Recent Trends in Development of Active Magnetic Bearings

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Since 1983, research and development of active magnetic bearing technology have been carried out at Koyo Seiko R&D center. Digital control technology based on the digital signal processor was applied to Koyo active magnetic bearing in 1995. Herein recent trends in development of active magnetic bearing are described.

Key Words*: active magnetic bearing, digital control, monitor, diagnosis, performance*

1. Introduction

An active magnetic bearing which supports a non-contact floating rotor by adjusting the attractive force of an electromagnet has been used for various industrial rotating machinery from the mid 1970s. The active magnetic bearings are classified into several types depending on the number of control axes thereof. The most frequently-used type is a five-degree-of-freedom-controlled active magnetic bearing which controls a total of five axes of four radial axes (X1, Y1, X2, and Y2) and the axial axis (Z). A turbo molecular pump which is used as a mechanical vacuum pump for a semiconductor manufacture equipment can be pointed out as the most successful applications of the active magnetic bearing. The active magnetic bearing, however, required a number of displacement sensors, complicated controllers, power amplifiers for driving the electromagnets or the like and thus had higher cost, consequently, still preventing itself from being used in other application fields. Conventionally, such application also has mainly used an analog controller which requires terribly long term of tuning process for the transfer function of the control circuit carried out by well-experienced rare expert engineers, which was another reason of higher cost.

However, the introduction of the digital control by the application of the digital signal processor (hereinafter abbreviated as DSP) after 1990 has allowed the active magnetic bearings to be increasingly used for rotating machines in various industrial fields[1]. This paper will describe the trends of technical development (mainly the digital control) and the international standardization of the active magnetic bearings.

2. Digital Control

The recent remarkable advance of the high-speed digital calculation processing technique exemplified by DSP allowed the field of the active magnetic bearing to use an increased amount of digital controllers. One of the reasons is that the rapid progress of peripheral techniques (e.g., a computer-aided engineering program for the design of a control system) or the environment. The recent optimization of surface-mounting techniques or heat release design techniques also allowed the control apparatus, which conventionally has occupied the major portion of the system, to have a dramatically-reduced size including the inverter for driving the rotor, now enabling the control apparatus to be attached to a holder of the rotating machine. **Figure 1** shows an example of Koyo five-degree-of-freedom-controlled, digitally-controlled active magnetic bearing system.

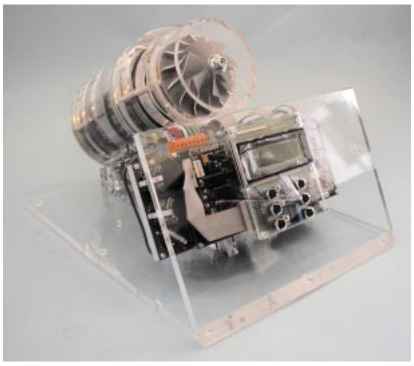

Fig. 1 Koyo digitally-controlled active magnetic bearing

<Electronic circuit section>
DSP board
Size : 100mm × 220mm
DSP : TMS320F240
Number of control axes: 5
Sampling : 10 kHz
Magnetic bearing amplifier
Size : 100mm × 250mm
Capacity : 50 V, 3A × 10 ch
Motor driver capacity (which is provided above magnetic bearing amplifier) : 300 W
LCD display function : 20 characters × 4 rows
<Mechanism section>
Bearing configuration : two pairs of radial bearings × 2
A pair of axial bearings
Diameter of main axis: 45mm
Motor : DC motor

3. Functional Enhancement by Digital Control

The technical transition from the analog control system to the digital control system provided Koyo active magnetic bearing with various innovations and the functional enhancement of the magnetic bearing system itself. Hereinafter, some of the innovations are described.

3. 1 Serial Communication Function

Koyo active magnetic bearing uses a DSP communication software named MAT2TMS to enable the communication function by which a personal computer (hereinafter abbreviated as PC) and a DSP board installed in a controller can communicate. Serial communication protocols for the communication are in general RS232C and RS485. **Figure 2** shows the system configuration including the communication function of Koyo active magnetic bearing.

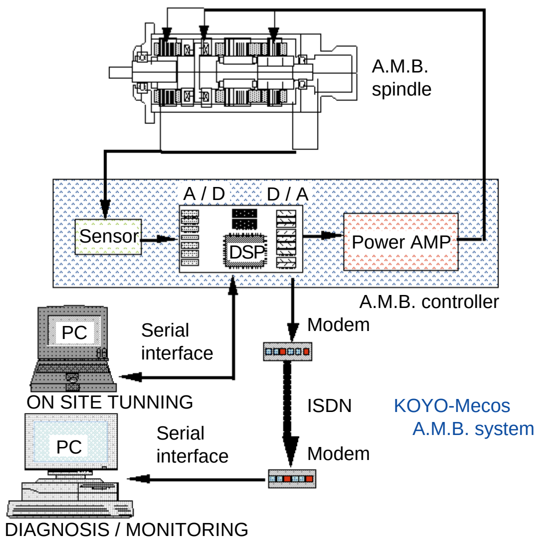

Fig. 2 Koyo active magnetic bearing and the configuration of the communication system

This system also supports the serial communication function by a modem, allowing the remote access to the system. This system realizes the functions as follows:

1) recording the history of fault occurrence;
2) monitoring the operation status; and
3) carrying out the diagnosis of the rotating machine.

3. 1. 1 Memory of Fault History

Koyo active magnetic bearing has the function of recording the history of fault occurrence. This function records the details of the fault detected by the DSP while the magnetic bearing is being operated by allowing the DSP to automatically write into the flash memory pieces of information (e.g., the time and the rotation speed at which the failure has occurred, and the total operation time, the total floating time, and the total energization time until the failure), including:

① displacement fault;
② rotation pulse fault;
③ acceleration fault while the system is driven;
④ bearing over load fault;
⑤ warning and fault by unbalance; and
⑥ fault of temperature of DSP/amplifier.

The details of the fault written in the flash memory can be read out by the interface software for providing the communication between the PC and the DSP and can be conveniently used for analyzing under what circumstance the fault occurred.

Figure 3 shows a history example of fault occurence which has been read out from the flash memory by using this "memory of fault history".

```
Fault history retrievement from flash will take some time. Please wait
*************************************
* FAULT HISTORY STORED IN FLASH *
*************************************
Total number of faults: 04
Number of lost faults:  0
f1  : 10-Mar-98, 11h58, Speed = 19.4 Hz, INI File = AMD070K
      Hour Meter:0.18h Mains, 0.13h Floating, 0.07h Rotating
      Orig Fault: X-Displacement Fault at Control Channel 1
```

Fig. 3 Example of fault history

3. 1. 2 Operation Status Monitor

The operation status monitor function can be easily provided by allowing a user to push the function keys of the monitor dialogue box as shown in **Fig. 4** (which is equipped with the MAT2TMS as a standard unit).

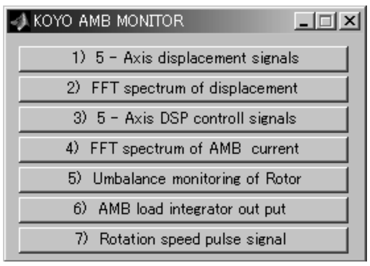

Fig. 4 Function keys for monitoring the operation status

This function keys can monitor the following various operation statuses of:

① radial and axial displacements signals;
② FFT analysis of the displacement signals;
③ radial and axial electromagnet current signals;
④ FFT analysis of the current signal;
⑤ the amount of unbalance;
⑥ bearing load; and
⑦ rotation pulse signal.

The measurement of the above parameters is automatically performed by pushing the function keys. Time waveforms and FFT data or the like obtained by the measurement are automatically displayed in the dedicated window on the PC screen.

Figures 5 and **6** show examples of monitoring the unbalance amount of the rotor. **Figure 7** shows an example of monitoring the rotation pulse.

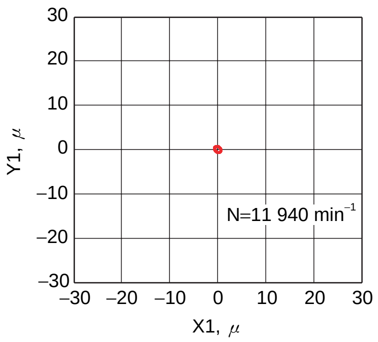

Fig. 5 Example of monitored unbalance in X1-Y1 plane

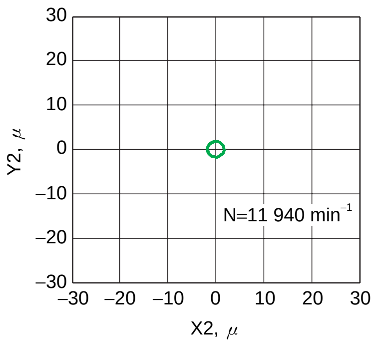

Fig. 6 Example of monitored unbalance in X2-Y2 plane

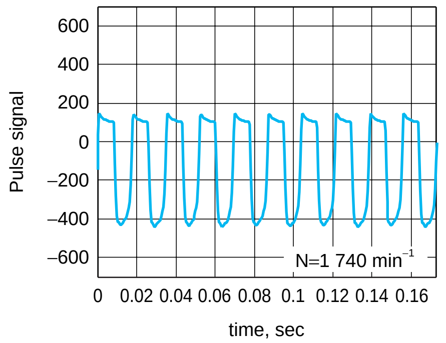

Fig. 7 Example of monitored rotation pulse

3. 1. 3 Diagnosis Function of Rotating Machinery

The active magnetic bearing is included in the feed-back control system which detects the displacement signal of the rotor to control the attractive force of the electromagnet for floating the rotor. Generally the measurement of the stiffness of the rotor system supported by bearings should be carried out by means of a contact-type acceleration sensor or displacement sensor with hammering. Koyo active magnetic bearing, on the other hand, does not require any additional signal input/output apparatus for the measurement in the conventional feed-back loop, thus allowing Koyo active magnetic bearing to easily measure the suspension stiffness of the rotor supported by the active magnetic bearing by the method as described below.

When the superposed signal from the control DSP is outputted with an excitation signal for exciting the rotor while the active magnetic bearing supports the rotor to allow the rotor to float, the digital signal is transmitted as analog amount to the power amplifier for driving the electromagnet via D/A converter and then is inputted to the electromagnet for floating the rotor. The electromagnet for floating the rotor then still continues to support the rotor in a non-contact manner. Then, an excitation signal component becomes a fluctuation component of the attraction to provide an excitation force for wobbling the rotor. The rotor displacement by this wobble is again inputted as a digital displacement signal from the A/D converter to the DSP. The excitation method as described above is only enabled by the active magnetic bearing and thus is called by the authors as the magnetic hammering method.

The stiffness generally has a frequency characteristic and can be represented by the following formula.

$$K(\omega) = F(\omega) / X(\omega) \quad \cdots\cdots (1)$$

The DSP for controlling a magnetic bearing can provide, as described above, both of the excitation force (signal) = force (F) outputted therefrom and the resultant displacement signal (X) at the same time. This allows the DSP to perform the calculation of the formula (1) while changing the excitation frequency into the desired frequency.

The dynamic stiffness characteristics thus obtained includes a large piece of information needed for judging the integrity or the aging of the rotation machine.

The MAT2TMS includes a diagnosis dialogue box as shown in **Fig. 8** as a diagnosis function for the rotating machine by which the stiffness characteristic of the rotating machinery can be measured.

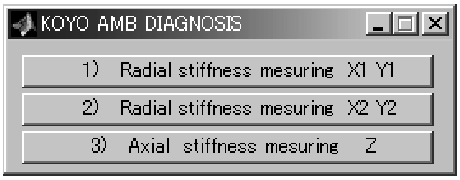

Fig. 8 Dialogue box for the diagnosis of rotating machine

This dialogue box can measure:

① the stiffness in the X1 or Y1 control axis;
② the stiffness in the X2 or Y2control axis; and
③ the stiffness in the Z control axis.

Figures 9, **10**, and **11** show examples of the above measurements of the stiffness.

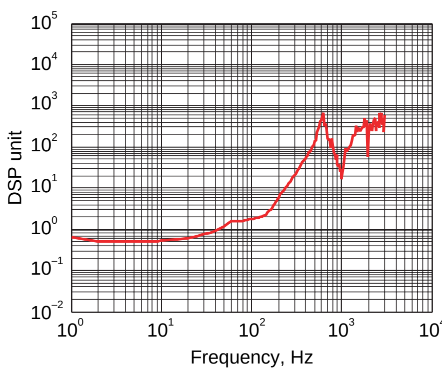

Fig. 9 Example of measured dynamic stiffness in X1 direction

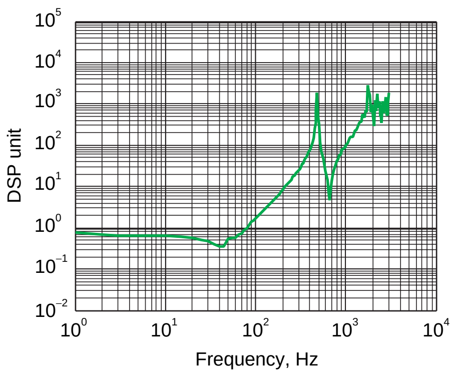

Fig. 10 Example of measured dynamic stiffness in X2 direction

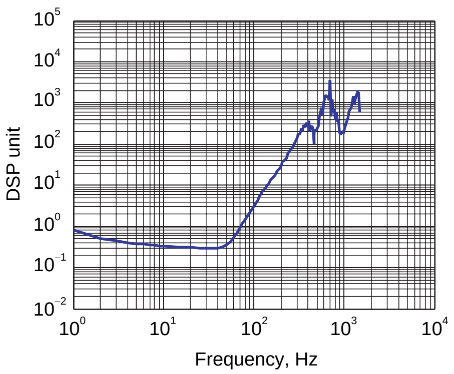

Fig. 11 Example of measured dynamic stiffness in Z direction

The active magnetic bearing is generally used together with a rolling bearing called a touch-down bearing for supporting the rotor when the magnetic bearing is not operated. The clearance between the rotor and the touch-down bearing in the radial direction is set so as to be smaller than that between the rotor and the sensor or the electromagnet in the radial direction, thereby allowing the rotor and the sensor or the electromagnet not to contact even when the touch-down bearing contacts with the rotor.

Specifically, the active magnetic bearing having the above configuration has:

(1) the center of the touch-down bearing = the floating position;

(2) the center of the sensor; and

(3) the center of the electromagnet.

The floating position of the rotor at which the active magnetic bearing supports the rotor in the radial or axial direction is generally controlled by setting the center of the clearance of the touch-down bearing as the target position.

However, the mechanical centers as described above generally show a very little discrepancy thereamong within the tolerance range of the machining accuracy. The above centers also have discrepancies due to the assembly errors caused by the assembly accuracy of each part of the system. Thus, the above discrepancies among the centers, when combined with an electrical unbalance or discrepancy due to the dispersion of various displacement sensors and the error of the number of the windings of electromagnet coils or other factors, have an influence on the performance of the magnetic bearing and even have a possibility of causing the low performance.

Thus, Koyo active magnetic bearing also provides a diagnosis function by which the error between the center of the touch-down bearing and the center of the electromagnet is checked by the following method.

Opposing control currents flowing through the electromagnet at each control axis are perfectly equal when the rotor is floating at the center of the magnetic bearing. But the opposing control currents flowing through the electromagnets are not equal when the rotor is not floating at the center of the magnetic bearing. The difference of these opposing control currents is outputted by integrated outputs of the DSP control system. In other words, the difference between the integrated outputs can be used to estimate the error between the center of the touch-down bearing and the center of the electromagnet. It is also possible to change the floating position to find the floating position at which this integrated output is "zero" (i.e., the center of the magnetic can be detected).

The MAT2TMS has a dialogue box shown in **Fig. 12** through which the magnetic center can be detected in a very short time.

Fig. 12 Dialogue box for measuring the magnetic center

Figures 13, **14**, and **15** show the examples of the measurement of the above centers. In **Figures 13** and **14**, the measurement of the center in the radial direction shows a small ○ because the position of the measured magnetic center is small and shows the deviation of 2 micrometers in the X1-Y1 plane and the deviation of 20 micrometers in the X2-Y2 plane. Acceptable deviation values are also displayed and any of the results in **Figs. 13** and **14** is judged as a specified value. The result of **Fig. 15**, on the other hand, shows no detected deviation. Such a function for detecting the magnetic center is enabled not only by the use of the MAT2TMS but also by the DSP alone.

The monitor and diagnosis functions as described above can be efficiently used for the quality control of not only delivered products but also pre-delivery products. Customers of Koyo active magnetic bearings also can use the MAT2TMS to obtain the quality control of the entire rotating machine as a final user product including Koyo active magnetic bearing. Therefore, Koyo can license the MAT2TMS for Koyo active magnetic bearings to such customers.

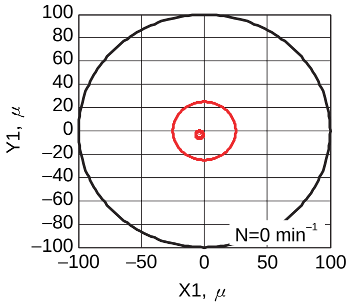

Fig. 13 Example of measured magnetic center in X1-Y1 plane

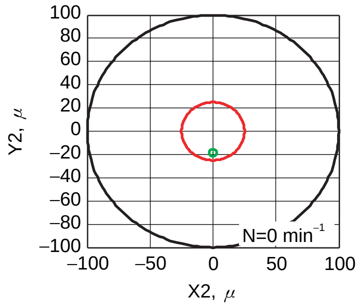

Fig. 14 Example of measured magnetic center in X2-Y2 plane

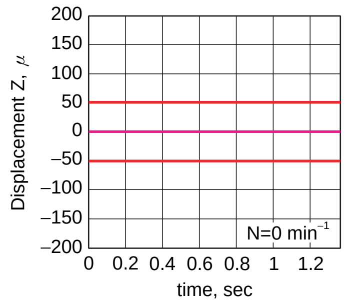

Fig. 15 Example of measured magnetic center in Z direction

The following functions are obtained by using a surplus of computing capability by the DSP for controlling the magnetic bearing without adding any particular hardware (e.g., a dedicated IC) for the support of each function. This contributes to the reduced cost of the entire system as compared to the one in which microcomputers are required for supporting each function.

3. 2 Control of LCD and Interface

Koyo active magnetic bearing allows a user to use a liquid crystal display apparatus (LCD) provided at a front panel of the control apparatus to access various pieces of information as shown in **Table 1** regarding the operation, the internal parameters, and the settings in order to see and determine such information. The LCD generally displays a NORMAL display which shows the actual number of rotations but also displays the main menus or the sub menus as shown in **Table 1** by allowing the user to operate the four switches of MODE, UP, DOWN, and ENTER.

Optionally, these menus on the LCD also can be flexibly changed or modified depending on each case (e.g., addition of another function).

Table 1 Standard menu on LCD of Koyo active magnetic bearing

NORMAL display for displaying the actual number of rotations

Act Spd : 1 000 Hz
UFRC ON

M01	Param Input	Setting automatic adjustment of the sensor Serial communication setting Setting rotational speed* Temperature control command**
M02	Signals	Unbalance Over-loaded condition of magnetic bearing Operating condition of motor Temperature monitoring
M03	Hour Meter	Integrated energization time Magnetically floating time Rotating time
M04	Time & Date	Current time display Change of time setting Change of date setting
M05	Cal Values	Information on sensor adjustment
M06	Calibration	Request for automatic adjustment of sensor
M07	Fail Hist	Fault history display
M08	Alarm	Alarm (warning) information
M09	SN & Ver #	Display of serial number or the like
M10	Maintenance	Maintenance call

* When the inverter control function is used.

** When the temperature control function is used.

3. 3 Control of Inverter

In the case of the control apparatus for a vacuum pump, the vacuum pump includes a high-frequency inverter for driving an internal motor. The DSP for controlling the magnetic bearing also uses the surplus of computing capability to execute some calculation functions of an inverter control section. This allows not only the motor driving characteristic corresponding to the control characteristic of the magnetic bearing to be easily obtained but also the special driving characteristic required for the vacuum pump motor to be obtained.

The MAT2TMS also includes the dialogue box for this control of the inverter by which the start, stop, and free-run commands for the motor as well as the target rotational speed can be determined.

Fig. 16 Dialogue box for controlling inverter

3. 4 Control of Temperature Adjustment Apparatus

A vacuum pump used for the manufacture of semiconductors evacuates various process gases and thus sometimes causes the rotor to be adhered with the chemical reaction products. In order to prevent the rotor from being adhered with such products, the pump itself is usually attached with a band heater to raise the temperature of the pump. In order to adjust the temperature of the pump, such a heater requires to be controlled by measuring the pump temperature and by adjusting the power inputted to the heater so that the temperature of the vacuum pump can be maintained at an appropriate one. Thus, the control apparatus for Koyo active magnetic bearing for the vacuum pump also provides this temperature adjustment function by using the DSP for controlling the magnetic bearing (patented in U.S. and Taiwan).

4. General-purpose Magnetic Bearing Controller

It is obvious that the further expansion of the active magnetic bearings in various fields requires the active magnetic bearings to be provided with not only user-friendly hardware and software configurations as described above but also reduced cost. However, the active magnetic bearing has conventionally been recognized as a tailor-made one rather than as a serial product and thus has been separately designed to have a hardware configuration satisfying the requirement from an individual customer. The use of the digital control is expected to change such a conventional aspect of the active magnetic bearing.

For example, a minimum hardware configuration (i.e., main circuit components) of the electronic circuit section of the digital active magnetic bearing includes:

① sensor circuit;
② A/D circuit;
③ DSP;
④ D/A circuit;
⑤ serial communication section;
⑥ LCD display section;
⑦ other digital I/O sections; and
⑧ power amplifier.

It is estimated that the circuit for driving an electromagnet of ⑧ among the above components has different specifications of driving capacity depending on the bearing load conditions and/or the control frequency band. However, the rest of the electronic circuit sections have no power sections and thus can be used as a common part.

Based on such a concept, Koyo active magnetic bearing intends to reduce the controller (electronic circuit) cost by using the electronic circuit sections of ① to ⑤ as the general-purpose DSP boards for controlling the magnetic bearing to combine the digital I/O section of ⑦ and the power amplification section of ⑧ so that the above parts can be used as the common part. In the near future, this will allow a customer of Koyo active magnetic bearing to easily select an appropriate controller from a series of general-purpose controllers for the magnetic bearing.

Figure 17 shows the appearance of Koyo general-purpose controller MDCA3A for the magnetic bearing.

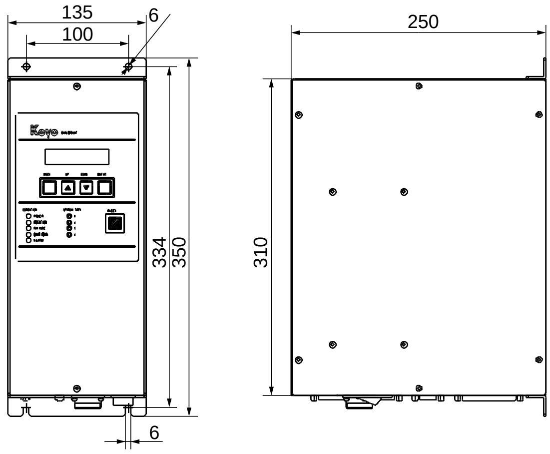

Fig. 17 General-purpose controller MDCA3A for Koyo active magnetic bearing

A conventional analog-controlled magnetic bearing requires the calibration and the adjustment of a displacement sensor when the combination of a rotating machinery and a control apparatus is changed. The presently-developed Koyo general-purpose controller for the magnetic bearing uses the digital control system to allow a customer to select the tuning-free start mode or the matching-free start mode in which the adjustment of the displacement sensor can be automatically performed. Specifically, the DSP board as described above in which the electronic circuit sections of ① to ⑤ are integrated is used to allow the DSP to be also responsible for the control of the oscillation circuit of the displacement sensor. This allows the change of the oscillation frequency and the adjustment of the gain of the displacement sensor or the offset signal to be automatically performed, thereby eliminating any trimmer adjustment operations.

This controller also can simultaneously store four different sets of control parameters and thus provides the coupling-free mode in which four types of rotors are automatically discriminated for the start of the system.

5. International Standardization of Active Magnetic Bearing

Since 1997, with an objective of allowing the active magnetic bearings to be widely used in various industrial machinery, the international standardization for the active magnetic bearings has been actively discussed. Now ISO · TC108 (Technical Committee on "impact and vibration of machinery") and SC2 (sub-committee) are gathering experts on the field of the active magnetic bearing as members of WG7 (working group) to allow the members to communicate with the members of Deutsches Institut fur Normung (DIN) for some items of the international standardization of the active magnetic bearings. The convener of this WG7 is Professor Osami Matsushita of Department of Mechanical Engineering of National Defense Academy in Japan. Thus, it is notable that the international standardization of the active magnetic bearings is the first one which is led by a Japanese organizer.

The efforts for the international standardization of the active magnetic bearings are also performed by A.M.B Standardization Committee held by The Japan Society of Mechanical Engineering (which is also led by Professor Osami Matsushita). This allows the active magnetic bearings to be thoroughly researched as to what standardization is the best for the active magnetic bearings as a part of industrial machinery. One of the achievement of the activities is "Manual for Design of Magnetic Bearings"[2] which was issued by A.M.B Standardization Committee in 2003.

5. 1 Definition of Terms for Active Magnetic Bearing (ISO14839-1)[3]

This ISO14839-1 standard specifies the names of the functional sections in sensors, actuators (electromagnets), and controllers and particularly the technical terms for the active magnetic bearings and the definitions thereof. In 2002, this standard was formally approved as an international standard through the vote by ISO member countries. This international standard will soon be translated into Japanese to be established as a JIS standard by Japanese Standards Association. **Table 2** shows the names of the main sections in an active magnetic bearing.

Table 2 Technical terms for main parts of an active magnetic bearing

Stator side	Rotor side
Radial stator	Radial rotor core
Radial sensor	Radial sensor target
Axial stator	Axial rotor disc
Axial sensor	Axial sensor target

A technique of which a magnetic bearing in the radial direction is controlled so that the rotor can rotate around the main axis of inertia is known as one of the big features of the active magnetic bearing. For this technique, the automatic balancing system (ABS) developed by a French magnetic bearing expert maker is famous as the one embodying this technique. This technique for controlling the magnetic bearing in the radial direction, however, is actually the one for reducing the unbalanced vibration of the rotor, not the one that automatically takes the balance of the rotor. It is noted that from this standpoint, the international standard defined this technique as "Unbalance Force Rejection Control (UFRC)".

5. 2 Evaluation of Vibration in Active Magnetic Bearing (This standard is to be specified as ISO14839-2)

The objective of this standard is to specify the vibration of rotating machinery equipped with the active magnetic bearing while the rotor is rotating. Standard vibrations while the rotating machinery is rotating to be specified by this standard are classified into four zones of A, B, C, and D depending on the ratio (%) to the clearance of the touch-down bearing in the radial direction. **Table 3** shows the standard vibrations of the rotating machinery equipped with the magnetic bearing according to the idea of this standard. In accordance with the idea of vibration standard, Koyo active magnetic bearing is programmed to make the controller output the warning signal when the vibration goes out of zone A and output a displacement failure signal when the vibration goes out of zone C. **Figure 18** shows the warning level (blue) and the failure level (red) of Koyo active magnetic bearing when the radial direction clearance is 100 micrometers. This idea of the international standard is at the final stage of the working group draft.

Table 3 Standards for vibration of rotating machine equipped with active magnetic bearing (Vibration value is a value to a clearance in radial direction.)

Zone	Vibration value	Note
A	30% or less	Newly-provided rotating machine
B	40% or less	Still capable of operation for long time.
C	50% or less	Capable of operation for short time.
D	More than 50%	In the range in which operation should be stopped.

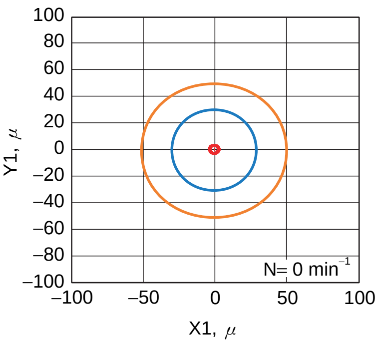

Fig. 18 Warning level (blue) and failure level (red) of Koyo active magnetic bearing
(clearance in the radial direction = 100 micrometers)

5. 3 Evaluation of Stability of Active Magnetic Bearing (This standard is to be specified as ISO14839-3)

It is not too much to say that the core technique of the active magnetic bearing by which the attractive force of the electromagnet is controlled to float the rotor is how to stabilize the primary and secondary bending vibrations of the rotor. The objective of this standard is to specify the evaluation of the bearing stability of the rotating machinery with the active magnetic bearing, as shown by the title of this section. Now working group and other members have active discussions on this standard in which the sensitivity function from the viewpoint of the control system is to be used as a standard for judging the stability.

6. Conclusions

By expanding the application of the digital control technique the active magnetic bearing can provide:
1) more flexible design of the control system and reduced the adjustment work time;
2) the use of a common hardware (DSP) (e.g., general-purpose controller) for volume efficiency and further-reduced cost;
3) the control of unbalanced forces which is a special function of the active magnetic bearing;
4) the monitoring of the floating status, the rotation status, and the action force;
5) a functional enhancement component such as a rotor diagnosis function
6) an automatic adjustment function of a displacement sensor (i.e., tuning-free function); and
7) the addition of the rotor discriminating function of the control system (i.e., matching-free function).

Such convenient features will allow the active magnetic bearings to be increasingly used for various industrial rotating machinery. The international standardization of the active magnetic bearing is also being intensely discussed. This will allow the active magnetic bearings to be used in various applications with acceleration.

References

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2) Jikijikuuke Sekkei Manyuaru, Nihon Kikai Gakkai Jikijikuuke Hyoujyunka Iinkai Hensan.
3) ISO14839-1 Seigyogata Jikijikuuke no Gijyutuyougo.

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