INDUSTRY ACCEPTANCE OF MAGNETIC BEARINGS THROUGH STANDARD SPINDLE SOLUTIONS

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ABSTRACT

Magnetic bearings are able to provide real value to users in many different industries. They often provide solutions to difficult problems where other bearing technologies fail. Until now, magnetic bearings have typically required high non-recurring engineering costs to address individual customer requirements. This can translate into an initial purchase price that outweighs the benefits and reduces customer accessibility of magnetic bearing solutions. To increase industry acceptance of magnetic bearings the authors' are presenting a two-tiered solution to reduce non-recurring engineering costs and increase customer accessibility to magnetic bearings. This paper will present the authors' approach to developing this solution together with a case study example.

INTRODUCTION

Often, a magnetic bearing user will have a payload design (e.g. turbomolecular pump (TMP) rotor, neutron chopper slit package, turbo blower for power lasers, copper tube groover) that they wish to rotate over a desired speed range. Incorporation of magnetic bearings into a rotating machine design can provide reliable operation, high-speed rotation, high precision rotor positioning, low casing vibration and low rotor losses. Magnetic bearings may be tailored to operate in a wide range of difficult environments, including high vacuum or caustic environments.

Magnetic bearing solutions provide many advantages to customers who seek solutions to highly specialized system applications. The range of payload designs between users varies widely in mass and inertia properties. Furthermore, magnetic bearing users intend to satisfy a wide range of performance requirement specifications. For example, a pump designer may require high load capacity, tolerance to pump surge and operation in a caustic fluid environment while on the other hand, a TMP designer may require extremely low housing vibration levels, low rotor heating and operation in a vacuum environment. Consequently, high non-recurring engineering (NRE) costs exist because of the high level of customization required to meet the specific needs of rotating machinery designers.

BARRIERS TO INDUSTRY ACCEPTANCE OF MAGNETIC BEARING SOLUTIONS

Customization of a magnetic bearing solution necessitates sizing of a spindle to meet customer requirements. This involves sizing the rotor, bearings, and motor to achieve the desired rotordynamics, bearing capacity, and motor power and speed requirements. Tuning of the magnetic bearing control is necessary to integrate the spindle into the customer environment, insure robustness and meet customer performance specifications. This approach typically results in high NRE costs reducing customer accessibility of magnetic bearing solutions.

INCREASING INDUSTRY ACCEPTANCE OF MAGNETIC BEARINGS

The authors' objective is to increase industry acceptance of magnetic bearings using standard spindle solutions. To accomplish this objective the authors are presenting a two-tiered solution to reduce the amount of NRE costs and increase customer accessibility to magnetic bearings. The first tier is a line of standard spindles that covers a large part of the range of customer requirements and allows for the application of a wide range of payload geometries. The second is a rapid prototyping software tool that allows modeling, simulation, and control synthesis to be quickly and efficiently performed by the application engineer.

Standard Spindle Solutions

A range of Revolve/SKF Hyperspin™ spindles exists to cover the large range of customer requirements and wide range of payload geometries. Hyperspin™ spindles all have the following characteristics: overhung payload attachment, integral motor (synchronous or asynchronous), simple interfaces (shaft, housing and electrical), standard payload attachments, low cost, validated rotordynamic models, manufacturing documentation and proven consistency between builds. A sample list of Hyperspin™ synchronous spindles and specifications is tabulated below.

Table 1: Sample of Hyperspin™ synchronous spindles

Revolve/SKF Synchronous Spindles				
	300DC43	500DC34	900DC36	900DC60
Speed max [rpm]	43000	33600	36000	60000
Shaft diameter [mm]	21.4	30	30	29.5
Housing diameter [mm]	89	105	170	170
Overall length [mm]	219	216	315	315
Power output [W]	300	500	900	900
Cooling (None, air, liquid)	Optional	Optional	Optional	Optional
Radial bearing capacity [N]	54	98	267	267
Thrust bearing capacity [N]	205	356	222	222
Casing vibration (µm)	<0.01	<0.01	<0.01	<0.01
MB controller	MB240 or MB350	MB240	MB350PC	MB350PC
Typical Applications	TMP	TMP	neutron chopper	hydrogen circulator
Operating environment	Air, vacuum	Air, vacuum	Air, vacuum	Air

Every standard spindle takes advantage of the inherent benefits of magnetic bearing technology. The overhung capability allows customers to mount an existing payload to the magnetic bearing spindle with little or no NRE. The integral motor allows a turnkey solution without extra interfaces to drive the spindle. The shaft and housing interface design enables the payload and housings to bolt directly to the spindle with minimal redesign. The housing flange uses a simple bolt pattern with an optional o-ring groove to seal in any vacuum or gas environment. The electrical connectors can be hermetically sealed and plug directly into a standard cable that interfaces with a standard digital controller. Shaft interfaces include a choice of a straight bolt on attachment, taper attachment, taper locking element attachment, or welded attachment. These elements combine to make the decision to move to a magnetic bearing platform easier, even for users simultaneously considering non-magnetic bearing solutions.

An envelope of payload specifications including payload mass, polar and transverse inertias, length of payload centre of gravity to attachment point, operating speed and motor power requirement is defined for each of the standard spindles. This "payload space" is used to determine whether a standard spindle solution is feasible for the customer application. Thus, a user is able to select a spindle by simply providing the following payload information: Speed, Inertia, Mass, Power, Length (SIMPL). Determining the suitability of a standard spindle for a given application is accomplished by assessing whether the SIMPL parameters fall within the standard spindle "payload space".

MBSynthesis Rapid Prototyping Software

The MBSynthesis rapid prototyping software allows the application engineer to quickly model customer payloads and synthesize control solutions that meet customer performance specifications. The software is then used to perform simulations of the spindle/payload system in operation subjected to requirements for unbalance and external disturbances. The effects of additional control techniques such as Low Bias Linearization (for low rotor losses) and Adaptive Vibration Control™ (for low housing vibration) are evaluated using the MBSynthesis software tool.

MAGNETIC BEARING USER CASE STUDY

This section presents a case study of a magnetic bearing user to illustrate the authors' two-tiered solution. The user identifies the value of magnetic bearing solutions for their high speed and low housing vibration.

Impeller Payload Characteristics

The impeller has the following mass and inertial properties shown in Table 2 below:

Table 2: Impeller mass and inertial properties

Mass	J	I
3.41 kg	2.73e-3 kg•m^2	1.95e-3 kg•m^2

where J is the polar inertia and I the transverse inertia about the payload centre of mass.

Customer Requirement Specifications

The objective of the magnetic bearing system is to spin an impeller over a desired speed range subject to small aerodynamic loads (700 W mechanical power requirement). The magnetic bearing control system must be stable from zero to over the maximum operating speed range, be tolerant to aerodynamic loading and minimize the need for rotor balancing.

MAGNETIC BEARING CASE STUDY SOLUTION

The first step is to select a standard spindle with the capacity to satisfy customer requirements. The second is payload modeling, controller synthesis and analysis using the MBSynthesis rapid prototyping software to insure a magnetic bearing solution that achieves customer performance requirements.

Selection of Standard Spindle Solution

The first part of the two-tiered solution method is to select a standard spindle suited to the system requirements. A standard spindle offers a solution with very little NRE costs compared to designing a custom spindle for the application. Selection of a standard spindle is based on the SIMPL payload specification.

The spindle motor must satisfy the customer power requirement and system losses due to windage, magnetic bearing, and motor losses. In this example, the customer power requirement (700 W) and total system losses (100 W) result in a total motor power requirement of 800 W. Based on the SIMPL payload data a 900DC60 spindle is selected from Table 1 for the case study example. This spindle is able to run to a maximum speed of 60,000 rpm and has a motor power output of 900 W to satisfy the customer requirement specifications. A mechanical design model of the 900DC60 spindle with impeller attachment is illustrated in Figure 1 below.

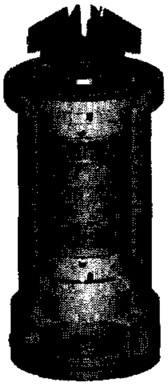

Figure 1: Revolve/SKF 900DC60 spindle with impeller

Use of MBSynthesis Rapid Prototyping Software

The second part of the two tiered solution method uses the capabilities of the MBSynthesis rapid prototyping software. It allows the application engineer to quickly model the payload, formulate a control law design, and perform closed-loop analysis and simulation to verify control system achieves stability and performance criteria. These steps are described below.

Rotordynamic Modeling. Rotordynamic models of the Revolve/SKF standard spindles exist for control system design and analysis. These models are validated against actual spindles using ring test data with a manufacturing process to insure repeatability of rotordynamic characteristics. The spindle with attached impeller uses a lumped mass model that augments the standard spindle model with impeller mass and inertia values.

The application engineer is able to quickly model the shaft/impeller rotordynamics using the MBSynthesis rapid prototyping software. The shaft geometry and rotordynamic output with added impeller properties is depicted in Figure 2.

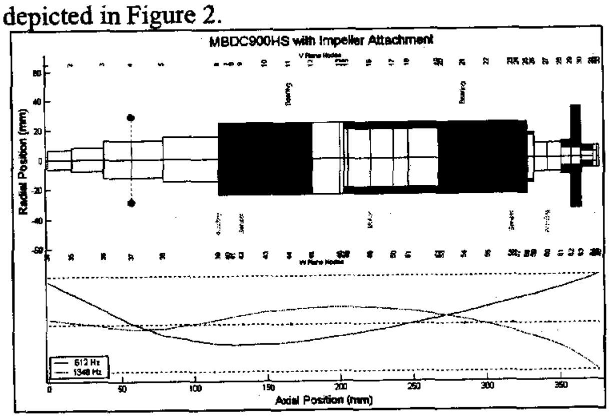

Figure 2: Model of 900DC60 with impeller

The predicted bending modes of the shaft with impeller attachment are shown in Table 3.

Table 3: Model results of 900DC60 with impeller

Mode	Frequency
1st bending	612 Hz
2nd bending	1348 Hz

The modes split with increasing rotor speed into a forward (higher frequency) mode and backward (lower frequency) mode due to rotor gyroscopics.

SISO Tuning. Typically, magnetic bearings are controlled in a Single-Input Single-Output (SISO) manner. SISO control works very well for rotors with small gyroscopic effects. In these situations, an augmented proportional-integral-derivative (PID) transfer function is used. By selecting the proportional, integral, and derivative gains, and adding a low pass filter and occasionally one or two notch filters, well designed non-gyroscopic rotors can be stabilized for their entire speed range with well-damped rotor natural frequencies. This process of selecting gains is referred to as "tuning".

The MBSynthesis rapid prototyping software allows an application engineer to tune a SISO controller and perform a linear closed-loop unbalance response to evaluate the sensitivity of the control system to rotor unbalance. The position and current responses to an unbalance scenario are depicted in Figures 3 and 4.

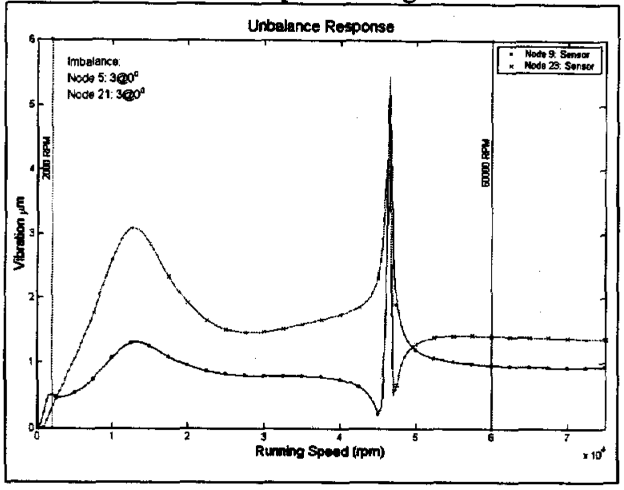

Figure 3: SISO position unbalance response

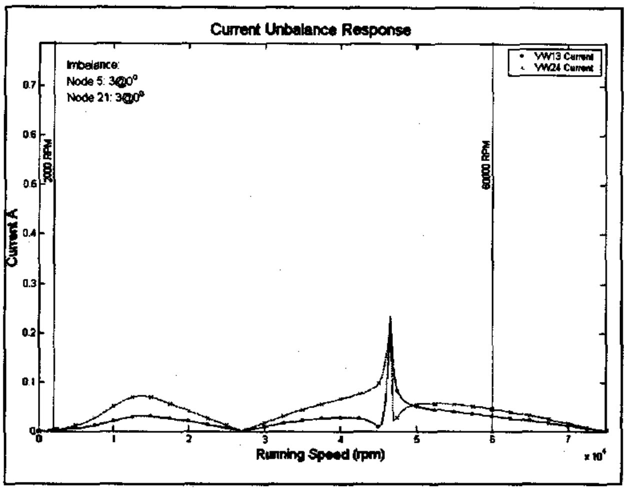

Figure 4: SISO current unbalance response

The position unbalance response in Figure 3 depicts the response of the rotor at the sensor locations to an unbalance excitation. The unbalance excitation uses 3 g•mm of unbalance mass applied in-phase at each end of the rotor. There is a large response to the unbalance excitation at 46,500 rpm corresponding to the forward mode of the rotor. This response can also be seen from the peak in the current response depicted in Figure 4. The tuning is marginally stable at the forward mode rotor frequency only when operating at high speeds.

The tuning is sensitive to rotor unbalance, evident from calculation of the amplification factor defined by API Standard 617 [1]. The standard covers the minimum requirements for centrifugal compressors used in petroleum, chemical, and gas industries that handle air or gas. Evaluation of the peak in position response at 46,500 rpm illustrated in Figure 3 results in a very poor amplification factor of 70. According to API a separation margin of 26% from the critical response peak is required allowing an impeller operational speed range of 0 to 34,000 rpm.

MIMO Control System Synthesis. Fundamentally, a 5-axis magnetic bearing system represents a coupled system. This is also referred to as a Multi-Input Multi-Output (MIMO) plant and implies that an input to the system will generally affect all outputs. For the magnetic bearing system, a force input at the bearing input to a levitated rotor produces a position displacement in-plane with the force input at each of the two sensor outputs. This behaviour is consistent for rotors that are non-gyroscopic in nature. A rotor that is gyroscopic in nature results from a rotor with a higher ratio of polar to transverse inertia (referred to as the J/I ratio). A higher ratio causes an angular speed dependent cross-coupling between orthogonal rotor axes. This cross-coupling causes a force in one plane to create a position displacement in the orthogonal axes. Thus, the same force input applied to a gyroscopic rotor will also produce position displacements at each sensor output in the orthogonal axes.

SISO tuning has been successfully applied to a wide variety of machines. However, when gyroscopic effects are added applying more sophisticated control techniques can make improvements. To provide optimal control for gyroscopic rotors a MIMO control approach is appropriate, which uses the signals from all position sensors to control force applied by each bearing actuator. This allows the controller to close feedback loops around all of the cross-coupled gyroscopic effects, thus enabling the controller to stabilize the rotor.

Application of advanced control algorithms can often greatly enhance machine performance. However, this increases the complexity of the control task. Advanced control algorithms require the development of rotor modeling, controller design and simulation tools. These tools are included in the MBSynthesis rapid prototyping software to allow application engineer to synthesize advanced MIMO control algorithms and evaluate closed-loop designs. Linear closed-loop unbalance responses are presented for a MIMO control law synthesized for the case study example and compared to initial SISO tuning results. The position and current responses for the MIMO control design are depicted in Figures 5 and 6 below. The same unbalance configuration is used as in the SISO tuning example.

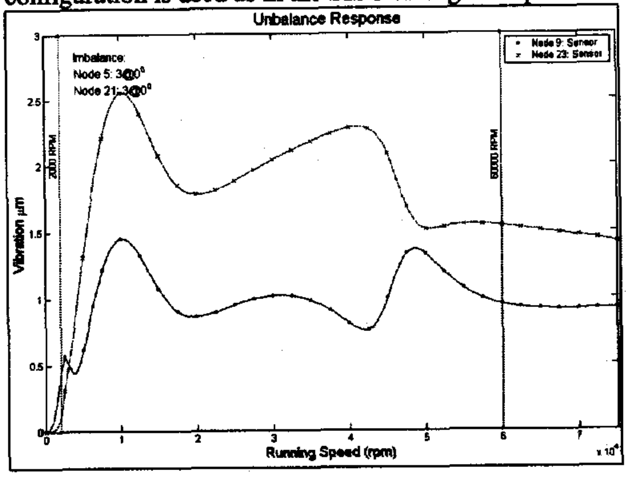

Figure 5: MIMO position unbalance response

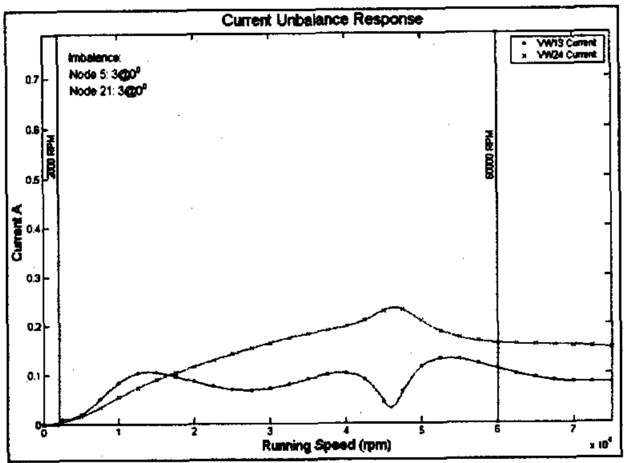

Figure 6: MIMO current unbalance response

The position unbalance response in Figure 5 illustrates the response at the sensor locations of the shaft to the unbalance excitation. The control provides a closed-loop system that is stable and well damped throughout the operating speed range. The position response illustrated in Figure 5 results in a response with no amplification factor, according to API Standard 617 the response is critically damped, and no separation margin is required. The current unbalance response depicted in Figure 6 demonstrates acceptable magnetic bearing current levels. Thus, the magnetic bearing system is stable and able to provide an impeller operational speed range from 0 to 60,000 rpm.

Additional Control Solutions. Additional control techniques such as Adaptive Vibration Control™ (AVC™), for low vibration, and Low Bias, for low rotor loss, allow the application engineer to address specific user needs. AVC™ is a control algorithm that measures and injects forces through the magnetic bearings to cancel synchronous unbalance and reduce rotor vibration levels. Alternatively, AVC™ may be used to cancel synchronous currents and reduce housing vibration levels.

Low Bias uses lower DC control currents to reduce rotor losses and subsequently reduce rotor heating. This is important in applications, such as operation in a vacuum, where heating concerns are critical and radiation is the only form of heat transfer for the magnetic bearing system. Reducing DC currents remedies heating concerns but may result in a reduced dynamic capacity. A tradeoff between the conflicting requirements may be evaluated by the application using the MBSynthesis software for a solution that satisfies the customer requirement specifications.

CONCLUSION

The authors have presented an approach that enables many rotating machinery designers to apply magnetic bearings to their equipment. Frequently, a large portion of the cost of adopting magnetic bearing technology is the non-recurring engineering cost of building a prototype unit. The authors have presented an approach to reducing this NRE expense by providing a line of standard spindle solutions capable of carrying a wide range of payloads while meeting customer performance specifications. Application of the payload to the chosen standard spindle is facilitated using a set of rapid prototyping software tools, which allow efficient and complete modeling, control synthesis, and simulation of the spindle/payload system in operation.

This approach will allow cost effective demonstration of the many advantages of magnetic bearings in a wide range of applications to which applying this technology was previously cost-prohibitive.

References

1. American Petroleum Institute, Centrifugal Compressors for Petroleum, Chemical, and Gas Service Industries, API Standard 617, 6th Edition, Washington, D.C. Feb. 1995