WIDE GAP MAGNETIC BEARING SYSTEM FOR A MAGNETICALLY SUSPENDED CLEAN PUMP

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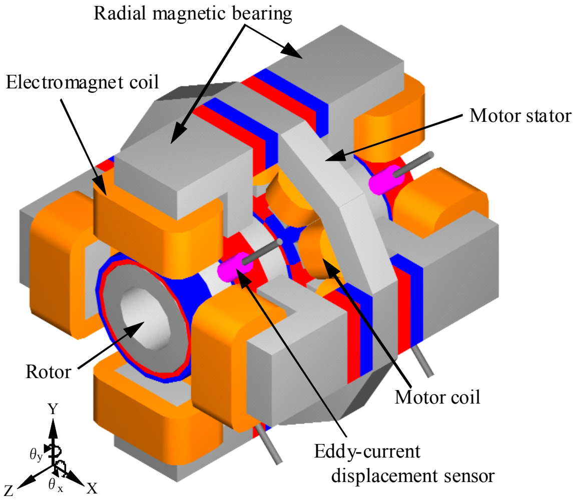
ABSTRACT
A new hybrid magnetic bearing and motor system for magnetically suspended clean pumps with wide air gaps has been developed. The permanent magnet geometry is examined by three dimensional magnetic field analysis with the finite element method. The optimization method to determine the optimal values of the design parameters has been developed based on magnetic equivalent circuit technique, genetic algorithm (GA) and three dimensional magnetic field analysis. The size of the hybrid magnetic bearing C core, the thickness of the permanent magnets, and the turn number of the electromagnets are optimized by the method.

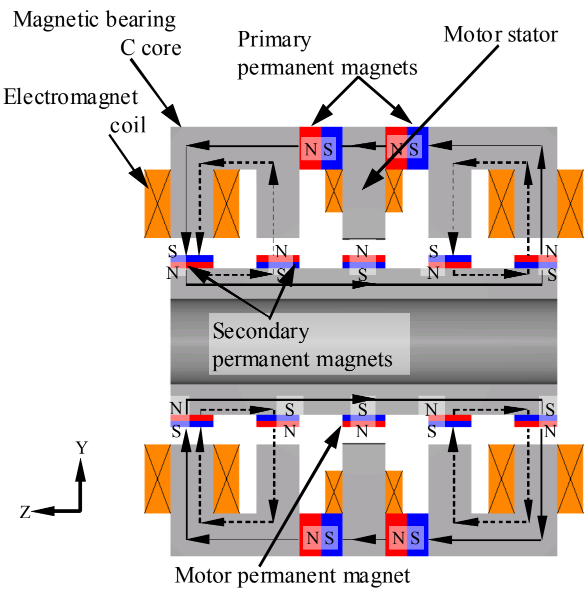
The designed HM bearing and motor system has an outer diameter of 100 mm, a length of 140 mm, and air gaps of 3.5 mm. The optimized system produces a target attractive force of 20 N with an excitation current of 0.5 A and the ratio of force to excitation current is 40 N/A. The devised hybrid magnetic bearing indicates sufficient bearing performance for the target clean pump and the developed optimization method displayed sufficient ability to design the hybrid magnetic bearing.

INTRODUCTION
Clean pumps, which are used to transport solutions such as blood in artificial hearts or ultrapure water in semiconductor manufacturing pumps, need high grade cleanness at the pump mechanism to prevent debris in the system. Magnetic suspension technology is a key to keeping the turbo pump clean by eliminating mechanical bearings [1-5]. Canned pump mechanism is required for the clean pump to prevent debris production in the pump. As such the magnetic bearing for the clean pump must be driven with a wide gap space. Therefore, hybrid magnetic (HM) bearings, which have bias permanent magnets to enhance the produced attractive force is a candidate as a high performance magnetic bearing. Optimization of the structure and design parameters of the HM bearing is essential for the development of the high performance clean pump. In this paper, a new structure of the HM bearing and novel optimization method of the HM bearing design are presented.

METHODS
HM bearing and motor system
Figure 1(a) shows an exterior view of the HM bearing and motor system. The HM bearing and motor system has two radial magnetic bearings set on either side of the motor stator. Figure 1(b) shows a cross sectional view of the system. Primary bias permanent magnets (PMs) are set between the motor stator and the bearing C cores to produce the main bias magnet flux. The path of main bias magnetic flux is indicated with solid lines in figure 1(b). Secondary bias PMs are set on the circumferential surface of the rotor to produce enhanced bias magnetic flux and to restrict the flux path. The path of the enhanced bias magnetic flux is shown with dashed lines in figure 1(b). The main bias magnet flux passes through one side of the C core, the rotor and the motor stator to close the magnetic circuit. Electromagnetic coils are wound on the C cores of the HM bearing. The control magnetic flux generated by electromagnets passes through the same path as the enhanced bias magnetic flux. The magnetic flux in the gap space between the one side of the C core and the rotor is regulated with the control magnetic flux to control the radial position of the rotor. Four eddy current displacement sensors are used to measure the rotor position in the radial direction and its tilt angles.



(a) Exterior view



(b) Cross sectional view

FIGURE 1: The HM bearing and motor system

A motor mechanism is constructed at the center of the device. The motor stator has twelve poles which have windings excited with three-phase alternating current. Eight PMs are set on the surface of the rotor. Four spatial degrees of freedom of the levitated rotor, radial position and tilt of the rotor, are controlled actively by the bearing system. The axial movement of the levitated rotor is restricted by the passive stability of the HM bearing and the motor mechanism. All PMs are made of Nb-F-B.

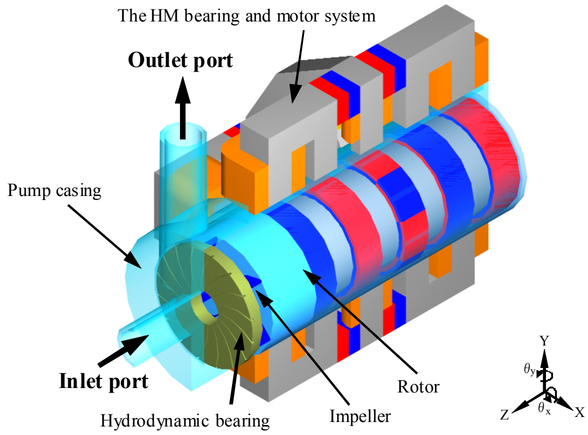


FIGURE 2: The magnetically suspended clean pump

Magnetically suspended clean pump

Figure 2 shows the structure of the magnetically suspended clean pump. A centrifugal pump impeller is attached at the end of the rotor. The rotor-impeller is encased by the pump casing. Therefore, the gap space between the stators and the levitated rotor is wider than that in usual magnetic bearings and motors because it must contain the pump casing. The stators of the HM bearings and the motor are set at equal intervals around the pump casing. In figure 2, the fluid flows from the inlet port, is accelerated by the impeller and is pumped from the outlet port. The target pump performance of the developed magnetically suspended pump is a flow rate of 16.7×10^{-5} m^3/s (10 L/min) against a head pressure of 58.8 kPa (6 mH_2O) with a rotational speed of 6000 rpm.

HM bearing system design

Configuration of secondary bias PMs. A set of permanent magnets is used to generate a secondary bias magnet field to enhance the attractive force. The optimal configuration of the secondary bias PMs to generate the largest attractive force was examined using three dimensional magnetic field analysis based on the finite element method. Figure 3 shows the dimensions used in the analysis and the positions of the secondary bias PMs. The secondary bias PMs are designated A-E and Table 1 shows six combinations of pairs of secondary bias PMs. The magnetic bearing pole closest to the motor stator is called the inner-pole, and the outside pole is called the outer-pole. PM position A is the surface of the rotor opposed to the outer-pole of the C core, position B is the end of the outer-pole of the C core, position C is the surface of the rotor opposed to the inner-pole of the C core, position D is the end of the inner-pole of the C core and position E is the base of the inner-pole of the C core.

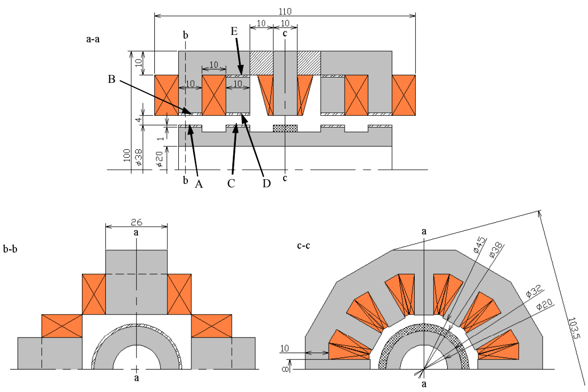


FIGURE 3: The model of secondary bias PMs configuration

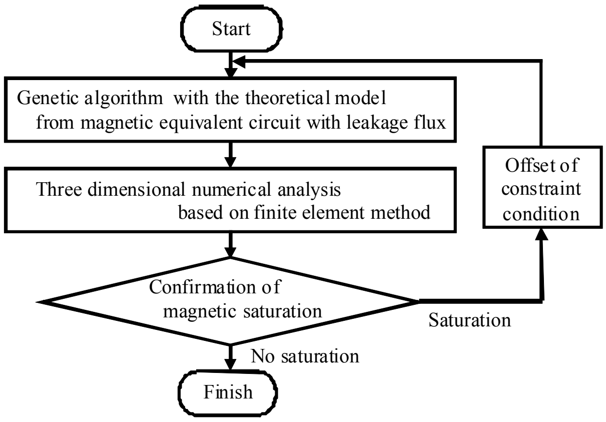


FIGURE 4: The parameter determination method

TABLE 1: The combination of secondary bias PMs configuration

The No. of the combination	Combination of the secondary bias PMs
1	A-C
2	A-D
3	A-E
4	B-C
5	B-D
6	B-E

The analytical model has an outer diameter of 104 mm, a length of 110 mm, a primary bias PMs thickness of 10 mm, a secondary bias PMs thickness of 1 mm, an air gap of 4.0 mm, and electromagnetic coils of 300 turns. The excitation current of the electromagnet was assumed to be 1 A.

The parameter optimization method. The optimization method to determine the optimal values of the design parameters, such as the size of the magnetic bearing C core and the turn number of electromagnets has been developed based on magnetic equivalent circuit technique, genetic algorithm (GA) and three dimensional magnetic field analysis [6]. Figure 4 shows the flow chart of the developed optimization method. The best values of design parameters are searched for using the GA. The GA is a suitable technique for finding a better solution or approximate solution from a wide design space in a short time with the trade-off conditions that a HM bearing has [7][8]. The criterion for the optimization is the attractive force produced by the HM bearing. The attractive force is calculated using theoretical equations derived from the magnetic equivalent circuit including leakage flux effects [9-11]. After an optimized parameter set is determined with the GA, three dimensional magnetic field analysis using the parameter set is performed to obtain more accurate attractive force results and magnetic saturation values in the magnetic circuit. If magnetic saturation was observed in the results of the numerical analysis, the GA will be executed again with the compensated constraint condition of the magnetic saturation. The GA and magnetic field analysis will be performed until magnetic saturation is not observed.

Target attractive force of the HM bearing, required by the specification of the magnetically suspended clean pump, is 20 N. The constraint conditions follows as the magnetic flux density in the core is less than 1.5 T, the outer diameter of the HM bearing system is less than 100 mm, the length of the HM bearing system is less than 140 mm. The following parameters of the system are fixed as constants. The excitation current into the electromagnet is 1 A. The outer diameter of the rotor is 38 mm. The motor stator length is 20 mm. The thickness of surface mounted PMs of the motor is 3 mm. The air gap spacing between the stators and the rotor is 3.5 mm.

Finally, the relationship between the excitation current into the electromagnets and the attractive force was examined using three dimensional magnetic field analysis to check the suitability of the optimized design.

RESULTS

Secondary bias PMs configuration

Figure 5 shows the relationship between the secondary bias PMs configuration and the generated attractive force. The configuration of the secondary bias PMs that generated the largest attractive force is combination No. 1, which corresponds to the combination of position A and position C. The maximum attractive force is 16.2 N with this combination. The difference of the attractive force for the different magnet configurations is about 2N.

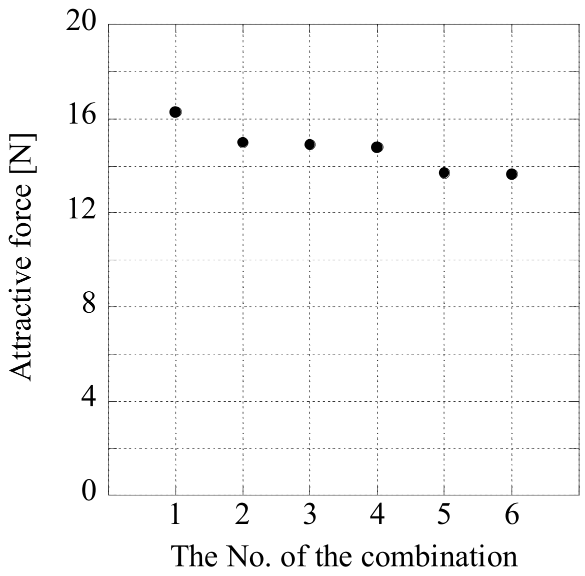


FIGURE 5: The combination of secondary bias PMs configuration and the generated attractive force

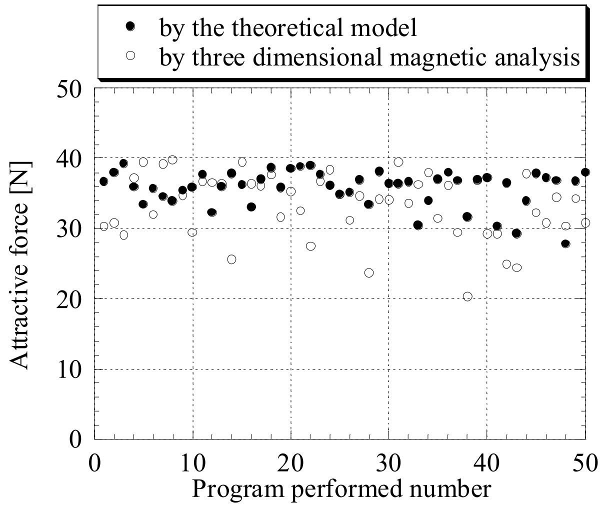


FIGURE 6: The attractive force estimated with the equivalent circuit model and three dimensional magnetic field analysis

The parameter optimization of the HM bearing system

Optimized parameter searching was performed 50 times. Figure 6 shows the estimated attractive force with the equivalent circuit model and with the three dimensional magnetic analysis. At optimization #8, the maximum attractive force of 39.8 N was obtained. Figure 7 shows the optimized dimensions of the HM bearing and motor system of optimization #8. The thickness of the primary bias PMs is 1.3 mm, the secondary bias PM thickness is 1.6 mm, and the turn number of the electromagnetic coil is 465. The outer diameter and the length of the system are set to 100 mm and 140 mm, respectively. Figure 8 shows the relationship between the excitation current into the electromagnetic coil and the generated attractive force of the optimized HM bearing. The optimized HM bearing produces an attractive force of 20.1 N, which is the target force, with an excitation current of 0.5 A. The linear relationship between the attractive force and the excitation current is displayed. The force coefficient is 40 N/A.

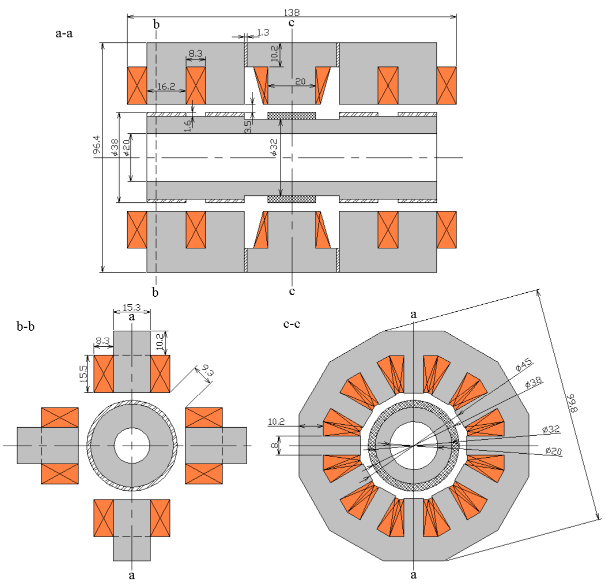


FIGURE 7: The designed size of the HM bearing and motor system

DISCUSSION

The difference in attractive forces among the different secondary PM configuration is 2.6 N. Combination No. 1 indicated larger attractive force because the magnitude of the leakage magnetic flux is minimized and the magnetic flux density in the air gap is maximized. This result reveals that the location of the bias PM affect the bearing performance significantly.

The variations of estimated attractive force with the equivalent circuit model are smaller than that with the magnetic field analysis. This is caused by the simplified estimation of the leakage flux. The effect of the leakage flux varies widely when the dimension of the magnetic circuit is changed. The numerical field analysis could follow this changing but the leakage flux model in the equivalent circuit could not follow this change well. However, the relative effect upon attractive force due to the dimension change could be represented with the equivalent circuit model.

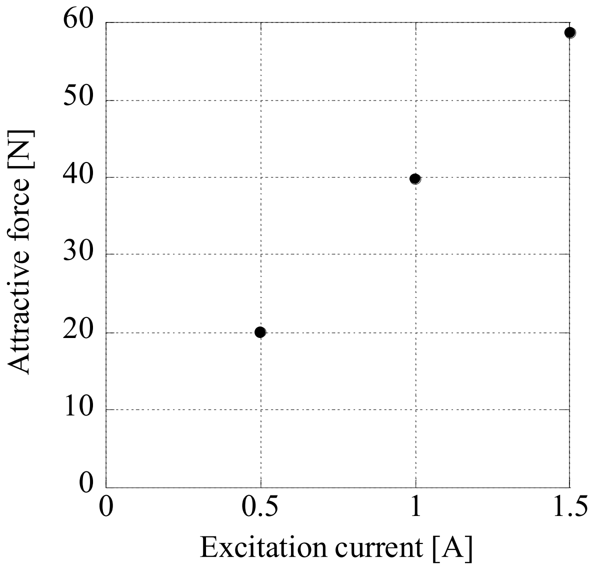


FIGURE 8: The HM bearing performance

The model calculation is useful for optimizing the design parameters quickly because the estimated maximum attractive force with the model is similar to the magnetic field analysis.

The optimized system produces a target attractive force with an excitation current of 0.5 A and maximum attractive force of 58.7 N with an excitation current of 1.5 A. The designed HM bearing indicates sufficient bearing performance for the target clean pump.

CONCLUSION

New hybrid magnet bearing structure and novel optimization method are invented to develop high performance magnetic bearing for clean pumps. The HM bearing and motor system which has an outer diameter of 100 mm, a length of 140 mm, and an air gap spacing of 3.5 mm are designed and the configuration of the bias permanent magnet and the dimension of the magnetic bearing are optimized. The optimized system produces an attractive force of 20 N with an excitation current of 0.5 A and the ratio of force to excitation current is 40 N/A. The displayed hybrid magnetic bearing indicates sufficient bearing performance for the target clean pump and the developed optimization method displayed sufficient ability to design the hybrid magnetic bearing.

References

1. Masuzawa T, Ezoe S, Kato T, Okada Y, Magnetically suspended centrifugal blood pump with an axially levitated motor, Artificial Organs, 27, 10, pp. 887-891 (2003).
2. Onuma H, Murakami M and Masuzawa T, Novel Maglev pump with a combined magnetic bearing, ASAIO Journal, 51(1),pp.50-55, (2005).
3. Masuzawa T, Kita Y, Matsuda K and Okada Y, Magnetically Suspended Rotary Blood Pump with Radial Type Combined Motor-Bearing, Artificial Organs, 24, 6, pp.468-474 (2000).
4. Masuzawa T, Onuma H, Kim SJ, Okada Y, “Magnetically suspended centrifugal blood pump with a self-bearing motor,” ASAIO Journal, vol.48, 437-442 (2002).
5. Masuzawa T, Kita Y and Okada Y: An Ultradurable and Compact Rotary Blood Pump with a Magnetically Suspended Impeller in the Radial Direction, Artificial Organs, 25, 5, pp.395-399, 2001.
6. Katoh A, Masuzawa T, "Optimized Design for a Hybrid Magnetic Bearing for the Artificial Heart", Proc. for the 10th Int. Symp. on Magnetic Bearings: CD-ROM, (2006).
7. Goldberg DE, Genetic Algorithms in Search, Optimization and Machine Learning, Addison-Wesley Publishing Company, Inc., (1989).
8. Davis L, Handbook of Genetic Algorithms, Van Nostrand Reinhold, A Division of Wadsworth, Inc., (1990).
9. Fizgerald AE, Kingsley C Jr, Umans SD, ELECTRIC MACHINERY, McGrow-Hill Book Company press, (1992).
10. Toshirou I, Shigehiko I, Sumio M, Design and application of “Koucyoku” magnet, Ohmsha, Ltd., pp.22-27, (1957)
11. Takyoshi N, Shoukichi I, Yoshihiro K, Design and application of “Koucyoku” electromagnet by finite element method, pp.20-22, 162, 164 , Morikita Publishing Co., Ltd, (1991)