Development of High Speed Flywheel Rotated in a Vacuum Chamber*

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Abstract
For the development of high speed flywheel rotation in a vacuum chamber, technology for establishing ultra low loss magnetic bearings and measures for preventing spillover vibration are necessary. For these purposes, tests on two rigs, one involving active magnetic bearings (AMBs) and the other, a medium-size flywheel, were conducted in the present study. With the former, a technique for reducing AMB loss was investigated. In the latter, many trials were carried out in an attempt to find a means for preventing spillover vibration. Based on the results, two important findings were made. First, AMB loss could be reduced to 1/6 of that in conventional control through the use of zero-power control and homo-polar magnetic poles. Secondly, flywheel rotation as high as 12,000 rpm was possible with no significant vibration through phase lead adjustment and the use of a stabilizing filter. Both these possibilities may be attributed to the very precise measurement of natural frequency and the damping ratio.

Key words: Magnetic Bearing, Vibration of Rotating Body, Critical Speed, Digital Control, Vibration Control

1. Introduction
In order to develop a flywheel that rotates at high speed inside a vacuum chamber, it is necessary to develop an ultra low loss AMB and measures for preventing unstable spillover vibration at high speed. As they interact with each other; many issues often coexist, and even AMBs must have maximum ultra low loss for rotation in a vacuum chamber. Therefore, loss reduction takes precedence. Altering the control method of AMBs in order to reduce loss will necessitate the spillover vibration problem to be resolved starting from the beginning. So, the development of the AMB in ultra low loss shall be described first here. And then the spillover vibration problem, an extremely troublesome problem, shall be described. The design and manufacturing methods of the flywheel itself are also critical issues, although they will not be discussed here because they are not specialties of the authors.

2. Magnetic Bearings with Ultra Low Loss
2.1 Comparison between hetero-polar magnetic poles and homo-polar magnetic poles
It is desirable to use a test rig which is convenient and easy to use in order to reduce...
loss in a magnetic bearing. A test rig called the magnetic bearing test rig was created. Figure 1 shows the cross-sectional view of this rig. In this rig, the thrust load (vertical) is supported by the lower spherical spiral groove bearing (SGB) and four axes are controlled by AMBs in the radial direction (horizontal). The magnetic poles have a structure of laminating 0.35 mm thick magnetic steel sheets in order to suppress eddy current loss during rotation. On the rotor side, 0.1 mm thick magnetic steel sheets (6.5% Si) are laminated.

Similar to a medium-size flywheel which will be described later, this magnetic bearing test rig is the outer rotor type and has a built-in permanent magnetic type motor inside the rotor. The rotation test was conducted inside the vacuum chamber in order to reduce the effect of windage loss.

Two types of magnetic poles as shown in Fig. 2 were installed in this test rig. After increasing the speed of the rotor up to 12,000 rpm, a free-running stop test was carried out, and rotation loss was measured. The control method employed for both types was the conventional PID control. Figure 3 shows the results of measured losses. The figure also shows the losses of the motor and a spherical SGB. The AMB rotation loss with constant bias current of 1.5A is obtained by subtracting the calculated losses of the motor and SGB from the measured rotation loss. The loss of the homo-polar magnetic pole type obtained
this way is approximately 120 W at 12,000 rpm, and approximately 380 W for the hetero-polar magnetic pole type; the homo-polar magnetic pole type has much lower loss of approximately 1/3.

We measured the losses by altering the bias current for these magnetic pole types. Figure 4 shows this result. Both types increased the losses as the bias current increased, but it is apparent that the hetero-polar magnetic pole has a larger ratio of loss increase as the current increases. It is considered that the hetero-polarity in which the magnetic flux changes –N-0-S-0-S-0-N- in the circumferential direction, as seen from the rotating rotor, has a larger change of the static magnetic field due to bias current, when compared with the homo-polar that only changes –N-0-N-0-. Therefore it can be said that homo-polar magnetic poles are suitable to reduce the rotating loss of AMB.

2.2 Loss reduction by zero-power control

Zero power control (1)(2) was created by Nonami and Ariga as a nonlinear control method without using bias current. Even without bias current, loss itself occurs because control current is constantly flowing to maintain the rotor at the center. This control method guarantees stability in regard to the rigid body vibration modes, but it does not guarantee anything in regard to spillover vibration; thus, other measures are required for securing stability of the elastic vibration modes.

Figure 5 shows the losses of hetero-polar magnetic poles by using the zero-power control or by using PID control (bias current 1.5A). This figure also shows a loss using PID control (bias current 1.5A), with homo-polar magnetic poles. The AMB rotating
losses are 120 W for zero-power control and 240 W for PID control at 10,000 rpm; thus, the loss can be reduced to approximately half by using zero power control. By the way, it is difficult to compare zero power-control with PID control directly, because the zero-power control does not utilize bias current. Here, data are compared under the condition that made the first critical speed in rigid body mode equal.

We consider that we have accomplished a reduction in the loss of the PID control with hetero-polarity to approximately 1/6 by changing hetero-polar to homo-polar and furthermore adopting zero-power control. As a result, temperature rise of the rotor had been suppressed even if the flywheel was rotated at high speed in a vacuum chamber.

3. Development of Spillover Vibration Suppression Technology

3.1 Features of the test rig and the vibration characteristic analysis results

This test rig was created to experiment with the vibration characteristics of a superconducting flywheel in which the thrust load is supported by a high temperature superconducting magnetic bearing (SMB) and position control and vibration control in the radial direction are controlled by AMBs. Here, this rig is called the medium-size flywheel, and its cross-sectional view is shown in Fig. 6. It is suspended by a thrust AMB instead of the SMB. The structure is the outer rotor type; it will be almost the same as the superconducting flywheel if the SMB is built into the rotor.

In terms of the superconducting flywheel (3), (4), it has been considered that the levitation force density of SMB would be about 100 kPa at most, even if the performance of high temperature superconducting bulk is improved. Therefore, it is difficult to levitate the flywheel with an axial-type SMB (disk shape). So we decided to use a radial-type SMB (cylinder shape) that utilizes flux pinning force. As a result, the rotor inevitably becomes the outer rotor type, and it was decided to install a motor inside of the rotor. Due to these restrictions, the rotor length was extended and three natural frequencies of elastic mode existed in a range of up to 1 kHz. Since each of the natural frequencies had forward and backward modes, it became necessary to prevent spillover vibration in these six modes. Additionally, the natural frequencies change significantly with rotation because the flywheel is a big rotating body and its gyroscopic effect is large. There conditions were extremely severe, and it became very difficult to prevent spillover vibration.

Figure 7 shows the natural frequencies and their mode shapes calculated for the medium-size flywheel before rotating tests. Among those natural frequencies, the first bending mode in which the rotor completely bends (“E”) has the highest frequency. The remaining two elastic modes (“C” and “D”) deform mainly in the hub which connects the flywheel and the rotor. Also, the rigid modes (“A” and “B”) have the lowest natural frequency.
3.2 Study of the size of magnetic poles and methods of increasing the damping of bending modes

If a magnetic pole is large, the phase lag of the control force of AMB at high frequency range causes spillover vibration due to eddy current loss. The phase lag is identified from the frequency response curve which is measured from a change in coil inductance of AMB. When actually measured, it was found that the phase laggd significantly, and that control in the high frequency range would not work well without improvement. Therefore, we divided a large single magnetic pole into four small magnetic poles. Then their two coils were connected in series, and the two rows created were connected in parallel. As a result, we have improved the characteristics of AMB in the high frequency range. Figure 8 shows the results. It turns out that the phase lag has improved by the small size magnetic pole.

Similar problems exist for the magnetic steel sheets mounted on the rotor. The magnetic flux will not enter inside the magnetic steel sheets if eddy current occurring in this
area is too large. Therefore control force will be decreased and phase lag will occur. And then the control of AMB will not work well in the high frequency range. Caution must be taken about the insulation between magnetic steel sheets because these problems often occur when the insulation is not normal for some reason.

Applying spillover vibration measures to the first bending mode, as shown in Fig. 7 "E"(845rps), is pretty difficult due to high frequency. Thus, it is desirable to make the damping ratio for this mode as large as possible. CFRP rings were installed inside the rotor because the damping ratio can only be increased by giving internal damping of the rotor. Although it was not possible to install them at the locations we wanted, the damping ratio was increased to some degree. Figure 9 shows the installation locations.

3.3 Study of the vibration control method

In this section the zero power control with phase lead compensation and the zero power control with a stabilizing filter for the first bending mode have been studied. Figure 10 (a) and (b) show the diagrams of control method respectively. Although the phase lag in high frequency range has been improved with the use of small magnetic poles, it was rather difficult to control the first bending mode. For instance, when trying to secure sufficient stability by phase lead compensation, gain increased and the system tended to respond excessively to disturbance such as noise. The presence of high gain in such high 

![Fig. 8 Frequency response in small magnetic pole](image)

![Fig. 9 Setting positions of CFRP rings](image)
frequency range causes abnormal vibration.

In other words, sufficient di/dt (allowed current variation per unit time) is required to respond correctly. If this amount becomes insufficient, correct current will not flow into the coil; control of AMB will not become normal for suppressing vibration even in lower frequencies range, causing spillover vibration. It is necessary to maintain the gain in high frequency range at a constant amount or lower. Since di/dt is inversely proportional to the coil inductance, it is also effective to minimize inductance by reducing the magnetic pole size from this point of view.

Figure 11 shows the measured transfer functions of the two control methods expressed in Fig. 10. In terms of the zero-power control with phase lead compensation, the peak of gain appears at 1.1 kHz because the phase of the first bending mode in the vicinity of 900 Hz has been led. On the other hand, by using a stabilizing filter it was possible to lower the gain at 1.1 kHz by approximately 7 dB, securing phase lead around 900 Hz. Therefore control stability was improved by the stabilizing filter.

![Figure 10: Block diagram of controllers](image)

(a) Zero-power control with Phase Bump filters

![Figure 11: Comparison of controller frequency response](image)

(b) Zero-power control with Stabilizing filter

Fig. 10  Block diagram of controllers

Fig. 11  Comparison of controller frequency response
3.4 Measurement results of natural frequencies and damping ratios

Figure 12 shows the comparison between the measurement results and analysis results of natural frequencies and damping ratios when the medium-size flywheel was rotated up to 12,000 rpm. Since the damping ratios of elastic modes are under 1%, they must be measured with an accuracy of 0.1% or less for the safety of the test. The natural frequencies and the damping ratios were obtained by the transfer function between displacement signal and excitation signal, which was overlaid to the control signal for AMB during rotation.

As seen in the figure, in terms of the natural frequencies the analysis result and the experimental one show good agreement. Also, a trend in damping ratios of 1% or less is observed. In the analysis, the elastic mode (analysis: △, experiment:▲) which has the natural frequency in the vicinity of 580 Hz is unstable at more than 200 rps. On the contrary, in the experiment, although it is not unstable, the tendency for deteriorating damping ratios from the vicinity of 160 rps corresponds to the analysis result. The forward of first bending mode (analysis: ○, experiment: ●) in which stability is secured with a stabilizing filter has almost constant damping ratios. This is because the influence of the gyroscopic effect is small and change in natural frequencies is also small.

In actuality, we did not reach the present point without any problems; after much trial and error, we found a good control method and finally reached the level where we could obtain these data.

Naturally the problem which occurred most was that a certain mode had a tendency of spillover vibration as the rotational speed increased. By accurately measuring the natural frequency and the damping ratio for each rotational speed, the symptom of spillover occurrence can be seen in advance in many cases. Thus, we took measures to slightly increase phase lead near the frequency of spillover vibration. At this time, it is important not to cause spillover vibration to other modes. This tuning is not easy; it must only be handled by experienced, skilled engineers. By conducting a number of tunings, the medium-size flywheel rotated stably from low speed to high speed without gain scheduling control.

The next problem which occurred was that the Nyquist diagram, which was a vector locus of a rotor displacement, started to move unnaturally. It moved normally up to a certain rotational speed, but suddenly it started changing linearly. This is apparently not a
normal vibration phenomenon. It is considered that unbalance which caused vibrations to get larger occurred somewhere in the medium-size flywheel. The medium-size flywheel used here was apparently an assembly rotor; some parts got loose at high speed and thus it was necessary to fix them each time. Therefore, it may look easy when the final state was shown, but it was possible to achieve high speed rotation of 12,000 rpm only after many tries and errors as well as modifications of the medium-size flywheel.

Based on the findings on this medium-size flywheel, the development of a 10 kWh flywheel levitated by a high temperature superconducting magnetic bearings had been conducted; however, this development is not directly related to the content of this paper and the authors are not specialized on the high temperature superconducting magnetic bearing, so it is not covered here.

4. Conclusion

The active magnetic bearing of which loss was reduced to the limit was developed so that it could rotate a high speed rotating machinery in a vacuum chamber where heat generation must be avoided. The loss could be reduced to 1/6 by the zero-power control with homo-polar magnetic poles, compared with the conventional PID control with hetero-polar magnetic poles. As a result of this, the temperature rise problem no longer occurred even if the flywheel was rotated at high speed in a vacuum chamber.

With combined use of zero-power control, phase lead compensation and a stabilizing filter for rotors that tend to cause spillover vibration problems, it became possible to rotate the flywheel from low speed to high speed without gain schedule control. In order to counteract spillover vibration problems, not only software but also hardware characteristics, such as the magnetic poles on the stator and the magnetic steel sheets on the rotor, must be suitable within the control frequency range.

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References