Qualified Active Magnetic Bearing Retrofits for Turboexpanders

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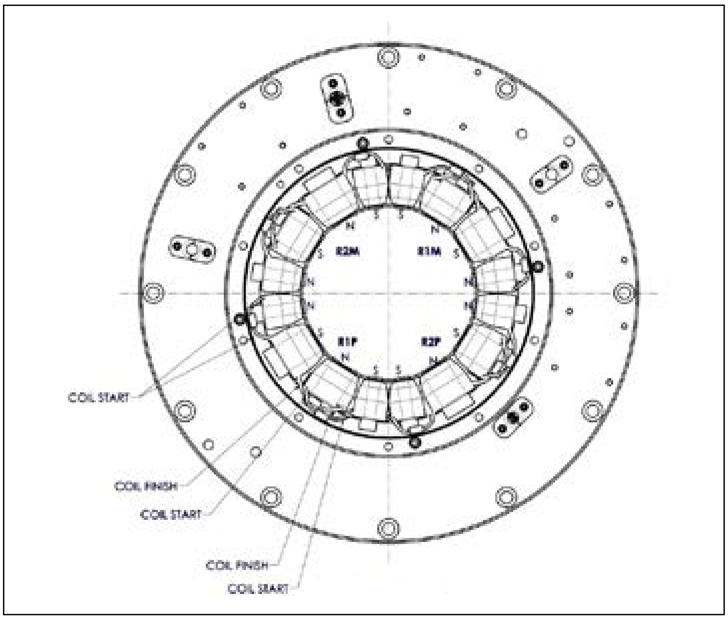
In today's competitive gas and power generation markets where turboexpander environments are becoming progressively more demanding, an upgrade of existing active magnetic bearing (AMB) systems may be the answer to achieving production goals.

An AMB upgrade can address:

- Trips due to aerodynamic loading
- Corrosion, erosion or fouling of AMB components
- Rotordynamic instability (subsynchronous vibrations)
- AMB components nearing obsolescence
- Limitations of analog AMB controllers
- Remote connectivity for increased availability and reduced mean time to repair (MTTR)

As with any bearing retrofit, the ideal solution provides the greatest improvement in performance and efficiency with the fewest machine changes and lowest total cost.

For the last 30 years, Waukesha Magnetic Bearings® has led the way in magnetic bearing technological advances. Waukesha's robust magnetic bearing hardware and advanced control technologies achieve 99.9% availability in even the most challenging environments. For magnetic bearing upgrades in turboexpanders, two scenarios are possible: a controller upgrade that maintains all of the original AMB hardware and sensors, or an upgrade of the controller and the AMB mechanical components.



Waukesha Magnetic Bearings has tested both options in partnership with L.A. Turbine, a leader in turboexpander design, manufacturing and aftermarket service. Presented here are the results, which confirm that both options qualify for the improved performance and robustness of turboexpanders.

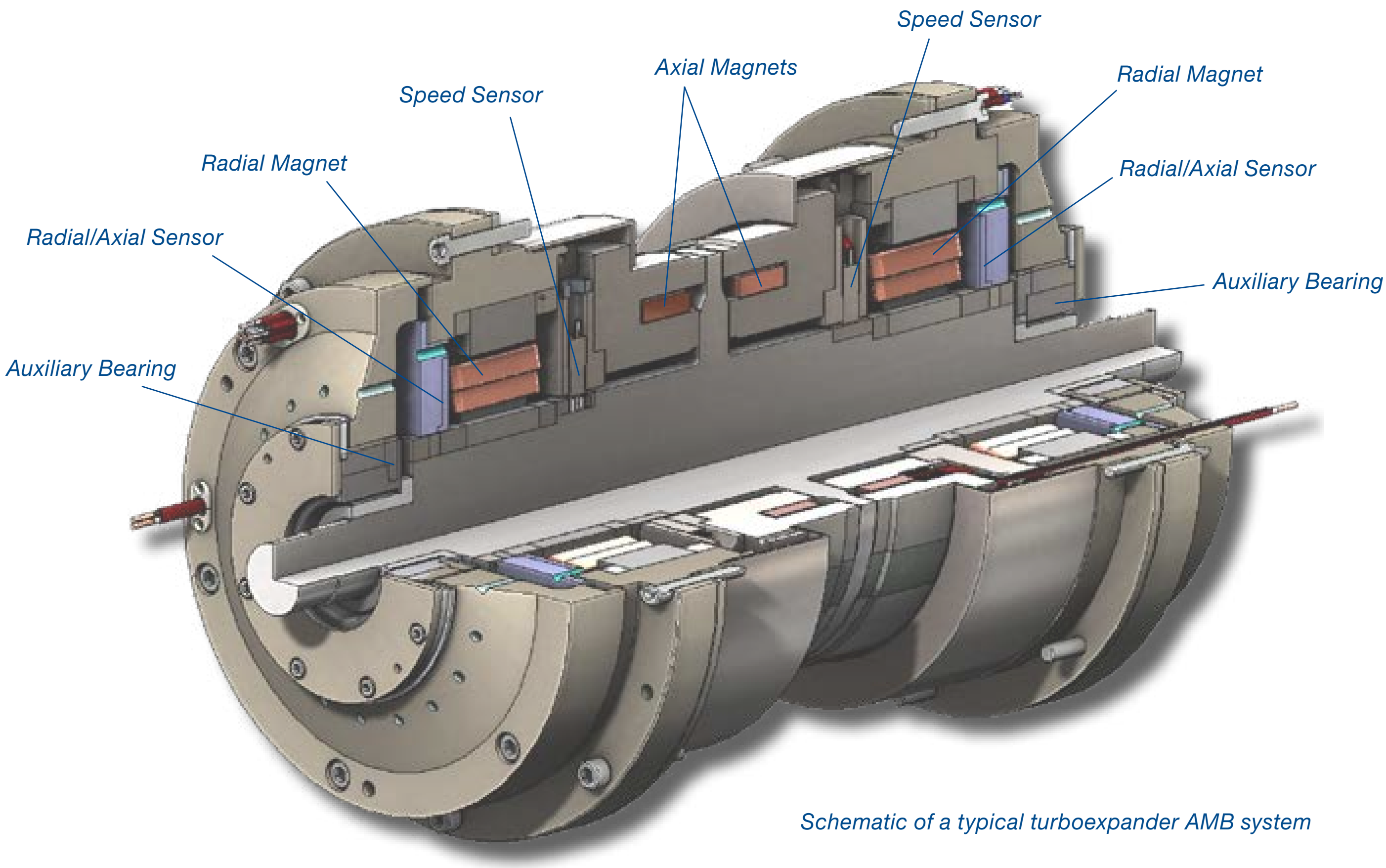
CASE IN POINT

A turboexpander in hydrocarbon processing service (Table 1) was experiencing instability when operating at high gas densities. Destabilising negative stiffness and cross-coupled stiffness effects were being created in the impellers and their associated labyrinth seals. As the machine was run up in speed, the forward tilt mode of vibration would destabilise at approximately 75% of the maximum speed (MCOS). The resulting trips significantly reduced overall plant availability.

Waukesha Magnetic Bearings worked with L.A. Turbine's engineering team to retrofit the turboexpander's original AMB system with Waukesha's latest technology, which uses a more advanced control law in the AMB controller. The implementation of the new controller proved to increase the rotordynamic stability margins of the machine. The advanced control law allows for a higher low-frequency stiffness, whilst maintaining adequate stiffness and damping at high frequencies. Consequently, the machine would be able to withstand the destabilising aerodynamic effects.

Rotor Mass	113.2 kg
Radial Bearing Diameter	150 mm
Radial Bearing Length	66 mm
Axial Bearing Disk Diameter	380 mm

Table 1: Characteristics of the turboexpander



Schematic of a typical turboexpander AMB system

OPTION 1: REPLACEMENT OF THE AMB CONTROLLER

The replacement of only the AMB controller is an attractive option for a retrofit, as the new controller is operated with the existing AMB hardware, pressure penetrators and cabling, no matter the original AMB vendor. This scenario does not require any changes to the mechanical parts of the system so could potentially be implemented on-site.

Several constraints are imposed, however, on the controller. Below are requirements of the new controller and their impact on the controller design.

REQUIREMENT	IMPACT ON DESIGN
Drive the existing position sensors with the existing cable structure.	The drive voltage and current must be consistent with the original drive electronics to ensure the sensor windings are not damaged and the sensor is not saturated. The sensor drive must also be sufficient to ensure a strong return signal.
Demodulate the position sensor outputs into a noise-free signal which can be used internally by the controller.	The signal range of the controller position input channels must be consistent with the existing position sensors.
Demodulate the output of the existing passive speed sensors.	The signal range of the controller speed sensor input channels must be consistent with the existing speed sensors across the entire speed range. (Note: The usable speed range of the existing speed sensors may be increased with the new controller.)
Drive the current in the windings of the magnets with the existing cable structure.	The drive voltage and current must be consistent with the original drive electronics to ensure the magnet windings and cable are not damaged.
Have sufficient magnet drive to ensure full load capacity of the bearing for both static and dynamic load.	Controller sampling, current slew rate, amplifier bandwidth and peak current capabilities must be at least as good as the original controller.

For the upgrade of the turboexpander in hydrocarbon processing service, a high-power Waukesha Magnetic Bearings Zephyr® controller (Table 2, Figure 1) replaced the digital controller from the original AMB vendor. The Zephyr controller was configured to meet all of the above requirements

Amplifier DC Link Voltage	390V
Magnet Drive Type	PWM switching amplifier
Peak Axial Magnet Drive	60A
Peak Radial Magnet Drive	30A
Sensor Type	Inductive sensor
Sensor Drive	22.5 KHz
Dimensions	90 x 33 x 50 cm (w x d x h)

Table 2: Characteristics of the Zephyr controller

Figure 1: Wall-mounted Zephyr controller

Figure 2: Turboexpander unit prepared for commissioning and testing at L.A. Turbine's test facility

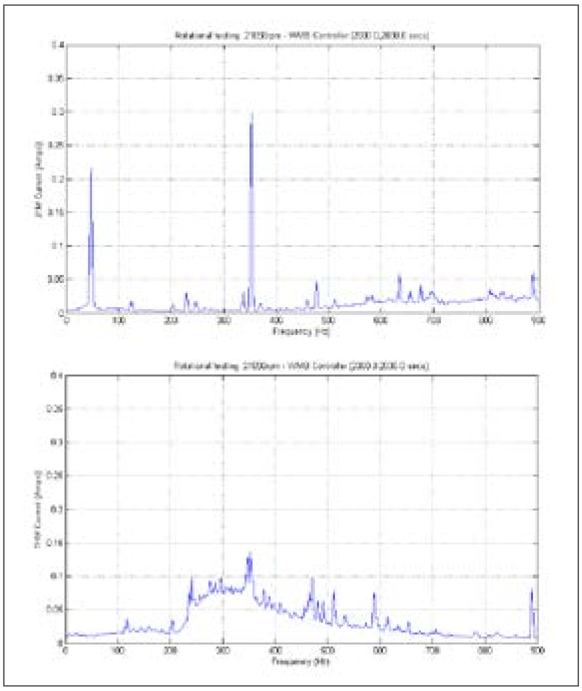


Figure 3: Measured currents during rotational testing with the replacement controller

For testing, the flange to flange turboexpander unit was built into a basic test circuit (Figure 2) at L.A. Turbine's test facility and the commissioning of the AMB system was undertaken.

With the new high-power controller, the turboexpander was successfully run to its full MCOS speed during the test. No trim balancing was required.

While the full gas densities at which field problems had manifested were not possible due to limitations of the simulated air test, AMB transfer functions were recorded at zero speed and during rotation (Figure 3). These results and the observed vibration behaviour correlated with the rotordynamic modelling without the seal effects, confirming the validity of the modelling for the prediction of rotor behaviour with the aerodynamic effects applied.

The Zephyr controller's Multi-Coordinate Control (MCC) algorithm, Multiple Input / Multiple Output (MIMO) design and higher order transfer function matrix capability provided more robust rotordynamic performance than the original controller. A complex eigenvalue analysis of the original configuration identified the aerodynamic and seal coefficients necessary to induce the instability observed in the field. When these aerodynamic and seal coefficients were applied to the rotordynamic model of the original AMB controller, the result at MCOS was a severely unstable forward conical mode, as expected. In contrast, when those coefficients were applied to the Zephyr controller model, it produced an amplification factor of 7.9 (logarithmic decrement of 0.4) in the subsynchronous forward tilt mode, greatly increasing the stability of the system and permitting full-speed operation. Time simulation plots for the two controller configurations are shown in Figure 4.

The tests performed with L.A. Turbine confirmed the ability of Waukesha Magnetic Bearings to achieve turboexpander performance targets when retrofitting a Waukesha controller into an AMB system with mechanical hardware from another vendor.

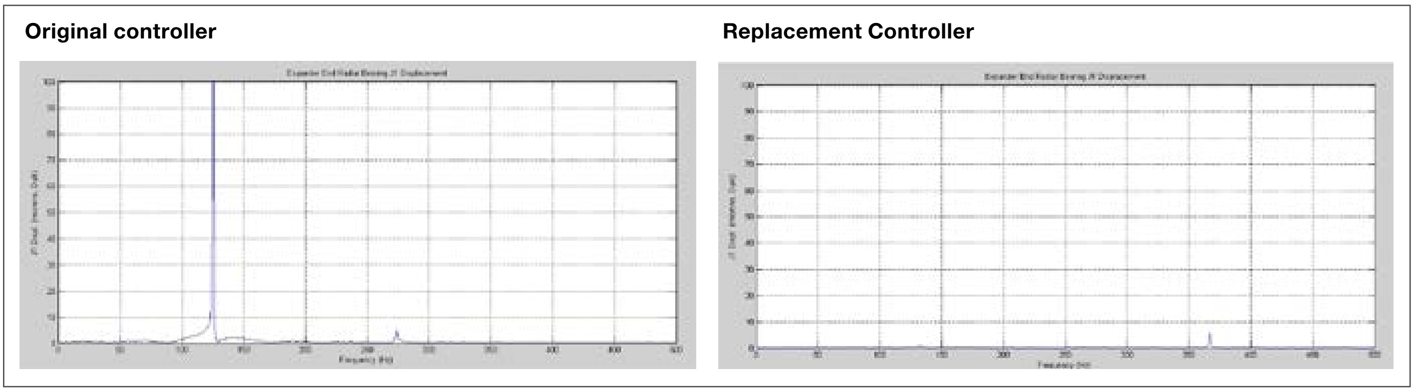


Figure 4: Time simulation plots showing displacement with the original and replacement AMB controllers

OPTION 2: REPLACEMENT OF THE AMB CONTROLLER AND STATOR PARTS

Expanding an AMB retrofit to include the AMB mechanical components as well as the controller allows optimisation of the bearing windings to make full use of the controller's power amplifier capabilities. Retrofitting with specialty hardware, such as sealed or canned stators and sensors and corrosion-resistant auxiliary bearings, can increase the robustness of the AMB system. This option also clarifies the scope of supply and associated responsibilities for the AMB vendor. The replaced hardware typically includes the magnets, position sensors, speed sensors, and auxiliary bearings, thus eliminating the controller design restrictions outlined in the previous section.

New constraints are introduced, however, to the AMB stator hardware. The stators must:

- Fit within the same envelope as the existing bearings
- Work with the existing pressure penetrator and cable structure
- Work with the existing AMB rotor hardware

For the turboexpander under discussion, after being tested with the controller-only upgrade, the machine was further retrofitted with new stator parts. The turboexpander required hardware, including AMBs and auxiliary bearings, for two radial bearings (Figure 5) and one thrust bearing. The bearing envelopes were consistent with the original hardware.

Figure 5: Replacement radial AMB hardware, including the stator, position sensors and speed sensors

The system was successfully run to close to full speed though, again, not with full density gas. The correlation of the transfer function measurements and the vibration response plots from the test (Figure 6) with the rotordynamic modelling established confidence in the model. With the aerodynamic and seal effects added to the model, predictions for the performance of the machine with full density gas were very similar to the results with only the controller upgraded. The system demonstrated high stability and robust rotordynamic performance permitting full-speed operation.

The turboexpander tests performed with L.A. Turbine confirmed the ability of Waukesha Magnetic Bearings to retrofit AMB mechanical components in place of hardware from another AMB vendor.

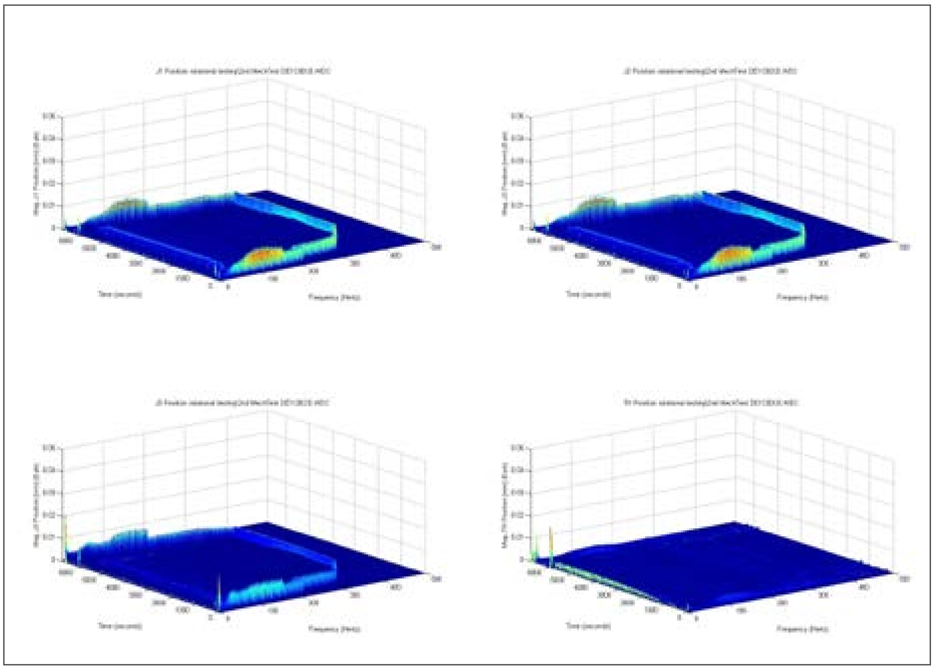
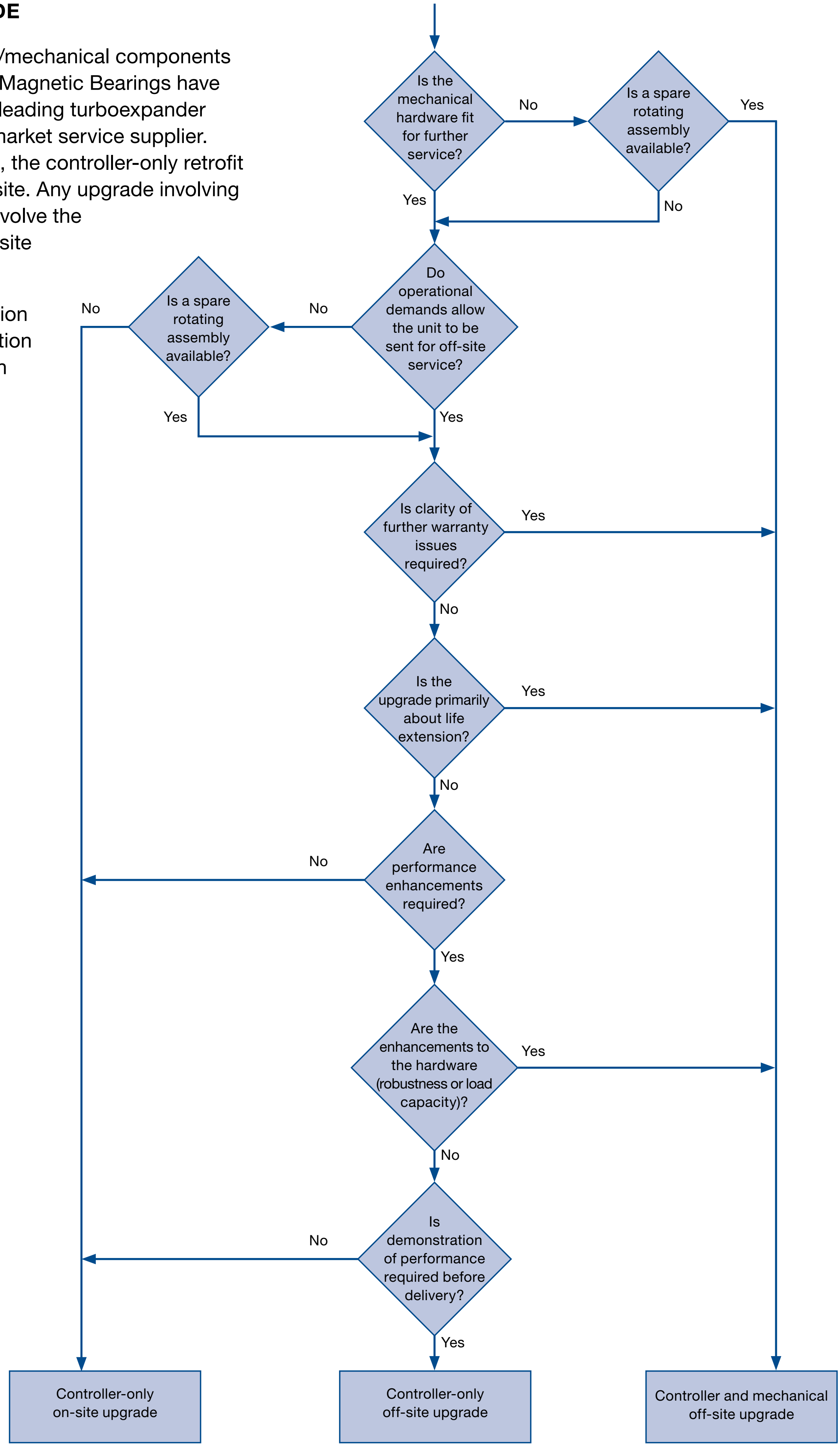


Figure 6: Measured vibration response with replacement AMB hardware

SELECTING AN AMB UPGRADE

Both the controller and controller/mechanical components retrofit solutions from Waukesha Magnetic Bearings have been qualified by L.A. Turbine, a leading turboexpander design, manufacturing and aftermarket service supplier. Depending on the circumstances, the controller-only retrofit can be addressed on-site or off-site. Any upgrade involving the mechanical hardware must involve the removal of the machine to an off-site repair location.

End users must evaluate application needs to determine the best solution for them. To the right is a decision flow chart.



QUESTION	IMPLICATION
Is the existing mechanical hardware fit for further service?	If the AMB mechanical hardware is no longer fit for service, it will need to be replaced. If the hardware's deterioration is due to chemical action of the process gas, it would be worth considering an upgrade to either sealed or canned magnetic bearing technology.
What is the operational demand on the turboexpander unit?	If the turboexpander cannot be taken out of service and shipped off-site due to constraints on process downtime, this tends to preclude the replacement of the AMB mechanical hardware. If a spare rotating assembly is available to be swapped in, however, the unit can be made available for refurbishment off-site. A controller-only exchange can be conducted on-site, though careful consideration must be given to the commissioning, particularly around unit start-up, especially if the turboexpander is closely coupled to the process.
Is clarity over responsibility for warranty claims required?	With a controller-only exchange, the turboexpander unit will end up with a mixed scope of supply. Failure of original AMB mechanical hardware subsequent to a controller upgrade could lead to a complicated warranty situation. Replacing both the controller and the hardware clarifies responsibilities and scope of supply.
Is the upgrade primarily about life extension?	If the upgrade is primarily about life extension / obsolescence management, then serious consideration should be given to replacement of the mechanical hardware, since this will give maximum continued service life.
What performance improvements are required?	For increased robustness of the mechanical components, the hardware must be included in the retrofit. A complete analysis of the chemical composition of the process gas will be required in order to determine the correct solution. The mechanical components must also be replaced if the retrofit is being undertaken to increase load capacity. Improved availability can be possible with a controller-only exchange through several types of performance enhancements: • Improved stability through use of a more sophisticated control algorithm • Modern data capture and monitoring capabilities with the sophisticated digital interfaces available on modern AMB controllers • Network-based maintenance support using remote connectivity options In principle, all of these controller upgrades can be done through an on-site upgrade.
Is demonstration of performance required prior to delivery?	If demonstration of performance is required prior to delivery, then the refurbishment should be done off-site.
Are enhancements to the data infrastructure around the machine required?	If enhanced web services data interfaces are to be used, then consideration should be given to the impact on the data historian system and distributed control system (DCS). If remote connectivity is to be added, suitable third-party access agreements should be put in place and compliance with the end user's data security protocols verified.

ENHANCED DIAGNOSTIC CAPABILITIES

The modern digital AMB controller, used in both controller-only and controller/mechanical component upgrades, offers superior data interfacing capability compared to earlier controllers. These capabilities include the use of conventional fieldbus interfaces in addition to modern TCP/IP-based web services, allowing connection to plant data systems and remote connection by the AMB vendor (subject to suitable third-party access agreements). The objective of these elements is to maximise availability and minimise maintenance support costs. When considering an upgrade to an existing AMB system, the proposed changes to the network infrastructure and associated data storage should be evaluated early in the project.

ABOUT THE AUTHORS

Richard Jayawant (+44 1903 275520, rjayawant@doverprevision.com) is Product Manager for Waukesha Magnetic Bearings. He graduated from University of Cambridge with an MA specialising in Control Engineering. Following work in a variety of control system application areas, he has been working in the field of active magnetic bearings for the last 27 years. His current focus is on the control systems applicable to this technology.

Houman Shokraneh, PhD, is Director of Engineering for L.A. Turbine, responsible for supervising, guiding and directing the company's global engineering team in turboexpander design. He is also responsible for identifying and defining research and development projects as well as directing the implementation of new ideas in turboexpander design for new and aftermarket equipment. He holds a BS in Aerospace and Mechanical Engineering from Sharif University of Technology in Tehran, Iran, and an MS and PhD in Mechanical Engineering from the University of Southern California. He is a member of the American Society of Mechanical Engineers (ASME).