ISO Standardization for Active Magnetic Bearing Technology

Abstract
Since the ISO TC108/SC2/WG7 AMB project was established in 1996, the standardization of active magnetic bearing (AMB) technology has been continued to expand AMB applications. Meantime, our project, supported by the NEDO grant, worked from FY2002 to FY2004 as the main members of WG7. The following three parts have been developed:

ISO 14839-1 Vocabulary; published in May, 2002.
ISO 14839-2 Evaluation of vibration; published in July, 2004
ISO FDIS 14839-3 Evaluation of stability margin; will be published in May, 2006.

Particularly, since Part 3, stability margin of AMB control systems, is a new subject not seen in conventional standards, a consensus has been missing for a long time due to each company’s internal knowledge. To resolve this dead lock, international collaborative test was successfully achieved in a three-year-program. This collaboration finally created the consensus and accelerated the standardization process toward publication. Our activity was given by the JSME "Standards Board Contribution Award" (2005).

Keywords: Active magnetic bearing, ISO, Vibration evaluation, Evaluation of stability margin, Rotating machine

1. Introduction
As core members of ISO TC108/SC2/WG7 Active Magnetic Bearing (AMB) project (Convenor Osami Matsushita, Japan), our NEDO team has been developing an ISO 14839 series for AMB rotating machinery. The following three standards, registered by ISO CS, have progressed:

ISO 14839-1 Vocabulary (published in May, 2002)
ISO FDIS14839-3 Evaluation of stability margin (now in the editing process for the final voting)

ISO Directives requires a voting process at each stage consisting of WD(Working Draft)-CD(Committee Draft)-DIS(Draft of International Standard)-FDIS(Final DIS) for publication.
Part 1 was published in 2002 after our final revision of the draft.
Part 2 was developed for AMB turbo machinery as well as vibration standards for machines equipped with
conventional bearings. At the early stage, we considered both the maximum values of vibration and AMB working current as the index to be regulated. No agreement was reached due to lack of adequate field data. Finally, we stated the vibration regulation in the main text and allocated the current regulation in the appendix. This compromise was made at the Tokyo meeting (2002) to agree with DIS of Part 2. Afterwards, it was published in 2004.

Part 3 was our main target. At the beginning, we encountered conflicting ideas regarding the stability margin, the difference from Q-value (ISO 10814), how to measure the stability margin using commercial FFT analyzers and etc. In order to resolve this non-productive situation, we invited experts from several countries to collaborate on testing according to the following 3-year plan:

FY2002 Planning of test rigs (Design a test rotor offered by Hitachi Industries, Co., Ltd)
FY2003 Setup of test rig (Manufacturing test rotor rigs and a digital controller for AMB)
FY2004 Collaborative testing called NEDO-ISO Joint Workshop (Conference and test exhibition)

Existing disagreements in the past were effectively solved by this workshop exhibiting vibration and stability analysis of AMB rotor and obtained test data. Successful experiences of applying Part 3 to actual machines were reported by company experts at the workshop conference. This workshop was most effective opportunity to agreement of DIS advancing the next step.


2. ISO 14839-1: Vocabulary

As we know, a new technology tends to produce new commercial terminology for the business propaganda. We also experience the confusion with dialects defined by individual companies and academies. There are so many cases of this nature in AMB business communication. In addition, AMB is a combined technology with mechanical and electrical engineers. We needed to define the “AMB-related-vocabulary” to make the bridge between both fields.

Part 1, titled “Vocabulary” contains six chapters as follows:
5. Dynamics, control and electronic and
6. Auxiliary equipment

Several definitions are shown from Part 1 as follows:

(1) Symbol of AMB
For rotating machinery equipped with active magnetic bearings, the graphical symbols for bearing are shown in Fig. 1.

(2) Active magnetic bearing, AMB
means to support a rotor, without mechanical contact, using only attractive magnetic forces based upon servo feedback technology which normally consists of sensors, electromagnet, power amplifiers, power supplies and controllers, as shown in Fig. 2.

(3) AMB system
system consisting of a rotor, position sensor or other means to
detect rotor position, controller(s), power amplifier and electromagnets to levitate and support the rotor by attractive magnetic force, as shown in Fig.2 and 3.

(4) unbalance force rejection control

special control method which allows the rotor to rotate around its principal axis of inertia while the transmitted unbalance force through the AMB is minimized, which leads to resulting vibration of the bearing casing, as shown in Fig.4. This definition is a typical example of defining the commercial wording.

3. ISO 14839-2 : Evaluation of vibration\cite{5,6}

3.1 Background

Most turbomachinery is still supported by oil-film bearings. Because of the high stiffness of oil-film bearings and very small clearances, e.g., $C/R = (\text{bearing radial clearance})/(\text{journal radius}) \approx 1/1000$, shaft vibration must be regulated within low levels to avoid oil-film rupture of the lubricant and metal contact inside the bearing, as stated in the ISO 7919 series for turbines, generators, pumps, compressors, etc.

In contrast, since AMBs support the rotor softly in large bearing clearance, e.g. $C/R \approx 5/1000$, large vibratory motions should be permissible as long as they do not produce rubs between the rotor and surround casing. In addition, the design of AMB for effective vibration control requires placement of the AMB actuator and its position sensor near the largest amplitude portion of the eigenmodes, as shown in Fig.5. Thus, the detection of large vibration is inevitable and can be allowable. This is the reason why AMB rotors require their own ISO standards.

3.2 Existing Standards

In the case of a process compressor equipped with AMB, a customer can comply with API617 regulation\cite{3}
which requests a low vibration level as follows:
\[ L_v = 25.4 \sqrt{\frac{12000}{N_{\text{MCS}}} \text{ and } L_v \leq 25.4 \mu \text{mpp}, \text{ where } N_{\text{MCS}} = \text{max. continuous speed, rpm.}} \]

For instance, if \( N_{\text{MCS}} = 9500 \text{ rpm, } L_v = 25.4 \mu \text{mpp} \)

If the existing ISO standard concerning the journal vibration of turbomachines equipped with the oil-film bearing is applied, the vibration zone limit values would be as follows:

ISO 7919-3 Coupled industrial machine\(^2\)

\[ S_{pp} = \frac{4800}{\sqrt{N}} \text{ where } N= \text{the maximum (trip) speed} \]

For instance, if \( N=12500 \text{ rpm, } S_{pp}=43 \mu \text{mpp} \) for Zone A.

These existing values are too small compared to AMB bearing clearances, e.g., \( 2C=500 \mu \text{m} \). Thus, the existing standards for oil-film bearings are too strict for AMB rotors. A new AMB standard is expected.

### 3.3 Scope of Part 2

Part 2 provides general guidelines for measuring and evaluating AMB rotor with respect to the following two indices:

- shaft vibratory displacement measured at or close to the AMBs, and
- working current and voltage measured in magnetic coils or power supply amplifiers. (As of this writing, there is not enough data to define a standard. Instead, these notes are include in the Annex.)

Both indices are measured under nominal operating steady-state conditions in house and/or on site. Since AMB equipment has its own position sensors within the feedback control system, the detected displacement values are subject to the ISO standard and no additional sensors are required.

This part applies to industrial rotating machines generating or consuming nominal power greater than 15 kW, and is not limited by size or operational rated speed. Large turbomachines like compressors, pumps, and turbines, as well as generators and other rotors supported by AMBs are included in this standard. Small AMB rotors such as turbomolecular pumps, spindles, etc are excluded.

### 3.4 Evaluation Criteria

If the rotor is not in contact with the stator, even large vibration levels are normal and permissible. The minimum radial clearance, noted \( C_{\text{min}} \), can be defined by the minimum gap measured when statically moving the rotor in any radial direction. The touch down bearing gap is generally set to be \( C_{\text{min}} \) by design.

The index \( D_{\text{max}} \) is the maximum value of shaft vibratory displacement measured by AMB sensors under steady-state operation. The corresponding zone limit table for AMB is given in Table 1.

<table>
<thead>
<tr>
<th>Zone Limit</th>
<th>Displacement ( D_{\text{max}} )</th>
<th>Case study if ( C_{\text{min}}=230 \mu \text{m} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/B</td>
<td>(&lt; 0.3 \ C_{\text{min}} )</td>
<td>(&lt; 69 \mu \text{m} \ &lt;138 \mu \text{mpp} )</td>
</tr>
<tr>
<td>B/C</td>
<td>(&lt; 0.4 \ C_{\text{min}} )</td>
<td>(&lt; 92 \mu \text{m} \ &lt;184 \mu \text{mpp} )</td>
</tr>
<tr>
<td>C/D</td>
<td>(&lt; 0.5 \ C_{\text{min}} )</td>
<td>(&lt; 115 \mu \text{m} \ &lt;230 \mu \text{mpp} )</td>
</tr>
</tbody>
</table>

Note: the definition of each zone

Zone A: The vibration of newly commissioned machines would normally fall within the zone.

Zone B: Machines with vibration within this zone are normally considered acceptable for unrestricted long-term operation.

Zone C: Machines with vibration within this zone are normally considered unsatisfactory for long-term continuous operation. Generally, the machine may be operated for a limited period in this
condition until a suitable opportunity arises for remedial action.

Zone D: Vibration, eccentricity and current within this zone are normally considered to be sufficiently severe to cause damage to the machine.

4. ISO DIS 14839-3 : Evaluation of stability margin

4.1 Background

Feedback control in an AMB system provides positive stiffness and positive damping so that the AMB operates to maintain the rotor stably at a centered position. There are two parts to this assessment of stable magnetic levitation.

First, the run-up behavior of the system is evaluated by the damping effect concerning critical speeds. This corresponds to the sensitivity to unbalance excitation at each critical speed, measured in a rotation test. As shown in Fig. 6, the sharpness of each peak amplitude, commonly referred to as Q-factor covered by ISO 10814 (Q-factors) [7,8] is evaluated. This damping effect is not the subject of Part 3.

The second part, which is covered by Part 3, deals with the stability of the system for safe and reliable operation of the AMB rotor system from the viewpoint of the feedback control. The stability margin is related to the robustness of the AMB control under system parameter variations (e.g. system variations caused by high temperature) and disturbances acting on the rotor (e.g. higher frequency noise).

4.2 Scope of Part 3

This standard concerns the system stability measured during normal steady-state operation in house and/or on site. The in-house evaluation is an absolute requirement for shipping of the equipment, while the execution of an on-site evaluation depends upon the agreement between the purchaser and vendor.

4.3 Transfer Functions

The closed loop of an AMB-rotor system is simplified, as shown in Fig.7, using the notation of the transfer function $G_c$ of the AMB control part and the transfer function $G_p$ of the plant (rotor). At a certain point of this closed loop network, we can inject excitation as harmonic or random signals from $E$ and measure the response signals $V_1$ and $V_2$ directly after and before the injection point, respectively. By using a 2-channel FFT analyzer, we can measure the ratio among these three signals in the frequency domain to obtain the following transfer functions.

The ratio of these $V_1$ and $V_2$ signals provides an open loop transfer function $G_o$:

$$G_o(s) = -V_2 / V_1(s)$$

At the same time, we can obtain the closed loop frequency transfer function $G_c$ and the sensitivity function $G_s$ using the following formulas:

$$G_c(s) = -V_2(s) / E(s)$$
$$G_s(s) = V_1(s) / E(s)$$

These transfer functions are mutually compatible with the open loop $G_o$ in the following mathematical
expression involved in FFT analyzer functions:

\[ G_\varepsilon = \frac{G_o}{1 + G_o} \iff G_o \iff G_S = \frac{1}{1 + G_o} \]  

(4)

4.4 Stability Index for Sensitivity Function

A typical example of the open loop transfer function \( G_o(j\omega) \) is displayed on Bode diagram in Fig. 8. It can be rearranged on a polar diagram with the form of amplitude \( |G_o(j\omega)| \) and phase \( \angle G_o(j\omega) \) as shown in Fig. 9. Such a diagram is called a Nyquist plot of the open loop transfer function. Since the characteristic equation is provided by \( 1 + G_o(s) = 0 \), the distance between the locus and the critical point (-1,0) on the Nyquist plot is directly related to the stability margin. Generally it can be stated that the larger the minimum distance from the critical point, the greater the system stability margin.

The shortest distance measured from the critical point is indicated by \( AB = D_{min} \), where a circle of radius \( D_{min} \) centered at (-1,0) is tangent to the locus. It is noted that the gain margin is the distance \( AG \) (an intersection between the locus and the real axis) and the phase margin is the angle \( \angle AOP \) (between the real axis and a line extending from the origin to the intersection between the locus and the unit circle).

Since the distance between \( G_o(j\omega) \) and the point (-1,0) on the Nyquist plot, we know \( D_{min} = \text{Min} [1 + G_o(j\omega)] \). From the relationship of Eq.(4), we can conclude the following formula:

\[ D_{min}^{-1} = \text{Max} \left[ |G_S(j\omega)| \right] \]  

(5)

The corresponding Bode plot of the sensitivity function is shown in Fig. 10.

The minimum distance on the Nyquist plot is equal to the reciprocal of the maximum value of the sensitivity function. In this example, the maximum sensitivity function appears with 7dB=2.2 at \( \omega_2 \) mode equivalently indicating the shortest distance=-7 dB = 0.45.

The measurement filter property should be extended to the max frequency defined by the greater value of (a) three times the rated speed =3X or (b) a maximum frequency of 2kHz.
\[ f_{\text{max}} = \text{Max}(3X, 2\text{kHz}) \]

Then, the index for evaluating the stability margin is obtained as defined in the following relationship:

\[ G_{r,\text{max}} = \text{Max}|G_{r1}(2\pi f)| \quad \text{for} \quad 0 \leq f \leq f_{\text{max}} \]

4.5 Evaluation Criteria

For evaluation of the stability margin, a zone limit table is proposed as shown in Table 2.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Sensitivity peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/B</td>
<td>9.5 dB = 3</td>
</tr>
<tr>
<td>B/C</td>
<td>12 dB = 4</td>
</tr>
<tr>
<td>C/D</td>
<td>14dB = 5</td>
</tr>
</tbody>
</table>

4.6 NEDO-ISO Joint International Workshop

For three years before the beginning of the NEDO grant in 2002, the ISO working group discussed the stability margin for AMB standards, but made little or no progress. In this discussion, we were confused by too many ideas concerning the definition of stability margin, difference from Q-value (ISO 10814), how to measure the stability margin using commercial FFT analyzers and so forth, producing essentially no product.

In order to resolve this impasse, WG7 has tentatively agreed that the stability index should be set by the maximum values of the sensitivity function. However, this idea was quite new for us so we did not have much experimental sensitivity data available for our assessment. Therefore, the NEDO project decided to focus on this issue in Part 3 and to establish a collaborative test program involving international experts. The following plan
was developed for the NEDO grant:
- FY2002 Planning of test rigs (Design a test rotor offered by Hitachi Ltd.)
- FY2003 Setup of test rig (Manufacturing test rotor rigs and a digital controller for AMB)
- FY2004 Collaborative testing called NEDO-ISO Joint Workshop (Conference and test exhibition)

As shown in Fig.11, this workshop included a conference, ISO meetings, and exhibition of the rotating test. This process resolved all existing disagreement.

![Controller layout with mode control and excitation ports](image1)

![Sensitivity function at normal condition](image2)

![Sensitivity depending upon change of total gain](image3)

![Sensitivity depending upon change of total phase lag](image4)

The NEDO rotor is described in Fig.12 and the corresponding controller layout is shown in Fig. 13. This AMB rotor is supported by modal control consisting of parallel and tilting modes. In each modal control loop, we injected excitation signals to measure the open loop transfer function and to extract the sensitivity function according to Eq.(4).

In this experiment, we obtained the sensitivity function at normal condition as shown in Fig. 14. To summarize the results, we find the maximum values of the sensitivity peak to be 8.5 dB, i.e., Zone A.

In addition, we set the parameter changes to the worst case scenario to investigate the stability limits. In fact, when we changed the total gain, the sensitivity value finally entered Zone D as shown in Fig.15. The change of total phase lag provides the stable limit as shown in Fig.16.
At the workshop conference, successful experiences in applying the standards of Part 3 to actual machines were reported by industry experts. This workshop was very effective in completing the DIS.

5. Case Study [5,6]

As stated in the literature [3], an AMB centrifugal compressor was installed at a refinery plant as shown in Fig. 17. The vibration level measured at the commission is shown in Fig. 18. This machine with the minimum clearance $C_{\text{min}} = 230 \mu\text{m}$ is judged within Zone A, referring to Table 1 of ISO 14839-2.

One of the open loop transfer functions is shown in Fig. 19. By rearranging the open loop transfer function to the sensitivity function according to Eq. (4), we find the maximum value of sensitivity gain to be 6dB. The stability margin of this machine is then categorized in Zone A, referring to Table 2 of ISO DIS 14839-3.

This machine has been operating normally without major trouble for approximately 10 years since its installation in December of 1992. The end user is satisfied with the reliability of this AMB rotor.

6. Conclusions

The NEDO team of the ISO TC108/SC2/WG7 AMB project has been developing ISO standards of the ISO 14839 series. Part 1 “Vocabulary” and Part 2 “Evaluation of vibration” have reached the final stage of publication. Part 3 “Evaluation of stability margin” has gained international consensus, allowing the advance of the ISO process to FDIS, which will be published in 2006.

We begin Part 4 “Technical guidelines”, referring to our book on AMB.

We hope that our effort to develop these valuable international standards encourages application of AMB technology to a wide range of rotating machinery and that our information will contribute to each phase of procurement, design, operation, and maintenance in the AMB turbomachinery business.
Acknowledgments

This study has been generously supported by the NEDO International Joint Research Grant 2002IS002.

References

[8] ISO 10814 Mechanical vibration – Susceptibility and sensitivity of machines to unbalance

This list of the most important papers and awards from the project.

Papers (Total 28)


Presentations (Total 87)


Awards (Total 2)