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DEVELOPMENT OF AN AXIAL MAGNETIC BEARING FOR VERTICAL-TYPE CENTRIFUGAL SEPARATORS

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ABSTRACT

This paper presents a new axial magnetic bearing for the centrifugal separators, which are used to separate into liquids and solids in chemical, material industries, and so on. In order to separate much original liquid into the liquid and the solid for a short time, the centrifugal separators with large volume and large capability are required. To satisfy the requirements, the large axial magnetic bearing with the maximum axial magnetic force of 7,200 N is proposed. The features are as follows: 1) the magnetic field does not influence on the flow of the original liquid, and 2) the stiffness is relatively high also in the radial direction. The structure of the proposed axial magnetic force is shown and the control system configuration is also introduced. The optimal sizes of the electromagnets and permanent magnets are derived by the analysed results using Finite Element Method (FEM). The radial and axial forces are also computed by FEM for the rotor motion in the parallel and conical modes, respectively. It is confirmed that the enough suspension force is generated to support the rotor suspension part in the proposed axial magnetic bearing, which is quite suitable as the axial magnetic bearing in the vertical-type centrifugal separator.

INTRODUCTION

The centrifugal separators are widely used to separate into liquids and solids in withdrawing the materials and treating wastewater in chemical, material industries and so on [1]. The centrifugal separators are, for example, used to withdraw nickel alloys and powders, which are included in the batteries in mobile phones. Most of the centrifugal separators are lateral types. However, the separated liquid stands in the bottom of the pipe in the lateral-type separators. Thus, the efficiency is lower to separate into the liquid and solid. On the other hand, the vertical-type centrifugal separators can fly out the liquid to any radial direction on the circumference; as a result, the efficiency is higher than that of the lateral-type.

In order to separate much original liquid into the liquid and the solid for a short time, the centrifugal separators with large volume and large capability are required. The angular contact ball bearing is equipped between the fixed pipe and the rotational pipe and the rotational pipe is supported by the angular bearing in the axial direction in the conventional centrifugal separators. The angular contact ball bearings with large diameter are necessary to expand the capability of centrifugal separators; however, there is a limitation in the diameter of the angular bearings in accordance with the rating, which are commercially available.

Instead of the conventional bearings with mechanical contact, the magnetic bearings and magnetic levitations have been attracted the attention in industry and transportation fields and the demands of them are increasingly expanded [2] [3]. Substituting for the angular contact ball bearings, in this paper, an axial magnetic bearing is proposed for the large vertical-type centrifugal separators. The structure and principle of the proposed axial magnetic bearings are introduced. The axial suspension force and also the radial force are computed by FEM (Finite Element Method) using an axial magnetic bearing model.

PPROPOSED STRUCTURE OF AXIAL MAGNETIC BEARING

Fig. 1 shows the structure of vertical-type centrifugal separator equipping the proposed axial magnetic bearing. The vertical-type centrifugal separator consists of a fixed pipe, a rotational pipe and a screw, where the rotational pipe is inside of the fixed pipe and the screw is inserted into the rotational pipe. The rotational pipe and the screw are rotated to the same direction; however, there is a slight difference between the rotational speeds of them, which is intentionally caused by the mechanical gears. The liquid and the solid are

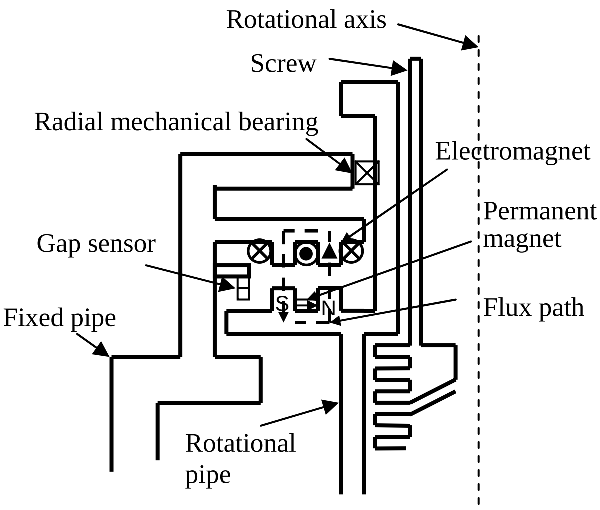


FIGURE 1: Structure of the proposed axial magnetic bearing

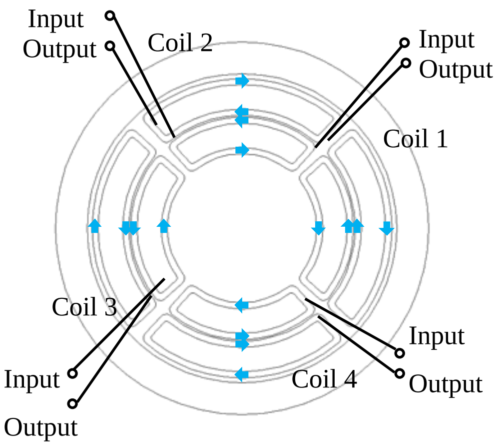


FIGURE 2: Cross section of electromagnets

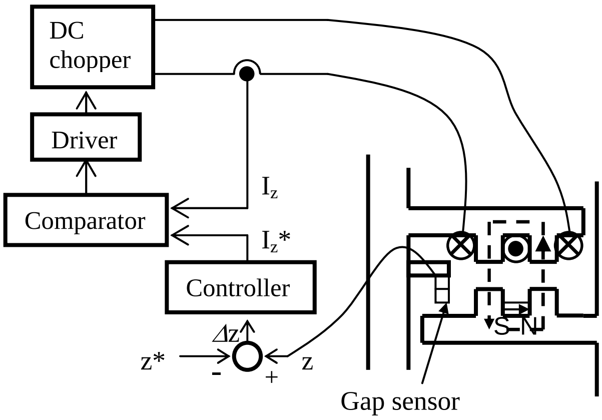


FIGURE 3: Control system configuration

separated by the centrifugal force and the difference of the specific gravities between them. The separation efficiency is significantly increased by the mechanism of the centrifugal separator and the powder materials can be successfully withdrawn.

The electromagnets are equipped in the fixed pipe and the permanent magnet (PM) is inserted between two teeth in the rotational pipe as shown in Fig. 1. The magnetization directions of the electromagnets and PM are same as shown in Fig. 1. The magnetic attractive force is generated by the electromagnets as well as the PM between the electromagnets and the rotor teeth; as a result, the rotational pipe is successfully supported without mechanical contact in the axial direction.

In the rotor, the ring-shape PM is inserted between the ring-shape tooth cores. Fig. 2 shows the cross section of the electromagnets. The electromagnets are divided into four parts. Each part consists of two electromagnets (inside and outside) where the coils are connected in series. Four gap sensors are set every 90 mechanical degrees above the rotor plate as shown in Fig. 1; i.e., a gap sensor is equipped per an electromagnet. The axial positions of the rotor plate are detected by the gap sensors and the electromagnet currents are independently controlled in accordance with the rotor axial positions. Thus, the axial position of the rotational pipe is actively controlled; in addition, the inclination of the rotor plate is also successfully controlled. The stiffness is relatively high by the core arrangement of the electromagnets and the rotor teeth due to the flux path as described in Fig. 1. The original liquid, which goes through the inside of the rotational pipe, is not influenced by the magnetic field of the axial magnetic bearing very much.

CONTROL SYSTEM CONFIGURATION

The coil current is independently controlled in each the electromagnet to support the rotor stably. Fig. 3 shows the control system configuration for an electromagnet. The rotor position z is detected by the gap sensor in the axial direction. The difference between the detected rotor axial position z and the position command z* is amplified by the controller; as a result, the current command I_z* is determined in the electromagnet coil. Then the detected current I_z is regulated to follow the current command I_z*. The currents in the other three coils are controlled by the same configuration as shown in Fig. 3, respectively. Each current is independently controlled in the four coils so that the rotor plate inclination as well as the rotor axial position is successfully controlled to support the rotor stably.

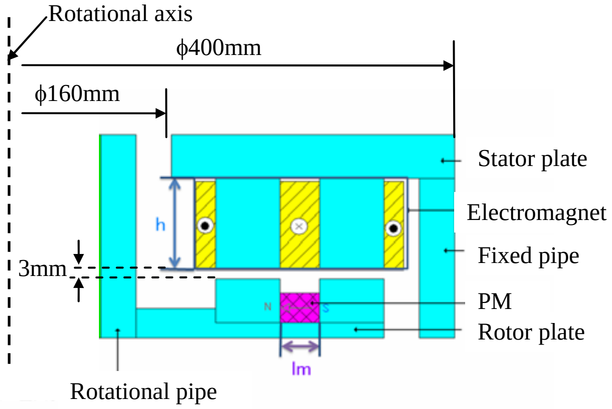


FIGURE 4: FE model of the axial magnetic

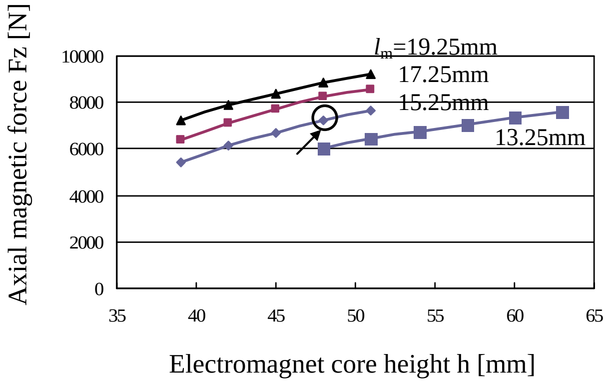
TABLE 1: Materials of FE model

Fixed pipe	Carbon steel
Stator plate	
Electromagnet core	
Rotational pipe	
Rotor plate	
PM	Nd-Fe-B (radial pre-magnetized)

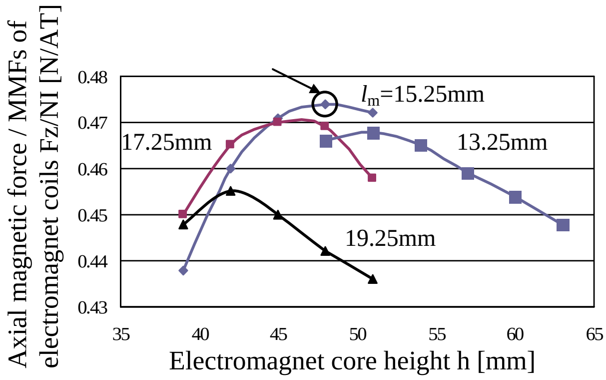
ANALYSES OF ELECTROMAGNETIC FORCE BY FEM

Design of Electromagnet and PM Sizes

The dimension of the proposed axial magnetic bearing is determined to generate the enough suspension force in the axial direction, which is necessary to support the rotor without the mechanical contact. To do it, the axial magnetic force is computed by FEM. Fig. 4 shows the FE model of the axial magnetic bearing. The airgap length, i.e., the distance between the electromagnet core and the rotor tooth core, is 3 mm. According to the limitation of the diameters of the fixed pipe (outside) and the rotational pipe (inside), the diameter of the fixed pipe is kept in 400 mm and the inner diameter of the stator plate is kept in 80 mm. The axial magnetic forces are computed as parameters of the height h of the electromagnets and the PM thickness l_m to generate the force rating of 7,200 N in the axial direction, which is 3 times the gravity of the rotational part (the weight of the rotational part). In addition, the number of electromagnet coil turns is determined by the space factor of 80%. The current density of conductor is 8A/mm^2; as a result, current rating is 9A. Table 1 shows the materials of the FE model. The simulation was implemented using JMAG (JRI Solutions, Ltd. Ver.9, 3 dimensions).



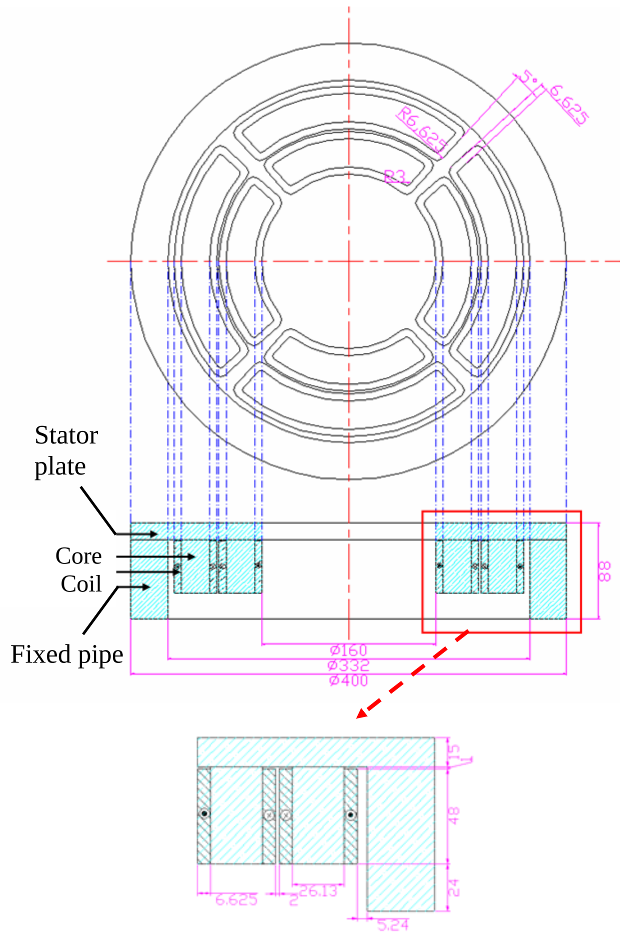
(a) Axial magnetic force



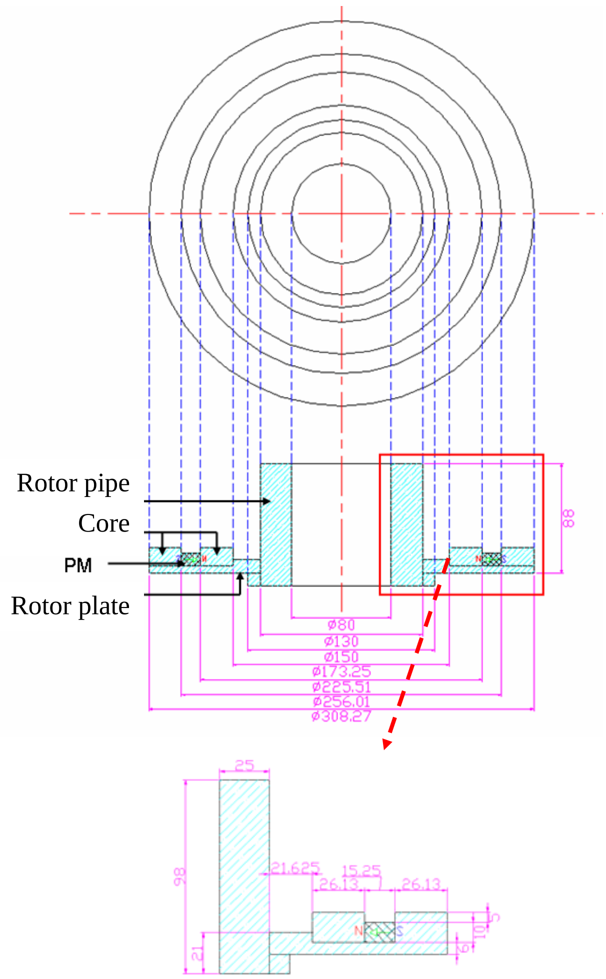
(b) Axial magnetic force for unity MMF of electromagnets

FIGURE 5: The computed results of axial magnetic force

Figs. 5 (a) and (b) show the axial magnetic force and the axial magnetic force for unity MMF of the electromagnet coils at the rotational speed of 3,000 r/min where the parameter is the PM thickness l_m, respectively. It is seen in Fig. 5 (a) that the axial magnetic force is increased as the electromagnet core is high. Also the magnetic force is increased as the PM thickness is increased; however, the increasing rate of the magnetic force for the increase in the height of electromagnet core becomes slow as the electromagnet core is high. It is caused by the magnetic saturation in the electromagnet core. In Fig. 5 (b), the axial magnetic force for unity MMF is defined as the ratio of the magnetic force to the sum of MMFs of four electromagnet coils. It is seen that the axial magnetic force for unity MMF is increased as the electromagnet core is high, and then it is reached to the maximum at a height of the core. However, the magnetic force for unity MMF is decreased due to the magnetic saturation in the electromagnet core. It is seen that the magnetic force for unity MMF is the maximum when the PM thickness is 15.25 mm and the height of electromagnet core 48 mm. Therefore, this is determined as the



(a) Stationary part



(b) Rotational part

FIGURE 6: Dimension of the axial magnetic bearing

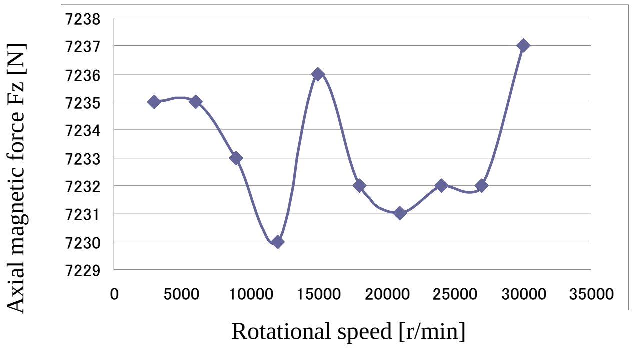
optimal design point. The axial magnetic force of 7,200 N is generated at this point which is enough to be 3 times the rotor gravity.

Figs. 6 (a) and (b) show the dimension for the overall axial magnetic bearing where both the stationary and rotational parts of the axial magnetic bearing are described. The number of electromagnet coils is 212 turns for a core, which the space factor is reached to 80% for each electromagnet.

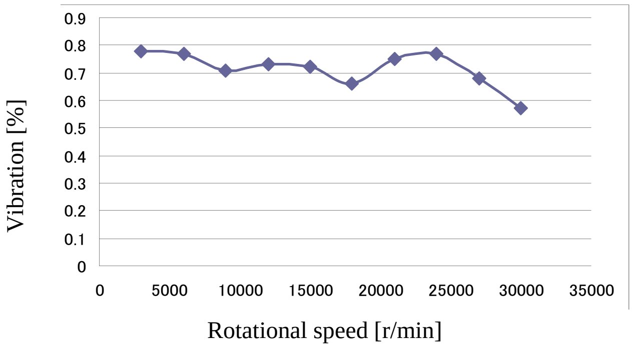
Axial Magnetic Forces at Starting and High Speed Operation

The rotational part of the axial magnetic bearing is touched down on the emergency bearings at standstill. The airgap length is 4 mm at standstill, i.e., the rotational part is levitated up by 1 mm as the airgap length is 3 mm at the operation as shown in Fig. 4. The axial magnetic force at starting is computed. According to the computed results by FEM using the model as described in Fig. 6, it is predicted that the axial magnetic force is 4,860 N at the rotational speed of 0 r/min. The magnetic force is larger than the rotor gravity, therefore it is enough to levitate the rotational part at starting.

The axial magnetic forces are also computed at high speed operation. Figs. 7 (a) and (b) show the axial magnetic force and the vibration on axial magnetic force in the high speed between 3,000 r/min and 30,000 r/min, respectively. Fig. 7 (a) shows the axial magnetic force at the current rating of 9A. It is seen that the axial magnetic force is almost constant and independent on the rotational speed. In the proposed axial magnetic bearing, the axial magnetic force is slightly vibrated with the rotor rotation due to the unbalance on the airgap flux density. Fig.7 (b) shows the vibration on axial magnetic force, which is defined as the ratio of the



(a) Axial magnetic force



(b) Vibration on the axial magnetic force

FIGURE 7: Axial magnetic force at high speed operation

the difference between the maximum and minimum forces to the average force at each rotational speed. The vibration is quite slight and lower than 0.8%. In addition, the vibration is calculated also at the rotational speed below 3,000 r/min. It is almost 0.5% at 10 r/min and 1,000 r/min. From these results, it is predicted that the rotational part is stably supported in the axial direction by the proposed magnetic bearing in the wide speed range till 30,000 r/min.

Analyses in Parallel and Conical Modes of Rotor Motion

The magnetic forces are computed in the parallel and conical modes in the rotor motion by FEM. Fig. 8 shows the radial magnetic force in the rotor parallel mode at the rotational speed of 3,000 r/min using the axial magnetic bearing model as shown in Fig. 6. The horizontal axis is the rotor radial displacement. The radial magnetic force is significantly generated in opposite direction against the rotor displaced direction. It means that the magnetic force is a recovery force in the radial direction. As introduced in the former chapter, the proposed axial magnetic bearing has the stiffness in the radial direction as well as the axial direction. The recovery force is increased as the rotor displacement is

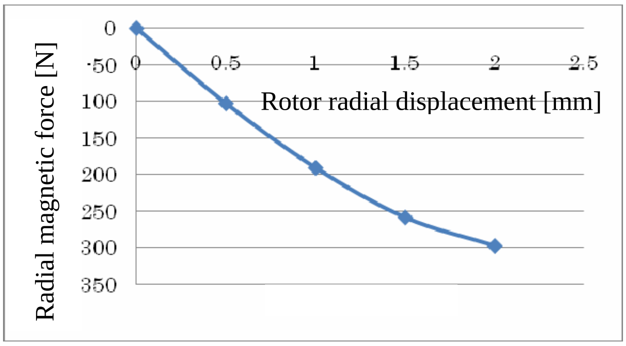


FIGURE 8: Radial magnetic force in rotor parallel mode

increased and the maximum force of 300 N is generated at the rotor displacement of 2 mm.

Fig. 9 shows the rotational pipe and the positions of the axial magnetic bearing and the radial mechanical bearing (low side) when the proposed axial magnetic bearing will be equipped into the centrifugal separator. The radial mechanical bearing is arranged at the bottom of the rotational pipe, which is lower than the axial magnetic bearing by 1,230 mm. In addition, another radial mechanical bearing is equipped above the axial magnetic bearing. In this analysis by FEM, the magnetic force is derived when the rotational pipe is inclined as the center of the bottom mechanical bearing. The loaded force on the upper mechanical bearing can be predicted by this analysis. Fig. 10 shows the computed result in the rotor conical mode when the rotational pipe is inclined in the x-positive direction and the rotational speed is 3,000 r/min. The radial magnetic force is varied with the rotor rotation in the conical mode due to the magnetic unbalance pull force. In Fig. 10, the magnetic force in the x-direction is computed in the rotor and the maximum values of the magnetic force are plotted, which are given at the rotor angular position of 0 degree as the rotational pipe is inclined in the x-positive direction. It is seen in Fig. 10 that the magnetic force is generated in the x-negative direction. It means that the magnetic force is a recovery force such as Fig. 8 also in the conical mode. The recovery force is increased as the inclined angle is increased and it reaches to 270 N at the angle of 0.075 degree.

CONCLUSION

The axial magnetic bearing has been proposed to equip on the vertical-type centrifugal separator which are used to separate into liquids and solids in chemical, material industries, and so on. The structure of the proposed axial magnetic bearing and the control system configuration have been introduced. The optimal electromagnet height and the PM thickness are derived on the basis of the computed results by FEM. At the

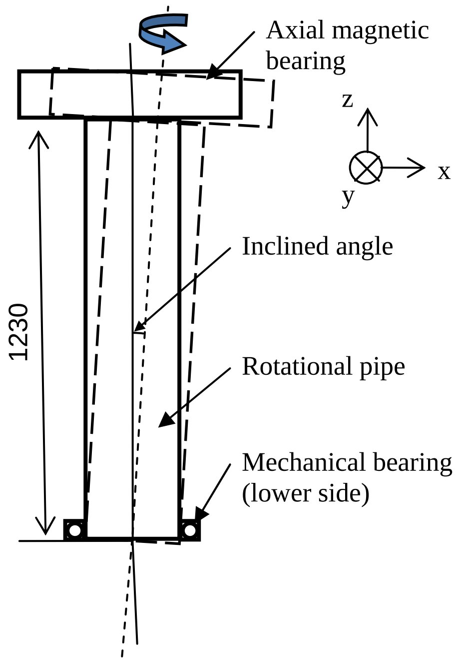


FIGURE 9: Conical mode of rotational pipe

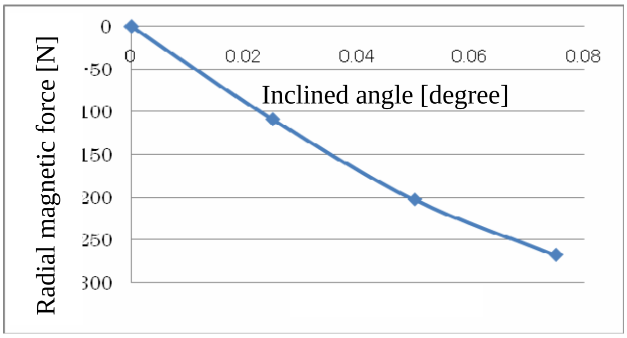


FIGURE 10: Radial magnetic force in rotor conical mode

optimal design point, the axial magnetic force of 7,200 N, which is 3 times the rotor gravity, is generated in accordance with our purpose and the axial magnetic force for unity MMF of the electromagnet coils is the maximum. The magnetic forces are also analyzed at the starting and high speed operation. The vibration on the axial magnetic force is slightly below 0.8% even at the high speed operation. In addition, the magnetic forces in the parallel and conical modes of rotor motion are also analysed. As a results, the stiffness has been confirmed also in the radial direction in the proposed axial magnetic bearing. It contributes to decrease the pressure loaded in the radial mechanical bearing. These analyzed results are enough to support the rotational pipe stably in the proposed axial magnetic bearing.

References

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