Paper

A trial manufacturing of 1kWh flywheel with high temperature superconducting magnetic bearing for energy storage system

Member	Masaharu Minami	(Mitsubishi Heavy Industries)
Member	Shigeo Nagaya	(Chubu Electric Power Co.)
Non-member	Hiroshi Kawashima	(Mitsubishi Heavy Industries)

As the high temperature superconducting magnetic bearing has the characteristics of low loss, research and developments of the flywheel with this bearing have been executed for energy storage system. This bearing has been planned to be used for the thrust bearing of CFRP flywheel, having the characteristics of high mechanical strength and a low specific weight. The verification tests have been performed of the maximum energy storage of 1.4kWh at 20,000rpm.

Keywords : high temperature superconducting, magnetic bearing, CFRP flywheel, energy storage system

1. Introduction

The flywheel system stores the energy as a form of kinetic energy and it is expected to be used for load leveling between at daytime and night, or peak power correspondence.

In case of the flywheel with mechanical bearing, it has not been developed into a practical application such as the above use due to the larger loss. Recently depending upon the development of such new materials as high temperature superconductor and CFRP, and also improvements in power conversion technologies, the feasibility of high efficient flywheel system is expected [1][2] .

In this paper the results of a trial manufacturing and the rotating test of 1kWh flywheel combined with high temperature superconducting magnetic bearing and CFRP flywheel are presented.

2. Energy Storage System with High Temperature Superconducting Magnetic Bearing and CFRP Flywheel

A high temperature superconducting magnetic bearing is based on the principle that magnetic repulsion force can be caused when the magnetic flux produced by a permanent magnet is pinned up in a superconductor. This bearing has the characteristics of very low loss, and can be used without any power supply and any complicated position control system required for the conventional magnetic bearings [3][4].

Energy "E" to be stored in a flywheel is defined by the formula (1).

$$E = K_s \cdot \sigma_\theta \cdot V \quad \cdots (1)$$

where "K_s" is shape coefficent for a flywheel, "σ_θ" is maximum circumferential stress produced in a flywheel and "V" is volume of a flywheel.

Flywheel weight "W" is calculated by the formula (2).

$$W = \gamma \cdot V \quad \cdots (2)$$

where "γ" is specific gravity weight of a flywheel material. It is better to take a larger value for "E" as possible in view of securing a quantity of stored energy, but a smaller value for "W" as possible in order to reduce bearing load and rotating loss. The above formulas (1) and (2) show that a material with a large specific strength σ_B/γ is preferable for a flywheel material. σ_B is the circumferential tensile strength of the material. Table 1 shows mechanical properties of candidate materials for a flyweel, and it has been clarified that the specific strength for CFRP is larger than that for other materials.

Table 1. Mechanical property of flywheel materials

	specific gravity weight γ (gf/cm^3)	tensile strength σ_B (kgf/mm^2)
Ti Alloy	4.5	100
GFRP	2.0	145
CFRP	1.6	310

3. Structure of 1kWh Superconducting Flywheel and Characteristics of the Elements

The schematic drawing of 1kWh superconducting flywheel is shown in Fig.1. CFRP produced by winding the carbon filament in the circumferential direction with epoxy resin is employed because of its larger specific strength. Multi ring construction composed of 3 layers shown in Fig.1 is used for the purpose of decreasing the radial stress [5]. The elasticity in the outer layer is larger than that in the middle layer and the elasticity in the middle layer is larger than that in the inner layer.

With regard to the connection between the flywheel and the rotating shaft, a partially spherical surface supporting disc is adopted so that the supporting disk can sufficiently follow the internal displacement during the operation.

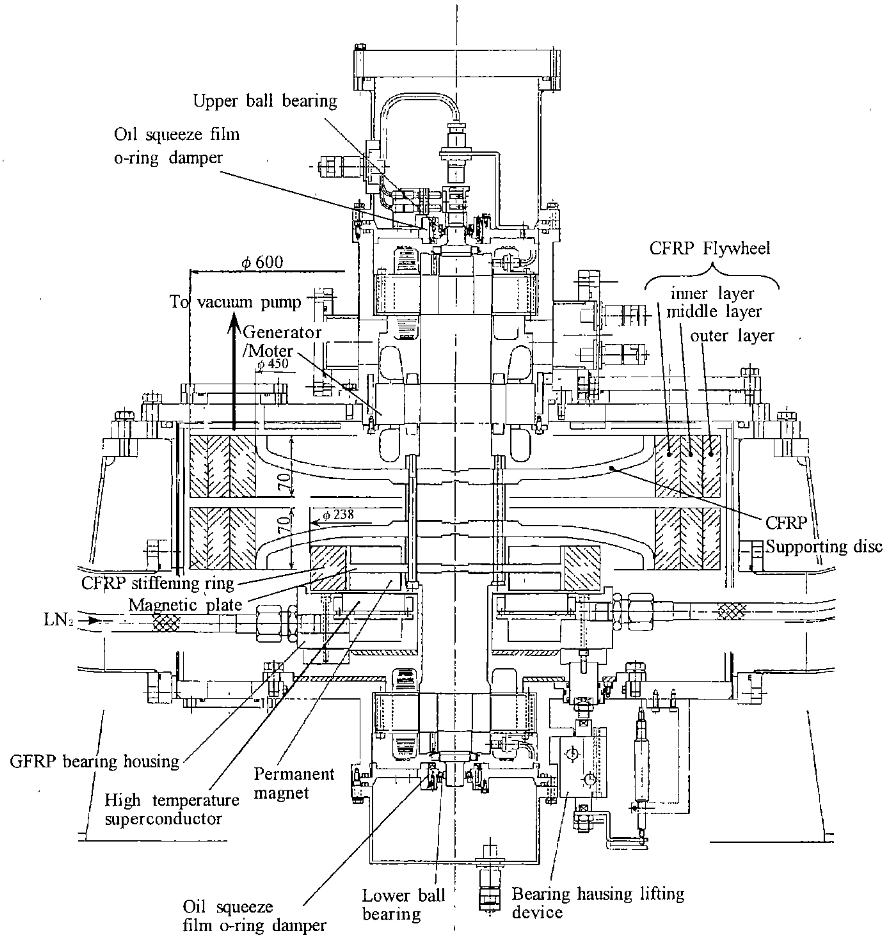


Fig.1. Schematic drawing of 1kWh superconducting flywheel

It is designed that the adhesive structure is used between the flywheel and the supporting disc, and the compressive stress acts on it for the whole speed range to ensure a safe operation because of disadvantage to the tensile stress. The rotor is rigidly connected to the supporting disk. Two flywheels of outer diameter of 600mm, inner diameter of 450mm and the hight of 70mm are used. The inner diameter is determined on the points of decreasing the radial stress and considering the following characteristics of the supporting disk.

If the inner diameter is too large, the peripheral speed and the internal displacement of the flywheel become large, and the supporting disk can not follow it, though the radial stress in the flywheel ring is small.

The peripheral speed of the outer diameter at 20,000rpm in this design is 628m/sec.

Prior to the final assembly with the flywheel rotor, a spin test on a single flywheel is performed to measure the stress and deformation and compare the results with the analytical values. The spin testing facility is shown in Fig.2.

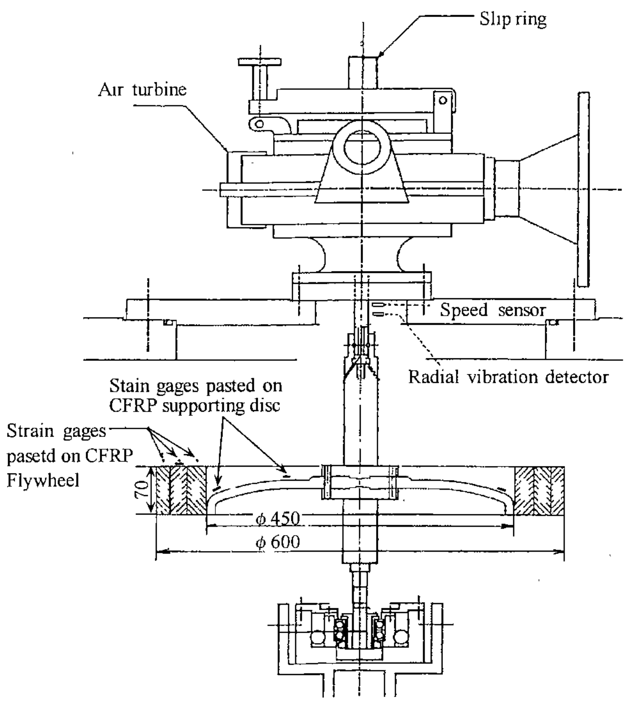


Fig.2. Spin testing facility

The test rotor is hanged and rotated by the air driven turbine. The spin test is performed in vacuum for the purpose of decreasing the windage loss.

The instruments for this facility are a speed sensor, a radial vibration detector and strain gages for investigating the hoop and radial stresses of the flywheel ring and the radial stresses of the supporting disk. The outputs of strain gages are taken out through the slip ring.

The spin tests at the rotating speed of 22,000rpm have been performed, and it has been confirmed that the test rotor was able to rotate having the margin of the speed of 1.35 times to designed rotating speed of 20,000rpm. The measured stresses of CFRP flywheel ring and supporting disk reasonably coincided with the results of analysis shown in Fig.3 [6][7].

As radial stress of inner position of supporting disk is the compression and that of outer posion is the tension shown in Fig.3[3], it is considered that the supporting disk presses the flywheel ring deforming spherically.

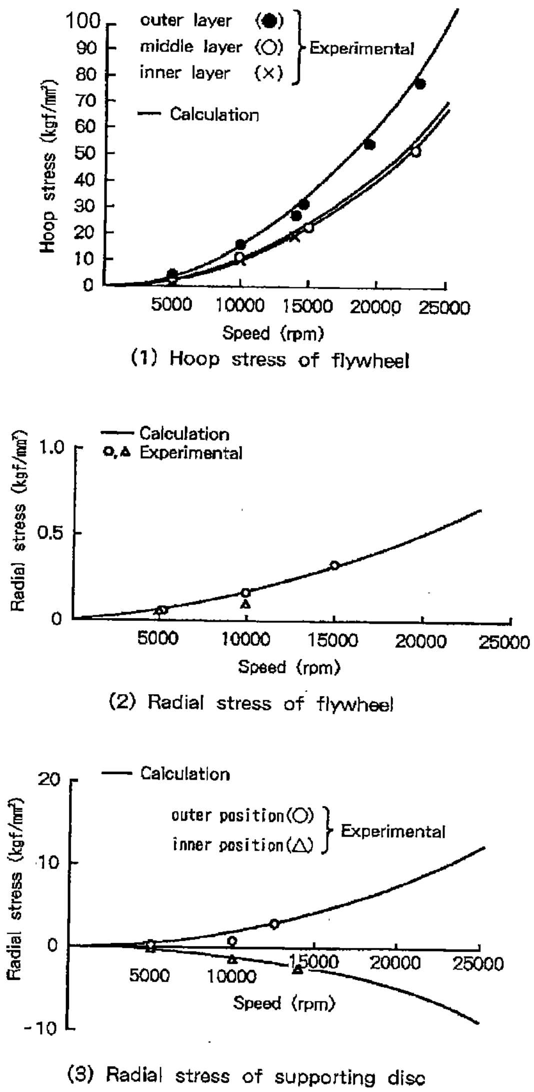


Fig.3. Spin test results for CFRP rotor

A vertical structure with a superconducting magnetic thrust bearing supporting the rotor weight of 76kgf is adopted, because it is necessary to decrease the rotating loss. Its bearing load in the surface area of the permanent magnets is $0.2kgf/cm^2$.

The permanent magnet is made of Pr-Fe-B. Its residual magnetic flux density at room temperature is 1.3T. CFRP stiffening ring with the characteristics of a light weight and high strength is adopted in order to reduce the rotating stress on the magnetic plate assembling permanent magnets. A spin test of the magnetic plate assembly was executued and its performance up to 23,000rpm has been confirmed.

High temperature superconductor is made of YBaCuO. Its current density measured in the magnetization method is $2.4\times10^4 A/cm^2$ at 77K, 0.3T.

The bearing housing containing the high temperature superconducting bulks is cooled by liquid nitrogen and lifts the rotor containing the permanent magnets. Fig.4 shows the model of high temperature superconducting magnetic bearing.

The trapezoidal high temperature superconducting bulks are arranged in a circular direction without leaving any space between them. GFRP bearing housing is used to prevent the occurrence of eddy-current losses due to the fluctuation of the magnetic field created by the rotating magnets and reduce the quantity of heat entering from outside. A lifting device is installed at the lower part of the bearing housing and adjusted the relative axial position between the rotor and the stationary parts. If a failure occurs in the superconducting magnetic bearing, the rotor moves downwards and it is supported by upper ball bearing after touching.

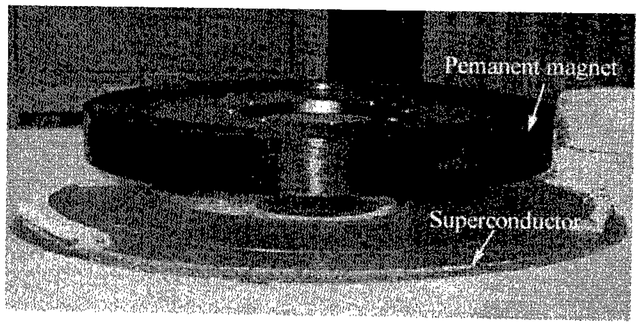


Fig.4. High temperature superconducting magnetic bearing

A floating characteristic of superconducting magnetic thrust bearing in the condition of zero field cooling and field cooling is shown in Fig.5, and it has been confirmed that measured bearing load reasonably coincided with the analytical values [8][9].

For layout of the rotor, two flywheels are placed opposite each other to minimize the shaft span. The induction-type generator/motor is installed on the upper side of the rotor, and the rotating permanent magnet is installed on the lower side shown in Fig.6 and Fig.7. The radial load of the flywheel is generated by the remaining mechanical unbalance and this can be reduced by an accurate assembly and a dynamic balancing. Ball bearings together with oil-squeeze film oring dampers which do not require complicated controls are used as radial bearings.

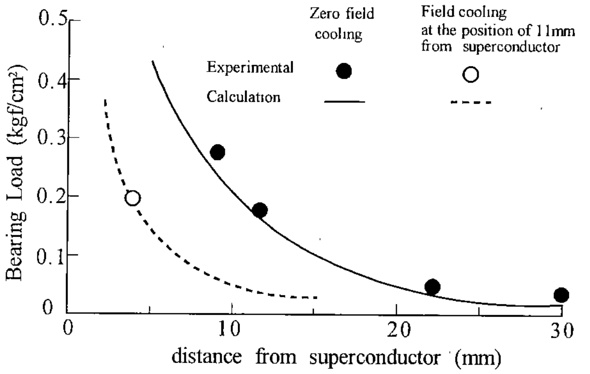


Fig.5. Floating characteristic of superconducting magnetic thrust bearing

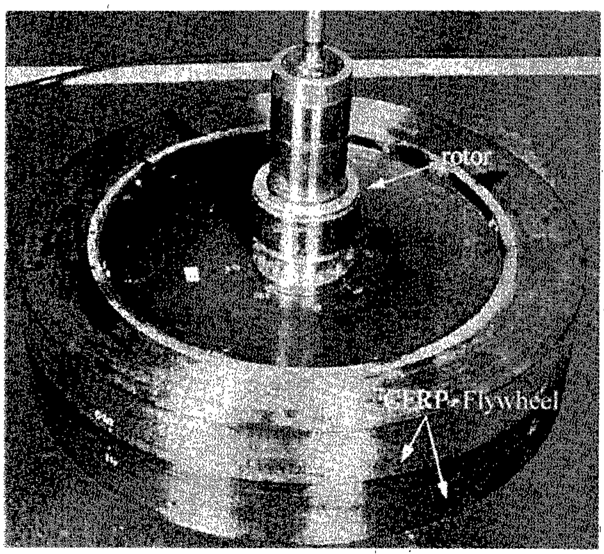


Fig.6 Upper view of the rotor

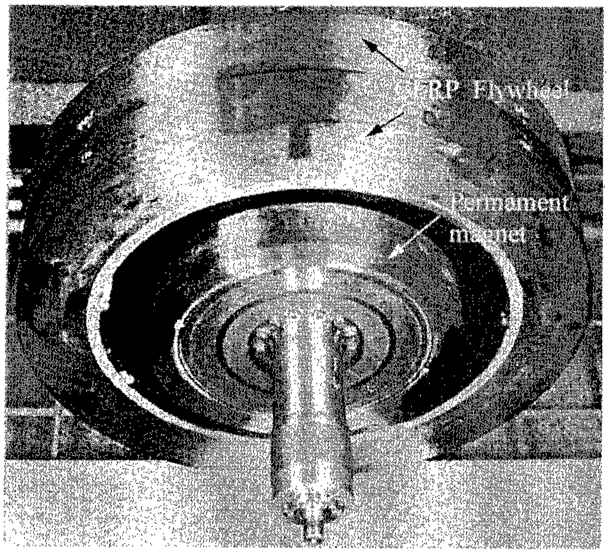


Fig.7 Lower view of the rotor

4. Verification Tests of 1kWh Flywheel

After several cooling down and rotational tests, the running test up to 20,000rpm was performed. It has been confirmed that the rotor rotated stably at 20,000 rpm without excessive radial vibration, noncontacting to the upper ball bearing. The high temperature superconducting magnetic bearing was cooled on the field cooling condition at the position of 11mm from superconductor, and the thrust bearing gap was set at the position of 2mm. At this time the distance from superconductor was 4mm shown in Fig.5 as the tkickness of GFRP bearing housing was 2mm. This gap was constant during the above running test. And the temperatures of outer GFRP bearing housing and ball bearing housing were constant at 173K and 353K during the above running test. And also the function of the touch bearing of the upper ball bearing was confirmed.

The rotating loss was measured at 10,000 rpm with the free run method. The measured loss was 120W, where the ball bearing loss was 104W and windage loss was 15W as calculated values. It is considered that the high temperature superconducting magnetic bearing loss is about 1W.

The view of verification tests of 1kWh superconducting flywheel is shown in Fig.8.

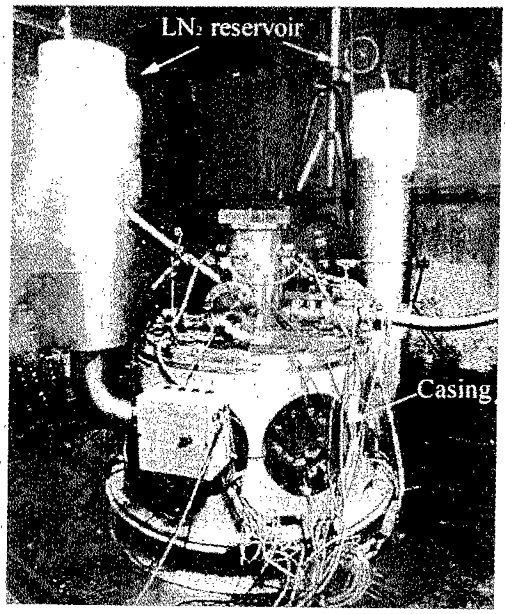


Fig.8 A view of 1kWh superconducting flywheel

5. Conclusion

(1) The new type 1kWh CFRP flywheel with the high temperature superconducting magnetic bearing was trail manufactured using the test results of key components.

(2) It was verified that its rotor floated on the position of 2mm apart from the thrust bearing.

(3) It was confirmed that the rotor rotated stably at 20,000rpm without excessive radial vibration, noncontacting to the upper

ball bearing. And the function of the touch bearing of the upper ball bearing was confirmed.

(4) The operation test by accelerating/decelerating the motor/generator was performed and the maximum energy storage of 1.4kWh at a speed of 20,000rpm was attained..

(5) On the basis of above results the research about the loss of this bearing and the development of 10-100kWh class flywheel with the high temperature superconducting magnetic bearing are planned.

(Manuscript received December 6, 1999, revised March 15, 2000)

References

(1) H.Higasa, N.Kawauchi, S.Nakamura and N.Ito, Technical problems of superconducting magnetic bearing and construction of flywheel power storage system, Proc. of ISS' 93, 1231 (1993)

(2) S.Nagaya, N.Hirano, M.Minami, and H.Kawashima, The study of the high-Tc superconducting flywheel for the energy storage system, Proc.of IWS 95, 158 (1995)

(3) M.Murakami, T.Oyama, H.Fujimoto, T.Taguchi, S.Gotoh, Y.Shiohara, Large levitation force due to flux pinning in YBaCuO superconductors fablicated by Melt-Powder-Melt Growth Process, J.J.Appl. Phys., Vol.29, 11, 1991 (1990)

(4) Edited by the Magnetic Levitation Technical Committee of the Institute of Electrical Engineers of Japan, Magnetic Suspension Technology, Magnetic Levitation Systems and Magnetic Bearings, Published by Corona Publishing Co, 66 (1993)

(5) Y.Tsutsui, S.Shimamura, A proposal of optimum design for FRP flywheel, J. of JSME, A, 49-443, 812 (1983)

(6) H.Kawashima, S.Nagaya, M.Minami, K.Sasaki, and K.Asano, Study on 1kWh CFRP flywheel for high temperature superconducting magnetic bearing for energy storage system, Proc. of ISS '96 1353 (1996)

(7) M.Minami, S.Nagaya, H.Kawashima, T.Sato, and T.Kurimura, Development on CFRP rotor for 1kWh superconducting flywheel system, Proc. of ISS' 97, 1305 (1997)

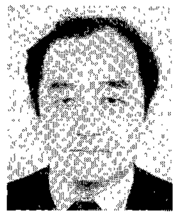
(8) M.Minami, S.Nagaya, H.Kawashima, and K.Yamashita, Study on high temperature superconducting magnetic beatings of 1kWh flywheel for energy storage system, Proc. of ISS' 96, 1357 (1996)

(9) Y.Sasano, K.Miya, S.Nagaya, M.Minami and H.Kawashima, Evaluation of magnetic force characteristics in high-Tc superconducting flywheel, Proc. of ISS' 97, 1309 (1997)

Masaharu Minami

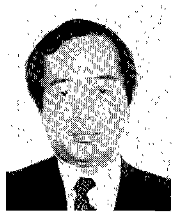
(Member) graduated a master course of mechanical engineering in Kyushu University in 1972 and is presently assistant chief engineer of applied physics laboratory in Takasago R&D center of Mitsubishi Heavy Industries. He has worked on research and development of superconducting magnets and so on.
Japan Society of Mechanical Engineers and Applied Electromagnetics and Mechanics member.

Shigeo Nagaya



(Member) graduated a bachelor course of chemical engineering in Nagoya University in 1981 and is presently chief engineer of superconducting group in Electric Power R&D center of Chube Electric Power Co. He has worked on research and development of superconducting materials, cables and so on.
Japan Society of Applied Physics and Japan Society of Metals and Technology member.

Hiroshi Kawashima



(Non-member) graduated a master course of mechanical engineer in Kyushu University in 1976 and is presently assistant chief engineer of new product development section in Takasago Machinery Works of Mitsubishi Heavy Industries. He has worked on research and development of power electronics and so on.
Japan Society of Mechanical Engineers member.