0 & 4.26 & -4.26 & 0 \\ 0.61 & 0.61 & 0.61 & 0.61 & 0.61 & 0.61 & 3.66 \\ -0.04 & 0.02 & 0.02 & -0.05 & 0.03 & 0.03 & 0 \\ 0 & 0.03 & -0.03 & 0 & 0.04 & -0.04 & 0 \end{array}\right] \quad (7)$$

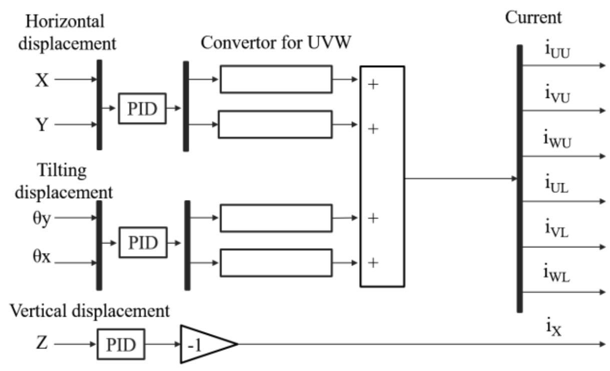

Fig. 11 Control method of the improved system

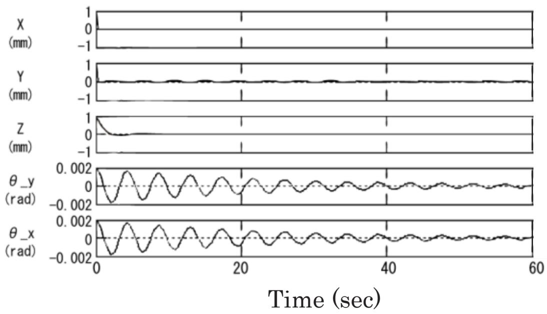

Fig. 12 A result of the linear control simulation in improved system.

5 Non-linear control simulation

5.1 Purpose

The exact displacement of the rotor in the case when the rotor is outside of the equilibrium position can be investigated by non-linear control simulation. This allows obtaining the controllable range of the rotor and index parameters to adjust the control gain.

5.2 Methodology

Non-linear control simulations were conducted by using Matlab and Simulink. The model of the non-linear rotor for this simulation is shown in fig. 13. Forces of XYZ-axis and torques acting on the rotor around XY-axis were calculated by using the results of FEM analysis, as shown in fig. 14. Torque around Y-axis was generated by modifying the current of the stator coils, lateral displacement along the X-axis and tilting displacement around Y-axis. Displacement along all 5-axis is given by eq. (8), (9), (10), (11). At Equilibrium position, the rotor is staying at the coordinate center, so the target values are all 0. The equilibrium potion of the rotor is 1mm below the default position, thus, in all simulations, the displacement of Z-axis was started from -1mm.

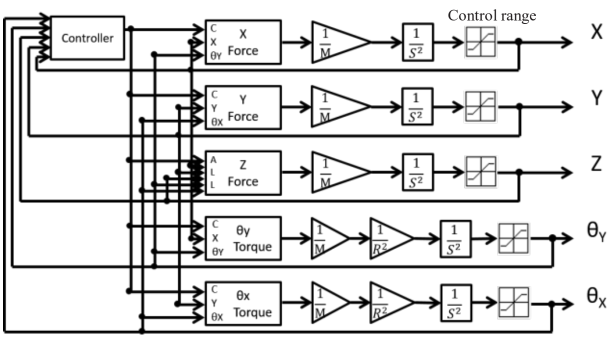

Fig. 13 The non-lineally model of the rotor.

$$a = \frac{F}{M} \tag{8}$$

$$x = \iint a \tag{9}$$

$$\alpha = \frac{\tau}{MR^2} \tag{10}$$

$$\theta = \iint \alpha \tag{11}$$

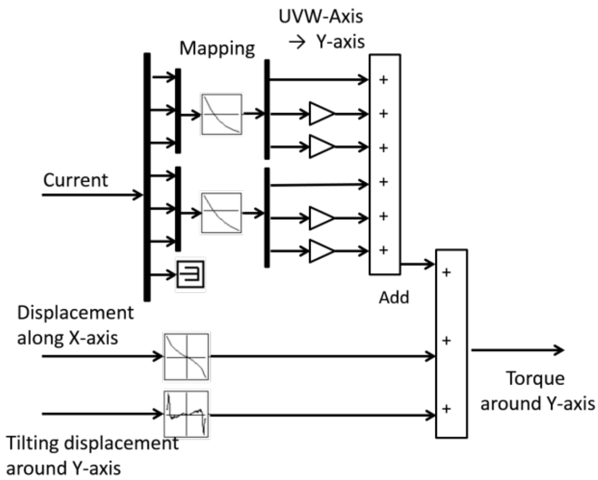

Fig. 14 The brock which calculate the torque on the rotor.

5.3 Result

Parameters of the PID controller were established by trial and error. PID parameters of the horizontal axis were $K_P: 50, K_I: 10, K_D: 1$, while those of vertical axis were $K_P: 10, K_I: 1, K_D: 1$, and those of tilting axis were $K_P: 100, K_I: 100, K_D: 30$. A result of the simulation when the rotor was controlled from the position of equilibrium, except for the Z-axis position, which was set to -1, is shown in fig. 15. Levitation of the rotor could be achieved with this setup. A result of the simulation when

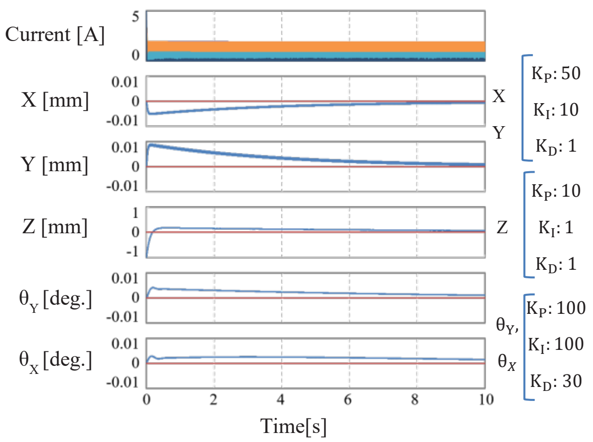

Fig. 15 A result of the non-linearly simulation. Initial conditions (X, Y, Z, θ_Y, θ_X):
= (0 mm, 0 mm, -1 mm, 0 degree, 0 degree)

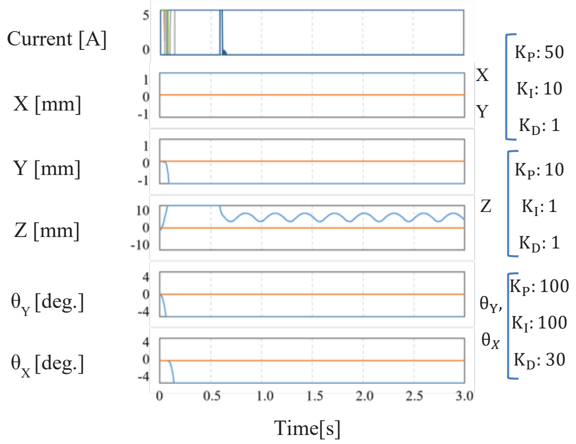

Fig. 16 A result of the non-linearly simulation.
First condition: $(X, Y, Z, \theta_Y, \theta_X)$
$= (1$ mm, 0 mm, -1 mm, 0 degree, 0 degree$)$

the rotor was controlled from the position of the X-axis at 1mm is shown in fig. 16. No levitation of the rotor could be achieved in this case. Figure 17 shows the control range and controllable range of the rotor on the horizontal axis. The controllable range is by 0.5mm smaller than the control range.

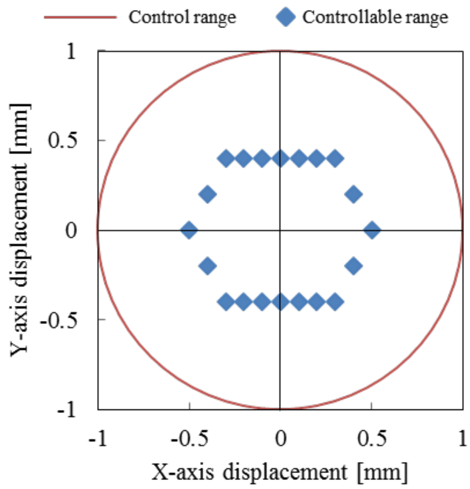

Fig. 17 Controllable range in horizontal axis.

5.4 Discussion

The non-linear simulation showed that the controllable range is smaller than control range. The reason for this supposedly is the change of the pulling force of the magnet according to the inverse-square law. The rotor must be controlled in the controllable range to achieve levitation.

6. Conclusion

Relationship between increase in the teeth inclination and decreases of the restitutive force and stability of the rotor was found by using FEM analysis and control simulations. The control principle of the prototype system of the bearingless motor was improved according to the simulation results to enhance the controllability. Additionally, a non-linear model of the rotor was constructed and analyzed. It was found that the levitation of the rotor can be achieved in the controllable range.

Float performance of the rotor was studied by simulations only. Further experimental and theoretical work is necessary to verify these results.

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