Japanese Proposal for International Standardization for Active Magnetic Bearing

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Abstract

A basic design for an active magnetic bearing has successfully been developed and trials of it's application to actual rotating machines are expanding widely in many industrial fields. However, there are a few industrial field where AMB is the best option in the selection of a bearing for rotating machinery. Accordingly, Japanese experts have proposed international standardization for AMB to the ISO. The objectives of the standardization are as follows:
(1) to serve as a design guide for AMB to achive compatibility , low priced products and wide-spread applications;
(2) to provide vibration and current criteria in commission and maintenance to rapidly resolve conflicts between venders and users and to assure users safe operation;
(3) and to define AMB terminology to promote mutual understanding between research engineers, development engineers, designers and users of AMB.

JSME/ATS10-25 Technical Section for Standardization on Active Magnetic Bearing is preparing a draft on vibration criteria and terminology and will propose the draft at a meeting of the ISO/TC108 in Sydney on 16 September 1996.This paper provides a draft of an initial list of terminology which contains nearly 100 relevant terms in English for AMB, and the fundamental ideas for the new regulation concerning the vibration of AMB equipped turbomachinery.

1. Introduction

A few types of active magnetic bearing(AMB) equipped rotating machinery are currently being successfully implemented in commercial business since the development phase of the AMB borne rotor. Some successful examples include turbo-molecular pump, expander in chemical plant, spindle in machine tool and centrifugal compressors in turbomachinery. The new concept of the AMB is indeed welcome due to its features of being contact free ,maintenance free, without mechanical losses,etc..

When considering centrifugal compressors, the stiffness of oil-film bearings is relatively high compared with AMB; the rotor vibration is suppressed within low vibration levels as regulated by ISO and/or API standards. On the other hand, the stiffness of the AMB is so weak that the rotor vibrations exhibit large amplitudes. However, this state is perfectly normal for AMB vibration control operation. In addition to the vibration level, the AMB operation requires a large current margin in the electric power supply unit. As seen in this comparison between these bearing types, the present ISO regulation for the conventional bearings is not valid for AMB equipped rotating machinery.

Generally speaking, customers require low vibration levels. Therefore, manufacturers must explain the new design and concept of AMB related rotating machinery that allows the relatively high vibration levels. This is a potential cause for conflict between customers and manufacturers.

ISO adopted standardization on vibration of Active Magnetic bearing as a new work item of ISO/TC108/SC2 in August 1993. JSME/ATS10-25 Technical Section for Standardization on Active Magnetic Bearing is preparing a draft on vibration criteria for AMB equipped rotating machinery. This effort will also include identification and eventual definition of related terminology in order to resolve expeditiously the conflict between customers and venders and to promote further application of AMB to many industries. JSME/ATS10-25 is interested in the standardization of (1) AMB related terminology, (2) vibration regulations for AMB rotor, (3) AMB hardware specifications and (4) AMB electronics specifications. Initially draft of (1) and (2) will be proposed and discussed at a meeting of ISO/TC108/SC2 /WG1 in Sydney on 16 September 1996.

In this paper, JSME/ATS10-25 prepared the draft list of terminology which contains nearly 100 relevant terms in English for AMB and the fundamental ideas for the new regulation for AMB rotor vibration. The collected terminology contains technical terms for mechanical and electrical hardware, electro-magnetics, rotordynamics and control and monitoring. The terminology is divided into two parts; primary words which are considered to have the most priority to be defined and secontary words will be defined at a later date. The vibration regulation is concerned with the permissible vibration level, the allowable vibration change during stationary operation and the current margin for the power amplifier. The committee would appreciate feedback on the draft from participating experts attending the symposium.

2. Terminology

2.1 PrimaryTerminology

(1) general

1-axis controlled bearing: a magnetic bearing which controls vibration and motion in the axial direction and has passive devices for radial directions

5-axis controlled bearing: a magnetic bearing which controls vibration and motion in all directions without spin axis

active magnetic bearing: a bearing to support the rotor at the center position using magnetic attractive force based upon servo feedback technology

bearing clearance: the clearance between the rotor yoke and the stator core

bearing loss: iron loss in the rotor and the stator, copper loss in coils, friction loss on the bearing rotor surface and circuit loss in the electric equipment

bias current: DC component added to the coil current to decrease the secondary power non-linearity of the attractive force against the coil current

bias flux: useful for non-linearity correction of force and coil current. Usually the bias current is prepared in the coil. But, permanent magnet can be replaced in stead of bias current. Of course, it is placed into the magnetic flux loop.

center of bearing: the center of the inner diameter of a radial bearing stator

dynamic load capacity: a maximum value of load varying with time supported by the AMB

DN. value: the product of the revolution per minute and the inner diameter of the stator of a radial magnetic bearing

effective bearing length: effective axial length of a radial bearing stator (L in fig.1)

flux saturation: flux saturation of the magnetic material

hybrid magnetic bearing: a magnetic bearing which has active and passive magnetic bearings

levitation: lifting a rotor by magnetic force in defiance of gravity

load capacity: a maximum load which a magnetic bearing can supports

load pressure: carrying load per projection area of a bearing

magnetic attractiive force: magnetic attractive force is caused between two magnetic materials in a magnetic field

magnetic bearing: a bearing which utilizes either magnetic attractive or repulsive force for levitation of a rotor

number of poles: total number of s-poles and p-poles

passive magnetic bearing: a magnetic bearing which has some permanent magnets and does not use a feedback control

projection area of bearing: multiplication of the inner diameter of a radial bearing stator by the bearing length

radial magnetic bearing: a magnetic bearing which supports radial forces exerted on a rotor

sensorless bearing: AMB includes the function of rotor position detection without the use of a displacement sensor.

shaft displacement: displacement of the rotational center of a shaft from the bearing center

static load capacity: a maximum load capacity, of which load doesn't vary with time

thrust magnetic bearing: a magnetic bearing which supports an axial force on the rotor

(2) rotor

mechanical(shaft)damper: a mechanical damper which is fitted on a shaft and has a tuned spring-mass system

radial yoke: a rotating side member consisting of radial magnetic bearing(ref.Fig.1)

flexible rotor: a rotor is considered to be flexible when the rotational speed is near or higher than the first flexural critical speed.

thrust yoke: a rotary part of the axial magnetic bearing, a disk on the rotor(same as thrust disk) (ref.fig.2)

(3) stator

allowable temperature: the ambient temperature which is allowed for the bearing operation

area of magnetic pole: the cross section area of each magnetic pole

dynamic damper: the mechanical casing damper which is fitted on a bearing casing and has a tuned spring-mass system

magnetizing coil: coils which give magnetic properties to the bearing core

radial coil: a magnetizing coil wound around poles of radial bearing or the radial electromagnetic pole itself

radial core: a stationary part of the radial magnetic bearing around which the magnetizing coil winds (ref.Fig.1)

stator core: a magnetic core of the stationary part of the bearing

thrust coil: magnetizing coils of the axial magnetic bearing

thrust core: a stationary part of the thrust magnetic bearing around which the magnetizing coil winds (ref.Fig.2)

(4) sensor

radial displacement sensor: a displacement sensor for detecting radial displacement of the shaft

thrust displacement sensor: a displacement sensor for detecting axial displacement of the shaft

displacement sensor: a sensor which is installed on stationary part and detects shaft displacement without contact

sensor target: an object installed on the rotor to detect a clearance between the rotor and the stator by a displacement sensor

(5) dynamics and control

allowable vibration: a vibration allowance under which the machine supported by the magnetic bearing operates continuously

auto-balancing control: a balancing method which automatically detects and corrects an unbalanced mass of the rotor by forces from magnetic bearing to minimize shaft vibrations.

automatic balancing: an automatic balancing of the rotor such as to rotate the rotor around its principal axis of inertia. As a result, shaft vibration remains, but the synchronous component of bearing casing vibration is minimized.

bearing damping: a force which is exerted on the rotor by a bearing and is proportional to the shaft velocity vibration

bearing stiffness: a stiffness from a magnetic force which is exerted on the rotor by a bearing and is proportional to the shaft displacement vibration

bending mode: a natural vibration mode of the rotor which is bent near resonant speeds

bending mode critical speed: a resonant speed with a natural frequency with a shaft bending mode.

bode diagram: a diagram for which the abscissa indicates frequency and the ordinates indicate gain and phase of a transfer function of a control system

conical rigid mode: a natural vibration mode for which the whirl shape is conical and straight.

critical speed: a rotating speed which coincides nearly with a natural frequency of the rotor and at which shaft vibration indicates maximum value.

critical speed of rigid mode: a critical speed for which the mode is rigid

cross-coupled control: a control method for radial bearing for which the displacement signal from a sensor of perpendicularly intersecting control axis is fed back to another control axis.

current feedback: a method which improves the electromagnet characteristics by sensing the electromagnetic coil current and feeding it back to the power amplifier

decentralized control: a control structure that has no interconnection between the five axes.

dynamic stiffness of bearing (closed loop): the bearing stiffness at a given frequency taking into account of the rotor inertia

dynamic stiffness of bearing (open loop): the bearing stiffness at a given frequency without taking into account of the rotor inertia

gain scheduled control: a control method which adapts or updates its gain or transfer function by a predefined way

negative stiffness: stiffness due to current in the bearing and that has negative sign

parallel and conical mode: translating and declining vibration modes of the rotor

principal axis of inertia: the central principal axis (one of the three such axes) most nearly coincident with the shaft axis of the rotor, sometimes referred to as the "balance axis" or the "mass axis"

rigid mode: a vibration mode which is determined by rigid rotor inertia and bearing stiffness

rigid rotor: a rotor for which the first bending natural frequency is higher than the operational speed

static stiffness: dynamic stiffness at frequency = 0

tuning: a process of adjusting the controller's gains at the initial operation so as to rotate a rotor in good condition with a magnetic bearing system

unbalance compensator: a compensator which offsets rotor unbalance to minimize shaft vibrations

(6)electronics

analog controller: a controller for a continuous system implimented by only analog devices

controller: electronics which regulates the magnetic control force

digital controller: a controller for a discrete-time system or sampled-data system implimented by digital devices

linear amplifier: a power amplifier in which the output quantity is essentially proportional to the input quantity

magnetic bearing control system: a system which controls magnetic bearing force and consists of displacement sensors, controller, power amplifiers, electromagnets and DC power supplier.

notch filter: a filter which has a characteristic like notch for suppressing or minimizing waves or oscillations of a selected frequency

phase lead-lag controller: a controller which shifts the phase of the signal to regulate a magnetic force

PID controller: a controller which has adjustable devices for proportional , integral and differential signal gains

power amplifier: an amplifier which can supply high voltage and large current output in order to get a strong force or to get high energy

PWM amplifier: a power amplifier which adopts the Pulse Width Modulation method

tracking filter: a filter for transmitting electric signals for which frequencies are synchronized with the rotational speed

(7) auxiliary equipment

back-up battery: a battery which operates during power supply failure

battery back up operation: an operation during which a back-up battery is used to continue normal operation during an emergency

touch down bearing: emergency bearings which are installed near the magnetic bearing to decelerate and stop a rotor safely without any damage in case of a control failure of the magneticbearing

touch down bearing clearance: a radial clearance between the inner diameter of the touch down radial bearing bore and the outer diameter of the sleeve of a rotor, or the axial clearance between the back face of a touch down bearing thrust bearing and the shaft shoulder

touch down test: a test that the rotor rotating in the maximum speed is dropped intentionally on an touch down bearing in order to simulate a complete failure of magnetic suspension.

2.2 Supplementary Terminology

(1) general

allowed temperature, axial bearing, bearing width, can, clearance, cooling method, copper loss, dynamic load, eddy current loss, effective bearing width, front bearing, journal bearing, length of coil end, magnetic bearing-motor, magnetic material, magnetic repulsion force, magnetically levitated electric motor, non magnetic material, opposite side (contact) area, permanent magnet, phase, rear bearing, Side_1 ,Side_2, split type radial bearings, stacked journal core, superconductivity, thrust bearing, using circumstance, windage loss

(2) rotor

axial rotor disk, diameter of journal, electrical runout, journal, journal sleeve, laminated yoke, mechanical runout, radial yoke, shrink fit, stopper ring, thrust armature, yoke

(3) stator

axial disk, axial magnet, bearing stator, bias coil, coil , coil windings, coil inductance, core, E-shape core, C-shape core, electromagnet, exciting coil, laminated core, length of core, number of coil turn, pole arrengement, radial electromagnetic stator, radial magnetic pole, sleeve flange of radial bearing, stator, stator coil, thrust collar, width of coil windings

(4) sensor

capacitance displacement sensor, optical (displacement) sensor, sensor yoke

(5) dynamics and control

attenuation constant, attractive motor force, backward whirl, balancing, Campbell diagram, damping coefficient, disturbance, eccentric touch, eigenvalue, forced vibration, forward whirl, free-free mode, frequency characteristics , high speed dynamic balance, magnetic center, magnetic unbalance force, N component, natural frequency, natural mode, nuetation, Nyquist plot, open loop balancing, optimal regulator, peak gain, precession, resonance/anti-resonance, rotation center, self-excited vibration, shaft vibration, sliding mode control, spring coefficient, static load, stiffness curve, synchronous component, tuning free, unbalance response, unstable root

(6) electronics

band pass filter, band width, bias current, closed loop, conductance, constant current drive, control current, current monitor, current slew rate, differentiator, direct power supply, direct resistance, drift, electromagnetic noise, exciting current, flux density, flux leakage, gain, GB-product, leak flux, low-pass filter, magnetic circuit, magnetic permeability, noise, non-sensible zone, observer, phase lag, phase lead, phase shift, power factor, power loss, root locus, sampling time, suspension controller, suspension current, switching frequency

(7) auxiliary equipment

batteryless, carrier frequency, current-carrying capacity, maximum current, number of touch down, eddy current proximity sensor, power supply voltage, pulse -type rotary sensor, speed sensor, stop(landing), touch down sleeve, UPS

3. Vibration

3.1 Background

The main part of the rotating rotor in turbomachinery is still supported by oil-film lubricated bearings. The rotor vibrations are suppressed within low vibration levels. Vibration regulations with respect to vibrations of the stationary and/or rotational parts of the machine for the current type of rotating machines are covered by ISO standard(the ISO 7919/1-8). These ISO regulations consequently require low values for the permissible vibration level.

On the other hand, the design of AMB for effective vibration control requires the placement of AMB at the location of vibration portions of the rotor's eigen modes. Large vibration amplitude is inevitably induced due to the weak supports, through it is normal for AMB control. In addition to considering reasonable vibration levels aspart of the regulation, current margin in the electric power supply is required for AMB safety.

In the case of a process compressor equipped with AMBs, a customer can require compliance with API 617[1] regulation which provides for a low vibration level in the same manner as if the compressor were supported by oil-film lubricated bearings. Similarly the ISO standard, ISO 7919/3

(2) Zone A, also indicates low value for permissible vibrations. These values are too strict for the AMB rotor. Customers generally require low vibration levels. Therefore, manufacturers must explain the new design and concept of AMB related rotating machinery that allows the relatively high vibration levels. This presents a potential conflict between customers and manufacturers. This gap compels us to waive the current ISO standard and, instead to recommend the acceptance of relatively high vibration levels for AMB operation.

Proposed ISO 7919/9:

Vibrations of Active Magnetic Bearing Equipped Rotor

3.2 Scope and Field of Application

ISO/TC108/SC2 discusses the vibration regulation for turbomachinery, turbines, generators, compressors, pumps and so on. The regulation proposed in this paper applies to these large scale rotating machine excluding small scale rotors such as turbo molecular pumps, spindles, flywheels, etc. The regulation covers AMB rigid Rotors and AMB Flexible Rotors.

3.3 Measurement Procedure

AMB equipment in rotating machines has its own displacement sensor for detecting shaft motion within the servo feedback system. The detected value of shaft vibration by the AMB sensor equipment is subject to this regulation. The vibration of the stationary parts of the machine is not included.

3.4 Present Regulations

If the present regulation ISO 7917/3 concerning the bearing vibrations of large scale turbomachines were applied, the vibration regulation would be as follows:

ISO 7919/3 Coupled Industrial Machine

Zone A Spp = $4800/\sqrt{N}$

(Spp = 43 μm_{pp} if TRIP=12500 rpm)

Zone B Spp = $9000/\sqrt{N}$

(Spp = 82 μm_{pp} if TRIP=12500 rpm)

According to the API 617-6 standard regulating centrifugal compressors, the vibration regulation as follows:

$$\text{API 617-6}\ Lv = 25.4\sqrt{\frac{12000}{N_{MCS}}} \text{ and } L_V \leq 25.4\mu m$$

where N_{MCS} =maximum continuos speed

(Lv = 25.4 μm_{pp} if MCS = 9500rpm)

These values are very strict for the commission.

3.5 Recommended Regulations

One of the features of the AMB is large clearance. If the rotor does not contact with the stator, even large vibration is still normal. Therefore, based upon the characteristics of AMB, the vibration criteria are derived from the following parameters:

No contact with bearings, adjacent displacement sensors and touch bearing,

No contact with stationary labyrinth seals and

Limit of current compared to power amplifier capacity.

The first two parameters concerning the clearance indicates bearing clearance, for example, 250 μm for avoiding the rotor rub. As an allowable limit for Zone B, it is recommended that the values of vibrations and current be 60 %, because these values should be a design point. The zone table, therefore, is proposed as follows:

Table 1 Proposed regulations

	Zone value,	compared with	
Zone	clearance	current capacity	Evaluation
A	≦40%	≦40%	good
B	≦60%	≦60%	accepted
C	≦80%	≦80%	be modified
D	>80%	>80%	not accepted

According to this regulation, vibration amplitude less than 150 μm_{p-p} is accepted for 250 μm in clearance. These values are rather large compared with the present ISO or API 617 regulations.

ISO standard regulates that the change in the vibration compared with the average values must be less than 25%

3.6 Experimental Data

As stated in the literature[3] an AMB centrifugal compressor was installed a refinery plant as shown in Fig.3, The vibration for the commission is about 60% of the clearance,i.e.,150 μm_{p-p} as shown in Fig.4. The corresponding field data indicates about 50 μm_{p-p} in vibration amplitude. This machine has been operating in a normal condition since its installation 3.5 years in December of 1993.

Table 2 Radial Bearing Specification

Radial Bearing	Low Pressure Casing	High Pressure Casing
Inner Diameter	147mm	147mm
Bearing Length	150mm	150mm
Avg.Load per Brg	3.82kN	4.55kN
Bearing Capacity	10.13kN	10.13kN
Radial Clearance	0.5mm	0.5mm

4. Conclusions

JSME/A-TS-10-25 Technical section for Standardization on Active Magnetic Bearing has prepared a draft list of terminology and a draft of vibration criteria related to the

AMB technology. This paper contains nearly 100 important terms along with their definitions, more than 150 undefined terms and a preliminary version of proposed regulation on vibration and control current for magnetic bearings. The committee would like to solicit the review of this draft from experts in many countries in order to work together to refine these proposed standards on magnetic bearing.

References

[1] API-617/6 Centrifugal Compressors for Genaral Refinery service(1995)

[2] ISO 7919 : Mechanical vibration of Non-Reciprocating Machine - Measurements on Rotating shafts and Evaluation.

[3] Y. Fukushima, et. al 4, Totally Oilless Centrifugal Compressor in Oil Refinery Service, Proceeding of Advancement in Bearing and Seal Technologies, June 13-16, 1994, Calgary, Canada

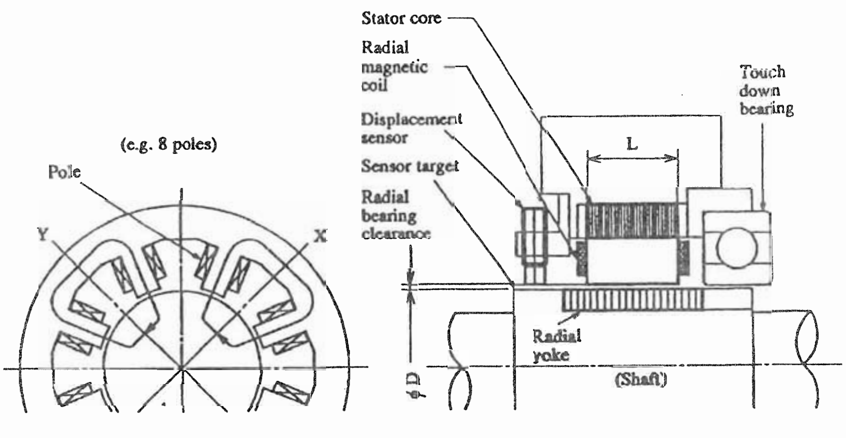

Fig.1 Radial Magnetic Bearing

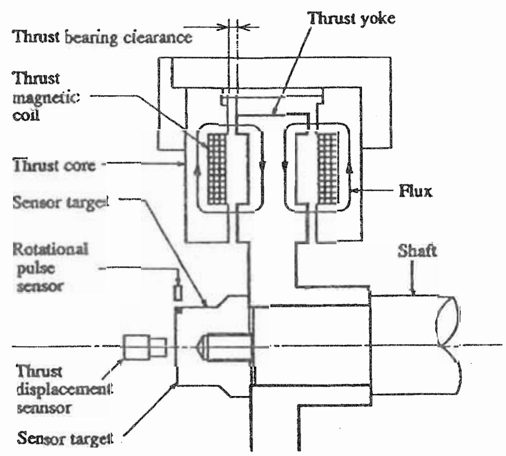

Fig.2 Thrust Magnetic Bearing

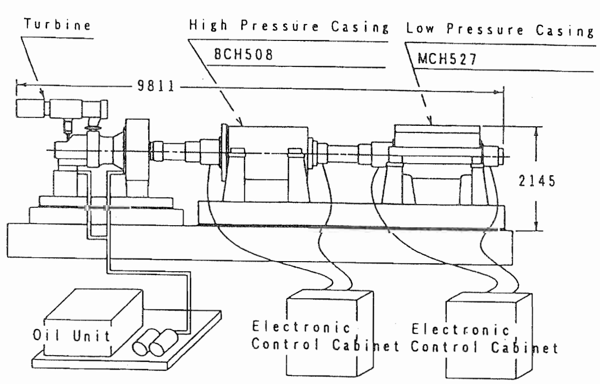

Fig.3 Arrengement of centrifugal Compressor with Magnetic Bearings

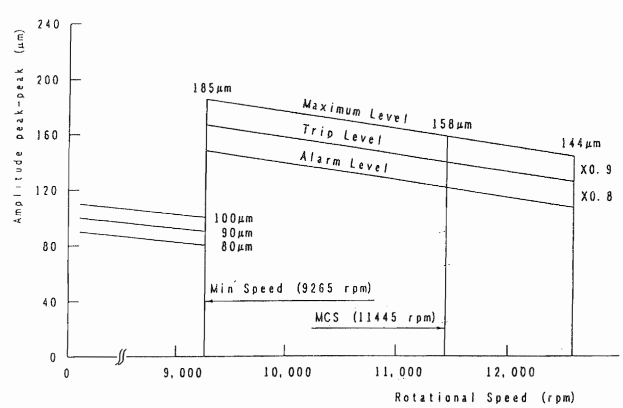

Fig.4 Limitation of Vibration Level for Magnetic Bearing sensors (Low Pressure Casing)