(Registration number: 2001EF001)

Compact Flywheel Energy Storage System

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Duration：April, 2001 – March, 2004

Abstract

A purpose of this research is the development of a flywheel energy storage system which can replace a lead battery, inducing maintenance and environmental problems. Specifications were chosen for "a system of the 1kWh class where 300W power supply backup during 3 hours was possible". The system was called : “ ComFESS : Compact Flywheel Energy Storage System ” . The main challenging issues of the ComFESS were reduction of windage and rotational losses. Therefore, the flywheel rotor was put in a vacuum container, and active magnetic bearing (AMB) was adopted.

A rotational test of the system shows that the following technological goals have been achieved.

1) Establishment of a low loss hysteresis motor by suitable drive technique
2) Establishment of a suitable design technique of the rotor (the method of relation of Ip/Ir and natural frequency of the rotor)
3) Reduction of power consumption of active magnetic bearing by using attractive force of a permanent magnet to compensate for the rotor weight
4) Reduction of power consumption of active magnetic bearing by developing a zero power non-linear control

Ip : polar mass moment of inertia Ir : radial mass moment of inertia

Keywords: Flywheel, Active magnetic bearing, Permanent magnet, Hysteresis motor

1. Introduction

Accompanied by the progress of IT revolution, unexpected interruption of the correspondence and the communication imply more and more severe issues in society. Many of lead electric batteries are used for the back-up charge and their number is still increasing now. But this type of battery has a short life span, about three to four years, needs additional maintenance, and chemical materials used imply environmental problem, such as poisoning such of human, animals and plants too. Under such circumstances, development of a high efficient and clean energy storage system instead of lead electric battery seems crucial.

In this project, we will develop a flywheel type electric power storage system instead of a lead battery which causes environmental problems. The new system is called “Compact flywheel energy storage system (ComFESS)”.

The specification of the system are following : a 1kWh class energy storage capacity with an output electrical power of 300W during 3 hours. It is important for the system that windy and bearing losses of the flywheel are reduced in order to keep electrical power for several hours. Therefore the flywheel is suspended without contact by active magnetic bearings (AMB) and is located in a vacuum chamber.

2. Methods, Results and Discussion

2.1. Target of loss

In order to minimise the dimension of the ComFESS, the diameter of the Carbon Fiber Reinforced Plastics (CFRP) flywheel was defined to ø440mm for the outer diameter. The rotational decay characteristic of the ComFESS with this flywheel was calculated. In this calculation, it was considered that AMB controller and inverter of the generator are supplied by the ComFESS. The flywheel was slowed down from the rated rotational speed (24,000rpm, 1.6kWh), while consuming 300W of load. The result of this calculation is shown in Fig. 1. In this figure, “Conventional” shows the rotational decay characteristic of FESS with conventional AMB and motor/generator. In this result, it was supposed that the control method of AMB was a linear control method with bias current [1] and that the motor/generator design is based on a induction motor with conventional power converter. The result of “Conventional” of Fig. 1 runs only about 1.5 hours, which is not enough to consume the power. Here, the loss of ComFESS at 24,000rpm was classified into the loss of AMB, the windage loss and the loss of motor/generator shown in “Conventional” of Table 1.

The “Target” value of windage loss was estimated to be 50W. It is difficult to reduce the windage loss more than this value, because the degree of vacuum was supposed to be about 2Pa. Furthermore, the “Target” value of motor/generator loss was estimated to be 95W by lower losses motor/generator than induction motor/generator. The result of “Target” in Fig. 1 shows the rotational decay characteristic, using the “Target” values of Table 1. “Target” in Fig. 1 shows that it is possible to consume 300W of power during 3 hours from the initial stored energy. [2]

Table 1：Classified Losses of ComFESS

@24,000rpm

	Conventional [W]	Target [W]
Loss of AMB	500	100
Windage Loss (at 1Pa)	50	50
Loss of Motor/Generator	200	95
Total	750	245

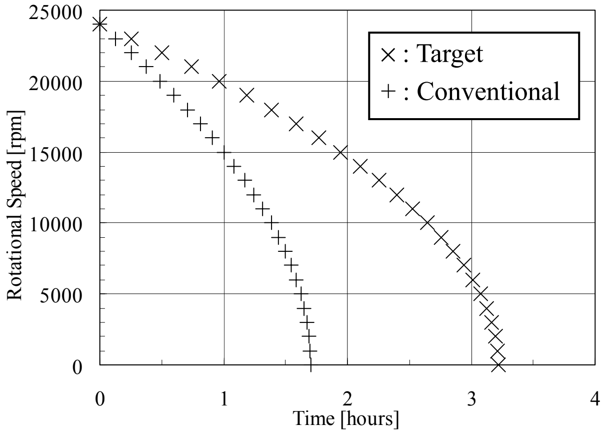


Fig. 1 : Estimated Rotational Decay of the Rotor

2.2. Design of ComFESS

The design of ComFESS was carried out to achieve the above aim. Results are described in the following section;.

2.2.1. The motor/generator with its electronic converter

Two alternatives are possible: Hysteresis motor and permanent magnet motor. For this low power (300 W) application, the final choice was made for the hysteresis motor:

- More robust, simple and more cost effective design
- Lower electrical losses possible (p.m. motor has 4 to 5 times higher losses).
- No converter development (A commercially IGBT converter type of Siemens being available)

2.2.2. Active magnetic bearing (AMB)

2.2.2.1 PM biased axial electromagnet

In this study, in order to avoid the loss increase, the magnetic force compensating for the weight of the rotor was substituted by the attracting force of a permanent magnet (PM).

2.2.2.2 Radial Active Magnetic Bearing

It is also necessary to reduce the power consumption of RaAMBs. In this study, “zero power nonlinear control” was used in order to avoid the bias current of RaAMBs.

2.2.3. Rotor

The rotor of ComFESS is composed of the main shaft and the CFRP flywheel. The calculated natural frequencies of the rotor are shown in figure 2. The designed ComFESS is shown in Fig. 3 and specifications are shown in table 2. [3]

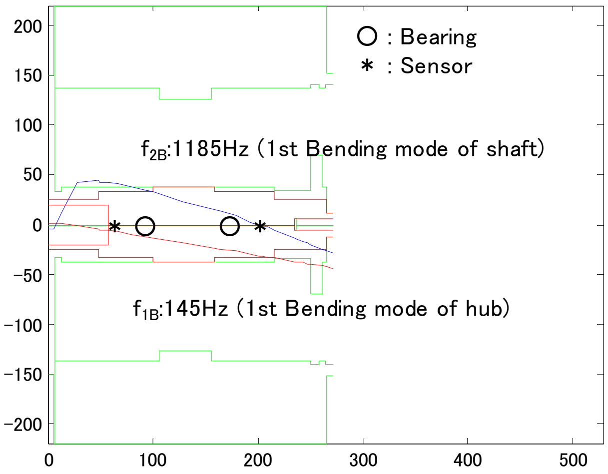


Fig. 2 : Result of mode simulation

Table 2 : Main Specification of ComFESS

Rotor	
Total Mass of Rotor:	75kg
Main Shaft:	Outer dia. ø 75mm Length 258mm
Flywheel:	Outer dia. ø 440mm Inner dia. ø 300mm Length 260mm
Energy Storage Capacity	900Wh (effective)
Kinetic Energy of the Rotor	1.6kWh (@24,000rpm) 0.1kWh (@5,000rpm)
Power Capacity	300W during 3hours
AxAMB	AMB (1 DOF) PM biased AxAMB
Control method:	Nonlinear control
RaAMB	AMB (4 DOF)
Control method:	Linear control
Electromagnets:	Hetero-polar
Rotor lamination:	Silicon steel plate
Touch Down Bearings	Emergency support for
Upper Side:	Radial direction
Lower Side:	Radial direction and axial direction
AMB Controller	
Power supply for magnets:	80～150DCV 40A(total)
Max. current for AMB:	8A (max) for each electromagnets
Amplifier :	PWM

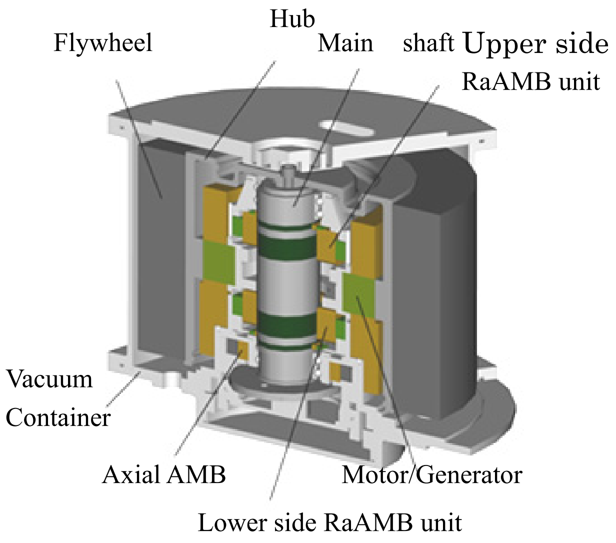


Fig. 3 : 3D drawing of ComFESS

2.4. Basic element test

The Basic element tests were carried out to confirm performance of each element in basic design. Therefore three kinds of test machines were designed and manufactured. The first one was ComFESS BB. The flywheel was made of CFRP, and the main shaft including the flywheel and hub supported by only ball bearings. The machine was used for element tests of the motor, the flywheel and the vacuum container.

The second was Dummy ComFESS. The flywheel was made of Bakelite. The rotor was supported by AMBs. It was used for element tests of AMB and the natural frequencies of the rotor.

After all element tests, ComFESS with AMB and CFRP flywheel was assembled by using some parts of Dummy ComFESS and ComFESS BB as shown in Fig. 3.

The third was Flywheel-AMB System, AMX095, for zero power control studies.

The results of each basic element test are described subsequently.

2.3.1. Measurement of losses

The loss data of all elements measured at 21,000rpm in ComFESS BB are shown in Table 3.

The loss of Motor/Generator controller was largely reduced to 20W for a target of 70W. The total loss was achieved to 300W for a target of 345W.

Table 3 : Measurement of loss ComFESS BB

		Target	ComFESS BB
			Measurement
Motor/Generator (W)		25	30
M/G controller (W)		70	20
M/G total Loss (W) A	ComFESS BB	95	50
Ball Bearing (W)		200	200
Windage loss (W)		50	50
Rotational loss (W) B	ComFESS BB	250	250
Total loss (W) A+B	ComFESS BB	345	300

2.3.2. Rotor dynamics inspection test

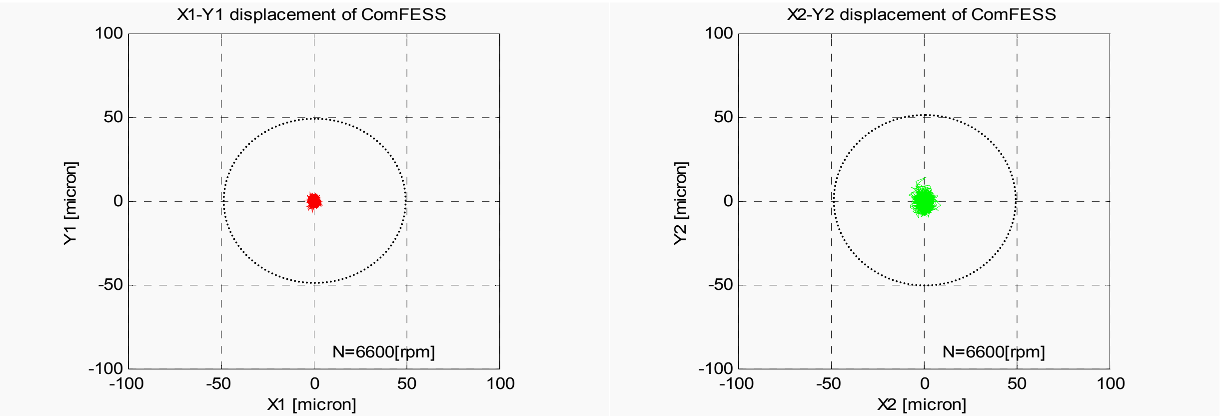
2.3.2.1. Rotational test of ComFESS with bias current control AMB

ｉ） Test method

For rotor dynamics validation, the rotational test of ComFESS with AMB by using the conventional bias current control was carried out. An umbalance force rejection control (UFRC) was adopted to restrain housing vibration. As a result of it, the flywheel rotates around the inertia center.

ii） Test result

Test results are shown in Fig. 4. At 6,600rpm, a stability rotation less than10 μ m orbits of the rotor was was achieved.



(a) Orbit at upper Radial AMB

(b) Orbit at lower Radial AMB

Fig. 4 : Orbits of the rotor of ComFESS（at 6,600rpm）

2.3.2.2. Measurement of campbell map of rigid mode

ｉ） Test method

An unstable phenomenon was the orbit becoming larger when the rotor turns over 6,600rpm. One of the causes of this unstable phenomenon was thought to be the rotational speed frequency approaching the natural frequency of a rigid mode of the shaft, depending on the spring constant of magnetic bearings.

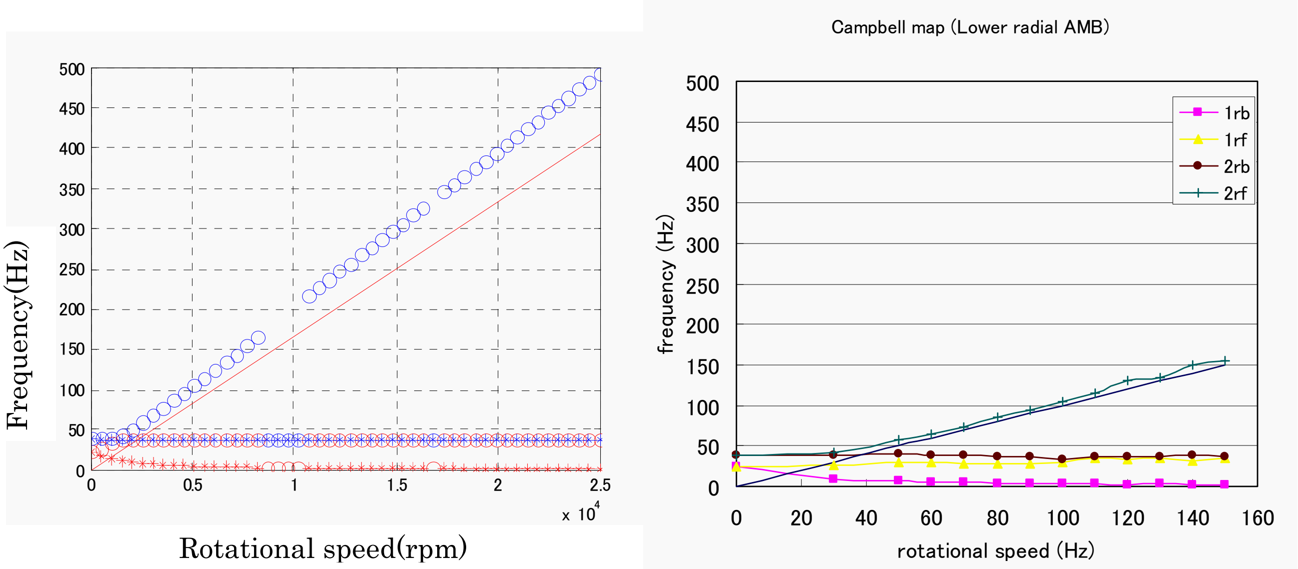
In this case, the natural frequency is excited with a rotational speed frequency higher than 6,600rpm, and orbit becomes larger. Dynamic stiffness was measured during rotation speed from 0 to 9,000rpm in order to grasp this phenomenon. We detected the natural frequencies of various rigid modes which varied with the rotational speed.

ⅱ） Test result

The measured natural frequencies of rigid modes are shown in Fig. 5 (b). The forward natural frequency of the 2nd rigid mode gorvery close to the rotational line. This means that an unstable state follows the acceleration of the rotor.

The natural frequencies calculated in the basic design step are shown in Fig. 5 (a). The forward natural frequency of the 2nd rigid mode approached the rotational line. However, it staid away from rotational line while accelerating. Therefore even if resonance problem occurred, it vanishes by accelerating.

In a rotor design, a continue resonance in the case of Ip/Ir =1 and be avoided. In this research, the Ip/Ir of rotor in ComFESS is 1.3.



(a) Simulation（In rotor design）

(b) Measurement

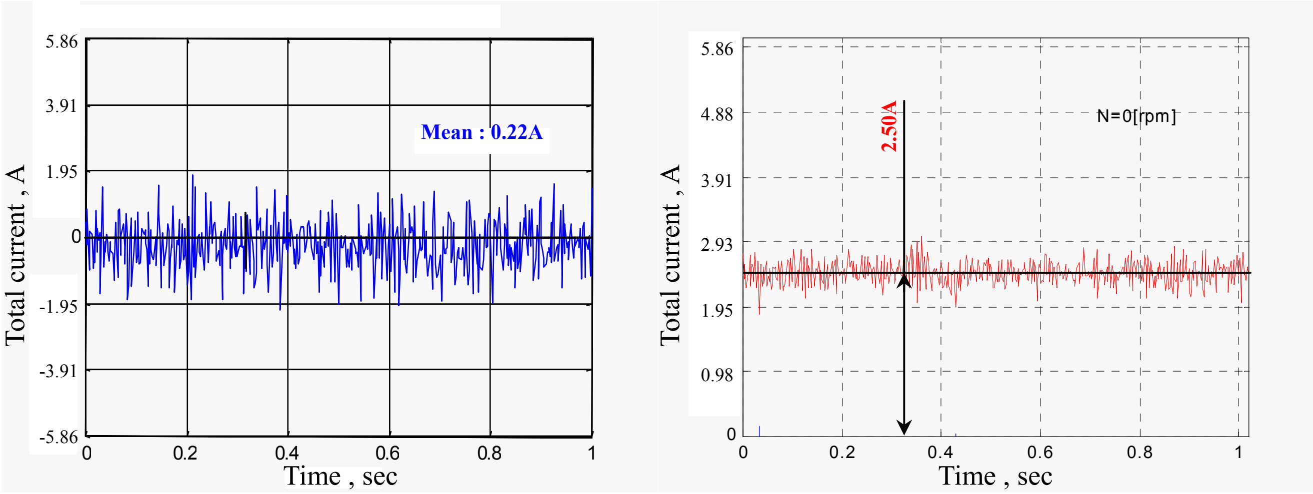
Fig. 5 : Campbell map of rigid mode

1rb：1st rigid backward mode
1rf：1st rigid forward mode
2rb：2nd rigid backward mode
2rf：2nd rigid forward mode

We devised new design techniques to avoid this resonance problem. One of these techniques is to lower the forward natural frequency of the 2nd rigid mode without changing Ip/Ir = 1.3.

2.3.3 PM biased Axial AMB

A stable levitation of the ComFESS rotor was achieved successfully. The measured results of total current are shown in Fig. 6. The mean value of total current supplied to the PM biased AxAMB was about 0.22A. This result means that the reduction of the power consumption of AxAMB by using PM biased AxAMB is sufficient. (In the case of conventional AxAMB, the total current was about 2.50A.)



(a) PM biased AxAMB

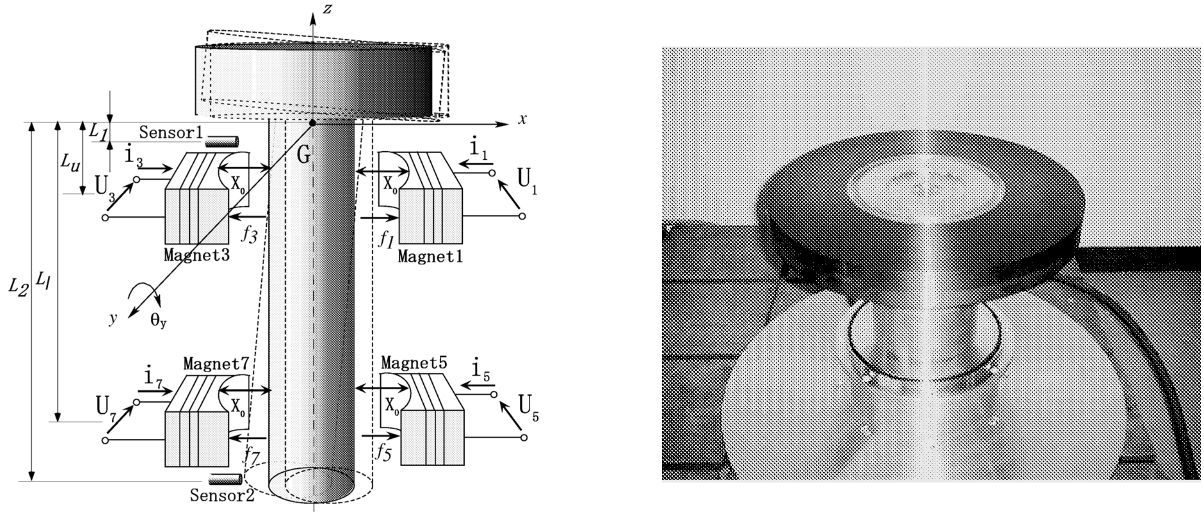
(b) conventional AxAMB

Fig. 6 : Measured results of PM biased AxAMB

2.3.4. Zero power control

2.3.4.1 Test System

The vertically designed five axis controlled active magnetic bearing system shown in Fig.7 is used for modeling, simulations and experiments. The AMB system consists of a CFRP flywheel-AMB, a control unit and a high-frequency inverter. The parameters of the AMB system are given in Table 4.



(a)Model of System

(b)Picture of System

Fig. 7: Flywheel-AMB System (AMX095)

Table 4: Parameters of the rotor-AMB system

Symbol	Value	Unit
M	13.672	kg
I_r	0.173	kgm^2
I_a	0.186	kgm^2
L_u	0.0499	m
L_l	0.1676	m
L_1	0.02535	m
K_u	4.47×10^{-6}	Nm^2/A^2
K_l	4.47×10^{-6}	Nm^2/A^2
X_0, Y_0	0.25×10^{-3}	m

2.3.4.2 Experiments

A feedback control system is built with a digital signal processor(DSP) to realize experiments. The control system is a multi-input multi-output structure with four displacements measured by four eddy-current position sensors and eight computed control current signals for actuators. The control inputs are supplied to electromagnets through D/A converters and power amplifiers.

The trajectories of the geometric center point of the rotor is generally used to evaluate the control performance. The orbits of the rotor obtained at 110 Hz are shown in Fig.8 for lower and upper actuator locations. The control currents in the x direction of the upper and lower electromagnets during the rotational experiment are shown in Figs.9. As showed in figures, only one electromagnet has a current flow at any given time, depending on the rotor displacement.[4] The basic movement was confirmed.

But, by imbalance of the rotor, the control electric current is still big. The control electric current will be lowered by applying unbalance power rejection control (UFRC) in future.

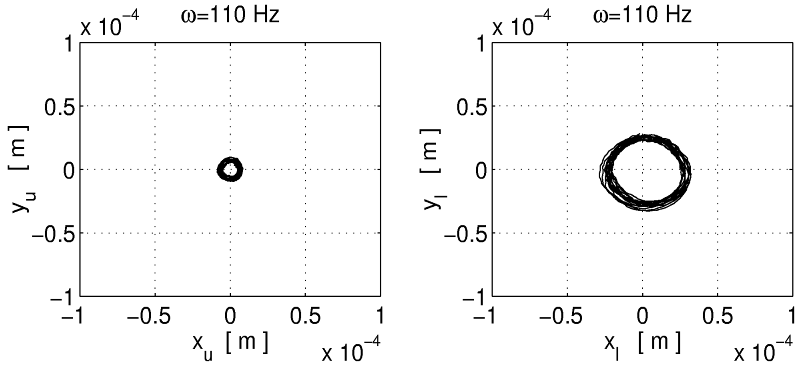


Fig. 8: Orbits of the rotor($\omega = 110$ Hz)

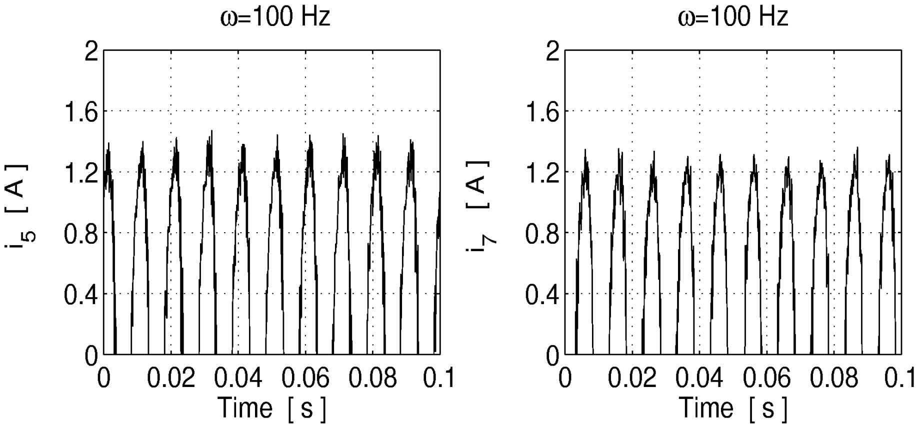


Fig. 9: Control currents($\omega = 110$ Hz)

Table 5: Rotational frequency vs Power consumption

	Rotational frequency (Hz)			
	0	10	20	30
Zero-bias method (W)	64.8	64.4	64.4	70.9
Bias method (W)	112.2	111.7	112.1	112.1
Energy reduction (%)	48 %	47 %	48 %	41 %

The authors have already succeeded in nonlinear control experiments of zero power and zero loss with the normal conducting magnetic bearing alone. In particular, the control technology that reduced 60% of the energy consumption of conventional magnetic bearings can be described as epoch-making and innovative. This success is making a high-efficiency energy storage flywheel system more feasible. This technology has already been verified to be applicable to a system of strong gyro effect and an elastic rotor. Ultrahigh-speed rotations are expected to further improve the performance and realize perfect zero-power control.

2.4. Achievement possibility of 300W *3 hour system

Three achievements are necessary to establish this system. Total loss of the system, a rotor design for high-speed rotation, and the application of zero power control to ComFESS. They are described in the following.

2.4.1. The total loss of the system

The calculated rotational decay that reflects the basic element tests of this study, is shown in figure 10. Results that reflect effect of hysteresis motor on conventional technology (+) is shown in ▲. Effect of adding a PM bias AMB is shown in ■. Zero bias control is shown in ◆, and target (×) achieved by applying zero power control including unbalanced control is shown in □.

2.4.2. Rotor design for high-speed rotation

We established a suitable technique of rotor design in order to go beyond the rigid body mode natural frequency at low rotational speed. It is possible to reach high speed by designing the rotor with this technique.

2.4.3. Application of zero power control to ComFESS

The unbalance force reduction control (UFRC) is necessary in order to get a high speed rotation of flywheel in ComFESS. Unbalanced force reduction control that can work in all rotational region is necessary to apply zero power control to ComFESS. Furthermore, reduction of power consumption will become possible.

Therefore, ComFESS will be established according to prior results.

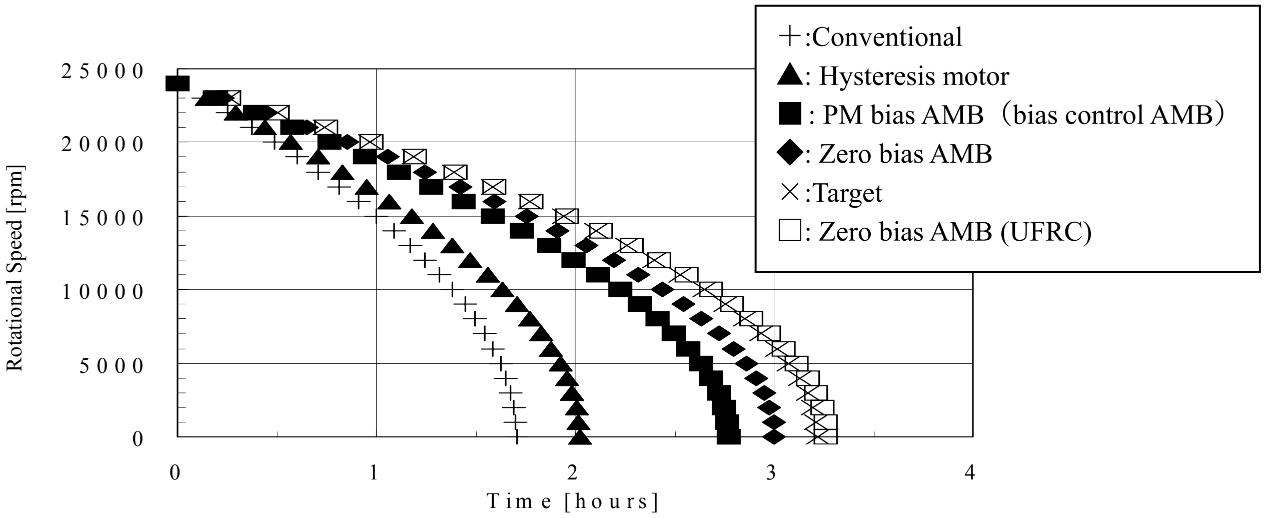


Fig. 10: Rotational Decay of the Rotor

3. Conclusion

A rotational test of the system shows that the following technological goals have been achieved.

1) Establishment of a low loss hysteresis motor by suitable drive technique

2) Establishment of a suitable design technique of the rotor (the method of relation of Ip/Ir and natural frequency of the rotor)

3) Reduction of power consumption of active magnetic bearing by using attractive force of a permanent magnet to compensate for the rotor weight

4) Reduction of power consumption of active magnetic bearing by developing a zero power non-linear control

On the other hand, we was able to clarify the following problem and improvement methods toward practical use.

1)The unbalanced control is necessary to apply zero power non-linear control to ComFESS. Furthermore, reduction of power consumption will become possible.

2)The rotor of ComFESS suspended by AMB with bias current control, was rotated up to 9,000rpm to clarify relation of Ip/Ir and natural frequency. We will achieve the target speed if we design the rotor again by using the design method provided newly in this research.

In this research and development of the ComFESS, we were able to clarify feasability of the that project.

4. Prospects

A commercialization will become possible if a development with practical aspects is undertaken. There is also development needs of other systems. For example, a power supply backup system for several hundred kW during 1 minute. We will go into these element technology in depth and we will apply them to systems with large output power during short time.

Acknowledgement

We acknowledge the generous support of NEDO, which is indispensable for conducting this international joint project. We would like to thank Prof. Schlosser from the Technical University Eindhoven (Netherlands) and Mr.Nishimoto (president of NTRK CO., LTD.) for their support.

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[4]S. Sivrioglu, K. Nonami, R.Takahata and A.Kubo "Adaptive Output Backstepping Control of a Flywheel Zero-Power AMB System with Parameter Uncertainty", Proceeding of 42nd IEEE Conference on Decision and Control(CDC), pp.3942-3947, Hawaii-USA, 2003.

The list of the most important papers and presentations from the project

Papers

[1]H. Kameno, A. Kubo and R. Takahata, “Basic Design of 1kWh Class Compact Flywheel Energy Storage System”, Koyo Engineering Journal No.163, March 2003

[2] S. Sivrioglu, K. Nonami, R. Takahata, A. Kubo, “Low Energy Consumption Nonlinear Control For an Active Magnetic Bearing”, IEEE/ASME Transactions on Mechatronics,

[3] S. Sivrioglu, K. Nonami, R. Takahata, A. Kubo, “Low Energy Consumption Nonlinear Control for an Active Magnetic Bearing”, Journal of Vibration and Control

[4] K. Nonami, S. Sivrioglu, R. Takahata, A. Kubo, “Adaptive Output Backstepping Control of a Flywheel Zero-Bias AMB System with Parameter Uncertainty”, IEEE Control System Technology

[5] M. Hirata, T. Nakamura, K. Nonami, R. Takahata, A. Kubo, “Zero Bias H-Infinity Control of Active Magnetic Bearings For Energy Storage Flywheel Systems”, Transaction Japan Society of Mechanical Engineers

Presentations

[1]H. Kameno, A. Kubo and R. Takahata, “Basic Design of 1kWh Class Flywheel Energy Storage System” , The 8th International Symposium on Magnetic Bearings, Mito, 2002.8.28

[2]A. Kubo and R. Takahata, “Dynamic Analysis and Levitation Test in 1kWh Class Flywheel Energy Storage System”, The 7th International Symposium on Magnetic Suspension Technology, Fukuoka, 2003,10,29

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[9]K. Nonami, “Flywheel Zero-Power AMB System Using Adaptive Unbalance Signal Cancellation Algorithm”, The 7th International Symposium on Magnetic Suspension Technology, Fukuoka, 2003.10.28

Award

[1] Paper Award of The Japan Society of Applied Electromagnetics and Mechanics, “Zero Power Control of 10MWh Class Energy Storagy Flywheel System”, March 25, 2003