Development of Flywheel Energy Storage System with Hybrid AMB-SMB

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Abstract: Structure of flywheel rotor for 1 kWh class energy storage system are discussed. The flywheel will be made of CFRP material which is light weight and has high tensile strength. The rotor weighing about 50kg will be supported by superconducting magnetic bearing in axial direction and will accelerate up to 40,000rpm with active magnetic bearings assistance in radial direction. By means of natural frequency and stability analysis, a structure of rotor that mounted two flywheel disks at both ends of main shaft is proposed. At first step, a manufacturing prototype of 0.2kWh class energy storage was carried out.

1 Introduction

High-Tc superconductor $YBa_2Cu_3O_{7-X}$ (YBCO) with strong pinning force [1, 2] has allowed the realization of stable magnetic suspension with no control. Recently high temperature superconducting magnetic bearings (SMB) [3, 4] has been researched for friction less bearings. The SMB could be expected as the practical bearing for flywheel type energy storage system. Two of authors manufactured a prototype of 100Wh class flywheel energy storage system [5] and a utility of the SMB has been discussed. To increase the capacity of energy storage, it is necessary to achieve much higher speed with higher inertia of flywheel. In this paper, we present one of basic design of 1 kWh class energy storage flywheel rotor system. And a manufacturing prototype of 0.2kWh class energy storage was carried out for a first step.

2 Basic designing of flywheel rotor for 1kWh class energy storage using superconductor

2.1 Structure of flywheel rotor

The main flywheel element should be a cylindrical CFRP with 400mm in outer diameter, 76mm in thickness and 1.6g/cm^3 in density. The peripheral speed of the CFRP flywheel is set 838m/s (rated speed : 40,000rpm) in this design. The CFRP element will be assembled into a main shaft via aluminum hub.

A superconducting magnetic bearing consists of high-Tc superconductor YBCO at stator and a permanent magnet at rotor. The magnet having a outer diameter of 220mm, a thickness of 15mm and a density of 7.8g/cm^3 is reinforced by CFRP to avoid centrifugal burst. The superconductor is cooled down by liquid nitrogen at zero field cooling and is planned to have a levitation pressure of 0.5kgf/cm^2. This SMB is able to support the flywheel rotor weighing about 50 kg in axial direction.

The main shaft is assembled with a sensor target, a motor rotor and two parts of iron core which is used for active magnetic bearings (AMB) that control instability motion of the rotor in radial direction. The motor element is a induction type motor which can accelerate up to planed speed and regenerates rotational energy. The sensor target is used for axial displacement sensor and rotation speed sensor.

2.2 Analysed results and discussions

The rotor dynamics highly depends upon the installed position of the flywheel with its gyroscopic effect. Three types of flywheel rotor system as shown in figure 1 (1a),(2a),(3a) are simulated. The ratio of Ip/Ir (Ip : polar inertia moment, Ir : rotational inertia moment) is decreased in order of (1a),(2a),(3a). Generally speaking, a gyroscopic effect is proportional to the mentioned ratio.

Results of natural frequency analysis for these rotor systems including AMB dynamics are shown in figure 1 (1b),(2b),(3b). As shown in figure 1 (1b),(2b),(3b), 1R,2R show 1st and 2nd natural frequency, which is either rotational motion or translational one corresponding to Rigid mode. 1B,2B show 1st and 2nd Bending mode respectively. Each natural frequency will be splitted into the forward mode and backward one by a gyroscopic moment during acceleration. The rotational frequency is shown by dotted line as rotor speed. The points at which the rotor speed line crossing each natural frequency line are well known critical speed.

As shown in figure 1 (1b), the rotor type 1 passes each resonant frequency of 1R,2R at low speed, then crossing the 1st bending mode backward resonant frequency at 37,000rpm and then reaches the speed rated at 40,000rpm. But nominal rotational speed is locating very close to forward resonant frequency of 1B and back-

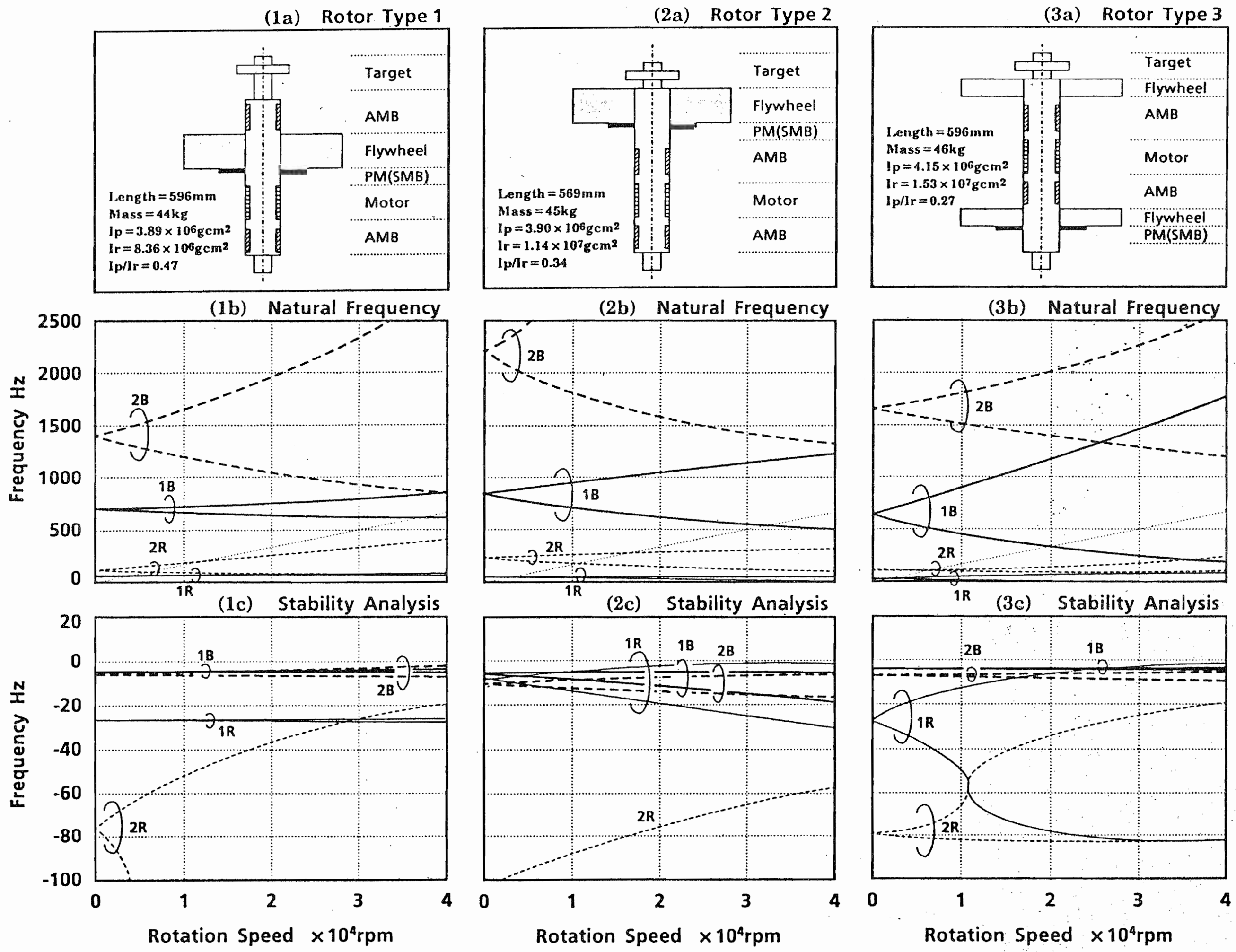

Figure 1: Natural frequency and stability analysis of three type rotors for 1kWh class energy storage flywheel rotor

ward one of 2B so that instability of rotor may occur. In figure 1 (2b), the accelerating line more departs from natural frequency of bending mode at rated speed. As shown in figure 1 (3b), the speed line of rotor type 3 departs from not only backward but also forward bending mode much more at rated speed.

By the way in rotor type 3 the natural frequency of rigid mode has a narrow divergence as a value of Ip/Ir is small. But it is considered significant that natural frequency 1B of the rotor type 3 has a very wide divergence caused by gyroscopic moment. It shows that a gyroscopic effect generated by 1B bending mode is very large in rotor type 3. In other words, the flywheel disks mounted at both ends of main shaft generates more large gyroscopic effect by 1B bending mode with its inclination. In the results the rotor speed line of the rotor type 3 is able to pass the backward natural frequency of 1B, which generally does not cause instability, at low speed and is away from forward and backward 1B bending mode at rated speed.

Analysed results of system stability for these rotor types are also shown in figure 1 (1c),(2c),(3c). Magnetic levitation of each type rotor are stable at 0 rpm, because the real part of eigen value of the system for each mode is negative. In rotor type 1, stability of 2R shown as rotational motion is larger than that of 1R shown as translational motion at 0 rpm but decreased by gyroscopic effect with acceleration and then is smaller over 30,000rpm. In type 2, stability of 1R for translational motion is a little at 0 rpm and decrease as the rotor accelerates. But that of 2R for rotational motion is very large. In type 3, stability of 1R (rotational motion) and 2R (translational motion) are large at 0 rpm and tend to decrease by gyroscopic effect.

Judging from the results of stability analysis, little stability of 1R or 2R natural frequency of rigid mode at rated speed will caused the rotor having vibration of low frequency by each mode. But it will be able to be stabilized by AMB control compensating for gyroscopic effect. By the way, stabilizing bending mode at high rotation speed locating high frequency is very difficult by AMB control due to its band width limitation of whole feed back system component. And then it is considered that a structure of rotor should be designed to minimize the possibility of the un-desired effect caused by bending mode as small as possible. Therefore the rotor system of type 3 could be recommended as the best structure in these types for 1kWh class flywheel energy storage.

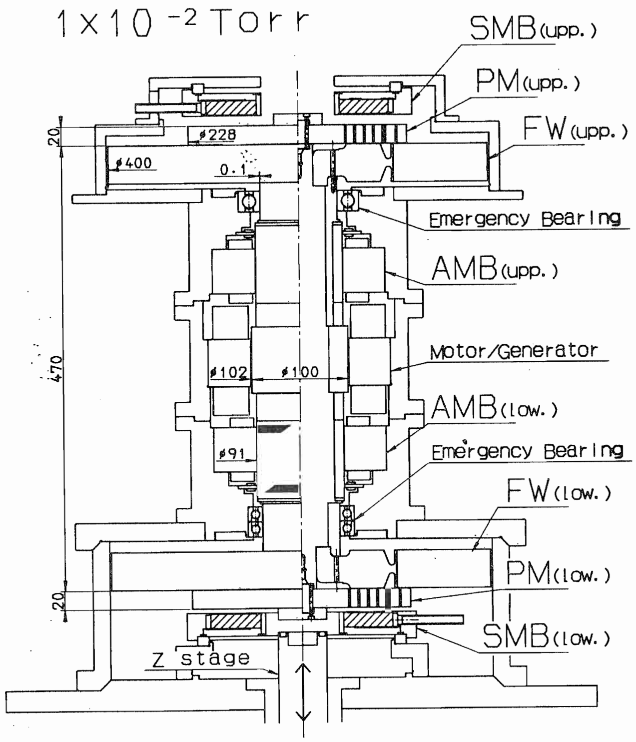

Figure 2: Cross-sectional view of prototype energy storage system (0.2kWh)

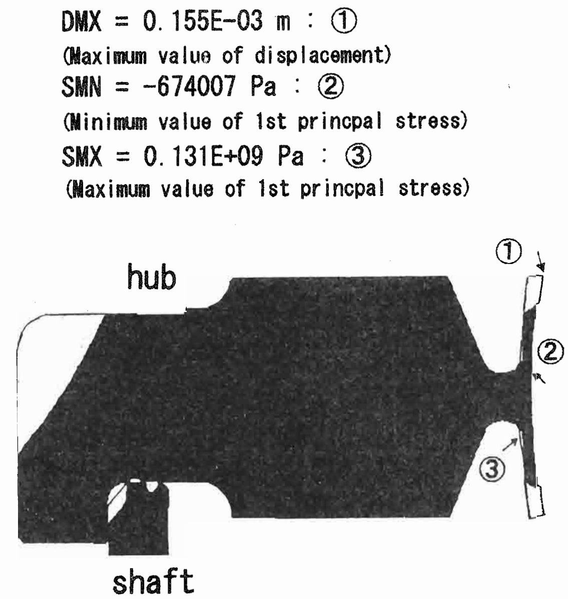

Figure 3: Stress calculation of the hub for flywheel (0.2kWh ; 20,000rpm)

3 Trial manufacture of system

It is necessary to develop construction of the flywheel and the permanent magnet in order to active a high speed 40,000rpm for energy storage system. At first step, a manufacturing prototype of 0.2kWh class energy storage was carried out.

3.1 Construction of system

A cross-section view of the flywheel system is shown in figure 2. The shaft is shurinked by one motor rotor and two rotor armatures for active magnetic bearing(AMB). And one flywheel disk(FW) and one permanent magnet(PM) are mounted at both ends of main shaft. The whole rotor system after detail design is weighing 47kg. This rotor is suspended by a repulsive force of lower SMB and an attractive force of upper SMB in axial direction. A vibration of rotor is controlled by AMBs in radial direction. Emergency bearings are also provided to protect stator members in case of emergency. An air gap between outer diameter of shaft and inner diameter of the emergency bearing is 0.1mm in radial direction. It is necessary to positioning the rotor shaft at cooling YBCO in order to operation SMBs. Then the rotor shaft is positioned by Z stage in axial direction and by AMBs in radial direction. This system is immersed in a vacuum chamber and liquid nitrogen is supplied to cryostat from an external liquid gas dewar. A controller for active magnetic bearing and inverter/converter for electric power are belong to the system.

3.2 Flywheel

The flywheel disk consists of an aluminum hub (outer diameter 200mm, inner diameter 30mm) and a CFRP ring(outer diameter 400mm, inner diameter 200mm, thickness 40mm). The hub has two slits in axial direction. Therefore an outer surface of hub is able to catch up with an inner one of CFRP ring. By the way, the hub is mounted on the rotor shaft. An inner surface of shaft at 60mm diameter is also able to do an outer one of the hub. The stress calculation due to centrifugal load for hub could be done with one part of shaft. Its result at 20,000rpm are shown in figure 3. In case of being shurinked by CFRP ring, a maximum main stress of hub is less. This design gives good results for 36,000rpm.

3.3 Permanent magnet

Cross-section of the permanent magnet is shown in figure 2. Four layer ring magnets magnetized in radial direction are each located between ring steels. The surface field of it had magnetic induction of 0.8T or more at maximum. An aluminum hub for mounting shaft and four layer ring magnets are hooped by two layer CFRP ring in order to prevent centrifugal burst. Then they had maximum compression stress. Therefore limit speed of this magnet is speed its stress becomes zero. The highest velocity in this design is 188m/s (20,000rpm).

3.4 Superconducting magnetic bearing

The superconducting magnetic bearing is a superconducting members mounted inside a flow liquid nitrogen cryostat. The superconducting members was assembled

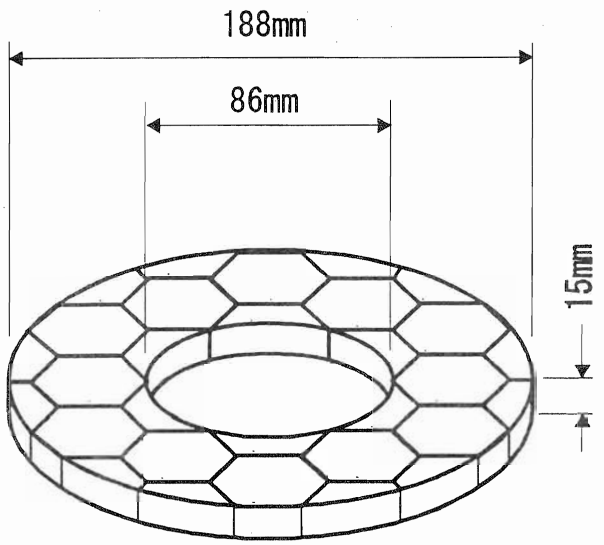

Figure 4: Superconducting magnetic bearing

by twenty one pieces of the quench and melt growth method [1] bulk YBCO (45 outer diameter, 16mm thickness) and covered by plastic film preventing from deterioration. The construction is shown in figure 4.
The cryostat was made from stainless steel and the lid of it is 1mm thickness. In this system, the rotor was supported by an attractive force at upper bearing and a repulsive force at lower one in axial direction. But the rotor was levitated by only lower bearing in this test.

3.5 Active magnetic bearing and motor

The system is suspended by two radial current-controlled active magnetic bearings(AMBs). It uses a PID controller by output signal of displacement sensor of inductance type. Data of AMBs is shown in Table 1. The rotor, which is controlled by a frequency converter, will be drived by a 2kW highfrequency induction motor/generator built in the middle of the rotor.

Table 1 : Data of active magnetic bearing

maximum voltage	120V
maximum current	1.5A
nominal air gap	0.4mm
diameter of bearing	91mm
rotor armature	silicon steel (0.1mm thickness)

3.6 Operation of flywheel system with hybrid AMB-SMB

A operation procedure of this flywheel system with hybrid AMB-SMB is as follows :
(1) Positioning of rotor shaft by Z stage in axial direction
Positioning of rotor shaft by AMB in radial direction
(2) Zero field cooling of lower SMB
and field cooling of upper SMB
(3) Releasing from axial positioning by Z stage
(4) Driving flywheel rotor by induction motor
(5) Converting energy to electric power

Then rotational property up to 20,000rpm of rotor supported by AMB-SMB at rated speed will be measured in near future.

4 Conclusions

Three different types of rotor structure for 1kWh class flywheel energy storage system were discussed. The new structure of rotor having two flywheel disks at both ends of main shaft is proposed. The rotor weighing about 50kg will be supported by superconducting magnetic bearing in axial direction and could be accelerate up to 40,000rpm with active magnetic bearings assistance in radial direction without inducing any instability during operation. At first step, a manufacturing prototype of 0.2kWh class energy storage was carried out. Then rotational property up to 20,000rpm of rotor supported by AMB-SMB at rated speed will be measured in near future.

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