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Research on the development of magnetically levitated pump using axial type switched reluctance self-bearing motor and radial type magnetic bearing

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Abstract

In devices used in the semiconductor industry, medical equipment industry, etc., there is a need for clean liquid transfer without sliding. This paper proposes a magnetic levitated regenerative pump using an axial type switched reluctance self-bearing motor (ASRSBM) and a radial type magnetic bearing (RMB) that does not use permanent magnets in the rotor. Computational fluid dynamics (CFD) of the pump and magnetic field analyses of ASRSBM and RMB were performed to examine the feasibility of the proposed magnetically levitated pump. CFD results of the pump showed that a flow rate of 5 L/min and a pressure of more than 10 kPa could be achieved when the rotor impeller rotation speed was 2000 rpm. It could be verified that the pump designed with two inlets and two outlets reduces the hydrodynamic forces and torques in x, y, z, tx, and ty directions associated with the magnetic support. The driving torque of about 0.09 Nm is required to rotate the rotor impeller. As a result of magnetic field analyses of ASRSBM, it was found that the driving torque, magnetic suspension force and magnetic suspension torque fluctuate during rotor rotation, and that those force and torques are generated in approximately proportion to the square of the magnetomotive force. Although magnetic levitation control is required to adjust those force and torque for each rotation angle of the rotor, we believe that the designed ASRSBM has sufficient driving torque, magnetic suspension force, and magnetic suspension torque. Magnetic field analysis results of RMB shows that the designed RMB has sufficient radial magnetic suspension force, axial passive magnetic support force and passive magnetic support torque. It is believed that a magnetically levitated pump using an axial-type switched reluctance self-bearing motor and a radial type magnetic bearing is quite feasible.

Keywords : Self-bearing motor, Bearingless motor, Magnetic bearing, Switched reluctance motor, Magnetically levitated pump

1. Introduction

Pumps are widely used as the main machinery in many factories and industrial equipment for the purpose of pumping fluids. In devices used in the semiconductor industry, medical equipment industry, etc., there is a need for clean fluid transfer without sliding. Research and development of magnetic levitation pumps using magnetic levitation technology is underway (Schweitzer, G. and Maslen, E. H., 2010). In addition, due to the demand for miniaturization of semiconductor devices and medical equipment, small magnetic levitation pumps are researching and developing (Onuma et al., 2017). Pumps used for chemical solutions must be designed to prevent the solution from coming into contact with the metal parts of the pump. Therefore, the rotor and stator of a magnetic levitation motor must be covered in a resin that is resistant to chemical solutions. Also, global issue is ensuring a stable supply and sustainable use of rare earth resources. So, it is necessary to reduce the use of permanent magnets. It is also necessary to reduce the power consumption of equipment.

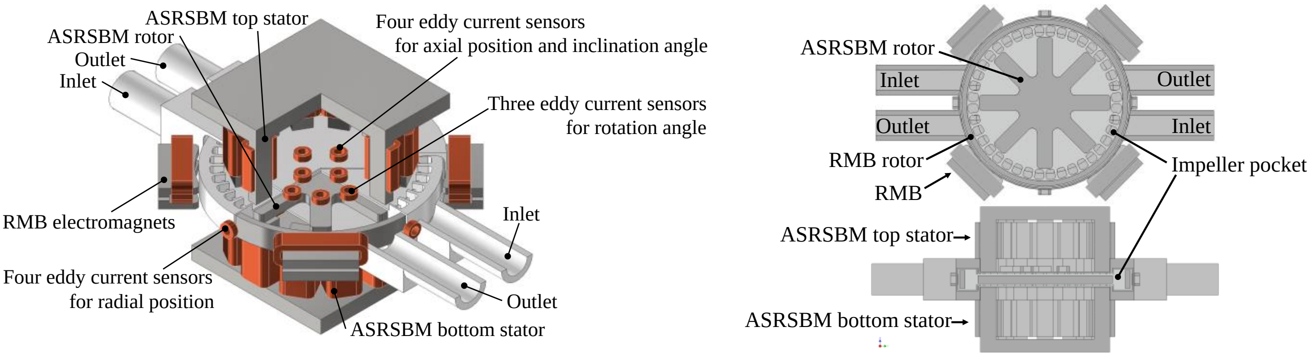
Regenerative pumps are one example of small pumps that generate high pressure (Horiguchi et al., 2008). A magnetically levitated regenerative pump using a radial self-bearing motor has been developed (Murakami et al., 2018) (Ukita et al., 2012). This magnetically levitated regenerative pump uses a surface-mounted permanent magnet motor to reduce size and energy consumption. However, if the pump is used for a long period of time in industrial applications, the rotor impeller may become a replacement part. From the perspective of the environment and cost, the rotor-impeller structure that does not use rare earth magnets is preferable. A switched reluctance bearingless motor that does not use permanent magnets has been developed (Chiba et al., 2005) (Nagira et al., 2018). Therefore, we propose a magnetic levitated regenerative pump using an axial type switched reluctance self-bearing motor and a radial type magnetic bearing that does not use permanent magnets in the rotor.

Regenerative pumps generate strong radial fluid forces. The radial magnetic support stiffness must be strong. For this reason, a hybrid magnetic bearing with a permanent magnet in the electromagnet is used for the radial magnetic bearing. Reducing the hydrodynamic force of regenerative pumps is an important research topic for the development of magnetically levitated pumps. In this device, an axially symmetrical structure with two inlets and two outlets is proposed and adopted to offset the radial hydrodynamic force and reduce the hydrodynamic force.

In this paper, as a first step in investigating the feasibility of a magnetically levitated regenerative pump that does not use permanent magnets, we report the results of designing a magnetically levitated regenerative pump using computational fluid dynamics and an axial type switched reluctance self-bearing motor and a radial type magnetic bearing using magnetic field analysis.

2. Magnetically levitated regenerative pump

Figure 1 shows a schematic diagram of a magnetically levitated regenerative pump that uses a 5-axis controlled magnetically levitated motor. The five-axis controlled magnetically levitated motor is composed of a three-axis controlled axial type switched reluctance self-bearing motor (ASRSBM) that actively controls the axial direction and inclination of the rotor, and a radial type magnetic bearing (RMB) that actively controls the radial direction. The rotor impeller is composed of an ASRSBM rotor yoke, a plastic impeller section radially outside it, and a ring shaped RMB rotor yoke on the outer periphery. To reduce the hydrodynamic forces acting on the rotor impeller, a regenerative pump with two inlets and two outlets in the pump section was adopted. Eddy current sensors are used to detect the rotor's radial position, axial position, inclination angle, and rotation angle.



(a) 3D shape diagram (b) Sectional view

Fig. 1 Schematic diagram of magnetically levitated regenerative pump.

Figure 2 shows a schematic diagram of the ASRSBM. The ASRSBM consists of two stators and a rotor. The ASRSBM rotor with eight salient poles is sandwiched from above and below by stators with twelve salient poles. Figure 3 shows the positions of the three eddy current sensors used to detect the rotor rotation angle. The eddy current sensors are placed between the salient poles of the stator at 30 degrees intervals. This allows the rotor rotation to be detected at 15 mechanical degree intervals. Figure 4 shows an overview of the method for controlling the magnetic levitation and rotation of the ASRSBM rotor. Figure 4 shows the exciting coils for driving torque, axial magnetic suspension force, and magnetic suspension torque around the x-axis when one of the rotor salient poles overlaps with a 0-degree stator salient pole. When generating driving torque, each stator generates a four-pole magnetic field. When generating axial magnetic support force, each stator generates a twelve-pole magnetic field. When generating magnetic support torque around the x-axis, each stator generates a three-pole magnetic field. As shown in Table 1, the rotation control magnetic field is switched according to the rotor rotation angle. The rotation control magnetic field is a 4-pole magnetic field. 1 or -1 is the ratio of the magnetomotive force applied to the coil of each salient pole. The rotation control magnetic field switches magnetic poles in synchronization with the rotation to avoid interference with the axial position control magnetic field and the tilt control magnetic field. Table 2 shows the axial position control magnetic field when a positive magnetic support force is generated in the axial direction, and the tilt control magnetic field when a positive magnetic supporting torque is generated around the x and y axes. The axial position control magnetic field is a 12-pole magnetic field. The tilt control magnetic field is two 3-pole magnetic field that excites the three salient poles diagonally on the top and bottom stators, respectively.

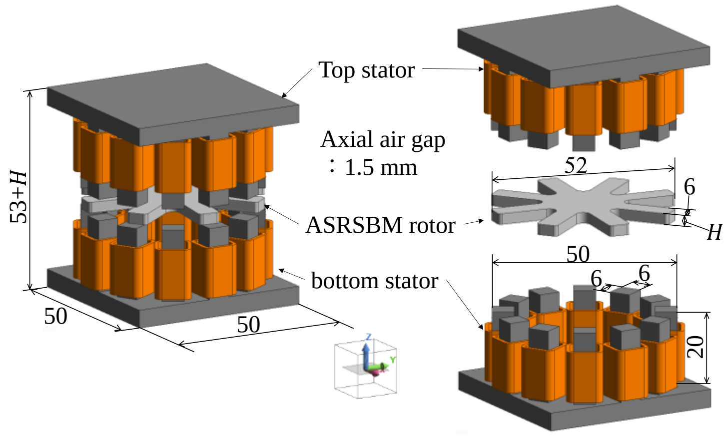


Fig. 2 Schematic diagram of the ASRSBM

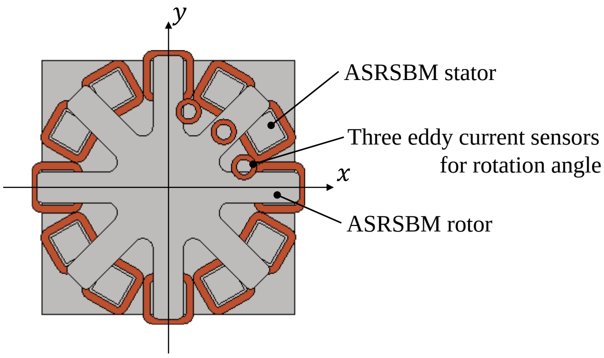


Fig. 3 Arrangement of eddy current sensors for detecting rotation angle.

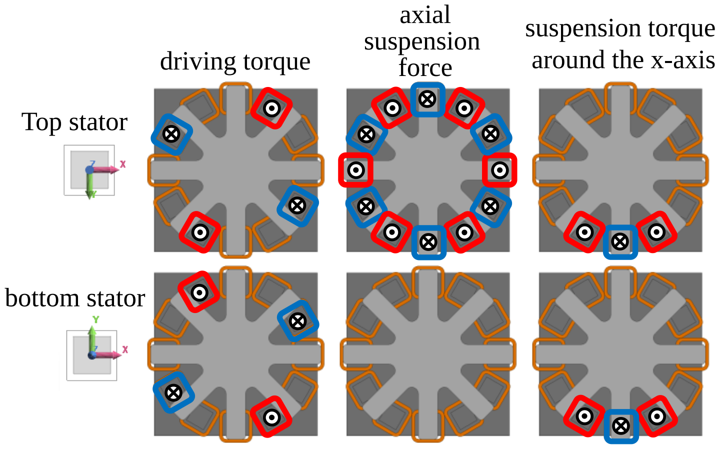


Fig. 4 Overview of the method for controlling the magnetic levitation and rotation of the ASRSBM rotor.

Table 1 Switching of the rotation control magnetic field according to the rotor rotation angle.1 or -1 is the ratio of the magnetomotive force applied to the coil of each salient pole.

Rotor angle position	Arrangement angle of stator's salient pole												
	0	30	60	90	120	150	180	210	240	270	300	330	
0			1			-1			1			-1	Top stator
			-1			1			-1			1	Bottom stator
15		-1			1			-1			1		Top stator
		1			-1			1			-1		Bottom stator
30	1			-1			1			-1			Top stator
	-1			1			-1			1			Bottom stator

Table 2 The axial position control magnetic field and the tilt control magnetic field around the x, y-axis. Arrangement of the control magnetic field when generating a magnetic supporting force and torque in the positive direction of the z axis and positive direction around the x, y-axis. 1 or -1 is the ratio of the magnetomotive force applied to the coil of each salient pole.

	Arrangement angle of stator's salient pole												
	0	30	60	90	120	150	180	210	240	270	300	330	
axial position control	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	Top stator
													Bottom stator
x-axis tilt control			1	-1	1								Top stator
									-1	1	-1		Bottom stator
y-axis tilt control						-1	1	-1					Top stator
	1	-1										-1	Bottom stator

Figure 5 shows a schematic diagram of the RMB. The RMB consists of four electromagnets and a ring shaped RMB rotor. The electromagnet has a permanent magnet. The opposing electromagnets are excited in opposite directions to generate a radial magnetic support control force. In addition, as shown in Fig. 6, the magnetic flux from the permanent magnet generates a passively stable magnetic support force and torque in the axial direction and around the x, y-axis.

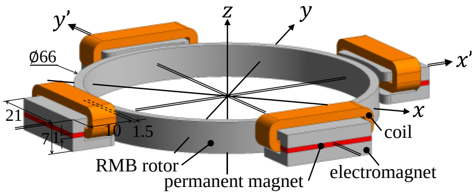


Fig. 5 Schematic diagram of the RMB

(a) axial direction

(b) tilt motion

Fig. 6 Passively stable magnetic support force and torque of the RMB

3. CFD of magnetically levitated pump

Computational fluid dynamics (Ansys CFX) of the pump was performed to obtain the design target values for the axial type switched reluctance self-bearing motor and the radial type magnetic bearing. Figure 7 shows the flow rate and pressure characteristics for each rotor-impeller rotation speed. The target specifications for this pump are a flow rate of 5L/min and a pressure of 10kPa or more. It was estimated that the target specifications could be achieved with the rotor-impeller rotation speed of 2000 rpm. Figure 8 shows the estimated hydrodynamic force acting on the rotor-impeller at a rotation speed of 2000 rpm. It could be verified that the pump designed with two inlets and two outlets reduces the hydrodynamic forces and torques in x, y, z, tx, and ty directions associated with the magnetic support. When the rotation speed was 2000 rpm and the flow rate was in the range of 1 L/min to 6 L/min, the hydrodynamic force in the radial directions x and y was about 0.03 N. The hydrodynamic force in the z-axis direction was about 0.3 N. In addition, the torque around the x-axis (tx) and around the y-axis (ty) due to the hydrodynamic force was about 0.001 Nm. It was found that a driving torque of about 0.09 Nm is required to rotate the rotor impeller.

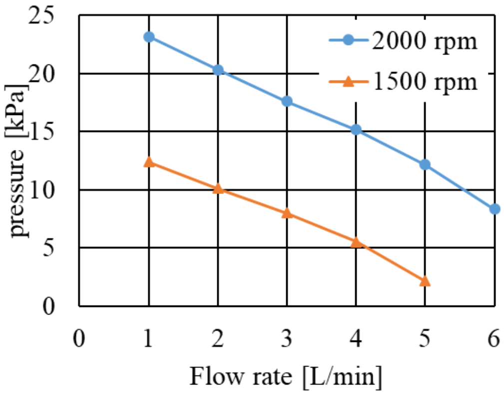


Fig. 7 Flow rate and pressure characteristics

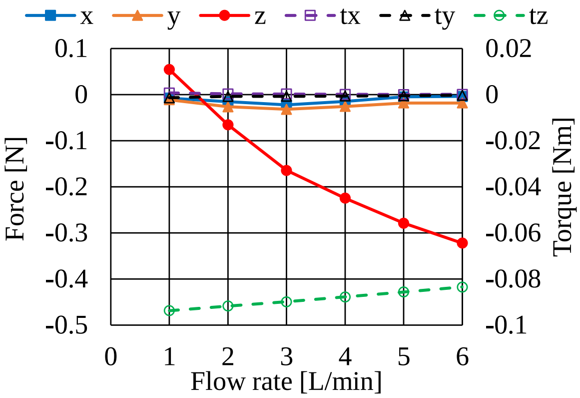


Fig. 8 Estimated hydrodynamic force acting on the rotor-impeller at a rotation speed of 2000 rpm

4. Design of ASRSBM

The ASRSBM was designed using magnetic field analysis (Femtet). The driving torque, axial magnetic suspension force, and magnetic suspension torque around the x-axis were estimated by magnetic field analysis.

The ASRSBM rotor thickness was examined. Figure 9 shows the results of the magnetic field analysis in which the thickness was changed from 2 mm to 6 mm in 1 mm increments. Using the control method and rotor position shown in Fig. 3, a magnetomotive force of 100 A was applied to each coil. The thinner the ASRSBM rotor thickness, the driving torque tends to be stronger. The thicker the ASRSBM rotor was, the stronger the axial magnetic suspension force was generated. The thicker the ASRSBM rotor was, the magnetic suspension torque around the x-axis tends to be stronger. The reason why these forces generated change depending on the thickness of the rotor is considered to be that the thinner the rotor, the shorter the distance between the upper and lower stators. Based on these results, the rotor thickness was decided to be 3 mm, with an emphasis on drive torque and the fact that a thinner rotor is lighter and has better controllability.

Next, to confirm the magnetic suspension characteristics in more detail when the rotor thickness is 3 mm, a magnetic field analysis was performed by changing the magnetomotive force from 0 to 600 A in increments of 100 A, and the results are shown in Fig. 10. As a result, it was confirmed that each force and torque was generated in approximately proportional to the square of the magnetomotive force. The rate of increase of the axial magnetic suspension force and the magnetic suspension torque around the x-axis decreased when the magnetomotive force was 400A or more. This is thought to be due to magnetic saturation. Then, the change in those force and torques generated due to the rotation of the rotor was estimated using magnetic field analysis. The rotor was rotated up to 60 degrees in 2.5 degree intervals. The magnetomotive force was set to 100 A, and the applied coil was switched every 15 degrees of the mechanical rotation angle of the rotor. The results of those force and torques generated as the rotor rotates are shown in Fig. 11. Periodic fluctuations in those force and torques were observed. These periodic fluctuations are considered to be caused by the relationship between the number of salient poles of the rotor and stators. The average values of the driving torque was 0.0032 Nm. The average values of the axial magnetic suspension force was 0.49 N. The average values of the magnetic suspension torque around the x-axis was 0.0046 Nm.

Assuming the torque required to drive the pump is approximately 0.09 Nm, it was found that a magnetomotive force of 530 A is required for the driving torque. It is believed that this will be sufficient to generate the necessary drive torque.

Since the hydrodynamic force acting on the rotor-impeller is thought to be small, it is believed that magnetic support in the z direction and inclination around x, y-axis can be achieved by using magnetic levitation control that adjusts the those force and torques for each rotation angle of the rotor.

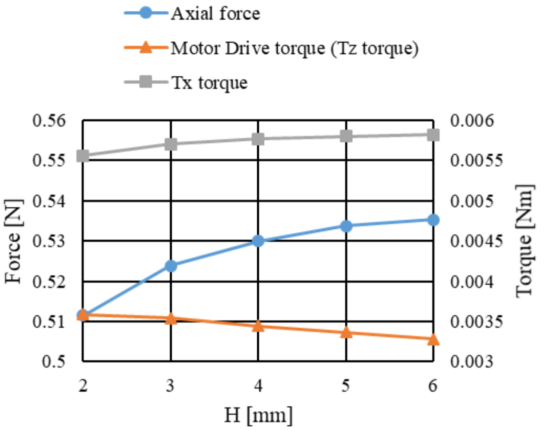


Fig. 9 Estimation results of magnetic attraction force and torque for rotor thickness.

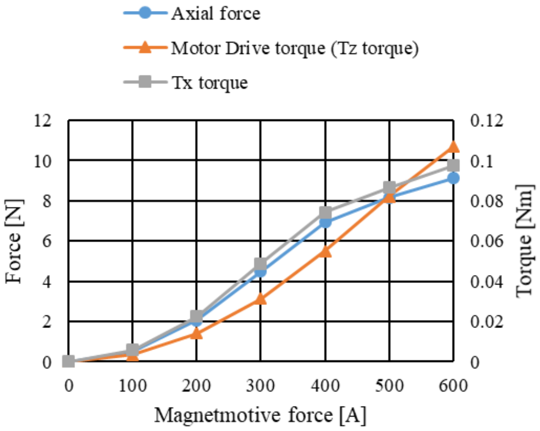


Fig. 10 Estimation results of magnetic attraction force and torque in response to magnetmotive force when the rotor thickness is 3 mm.

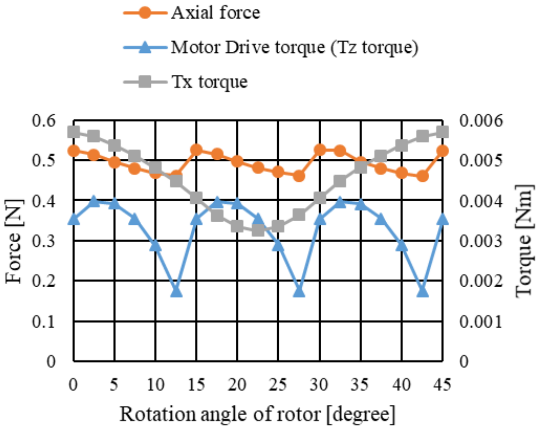


Fig. 11 Estimation results of magnetic attraction force and torque generated as the rotor rotates.

5. Design of RMB

The RMB was also designed using magnetic field analysis. The radial negative spring force, radial magnetic support force, axial passive magnetic support force and passive magnetic support torque around the x'-axis were estimated by magnetic field analysis.

Figure 12 shows the radial magnetic attraction force was generated when the RMB rotor is displaced in the negative x' direction to evaluate the negative spring force. The negative spring force was generated in the direction of displacement and was -0.87 N at a displacement of -0.5 mm. Figure 13 shows the radial magnetic attraction force when a control force is generated in the positive x' direction when the rotor is positioned in the center and in a position displaced -0.5 mm in the radial direction to evaluate the radial control force. When the rotor is positioned in the center, the radial magnetic attraction force was generated in proportion to the magnetomotive force, and is 2.45 N at 500 A. When displaced -0.5 mm in the radial direction, the rate of increase of the radial magnetic attraction force gradually decreases as the magnetomotive force increases. This is thought to be due to magnetic saturation. In addition, the radial magnetic attraction force turns positive at a magnetomotive force of 150 A. Even when considering the fluid force of the pump, it is believed that the radial magnetic support performance is sufficient.

Figure 14 shows the axial magnetic attraction force generated when the RMB rotor is displaced in the axial direction to evaluate the axial passive magnetic support force. The axial magnetic attraction force was generated in the opposite direction to the displacement and was 2.1 N at a displacement of -0.5 mm. Figure 15 shows the tilt magnetic attraction torque generated when the RMB rotor is tilted around the x-axis to evaluate the tilt passive magnetic support torque. The tilt magnetic attraction torque was generated in the opposite direction to the tilt, and was 0.0036 Nm at a tilt of -1 degree. It is believed that the magnetic support performance of the RMB has sufficient passive stability against the fluid forces of the pump. We also believe that the passive magnetic support performance of the RMB can assist the magnetic support of the ASRSBM.

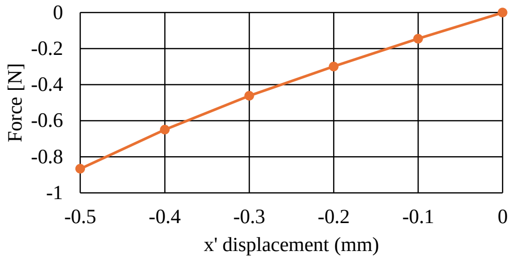


Fig. 12 Radial negative spring force of RMB

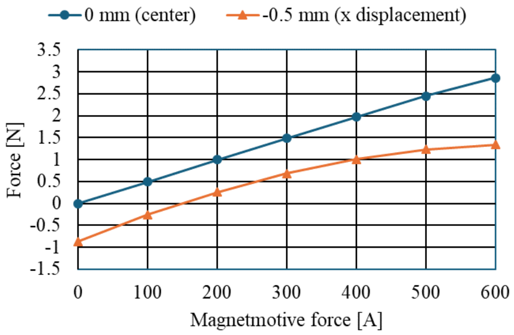


Fig. 13 Radial magnetic support force of RMB

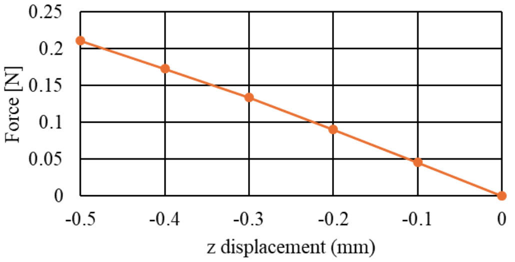


Fig. 14 Axial passive magnetic support force of the RMB

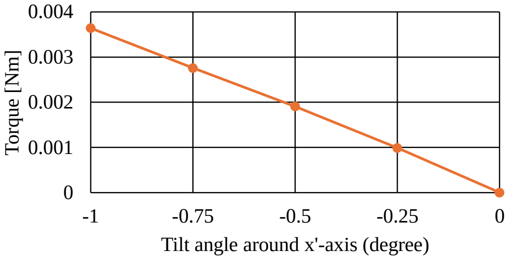


Fig. 15 Passive magnetic support torque around the x'-axis of the RMB

6. Conclusion

Aiming to realize a magnetically levitated pump that does not use permanent magnets in the rotor, we proposed a magnetically levitated pump that uses ASRSBM and RMB. Computational fluid dynamics of the pump and magnetic field analyses of ASRSBM and RMB were performed to examine the feasibility of the proposed magnetically levitated pump. CFD results of the pump showed that a flow rate of 5 L/min and a pressure of more than 10 kPa could be achieved when the rotor impeller rotation speed was 2000 rpm. It could be verified that the pump designed with two inlets and two outlets reduces the hydrodynamic forces and torques in x, y, z, tx, and ty directions associated with the magnetic support. The driving torque of about 0.09 Nm is required to rotate the rotor impeller. As a result of magnetic field analyses of ASRSBM, it was found that the driving torque, magnetic suspension force and magnetic suspension torque fluctuate during rotor rotation, and that those force and torques are generated in approximately proportion to the square of the magnetomotive force. Although magnetic levitation control is required to adjust those force and torque for each rotation angle of the rotor, we believe that the designed ASRSBM has sufficient driving torque, magnetic suspension force, and magnetic suspension torque. Magnetic field analysis results of RMB shows that the designed RMB has sufficient radial magnetic suspension force, axial passive magnetic support force and passive magnetic support torque. It is believed that a magnetically levitated pump using an axial-type switched reluctance self-bearing motor and a radial type magnetic bearing is quite feasible. In the future, we will manufacture the actual machine and evaluate its performance. In addition, since a large amount of motor power is required to drive the pump, research is needed into improving the pump and increasing the motor drive torque.

Acknowledgments

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