Active Magnetic Bearings

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Abstract

Active magnetic bearings (AMBs) are an alternative to conventional bearings that levitate a shaft by electromagnetic forces. They may be implemented in a wide range of rotating machinery, particularly hermetically-sealed compressors. They offer a number of advantages, however end-user experience is limited and their reliability is uncertain. The purpose of this project has been to explore the rotordynamics, reliability and failure modes of AMBs.

Available failure data for AMBs is limited and outdated. A preliminary reliability target was calculated by considering the components in conventional compression trains that would be replaced by an AMB system in a hermetically-sealed compressor. Failure modes were explored using an AMB test rig. Failures were most frequently related to high vibration, and downtime was largely due to controller tuning updates. A close and ongoing relationship with the AMB vendor is required.

1.   Introduction

1.1   Active Magnetic Bearing Industrial Motivations

Active magnetic bearings (AMBs) are an established technology and are applicable to a wide range of rotating equipment including cryogenic compressor-expanders, subsea, pipeline and other compressors, steam and gas turbines, pumps, generators, fans and electric drives (Swanson et al, 2014). Although AMB-equipped turbomachinery has been in operation for several decades, AMB technology is yet to reach widespread acceptance in the oil & gas industry. This primarily stems from limited end-user experience and uncertainty surrounding AMB reliability and life cycle costs.

AMBs offer several advantages over conventional bearings, including the elimination of oil lubrication systems, reduced equipment footprint and potentially higher reliability due to reduced overall equipment part count. They are a key enabling technology for compact, high speed, high power density, direct-drive turbomachinery, particularly hermetically-sealed, integrated compressors (Kleynhans, 2005). AMB rotordynamic capabilities also exceed those of conventional bearings, due to digitally adjustable physical characteristics such as stiffness and damping, and imbalance compensation algorithms (Schweitzer et al, 2009).

The notable disadvantages of AMBs are their lower load capacity, the restricted power range for AMB-equipped machinery and potentially higher capital expenditure.

1.2　　Active Magnetic Bearing Fundamentals

Active magnetic bearings are used to levitate a rotating shaft via electromagnetic forces. The rotor is regulated at the centreline via closed loop feedback using position sensors, a digital controller, power amplifiers and electromagnets. The system also includes an external power supply and auxiliary mechanical bearings that support the shaft in the event of AMB failure.
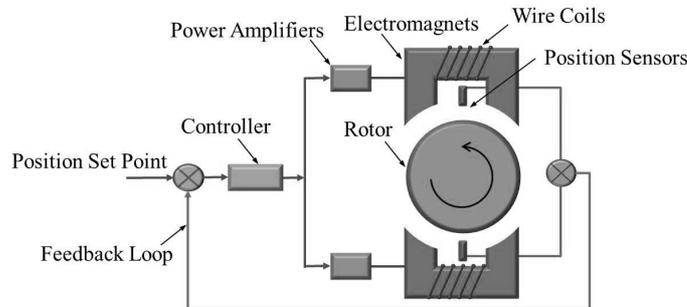
Figure 1　　Basic active magnetic bearing components

1.3　Literature Review

The literature regarding active magnetic bearings is overwhelmingly concerned with the design of advanced control algorithms, particularly with respect to minimising vibration due to shaft imbalance. A summary of these papers is provided in Schweitzer et al (2009).

Published reliability data is scarce and predominantly outdated. For example, the reliability considerations in Sears & Uptigrove (1994) focus heavily on components that are redundant or significantly improved in more recent AMB designs, such as chillers, analog control components and wiring insulation. Auxiliary bearings were noted as the most problematic mechanical component. This remains a persistent area of concern today. The discussion of reliability in Schweitzer et al (2009) is typical of the body of literature and is from the perspective of AMB design improvements, such as introducing redundant components. Failure rate and severity are not discussed. Reliability is consistently described in literature as being 'high' with little quantitative verification of this.

1.4　Project Objectives

The purpose of this project was to investigate the rotordynamics, reliability and failure modes of AMB equipment in order to assess their capability and address some of their surrounding uncertainty. This was undertaken via both theoretical and experimental methods.

2.　Project Methodology

2.1　Rotordynamic Experiments and Failure Modes

An active magnetic bearing test rig featuring two radial AMBs is used in this project, as shown in Figure 2. An external controller, responsible for shaft levitation and motor control, is connected to the test rig and manipulated via computer software. An external signal monitoring and injection module is also attached to the controller. This test rig is to be used for rotordynamic experiments and to investigate AMB failure modes.

Controller Junction Box — Speed Sensor — Radial Magnetic Bearings
Motor   Coupling   Mass Ring
Auxiliary Ball Bearings   Rotating Shaft   Electromagnets
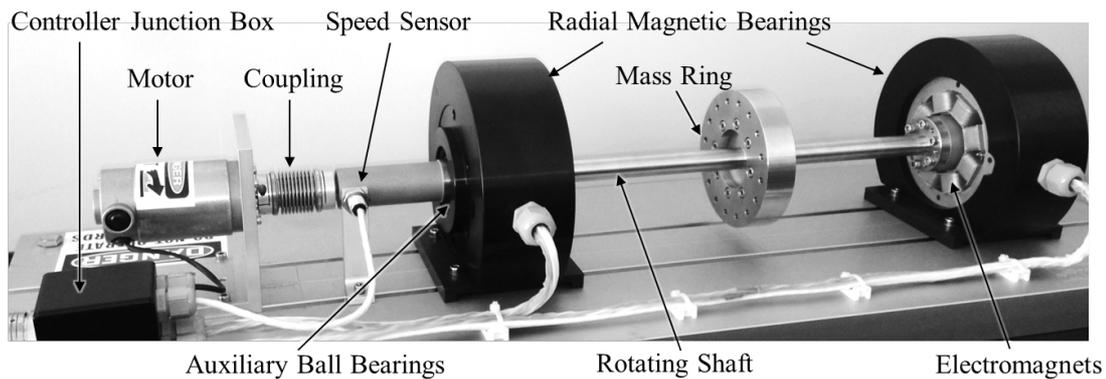
Figure 2   Active magnetic bearing test rig

The focus of the rotordynamic experiments is to understand how AMBs tolerate potential in-service conditions such as shaft imbalance, transient conditions, and foundation motion. The test program is ongoing at this time, with results to be presented in the final project report.

The test rig experience is providing valuable information regarding failure modes. One objective is to investigate a recent and existing AMB design to provide insight into the likely experience with industrial AMB machinery today. The failure modes observed to date are discussed in Section 3.2.

2.2   Compression Train Reliability Comparison

The reliability of AMBs is being studied in the context of various compression train configurations; the question being whether a compression train equipped with AMBs could achieve reliability at least equal to or greater than a conventional compression train. AMB failure data is known to be scarce, but numerous data are available for the components that are replaced by AMB systems. The objective of this comparison is the establishment of target reliability range for AMBs and their associated auxiliary equipment, which would make them comparable in reliability to conventional compressor configurations.

OREDA (Offshore Reliability Data) was the primary data source used for this comparison (SINTEF 2009). OREDA is a collaborative project between eight participating oil & gas companies with well-documented assumptions and limitations. A survey was also undertaken of major original equipment manufacturers (OEMs) to assist with this study.

Two conventional compression trains, with different drive configurations, were compared to a hermetically-sealed compressor. Both conventional trains are supported by fluid-film bearings and include a lubrication system and dry gas seals. The two driver options considered were a gas turbine connected via a gearbox (configuration 'A') and a high-speed electric motor controlled by a variable speed drive (VSD) (configuration 'B'). Active magnetic bearings are an integral component of the hermetically-sealed option, denoted configuration 'C'. In this design the motor and compressor both run on AMBs, and are directly coupled in one sealed casing.

A base case comparison using generic data is provided below which illustrates the study methodology. Note that central power generation dependencies were excluded from this base case analysis.

Data was extracted from OREDA for centrifugal compressors, aeroderivative gas turbines and electric motors. A trade-off was made between the refinement of the equipment taxonomy and the population size. For each equipment unit the following information was recorded: the listed maintainable items, total failure rate, and the number of failures caused by each maintainable item. A maintainable item is a constituent of an equipment sub-unit and is normally the lowest level in the equipment hierarchy during maintenance. For example, a pump is a maintainable item belonging to the lubrication system, which is one sub-unit included in a compressor.

The collected data was used to calculate failure rates for each maintainable item. A failure is defined as the termination or degradation of the ability of an item to perform a required function (SINTEF 2009).

3. Results and Discussion

3.1 Compression Train Reliability Comparison

The results of this study are presented in Table 1, where A, B and C represent the compression train configurations described previously. Maintainable items that were assessed as integral to equipment operation and are common between different configurations, e.g. the compressor rotor and impellers, are included under core components. Maintainable items that are eliminated in a hermetically-sealed compressor, e.g. fluid-film bearings, are presented separately. The total failure rates are calculated as the sum of the failure rates of the constituent parts.

OREDA does not present failure data for the maintainable items separated according to failure severity, so failure rates could only be calculated using the total recorded failures. The limitations of the data available are that a large percentage of failures are assigned as 'unknown', and that failures on valves and instrumentation are not presented separately for each sub-unit. These failures were attributed to core components and were therefore included across all configurations. Hence the target failure rates calculated for AMB systems represent conservative estimates.

Equipment	Sub-units	Contributing Failure Rates[1]		
		A	B	C
GT Driver	Gas Turbine + Gearbox	790.6	-	-
EM Driver	Core Electric Motor Components	-	32.7	32.7
	Variable Speed Drive[2]	-	31.7	31.7
	Fluid-Film Bearings + Lubrication + Cooling	-	4.7	-
Compressor	Core Compressor Components	366.4	366.4	366.4
	Fluid-Film Bearings + Lubrication + Dry Gas Seals	102.7	102.7	-
	AMBs + Control + Power + Cooling Loop	-	-	X
Cumulative Failure Rate (per 10^6 hours)		1259.7	538.2	430.8 + X

[1] Failures per 10^6 hours
[2] Data not available from OREDA. Source: Wikström (2000)

Table 1   **Cumulative failure rates, grouped by equipment sub-unit, for three different compression trains configurations**

By considering generic data sources only, hermetically-sealed compressors could achieve reliability equal to or greater than conventional compression trains if the failure rate for AMBs and their auxiliaries is less than 829 and 107 failures per 10^6 hours when compared to the conventional gas turbine and electric motor reference cases, respectively. This base case is a preliminary result and is to be refined by incorporating data provided by an oil & gas operator, AMB vendors and compressor OEMs.

3.2   Observed Failure Modes

The active magnetic bearing test rig used in this project was manufactured by an experienced magnetic bearing vendor, however only a small number of this particular design were produced. The project commenced with the test rig as-shipped from the OEM. It was therefore expected that some machine infancy problems would arise. A selection of the failure modes that have been observed during normal machine operation are summarised in Table 2.

Item and Function	Functional Failure	Failure Mode – Cause of Failure	Failure Effects
Radial AMB: Support shaft and attenuate shaft vibration	High vibration amplitudes	Super-synchronous vibration (non-integer multiple of shaft RPM) - Controller tuning unsuitable for damping structural resonances.	Shaft vibration amplitude exceeds allowable limit of 60 microns. Controller raises position alarm, brakes motor and delevitates shaft when RPM < 60. Downtime for new tuning to be validated up to 2 weeks.
	Chaotic radial vibration	Axial vibration - Coupling not sufficiently robust to damp axial vibration.	Axial vibration interferes with radial vibration attenuation. Combined shaft vibration causes severe coupling damage. Downtime approx. 3 weeks to validate and install a suitable coupling.
Controller: Control and monitor shaft rotation and levitation	Rotation deviates from command	CW motor acceleration following a deceleration to 0 RPM from CCW rotation. - Motor control logic failure.	The motor continues to accelerate while the controller perceives that the shaft is decelerating. Minimum speed set point must be > 0 RPM so that motor is inhibited at low speed.
	Rotation prevented	Rotation disallowed by controller – Max. allowed delevitations onto auxiliary bearings reached.	Inspection and recertification of auxiliary bearings required before controller fault can be overridden.

Table 2   Observed failure modes of active magnetic bearings

An observation from test rig operating experience is the influence of axial behaviour on radial vibration in AMBs. The primary cause of this is believed to be the axial separation between the position sensor and bearing actuator. Rotors are known to bend and tilt at high rotational speed which leads to differences in the radial displacement at the sensors and actuator locations. Axial vibration, particularly at frequencies in special relation to the shaft rotational frequency, exacerbates this problem and may cause the radial AMBs to exert erroneous forces. Even in the absence of axial loads, a robust coupling is required as a minimum and a thrust bearing should be considered.

Any change to the system configuration requires updated controller tuning, machine recalibration and control stability assessments, which all contribute to equipment unavailability. This is a cumbersome process, particularly during equipment startup where

incidents may be frequent. Controller tuning requires specialist knowledge, hence a close and ongoing relationship with the AMB vendor is required.

4.   Conclusions and Future Work

Active magnetic bearings offer numerous advantages in rotating machinery but are surrounded by significant uncertainty and are yet to gain traction in the oil & gas industry. The objective of this project was a study of AMB rotordynamics, reliability and failure modes. Work is ongoing in many project areas, particularly with respect to rotordynamics.A reliability comparison was made between hermetically-sealed compressors and two conventional compression trains. Target reliabilities were calculated for AMBs and their auxiliary equipment. These require refinement by incorporating more relevant data from an oil & gas operator and OEMs. The most frequent failures observed with the AMB test stand were related to vibration amplitude. Controller tuning is important and needs to be updated with every change to the physical system. Axial dynamics need to be suitably managed with a robust coupling or thrust bearing. The equipment commissioning process may be extensive and a close relationship with the AMB vendor is necessary.

5.   Acknowledgements

6.   References

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