Effects of Permanent-Magnet Passive-Magnetic- Bearing on a 2-axis Actively Regulated Low-Speed Bearingless Motor

Junichi Asama, *Member, IEEE*, Tetsuro Asami, *Student Member, IEEE*, Takashi Imakawa, Akira Chiba, *Fellow, IEEE*, Atsushi Nakajima, and M. Azizur Rahman, *Life Fellow, IEEE*

Abstract—Performance comparisons in a bearingless motor with and without passive magnetic bearings are presented. The bearingless motor is actively controlled in two perpendicular x-y axes. The axial and conical movements are supported by passive magnetic bearings. The experimental results are compared to the calculated ones by three-dimensional finite element method. Effectiveness of passive magnetic bearings is analytically and experimentally investigated in both static and dynamic tests. It is found that a rotational test is successful only with the passive magnetic bearings.

Index Terms—Bearingless motor, Passive magnetic bearing, Consequent-pole, Magnetic suspension, PM motor.

I. INTRODUCTION

A BEARINGLESS motor is a single electric device combining a motoring functionality and magnetic bearings. A bearingless motor can be suspended without touching the bearing journal surface. Therefore, the magnetic bearing characteristics can be realized in a bearingless drive. These are maintenance free, possible high rotational speed, and less friction. In addition, a bearingless motor possesses the advantages of a short shaft length and a simple structure. Therefore, the bearingless motor is suitable for space applications where durability and compactness are especially concerned. The authors are aiming to realize a bearingless reaction wheel employed in a microsatellite. It is needed to drive the rotor up to the nominal rotational speed of 1,000r/min [1], [2].

Recently, various bearingless motors have been developed with one to five-axis degrees of freedom of active magnetic suspension [3]-[25]. In four degrees of freedom active control, two rotor units are actively controlled in the two radial directions as well as in two conical directions. Five-axis active regulation requires active control in axial direction. Five-axis

controlled bearingless motors have high stiffness in radial, axial and conical directions. However, machine size is large and cost is rather high.

In two degrees of freedom active control, one rotor unit is actively controlled in the two radial directions [3]-[13]. Two-axis controlled bearingless motors are compact and simple. The notable development of a two-axis bearingless motor [3] has been adapted in canned pumps used in semiconductor industry. A rotor disk has to have a flat disk shape to enhance the passive stiffness of axial and conical direction movements. The flatness is represented by the aspect ratio, i.e., the ratio of a rotor outer diameter with respect to a rotor axial length in inner rotor motors. These ratios are in a range of 6.4 to 18 as specified in the references [4]-[10]. If the aspect ratio is high, then, the rotor has better stiffness in passive axes. Thus, the rotor has to have a flat disk shape. Successful magnetic suspension with a low aspect ratio is a challenging project.

The authors have proposed a new hybrid bearingless motor with the two-axis active positioning and passive magnetic bearings (PMBs) [23]-[25]. A prototype machine was constructed by two-axis active position regulation having one unit of a bearingless motor with a consequent-pole permanent magnet (PM) rotor [23], [24]. With the PMBs, the stiffness is enhanced in the three passive movements, i.e., axial and conical movements, thus, the rotor aspect ratio can be low. The experimental and calculated results of only static performance characteristics have been presented [25].

In this paper, dynamic characteristics are investigated. The experimental results of magnetic suspension and rotation are presented. The experimental results of the proposed bearingless motor with and without PMBs are compared with those obtained by three-dimensional finite element method (3D-FEM). The effectiveness of PMBs is experimentally and analytically investigated.

A short part of this paper, i.e., a principle, a structure and simple experimental results, has been presented in [26]. Significant improvements and additional test results, such as magnetic suspension characteristics, start up waveforms, successful rotational start up, are included in this paper. The results of rotational tests up to 1,000r/min have been successfully performed. It is found that successful magnetic suspension is possible only with PMBs in a test machine having the aspect ratio of 4.6.

J. Asama is with the Department of Mechanical Engineering, Shizuoka University, Shizuoka, 432-8561, Japan.

T. Asami and T. Imakawa are with the Department of Electrical Engineering, Tokyo University of Science, Chiba 278-8510, Japan.

A. Chiba is with the Department of Electrical Engineering, Tokyo Institute of Technology, Tokyo, 152-8550, Japan (e-mail: chiba@ee.titech.ac.jp).

A. Nakajima is with the Department of Electrical and Electronic Engineering, Shinshu University, Nagano 380-8553, Japan

M. A. Rahman is with the Discipline of Engineering and Applied Science, Memorial University of Newfoundland, Newfoundland A1B3X5, Canada.

Fig. 1. The proposed outer rotor bearingless motor with PMB.

II. STRUCTURE OF BEARINGLESS MOTOR WITH PASSIVE MAGNETIC BEARINGS

A. Structure of Bearingless Motor

Fig.1 shows the x-z cross section of the proposed outer rotor bearingless motor drive. A rotor of this prototype machine is in a ring shape surrounding the stator part. In the stator part, stator core is skewed in order to reduce cogging torque and ripple of radial suspension force. This machine is composed of three-layer parts. The center is bearingless motor part and the left and right parts are PMBs. The PMs of bearingless motor are radially magnetized. Around the static shaft, a stator core and concentrated windings are constructed. The bearingless motor generates the driving torque and provides the radial suspension force. PMBs are composed of axially magnetized PMs, iron ring, and a stator C-core. PMBs are designed thin and small so that dead space of coil ends can be used. With the PMBs, stiffness is enhanced in the three-axis movements, i.e., axial and conical directions. In this outer rotor machine, the aspect ratio is defined by the rotor inner diameter divided by the rotor axial length. The aspect ratio is 4.6 in the bearingless motor part only, however, it is 2.3 if the PMB part is included. The aspect ratio is rather low with respect to the bearingless motors in [4]-[10].

B. Principle of Radial Suspension Force Generation

Fig. 2 shows the x-y cross section of an outer rotor consequent-pole bearingless motor. In a consequent-pole bearingless motor, radially magnetized PMs are inset into the rotor iron poles. The bias fluxes by PMs are passing through

Fig. 2. Principle of radial suspension force generation of consequent-pole bearingless motor.

the air gap, stator core, and rotor core. Therefore, the iron poles at the rotor inner face are magnetized as S-poles. The rotor iron parts between the PMs are consequently magnetized. Therefore, this consequent-pole bearingless motor works as a 16 pole synchronous motor.

Fig. 2 also shows a principle of radial suspension force production in the x-direction. The suspension magnetic flux is generated by the current in the suspension windings. The flux densities at air gaps are unbalanced because of superimposition of the suspension flux and the PM bias flux. As a result, radial suspension force F_x is generated in the x-direction. The radial suspension force F_y in the y-direction is generated by perpendicular suspension windings. The radial suspension force is regulated by the vector sum of F_x and F_y .

In a consequent-pole bearingless motor, the radial suspension force is generated in mostly constant amplitude and direction with the dc suspension current, even though the rotor is rotated. Therefore, the detection of rotor rotational position is unnecessary. The drive system can be simple like an open loop inverter, or a general purpose sensorless inverter.

C. Principle of Axial Restoring Force Generation of PMBs

Fig. 3 shows the principle of axial restoring force generation of the PMB. The flux from a PM flows to a thin iron ring, an air gap, a confronting stator C-core and returns to the rotor PM. When the rotor is displaced in axial or conical directions, fringing fluxes generate restoring force. As a result, the axial and conical movements are passively adjusted. It is noted that this PMB is unstable in radial directions. Thus, radial stable force should be provided by the actively controlled bearingless motor.

D. Control Systems

Fig. 4 shows the control systems of the bearingless motor. The system is composed of magnetic suspension system and motor drive system. The rotor is magnetically suspended in the radial x and y positions. These movements are detected by

Fig. 3. Principle of axial restoring force generation of the PMB.

Fig. 4 Control systems block diagram of the bearingless motor.

eddy current sensors, and then, compared with the references and these errors are amplified by the PID controllers. The PID controller transfer function is adjusted as magnetic pull force is enhanced by the PMBs.

In order to compensate the current delay caused by a coil inductance, the current regulator is constructed with current feedback loops. The suspension winding currents are regulated so that these currents follow the current commands i_x^* and i_y^* . Based on the current error in two-phase system, voltage commands V_a^* and V_b^* are generated. Then, three-phase voltage commands V_u^* , V_v^* , and V_w^* are generated as,

$$\begin{bmatrix} V_u^* \\ V_v^* \\ V_w^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} V_a^* \\ V_b^* \end{bmatrix} \quad (1)$$

The voltage source inverter applies the commanded three-phase voltage to the suspension winding terminals.

The machine is driven by two units of three-phase inverters. One is for the magnetic suspension and another is for the motor drive. In motor drive, three-phase currents are supplied by the voltage source inverter based on an open loop speed regulation. Thus, the rotor rotational position is not detected both in motor drive and magnetic suspension. The two-phase ac current commands i_a^* and i_b^* are given by d-q current commands i_d^* and i_q^* as,

$$\begin{bmatrix} i_a^* \\ i_b^* \end{bmatrix} = \begin{bmatrix} \cos 8\omega t & -\sin 8\omega t \\ \sin 8\omega t & \cos 8\omega t \end{bmatrix} \begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix} \quad (2)$$

where, ω is an angular frequency of the current. The current regulation block, having the same structure of the one in the magnetic suspension block, provides three-phase currents to the motor windings.

Fig. 5 shows a photograph of the prototype bearingless motor with a controller and a driver. Iron rings and C-core of the PMB are made of bulk carbon steel. Two eddy current type displacement sensors are fixed on the base to detect the radial rotor position. In the controller, the radial positions are given through the displacement sensors. A custom-build controller-driver system is employed. Signal processing is realized in one chip CPU, then, two voltage source inverters with the rated voltage and current of 100 V and 3 A regulate the currents. A commercially available software is employed (PE-View, Myway Corp., Japan) for control system development. The sampling rates of the current regulation system and the magnetic suspension system are 10kHz and 3.3kHz, respectively.

III. MAGNETIC SUSPENSION CHARACTERISTICS

The magnetic suspension characteristics of the machine both with and without PMBs are measured. The radial suspension force, the unbalanced magnetic pull force and the axial and conical stiffness are shown in sub-sections A, B and C, respectively. The measured results are compared to the calculated ones using 3D-FEM, which is implemented by using a commercially available software (JMAG-Studio, JSOL Corp., Japan).

A. Radial Suspension Force

The static radial force and current characteristics are measured. By applying radial external force at the rotor in x-direction, the radial suspension force is measured. The derivative of the radial suspension force F_x with respect to the suspension current i_x is defined as a radial suspension force constant k_{ix} in this paper.

Fig. 6 shows the measured and calculated force results as a function of suspension current. The data points in Fig. 6 are subjected to the least-square fitting. The slope line is a radial suspension force constant, k_{ix} . Table 1 shows the values of the radial suspension force constant k_{ix} . It is shown that the k_{ix} has

Fig. 5 A photograph of a prototype machine, a controller, and a driver

Table 1 The suspension force constant k_{ix} .

Machine	Exp. (N/A)	Calculated (N/A)
Machine with PMBs	40.0	40.9
Machine without PMBs	40.1	42.7

Fig. 6 Radial suspension force at centre position.

a good correspondence with measured values not depending on PMBs as long as the rotor is suspended at the centre position.

B. Unbalanced Magnetic Pull Force

If the rotor is displaced in radial direction, the unbalanced magnetic pull force is resulted. The suspension current i_x is measured while the radial rotor displacement x is moved. The derivative of the suspension force F_x with respect to the displacement x is defined as k_x . A sum of the active force and the unbalanced magnetic pull force are written as;

$$f = k_{ix} i_x + k_x x \quad (3)$$

If the sum of force is zero, then, one can be derive k_x as;

$$k_x = -k_{ix} \frac{i_x}{x} \quad (4)$$

Based on this equation, k_x is derived in experiment. On the other hand, k_x is calculated using 3D-FEM, while the radial rotor displacement x is moved and no suspension current i_x is provided. The k_x is given as;

$$k_x = -\frac{f}{x} \quad (5)$$

Table 2 shows the values of an unbalanced magnetic pull force constant k_x . The measured k_x value with PMBs is 475 N/mm, and that without PMBs is 296 N/mm. The measured k_x is 1.6 times of that without PMBs. With PMBs, the unbalanced magnetic pull force undesirably increased. The increase makes the start up difficult.

C. Axial and Conical Stiffness

The axial and conical stiffness are calculated and measured. The axial restoring force F_z is calculated using 3D-FEM, while the axial displacement z is moved by 0.1mm at suspension current $i_x = 0$. The conical restoring torque T_θ is calculated using 3D-FEM, while the conical rotor

Table 2 The values of unbalance magnetic pull force constant k_x .

Machine	Exp. (N/mm)	Calculated (N/mm)
Machine with PMBs	475	551
Machine without PMBs	296	325

displacement θ is moved by 0.1deg around y-axis at the centre of gravity. On the other hand, the axial and conical stiffness are measured when the rotor is oscillated in conical direction. An impulse is given in conical direction, while the rotor is magnetically suspended at the centre.

The oscillation includes two components, i.e., axial and conical components. The axial displacement z and conical displacement θ are detected by two eddy current displacement sensors, S_1 and S_2 , which are set up at opposite position to the centre. The S_1 and S_2 are written as;

$$S_1 = z + \frac{D}{2} \theta \quad (5)$$

$$S_2 = z - \frac{D}{2} \theta \quad (6)$$

where D is the distance between the displacement sensors. Then, the axial and conical displacements are given as,

$$z = \frac{S_1 + S_2}{2} \quad (7)$$

$$\theta = \frac{S_1 - S_2}{D} \quad (8)$$

The impulse response in z and θ can be expressed as,

$$z = S_{z\max} e^{-\frac{\eta_z}{2m}t} \sin \omega_z t \quad (9)$$

$$\theta = \frac{2}{D} S_{\theta\max} e^{-\frac{\eta_\theta}{J_\theta}t} \sin \omega_\theta t \quad (10)$$

where $S_{z\max}$ and $S_{\theta\max}$ are the maximum amplitudes in axial and conical oscillation, η_z and η_θ are viscosity constants, ω_z and ω_θ are angular frequencies, m is 2.0kg, J_θ is $5.73 \times 10^{-3} \text{kgm}^2$.

The frequency characteristics are measured by a fast Fourier transform (FFT) analyzer. From the frequency characteristics, resonant angular frequency ω_z and ω_θ of axial and conical directions, respectively, are measured, then the axial stiffness k_z and conical stiffness k_θ are calculated as follows;

$$k_z = m \omega_{z0}^2 = m(2\pi f_{z0})^2 \quad (11)$$

$$k_\theta = J_x \omega_{\theta 0}^2 = J_x(2\pi f_{\theta 0})^2 \quad (12)$$

Table 3 shows the rotor weight, the moment inertia around x-axis and both axial and conical resonant frequency. A weight increase of PMBs is about only 10% of the total rotor weight. It is noted that the resonant frequency is high with PMBs.

Fig. 7 shows an analytical model and an example of 3D-FEM results. The structure of proposed bearingless motor with PMBs is shown in Fig. 7 (a). The number of nodes and

elements are about 180,000 and 900,000, respectively. To obtain precise force under movements in axial and conical directions, a cylindrical slide mesh is selected in the airgap between the rotor and the stator. The number of elements of the cylindrical slide mesh is about 1.5 times that of the automatically generated mesh. Fig. 7 (b) shows vector and contour figures of the PMB part when the rotor moves to the axial direction. The current of suspension windings is set to 0A. As the magnetic flux produced from a PM flows through an iron ring, an airgap and a confronting stator C-core, fringing fluxes in the airgap generate restoring force. Maximum flux density in the closed magnetic loop of the PMB is about 1.2T.

Figs. 8 (a) and (b) show the calculated axial restoring force F_z and conical restoring torque T_θ , respectively. The axial stiffness k_z at $z = 0$ is calculated by the derivative of the axial restoring force F_z with respect to the axial displacement z . The conical stiffness k_θ at $\theta = 0$ is calculated by the derivative of the conical restoring torque T_θ with respect to θ . The values k_z of the machine with and without PMBs are 73.5N/mm and 9.59N/mm, respectively. The values k_θ of the machine with

and without PMBs are 58.8Nm/rad and 2.65Nm/rad, respectively.

Table 4 shows the measured and calculated k_z and k_θ . In the machine without PMBs, axial and conical resonant frequencies f_z and f_θ are 5.5Hz and 5.0Hz, respectively. Then, the axial stiffness k_z and conical stiffness k_θ are obtained as 2.14 N/mm and 3.21 Nm/rad, respectively. The calculated axial and conical stiffness using 3D-FEM are 9.59N/mm and 2.65Nm/rad, respectively, as noted earlier. There is significant error in the axial stiffness in the machine without PMBs. The reasons of the error are due to the mechanical precision of the

Table 3 The weight of a rotor, m , the moment of inertia around x-axis, J_x , and the resonant frequency in axial and conical directions.

machine	$m(\text{kg})$	$J_x(\text{kgm}^2)$	$f_{z0}(\text{Hz})$	$f_{\theta 0}(\text{Hz})$
Machine without PMBs	1.8	3.21×10^{-3}	5.5	5.0
Machine with PMBs	2.0	3.51×10^{-3}	31.0	20.0

(a) Cross-sectional view of analytical 3D-model.

(b) Vector and contour figures of the PMB part at a rotor axial position of 1mm.

Fig. 7. A model and a result of 3D-FEM analysis.

(a) Axial restoring force

(b) Conical restoring torque

Fig.8 Analysis results of passive stiffness

Table 4 The axial and conical stiffness k_z and k_θ .

(a) The axial stiffness k_z

machine	Measured (N/mm)	Calculated (N/mm)
Machine without PMBs	2.14	9.59
Machine with PMBs	76.1	73.5

(b) The conical stiffness k_θ

machine	Measured (Nm/rad)	Calculated (Nm/rad)
Machine without PMBs	3.21	2.65
Machine with PMBs	55.4	58.8

fabricated bearingless motor, such as a misalignment of rotor and stator edges, a thickness error caused by laminated structure and an imperfect flatness. In the machine with PMBs, on the other hand, an axial resonant frequency f_z and a conical resonant frequency f_θ are 31.0Hz and 20.0Hz, respectively. The calculated axial and conical stiffness are 73.5N/mm and 58.8Nm/rad, respectively. The error is limited to 3.5% and 5.7%. The stiffness of the machine with PMBs are significantly higher than that without PMBs. The measured k_z and k_θ of the machine with PMBs are about 36 times and 17 times of those without PMBs, respectively. It is found that PMBs contribute significantly to enhance the axial and conical stiffness. This stiffness enhancement is a key of successful magnetic suspension in rotational tests with the low aspect ratio as shown in the next section.

IV. EXPERIMENT OF THE MACHINE OPERATION

The suspension start tests from touched down condition and rotation tests were performed. During rotation tests, the rotor was magnetically suspended. From the tests results, the effectiveness of PMBs is experimentally investigated by comparing the machines with and without PMBs.

A. Suspension Start Tests from Touched Down Condition

The suspension start tests are performed. The radial, axial and conical displacements are measured by eddy current displacement sensors when suspension system is switched on.

Fig. 9 shows the radial displacement waveforms in the machine without PMBs. Before the suspension system is activated, the rotor is touched down in the negative direction of the y-axis because of the gravity and attractive magnetic force caused by permanent magnets. When the system is

Fig. 9 Radial displacement waveforms in the machine without PMBs

Fig. 10 Radial displacement waveforms in the machine with PMBs

activated, the rotor moves to the centre. However, the oscillation is occurred in both radial and conical directions. The oscillation is within the limited x and y values of 0.3mm. The oscillation is caused by the low stiffness in axial conical directions.

Fig. 10 shows the radial displacement waveforms in the machine with PMBs. When the system is activated, the rotor moves to the centre. Then the rotor is stable at centre position without vibrations. Fig. 11 shows the axial and conical displacement waveforms in the machine with PMBs. Before the radial suspension system is activated, the rotor is touched down in the conical direction because of the gravity. When the radial suspension system is activated, oscillation is occurred because of the passive stability. After that, however, the oscillation is damped and then the rotor is stably suspended in passive directions, thanks to the PMBs.

B. Rotation Start Tests

The rotation start tests are performed. The radial, axial and conical displacements are measured by eddy current displacement sensors when rotation system is switched on during the suspension system is activated.

Fig. 12 shows the displacement waveforms in the prototype machine with and without PMBs when the rotation system is activated. Fig. 12 (a) shows the axial displacement. Fig. 12 (b) shows the conical displacement. In the machine without PMBs, before the rotation system is activated, the radial positions in the x- and y-axes are magnetically regulated without a contact at the centre position. The axial and conical positions are passively stable. When the rotation system is

(a) Axial displacement waveforms

(b) Conical displacement waveforms

Fig. 11 Start up tests in axial and conical directions in the machine with PMBs

(a) Axial displacement waveforms

(b) Conical displacement waveforms

Fig. 12 Rotation start test in the machine without PMBs.

activated, the serious oscillation in both the axial and conical directions is occurred. The rotor is touched down because the limited displacements are $z = -0.5\text{mm}$, $|\theta| = 10.3\text{mrad}$, respectively. The touchdown is occurred because the axial stiffness k_z and the conical stiffness k_θ are not high enough. The low passive stiffness is due to the low aspect ratio 4.6 of the test machine.

On the other hand, in the machine with PMBs, the rotor is stable in both axial and conical directions when the motor system is activated. It is shown that the rotor can be stably rotated without a contact. The maximum absolute displacements in the axial and conical directions are 0.1mm and 2.8mrad , respectively. The amplitude in the axial direction of the machine with PMBs is about 5% of that without PMBs. The amplitude in the conical direction of the machine with PMBs is about 25% of that without PMBs. It is shown that the rotor of the machine only with PMBs can be rotated. These are thanks to PMBs to enhance the passive stiffness in both axial and conical directions.

C. Rotation Tests in the Bearingless Motor with PMBs

The rotor of a bearingless motor is vibrated when the rotor is rotated because of mechanical imperfectness. Therefore, vibration amplitudes are measured by eddy current displacement sensors when the both suspension and rotation systems are activated. The measurements were able to be carried out only with PMBs.

Fig. 13 shows the vibration amplitudes against the

(a) Radial displacement waveforms

(b) Axial displacement waveforms

(c) Conical displacement waveforms

Fig. 13 Vibration amplitudes in the machine with PMBs.

rotational speed. The maximum rotational speed is $1,020\text{r/min}$. It is enough for an application to a reaction wheel employed in a microsatellite. Fig. 13 (a) shows radial vibration, Fig. 13 (b) shows axial vibration and Fig. 13 (c) shows conical vibration. The limited displacements are $x, y = 0.3\text{mm}$, $z = 0.5\text{mm}$, $\theta = 10.3\text{mrad}$, respectively. It is shown that the rotor is not touched down in all speed range.

Fig. 14 shows the radial, axial and conical positions at $1,020\text{r/min}$ for the one cycle rotor rotation. The maximum vibrations are about $x = 0.03\text{mm}$, $y = 0.03\text{mm}$, $z = 0.05\text{mm}$, $\theta = 2\text{mrad}$. The vibration amplitudes of the rotor at $1,020\text{r/min}$ are about one tenth those of the touchdown limits. When the

(a) Radial displacement waveforms

(b) Axial displacement waveform

(c) Conical displacement waveform

Fig. 14 Rotation tests of the machine with PMBs at 1,020r/min.

rotor has one rotation, i.e., for a duration of 60ms, the third harmonics are significantly included in radial directions. The reason is imperfect surface in a sensor target during machining process. In future works, rotation tests at higher rotational speeds will be examined.

V. CONCLUSION

In a 2-axis actively regulated bearingless motor, the experimental and calculated results of the machine with and without PMBs are compared. The rotor has rather low aspect ratio of 4.6, thus, passive stiffness is low. To enhance passive stiffness, passive magnetic bearing (PMBs) are constructed.

The passive magnetic bearings are composed of iron core and permanent magnets. In comparison, it is shown that axial and conical stiffness are improved by 36 times and 17 times, respectively. It is found that the rotation test was successful only in the machine with PMBs. These are thanks to PMBs to enhance the passive stiffness in both axial and conical directions. Moreover, the test machine with PMBs can be driven up to 1,020r/min with non contact magnetic suspension.

VI. ACKNOWLEDGMENT

The authors would like to thank Ms Yukiko Nakano who was a graduate student at Tokyo University of Science.

VII. REFERENCES

- [1] A. Nakajima and C. Murakami, "Research and Development of Magnetic Bearings", *Proceedings of the 16th International Symposium on Space Technology and Science*, Sapporo, Japan, 1998.
- [2] M. Scharfe, T. Toschke, E. Bindl, D. Blonski, and R. Seiler, "The challenges of miniaturization for a magnetic bearing wheel", *Proceedings of the 9th European Space Mechanisms and Tribology Symposium*, Liege, Belgium, 2001.
- [3] Natale Barletta, Reto Schob, "Design of a Bearingless Blood Pump", 3rd International Symposium on Magnetic Suspension Technology, 1995 NASA conf.pub 3335 pp.265-274
- [4] P. Karutz, T. Nussbaumer, J. W. Kolar, "Magnetically Levitated Slice Motors-An Overview," in Proc. ECCE2009, pp. 1494-1500, 20-24 Sep. 2009
- [5] Hiroya Sugimoto, Kosuke Kamiya, Ryo Nakamura, Junichi Asama, Akira Chiba, Tadashi Fukao, David G. Dorrell, "Radial Force Characteristics of Multi-Consequent-pole Bearingless Motor", Proc. of International Conference on Electrical Machines and Systems (ICEMS2008), SMP-147, 6 pages, 2008, Wuhan
- [6] P. Karutz, T. Nussbaumer, W. Gruber and J. W. Kolar : "Novel Magnetically Levitated Two-Level Motor," *IEEE/ASME Trans. Mechatronics*, vol. 13, no. 6, pp. 658 – 668, Dec. 2008.
- [7] W. Gruber, W. Amrhein and M. Haslmayr, "Bearingless Segment Motor With Five Stator Elements-Design and Optimization", *Industry Applications*, *IEEE Trans.*, pp1301-1308, July-Aug. 2009
- [8] T. Stallinger, W. Gruber and W. Amrhein, "Bearingless Segment Motor With a Consequent Pole Rotor", *Electric Machines and Drives Conference*, *IEEE International*, pp1374-1380, 3-6 May 2009
- [9] Toru Masuzawa, "Motor application in artificial heart", *Denshi Gijutsu* 2002-3 pp.38-42(in Japanese)
- [10] Yohji Okada, Tatsunori Shimonishi, Seung-Jong Kim and Hideki Kanebako, "Development of Hybrid type Self bearing slice motor for small and high speed rotary machines", *IEEE IAS Annual Meeting Record* 2001
- [11] S. Silber, W. Amrhein, P. Bösch, R. Schöb, and N. Barletta, "Design aspects of bearingless slice motors," *IEEE/ASME Trans. Mech.*, vol. 10, no. 6, pp. 611-617, Dec. 2005.
- [12] P. Karutz, T. Nussbaumer, W. Gruber and J.W. Kolar, "The Bearingless 2-Level Motor", in *Proc. The 7th International Conference on Power Electronics and Drive Systems*, pp.365-371, Nov. 2007.
- [13] J. Asama, A. Chiba, T. Oiwa, T. Fukao and M. A. Rahman, "A Design Consideration of a Novel Bearingless Disk Motor for Artificial Heart", *Proceedings of IEEE Energy Conversion Congress and Expo 2009, CD-ROM*, San Jose, CA, USA, Sep. 20-24, 2009.
- [14] J. Zhou, and K.J. Tseng, "A disk-type bearingless motor for use as satellite momentum-reaction wheel," in *Proc. IEEE 33rd Annu. Power Electronics Specialists Conf.*, Cairns, Australia, vol. 4, no. 10, pp. 1971-1975, Jun. 2002.
- [15] Y. Okada, N. Yamashiro, K. Ohmori, T. Masuzawa, T. Yamane, Y. Konishi, and S. Ueno, "Mixed Flow Artificial Heart Pump with Axial Self-Bearing Motor," *IEEE/ASME Trans. Mech.*, vol. 10, no. 6, pp. 658-665, Dec. 2005.
- [16] Ren, Z., and Stephens, L. S., "Force characteristics and gain determination for a slotless self-bearing motor", *IEEE Trans. Magnetics*, vol.42, no.7, pp.1849-1860, Jul. 2006.

- [17] W. K. S. Khoo, "Bridge Configured Winding for Polyphase Self-Bearing Machines", *IEEE Trans. Magnetics*, vol.41, no.4, pp.1289-1295, Apr. 2005.
- [18] Yang, S. M., and Lin, C. L., "Levitation and Torque Control of a PM Synchronous Self-Bearing Motor with a Single Set of Windings", in *Proc. the 33th IEEE Industrial Electronics Society pp.1033-1037 (IECON)*, Nov. 2007.
- [19] A. Chiba, T. Fukao, O. Ichikawa, M. Oshima, M. Takemoto, and D. G. Dorrell, *Magnetic Bearings and Bearingless Drives*, Amsterdam, The Netherlands: Elsevier, Mar. 2005, ISBN: 0 7506 5727 8.
- [20] Akira Chiba, Tazumi Deido, Tadashi Fukao and M.A.Rahman, "An Analysis of Bearingless ac Motors", *IEEE Trans. Energy Conversion*, vol.9, no.1, March, 1994, pp.61-68
- [21] J. Asama, M. Amada, N. Tanabe, N. Miyamoto, A. Chiba, S. Iwasaki, M. Takemoto, T. Fukao, M. A. Rahman, "Evaluation of a Bearingless PM Motor With Wide Magnetic Gaps", *IEEE Transactions on Energy Conversion* (in press).
- [22] Y. Asano, A. Mizuguchi, M. Amada, J. Asama, A. Chiba, M. Oshima, M. Takemoto, T. Fukao, O. Ichikawa, and D. G. Dorrell, "Development of a Four-Axis Actively Controlled Consequent-Pole-Type Bearingless Motor", *IEEE Transactions on Industry Applications*, Vol. 15, No. 4, pp. 1378-1386, 2009.
- [23] K. Asami, A. Chiba, M. A. Rahman, T. Hoshino, and A. Nakajima, "Stiffness Analysis of a Magnetically Suspended Bearingless Motor with Permanent Magnet Passive Positioning," *IEEE Trans. Magn.*, vol. 41, no. 10, pp. 3820-3822, Oct. 2005.
- [24] T. Yamada, Y. Nakano, J. Asama, A. Chiba, T. Fukao, T. Hoshino, and A. Nakajima, "Outer Rotor Consequent-pole Bearingless Motor with Improved Start-up Characteristics," *IEEE Trans. Magn.*, to be published.
- [25] Y. Nakano, T. Asami, J. Asama, A. Chiba, T. Fukao, T. Hoshino, and A. Nakajima, "Basic Characteristics of Improved Bearingless Motor with Passive Magnetic Bearings," in *Proc. 11th Int. Symp. Magnetic Bearing*, Nara, Japan, Aug. 2008.
- [26] T. Asami, Y. Nakano, J. Asama, A. Chiba, T. Fukao "Rotational characteristics of a bearingless motor with passive magnetic bearings", in *Power and Energy Society General Meeting*, Jul. 2009

VIII. BIOGRAPHIES

Junichi Asama (M'08) was born in Niigata, Japan, in 1979. He received the B.S., M.S., and Ph.D. degrees in mechanical engineering from the Tokyo Institute of Technology, Tokyo, Japan, in 2002, 2004, and 2006, respectively. During 2006, he was a Postdoctoral Researcher in the Precision and Intelligence Laboratory, Tokyo Institute of Technology. During 2007, he was a Research Associate in the Department of Electrical

Engineering, Faculty of Science and Technology, Tokyo University of Science, Chiba, Japan. Since 2009, he has been an Associate Professor in the Department of Mechanical Engineering, Faculty of Engineering, Shizuoka University, Hamamatsu, Japan. His research interests include bearingless motor drive systems and their applications. Dr. Asama is a member of the Institute of Electrical Engineers of Japan (IEEJ), Japan and Japan Society for Precision Engineering (JSPE), Japan.

Tetsuro Asami (S'09) received the B.S. degree from the Department of Electrical Engineering in the Faculty of Science and Technology, Tokyo University of Science, Chiba, Japan, in 2009. He is currently engaged in a bearingless motor project. He is a Student member of IEEE.

Takashi Imakawa received the B.S. degree from the Department of Electrical Engineering in the Faculty of Science and Technology, Tokyo University of Science, Chiba, Japan, in 2010. He is currently engaged in a bearingless motor project.

Akira Chiba (S'82-M'88-SM'97-F'07) was born in Tokyo, Japan in 1960. He received the BS., MS. and Ph.D. degrees in Electrical Engineering from the Tokyo Institute of Technology, in 1983, 1985 and 1988, respectively. In 1988, he joined the Tokyo University of Science as a Research Associate in the Department of Electrical Engineering in the Faculty of Science and Technology. From 1992 to 1993, from 1993 to 1997, from 1997 to 2004, and from 2004 to 2010 he was Research Lecturer, Senior Lecturer, Associate Professor and Professor, respectively. Since 2010, he has been Professor in the Department of Electrical & Electronic Engineering in the Graduate School of Science and Engineering in the Tokyo Institute of Technology. In 1990-91, he was an NSERC (Natural Science and Engineering Research Council of Canada) International Post-Doctoral Fellow in the Memorial University of Newfoundland, Canada. He has been studying magnetically suspended bearingless ac motors, super high-speed motor drives and HEV and EV motors. He has so far published more than 720 papers including the first book on "Magnetic bearings and bearingless drives" in 2005, and submitted 56 patents. He has been the Vice Chair in the Motor Sub-Committee in the Electric Machinery Committee in IEEE PES. He has been a member of the Electric Machine Committee and the Industrial Drives Committee in IEEE IAS. He is a member of IEEJ in Japan and Fellow, IEEE.

Atsushi Nakajima was born in Nagano, Japan in 1947. He received the BS and MS degrees in Electrical Engineering from Shinshu University in 1970 and 1972, respectively, and received the Ph.D. degree from Kyoto University in 1985. Since 1972, he has been studying space technologies, especially on the attitude control system on artificial spacecraft in JAXA (Japan Aerospace Exploration Agency, formerly, National Aerospace Laboratory). He was the project manager of the small satellite for the technology demonstration on magnetic bearing flywheel, which was launched in 1986. He is a Professor of Graduate School of Electrical and Electronic Engineering in the Shinshu University since 2008.

M. Azizur Rahman (S'66-M'68-SM'73-F'88, LF 2007) was born at Santahar, Bangladesh on January 9, 1941. He received the B. Sc. Eng. from Bangladesh University of Engineering and Technology (BUET), Dhaka, the M. A. Sc. from the University of Toronto, Canada, and the Ph.D. degrees from Carleton University, Ottawa, Canada all in Electrical Engineering in 1962, 1965 and 1968, respectively. In 1962, he joined BUET as a Lecturer and was promoted to Full Professor in 1975. In 1976, he joined the Memorial University of Newfoundland, Canada, where is a Professor and University Research Professor. He has 47 years of teaching including about 10 years of full-time and concurrent industrial, utility and consulting experiences at GE, Schenectady, GE Canada, Peterborough, Newfoundland Hydro, Dhaka Electric Supply, Teshmont Consultants, Iron Ore Company of Canada, etc. He has been a Visiting Professor and Research Fellow at the Imperial College, London, Technical University of Eindhoven, University of Manitoba and University of Toronto, Nanyang Technological University, Tokyo Institute of Technology, University of Hong Kong, Tokyo University of Science and University of Malaya. He has published more than 635 papers including eleven patents, and two books as well as 5 book chapters. His current research interests are in machines, intelligent controls, power systems, digital protection and power electronics and wireless communications. He has been bestowed upon with numerous awards including the GE Centennial Invention Disclosure Award in 1978, IEEE Outstanding Students Counselor's Award in 1980, IEEE Notable Service Award for contributions to IEEE and Engineering Professions in 1987, IEEE Industry Application Society's Outstanding Achievement Award in 1992, Association of Professional Engineers and Geoscientists of Newfoundland Merit Award in 1994, IEEE Canada Outstanding Engineering Educator's Medal in 1996, IEEE Third Millennium Medal 2000, IEEE Cyril Veinott Electromechanical Energy Conversion Award in 2003, IEEE William E. Newell Power Electronics Award in 2004, Khwarizmi International Award in 2005, IEEE Dr. -Ing. Eugene Mittelmann Achievement Award in 2007 and the IEEE Richard H. Kaufmann Technical Field Award in 2007, the A. D. Dunton Award of Distinction and the IEEE-PES Distinguished Service Award in 2008. He is a registered Professional

Engineer in the Province of Newfoundland and Labrador, Canada, a member of the Institution of Electrical Engineers, Japan, a Fellow of the Institution of Engineering and Technology, U.K., a Fellow of the Engineering Institute of

Canada and a Life Fellow of the Institution of Engineers, Bangladesh and a Fellow of the Canadian Academy of Engineering.