Specifying magnetic bearings

APPLICATION AND IMPACT OF NEW INDUSTRY STANDARD ISO 14839

PHILIPP RICHARD AND RENÉ LARSONNEUR
MECOS MAGNETIC BEARINGS

In the last ten years, active magnetic bearings have come out of the laboratory and become established alternatives to high-performance bearings (p. 16, Sept./Oct. 2006). As their use becomes more widespread, the turbomachinery industry has been asking for guidelines and standards for design, acceptance and operation of rotating machines equipped with magnetic bearings. Although standards, such as API 617, cover a broad range of topics related to bearings in turbomachinery applications, there is a need for a more specific code focusing on the unique properties and capabilities of magnetic bearings.

The ISO 14839 standard (Table 2), covering vibration, stability and robustness for magnetic bearings used in turbomachines, could satisfy this need. And it could help evolve an industry consensus on the requirements for the performance of these systems, deepen user understanding of magnetic bearing technology, and improve user-supplier relationships.

Insufficient codes

Several standards are in use today that deal with rotordynamics in turbomachines (Table 1). The best known is the API 617, which covers applications such as centrifugal, axial and integrally geared compressors, as well as expander-compressor systems. API 617 provides guidelines for the design, manufacturing, modelling and testing of these systems.

All these standards emerged from the needs of classical turbomachines equipped with oil bearings rather than magnetic bearings. Consequently, they do not account for the unique properties of magnetic bearing-equipped machines, which are fundamentally different from those of machines with oil bearings. For instance, components of magnetic bearing systems are not subject to wear and fatigue when exposed to high vibration levels from unbalance.

In fact, magnetic bearing-equipped machines are suitable for unlimited, reliable and safe operation even in the presence of "large" residual unbalance levels. By allowing the rotor shaft to rotate about its principal axis, they have the ability to nearly eliminate bearing reaction forces induced by unbalance. For this reason, the laborious and expensive process of establishing and verifying residual unbalance levels, as extensively described in API 617 and ISO 1940, is unnecessary and "obsolete" for magnetic bearings.

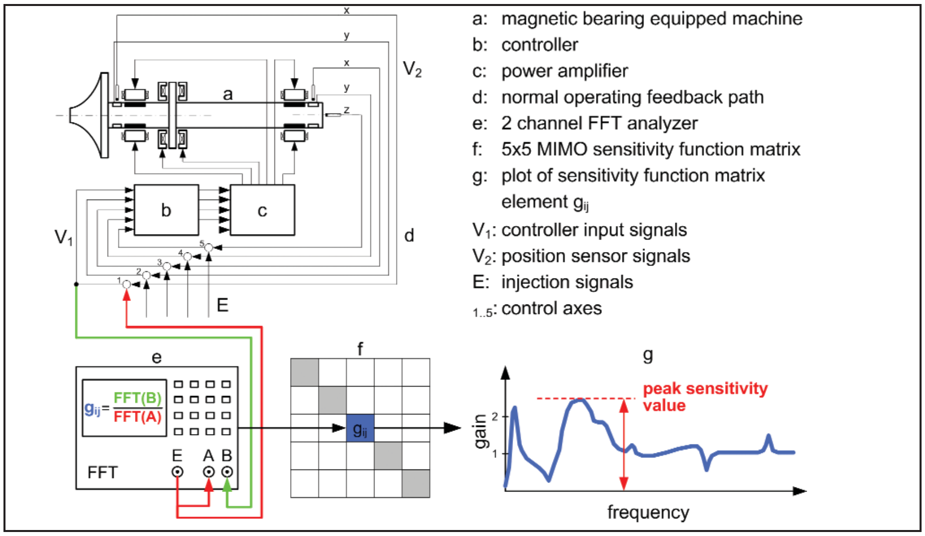

Figure: A set up that measures the "sensitivity function" of a magnetic bearing system for a turboexpander. The Multiple Input Multiple Output (MIMO) framework can help establish the "robustness" of the control system, as required by ISO 14839

Standard	Scope of application
API 617	Design, manufacturing, modelling and testing of turbocompressors and expanders
ISO 1940	Balancing grades
ISO 10814	Stability and transient vibration condition evaluation
ISO 7919-1	Vibration measurement of rotating shafts

Table 1: Current standards (above) do not take into account all the unique features of a magnetic bearing control system

Standard	Scope of application
ISO 14839-1	Vocabulary
ISO 14839-2	Evaluation of vibration
ISO 14839-3	Evaluation of stability margin (available as draft)
ISO 14839-4	Technical guidelines (under preparation)

Table 2: The proposed ISO standard targets magnetic bearing systems and evaluates the robustness of the bearing controller

Annex 4F of API 617, which is dedicated to magnetic bearing-equipped machines, does address this issue. The annex specifies a maximum allowable rotor movement relative to the center of the auxiliary bearing to assess unbalance vibration, and clarifies that "… this criterion supersedes all other vibration acceptance criteria as described for oil bearing machines …" While this is correct, there are other aspects of magnetic bearing systems, such as stability and robustness, that API 617 does not consider.

Magnetic bearings are actively controlled systems that rely on the feedback of the rotor position or other measurable system states and, therefore, represent a closed-loop system architecture. The rotor, the bearings, sensors and power electronics constitute a dynamic system with properties that can be set by designing a controller with the required closed-loop stability and robustness.

To date, the term "robustness" of a closed-loop system has not received adequate attention and is sometimes even equated with the term "stability." Typically, a controller is designed as per a mathematical model that simplifies a "real-world" situation. But no real physical system truly behaves like the differential equations used in the math. Therefore, controllers must be "robust"

Zone	Range of peak sensitivity value
A	0...3 (<=9.5 dB)
B	3...4 (<=12 dB)
C	4...5 (<=14 dB)
D	5...infinity (>14 dB)

Table 3: ISO 14839 lays down peak sensitivity values for achieving an acceptable robustness of the magnetic bearing control system

so that their properties do not change significantly if applied to a system slightly different from the mathematical one.

A closed-loop system can be "very stable," but at the same time, "not robust," i.e., it can be sensitive to changes in its nominal parameters. For instance, a rotor shaft whose bending mode is actively damped by magnetic bearings can be "very stable," depending on the amount of damping introduced. However, the system can become unstable if the resonance frequency changes "slightly," which could occur due to thermal effects on rotor shafts.

While closed-loop stability can be assessed by criteria such as amplification factors, i.e., the sharpness of vibration peaks near resonance frequencies, there has, to date, not been an appropriate measure to assess system robustness. Part 3 of the new ISO 14839 standard, which is available as a draft, addresses this problem by introducing a "sensitivity function" to measure system robustness. This approach is based on the latest control theory concepts.

Parts 1 and 2 of ISO 14839 incorporate Annex 4F of API 617. Assessment criteria and vibration zone definitions are similar, thus easing transition from the API to the ISO framework. However, ISO 14839-3 is self-contained and exclusively addresses system robustness.

New criteria

In control theory, the "Nyquist" criterion has long been used to assess a system's stability margin. But this criterion is typically under a Single Input Single Output (SISO) framework. ISO 14839-3 generalizes this concept and extends it to a Multiple Input Multiple Output (MIMO) framework to measure robustness.

For instance, for the turboexpander in the Figure, applying the ISO standard would mean that a five-by-five sensitivity function matrix involving all control axes of a magnetic bearing system should be measured. The matrix is defined by five sensor signals ($V_{1...5}$) and five excitation signals ($E_{1...5}$).

The measurement can be done by injecting suitable test signals into the feedback path (red signal in Figure), measuring the corresponding system response (green), and finally computing the transfer function (blue) between test and response signals through a Fast Fourier Transform (FFT). A two-channel frequency analyzer is capable of carrying out this task. But measurement channels will have to be sequentially switched from one control axis to another in order to determine all elements of the matrix. The process can be laborious and time-consuming.

However, the ISO standard provides a simplified method that only requires measurement of the five diagonal elements of the sensitivity function matrix. The error introduced by this simplification is negligible for magnetic bearing systems that are commonly used.

The peak value of each element of the sensitivity function matrix is determined, and the maximum of these values is considered for final assessment. Depending on the maximum peak value, the system is classified into zone A, B, C or D (Table 3). Systems with sensitivity function peaks within zones A and B are considered suitable for unrestricted, long-term operation. Their performance is not expected to deteriorate drastically due to changes in nominal parameters during machine life time.

Part 3 of ISO 14839 provides a simple and easily manageable evaluation method, as well as consistent assessment criteria, for system robustness. Thus, the standard not only simplifies commissioning and maintenance, but will also help to promote a consensus in the industry regarding performance requirements. It will improve mutual understanding between vendors and customers.

The turboexpander application described above takes advantage of an inherent feature of active magnetic bearing systems, namely its built-in instrumentation. In addition to levitation, the bearings also serve as actuators that transform the injection signals needed for stability and robustness assessment into superimposed excitation forces. Similarly, the position sensor signals are used for levitation control and system response measurement.

This idea can be extended to include the replacement of external signal generators and fourier analyzer units with software within the existing magnetic bearing controller. Signal injection, FFT computation, dynamic frequency response measurement, and functions performed by digital storage oscilloscopes can all be added, making external instrumentation virtually superfluous. All these make it easy to apply the ISO criteria.

A laptop computer used onsite or connected remotely is sufficient to do the job. Graphical output facilitates communication with the customer, who benefits from having a standardized reference for specification, acceptance and long-term monitoring of the machine.

Enhancing measurements

The built-in measurement capabilities can do more. An integrated measurement system *[1]* can offer:

- SISO and MIMO measurement of arbitrary open- and closed-loop transfer functions at any rotor speed
- Identification of gyroscopic effects and generation of Campbell diagrams (frequency vs speed plots) automatically
- Multi-variable signal injection with freely selectable frequency, amplitude, phase, and injection point
- Continuous monitoring and analysis of system states, such as displacement, temperature or balancing conditions
- A real-time and multi-channel oscilloscope with built-in trigger, step response measurement and FFT computation functionalities
- On-line rotor balancing tool
- Versatile control parameter design and simple download of complex parameter structures

An integrated measurement system has the flexibility to accomplish tasks that can be complex and time-consuming. For example, it is possible to continuously monitor bending mode frequencies as part of a preventive maintenance program and detect undesirable changes at an early stage.

Footnote:

[1] MECOS (www.mecos.com) offers an integrated measurement system that incorporates the capabilities and can be embedded on Matlab, a commonly used software.

Authors:

Philipp Richard is the product manager at MECOS TRAXLER AG (www.mecos.com). A power electronics engineer, he helped develop an integrated magnetic bearing and motor controller.

René Larsonneur is responsible for the development of control concepts and software tools at MECOS. He is a member of the ISO technical committee for the new magnetic bearing standard. 2007 marks his 25th year in magnetic bearings.