A Horizontal Axle Type Flywheel Energy Storage System Using High T_c Superconductor Bearings

Tae-Hyun Sung[a], Joon-Sung Lee[a], Sang-Chul Han[a], Young-Hee Han[a], Sang-Kyu Choi[b], and Sang-Joon Kim[a]

a) Power System Laboratory, Korea Electric Power Research Institute
Korea Electric Power Corporation, 103-16 Munji, Yusung, Taejon, Korea,
b) Rotordynamics Research Group, Structural Systems Department,
Korea Institute of Machinery & Materials, P.O. Box 101, Yusung, Taejon, Korea

Abstract

A new type of flywheel energy storage system that has a horizontal axle with high T_c superconductor bearings was proposed. The magnetic field intensity near the four types of permanent magnet arrangement was calculated along the axial direction for a fixed radial distance from the axis. The result of analyses showed that the rotor that we proposed was the best model for the formation of a high magnetic field. The dynamic properties, stiffness and damping, of the high T_c superconductor radial bearings applied in the flywheel energy storage system were experimentally estimated using the imbalance excitation method. The imbalance excitation method applied to this rotor-bearing system identified the direct stiffness and damping of the high temperature superconductor bearings to be 2.8 ~ 3.3 x 10^5 N/m and 175 ~ 204 N·sec/m respectively.

I. Introduction

Recent developments in new materials and permanent magnetic bearings using high temperature superconductors(HTS) levitation resurrect the interest of researchers in advancing the flywheel technology for energy storage applications[1]. Essentially being a mechanical battery, flywheel energy storage system, many believe, could be one of the most efficient means to solve two critical problems faced by the modern society: the rapid increase in the use of energy and the consequent impact of energy consumption on the environment.

The current technology of superconductor flywheel energy storage system employs the vertically stacked disc type [2-4]. This system has two problems. One is in stability. The other is in scaling up to a larger system. In the vertical type system, the flywheel is levitated over the superconductor plate. So if some force is added to the flywheel, the flywheel will escape easily from the stable state. And it is very hard to scale up for manufacturing the large scale energy storage system. There are two ways to scale up the system. One way is to make large flywheels. But it is very difficult to make huge magnets that can levitate larger flywheels with current technology. Therefore the way that files up many flywheels along the axle could be recommended. When many flywheels are stacked along the axle, the system needs active controllers to keep the rotor stable. Then the excess function in the system should be needed, that makes the efficiency lower.

This work is focused on a new type of flywheel energy storage system, which has a horizontal axle with high Tc superconductor bearings.

II. Magnetic field calculation

Magnetic field distribution near the four types of bearing journal is calculated. Typical magnetization curves of NdBFe magnetic material and soft iron are used for this numerical calculation.

Figure 1(a) to figure 1(d) are the cross sectional structures of magnetic components in the four bearing journal models used in the calculation. Figure 1(a) shows heteropolar serial arrangement of the cylindrical magnets, which is the most basic form of magnetic bearing journal. Figure 1(b) to figure 1(d) are homopolar arrangements of the magnets, each slightly modified. In figure 1(c) and figure 1(d), soft iron shims are put on the magnet pole faces to provide easy magnetic flux paths radially outward, so that the

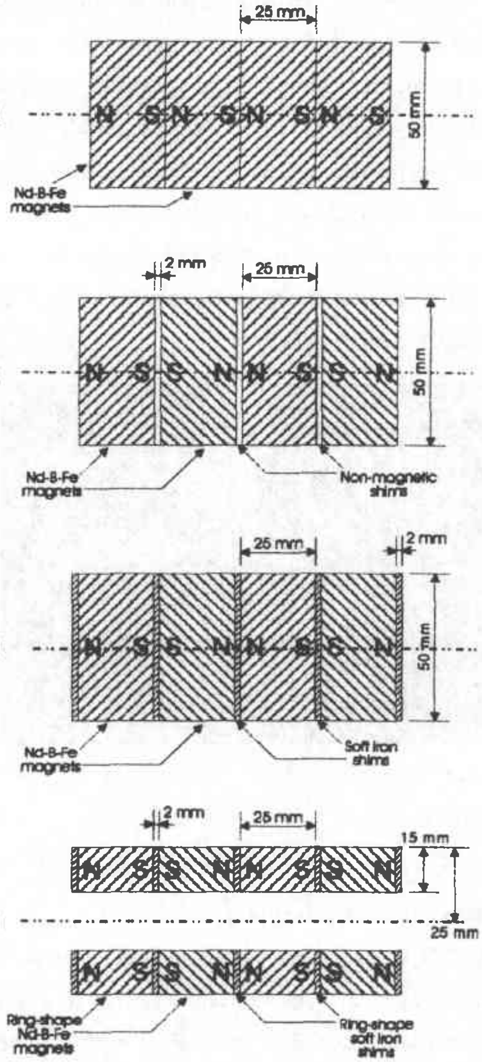

Figure 1. Cross sectional structures of magnetic components in the four bearing journal models used in the finite element analyses.

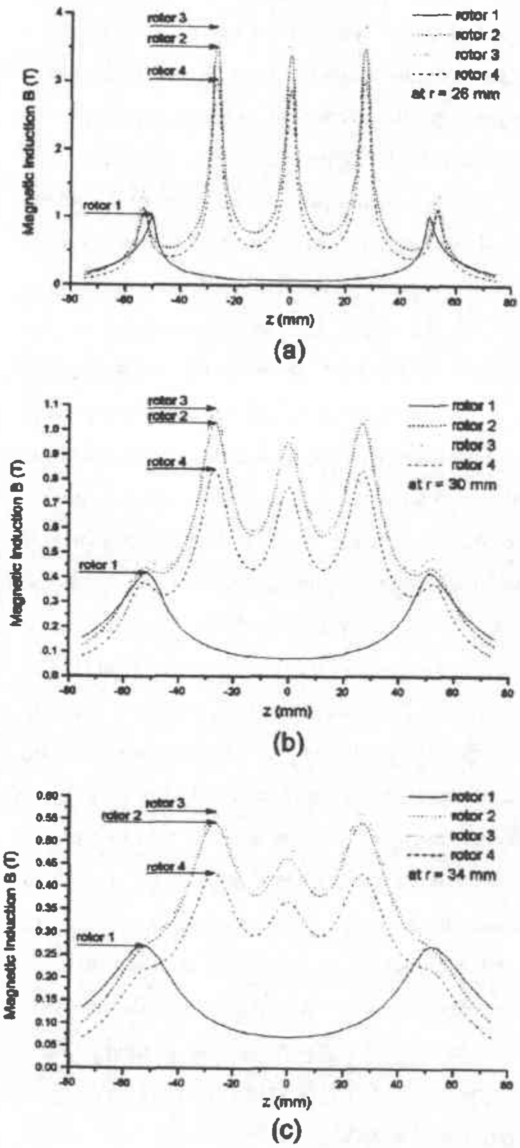

Figure 2. Magnetic field strength distribution outside each of the four rotors (a) at r = 26 mm, (b) at r = 30 mm, and (c) at r = 34 mm.

demagnetization factor can be effectively minimized to strengthen the magnetic field outside the bearing journal. A non-magnetic shaft can be inserted through the ring-shape magnets and the soft iron shims in figure 1(d) to enhance mechanical properties of the journal. Models shown in figure 1(a) ~ figure 1(d) are designated as rotor 1 ~ rotor 4.

Figure 2(a) to figure 2(c) are graphs of magnetic field intensity outside each of the four rotors, obtained by 2D finite element analyses of axisymmetric magnetostatic problems. Four curves in each of the graphs are the magnetic field intensity calculated along the axial direction for a fixed radial distance from the axis. In figure 2(a), peaks of the magnetic field intensity around the rotor 2, the rotor 3, and the rotor 4 are observed between the pole positions of magnets. These values are larger than three times those of the rotor 1. The effectiveness of the homopolar arrangement can be well explained by this result, for the magnetic field variation in the axial direction is directly related to the axial stiffness of the superconductor bearing. In addition, the magnetic field intensity outside the rotor 3 is higher than that calculated outside the rotor 2 and the rotor 4. It is the effect of the lack of ferromagnetic shims in the rotor 2, and the less volume of magnet due to the axial bore in the rotor 4. The change in magnetic field intensity from figure 2(a) to figure 2(c) represents the magnetic field variation in the radial direction. Similarly to the previous statement, this explains the effectiveness of the homopolar arrangement again, for the field variation in the radial direction is directly related to the radial stiffness of the superconductor bearing.

The result of these analyses suggests that the rotor 3 is the best model for a superconductor bearing journal, on the assumption that the journal part has no problem in mechanical aspects.

Ⅲ. Rotordynamic performance of high T_c superconductor bearings

High speed rotating machines including flywheel energy storage systems such as presented herein are potentially subject to vibrations at critical speeds, which are excited mainly by inherent rotor unbalances or other external disturbances. Since the excessive vibration can cause fatigue failure of the rotor and other supporting structures, and in turn cause the system to fail, it is highly recommended the rotor-bearing system be rotor dynamically stable so that the vibrations at critical speeds is not over the certain specified level. In order to design the vibrationless system, the static and dynamic properties of bearings must be known or identified *a priori*, which makes it possible to predict the system critical speeds, avoid severe vibrations near those and determine the system optimum operating point away from them. Thus, for more stable design of the flywheel rotor system, an attempt to characterize dynamic properties of the HTS bearings was made as follows.

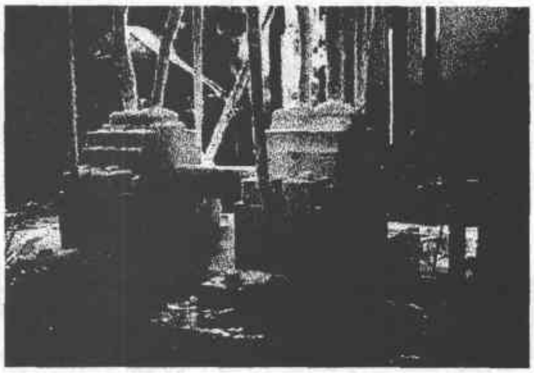

Figure 3. Experimental bearing test rig in operation.

1. Bearing test rig description

The HTS bearing used in the flywheel system of present paper has a rather unique feature in that it generates radial restoring force while most of other superconductor bearings vertical.

Since any theoretical method of estimating rotordynamic properties of superconductor bearings is

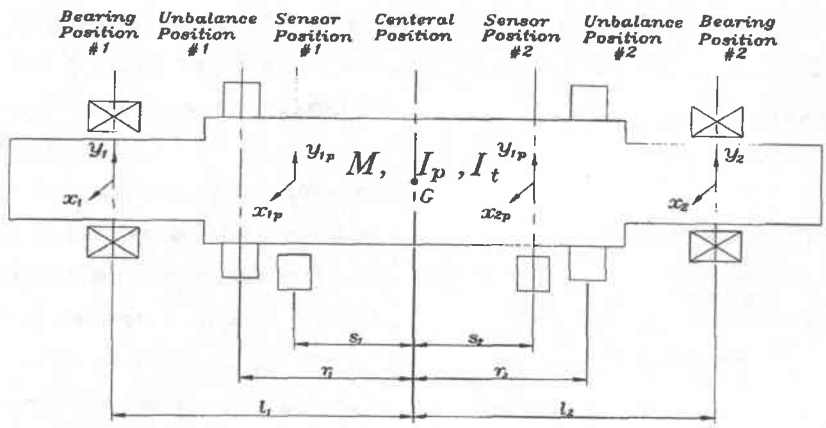

Figure 4. Schematic diagram of the test rig rotor mounted on high T_c superconductor bearings.

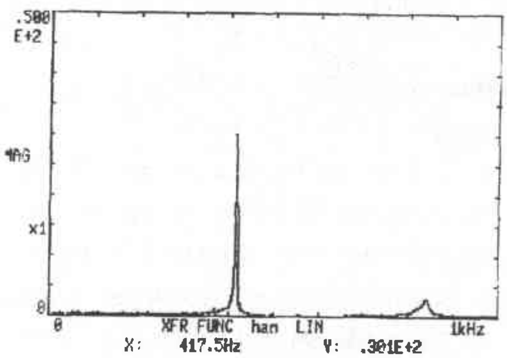

Figure 5. Impact frequency response function of the test rotor.

not known yet to the authors, a bearing test rig driven by an AC servo motor with eddy current type sensors to pick up vibration signals was devised for experimental study of bearing characteristics as shown in figure 3 and 4. The test rig was designed to have the 1st flexible mode located above 20,000 rpm with the rotor mass of 30 kg to ensure the rigid mode operation near bearing test speeds. The 1st flexible mode of the test rotor was experimentally identified by the impact method. Its frequency response function is shown in figure 5.

2. Experimental bearing parameter identification using rotor unbalances

The method of using inherent rotor unbalances (so called imbalance excitation method) has been frequently used in rotordynamics area to identify dynamic characteristics of rotor supports including bearings [5],[6]. This method was developed based on the assumption that, in the absence of any external disturbances, dynamic behavior of rotors are dependent only on the rotor unbalances, and thus, if the applied forces to the system, i.e. the amount of unbalances and the corresponding responses are known, the parameters governing the system motion can be identified. For the detail, please refer to the reference [6].

For this method, basically the following assumptions were made: 1) the rotor system is rigid, 2) the bearings are flexible and linear at the equilibrium state, 3) all forces on the rotor are transmitted through the bearings, 4) the rotor is symmetric about its axis of rotation, 5) all angular displacements are considered to be very small.

To estimate the dynamic properties of the HTS bearings applied in the test rig shown in figure 3 and 4, the above mentioned imbalance excitation method was applied. The test rotor mounted on the HTS bearings as in figure 3 was run up to 10,000 rpm and the unbalance response was obtained as in figure 6.

The imbalance excitation method applied to this rotor-bearing system identified the direct stiffness and

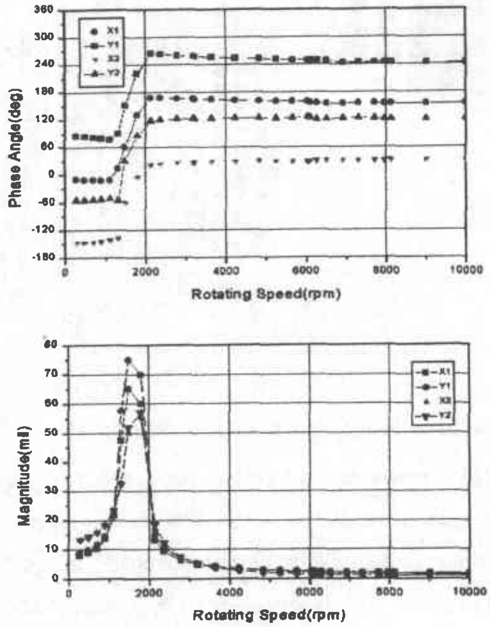

Figure 6. System responses.

damping of the HTS bearings to be 2.8 ~ 3.3 x 10^5 N/m and 175 ~ 204 N·sec/m respectively. The cross-coupled bearing stiffness and damping were found to be almost negligible.

Ⅳ. Conclusion

We proposed a new type of flywheel energy storage system which has a horizontal axle with HTS bearings. The magnetic field intensity near the four types of permanent magnet arrangement was calculated along the axial direction for a fixed radial distance from the axis. The result of analyses showed that the rotor which we proposed was the best model for the formation of a high magnetic field. The dynamic properties, stiffness and damping, of the HTS radial bearings applied in the horizontal axle type flywheel energy storage system was experimentally estimated using the imbalance excitation method. The test reveals that the superconductor bearings have very low stiffness compared to that of typical oil film bearings with similar geometry and almost the same amount of damping as in roller bearings, which may not be helpful for the system to pass through the critical speeds as shown in figure 6. However, it was found out that the cross-coupled stiffness and damping terms were almost negligible so that the system could be more stable than the one using oil film bearings. Also, with proper design of the rotor-bearing system and accurate balancing of flywheels, the HTS bearing is one of the most variable alternatives to the conventional ones due to its oil-free, non-contact running capability in a vacuum environment, which is very critical to the highly efficient flywheel energy storage systems.

References

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