Development and Test of Active Magnetic Bearings for Supercritical Carbon Dioxide Turbomachinery

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Abstract
Active magnetic bearings (AMB) provide a potential enabling technology for high-speed super critical carbon dioxide (sCO2) electric turbomachinery. AMB technology is commercially mature and many sub-components have been shown to be feasible in high (>500 C) temperature environments. However, material compatibility remains a major area of development for the technology to be commercially viable. Permanent magnets and several peripheral materials (bonding agents, electrical insulation material, etc) still require further testing to establish their feasibility in an sCO2 environment. Evaluating methods for cooling AMBs at high pressures also requires some further development and testing. A scale turbine-alternator-compressor supported on supported by AMB is tested in an sCO2 environment test flow loop to characterize thermal performance of the AMBs, cool methods, and rotordynamics from the sCO2 environment.

Keywords : Active Magnetic Bearings (AMB), Magnetic Bearing Dynamics, Super Critical CO2 (sCO2), High Temperature Materials

1. Introduction

Active magnetic bearings (AMB) provide a potential enabling technology for high-speed super critical carbon dioxide (sCO2) electric turbomachinery. However, material compatibility remains a major area of development for the technology. A main drawback of the application of active magnetic bearings to sCO2 turbomachinery is the thermal limitations of several commonly used materials in an active magnetic bearing. Evaluating the suitability of these materials at high temperatures and pressures is an important next step in evaluating the potential application of AMBs for SCO2 turbomachinery. To this end, an AMB-supported turbocompressor was operated in an sCO2 test flow loop. The design of the scale 100 kW turbine-alternator-compressor supported by permanent magnetic-biased homopolar active magnetic bearings. The purpose of the test rig is to characterize thermal performance of the AMBs, evaluate various cooling schemes for the AMBs, and evaluate cross-coupled stiffness coefficients at various pressures and temperatures typical of an sCO2 application. The AMB design used has been previously fielded at high volumes in an industrial CO2 environment, in the current configuration provides a maximum continuous operating speed of 40 krpm. The paper will provide some mechanical design and rotordynamic analysis of the turbocompressor along with preliminary data from the prototype mechanical run test including some cross coupled stiffness measurements. AMB technology is commercially mature and many sub-components have been shown to be feasible in high (>500 C) temperature environments; however. permanent magnets and several peripheral materials (bonding agents, electrical insulation material, etc) still require further testing to establish their feasibility in an sCO_2 environment. Evaluating methods for cooling AMBs at high pressures also requires some further development and testing.

2. Description of Test Rig and Retrofit

The test rig used for evaluating the active magnetic bearings (AMBs) is based on a turbo-alternator-compressor system that was originally designed with gas foil bearings for high-pressure and high-temperature supercritical CO2 (sCO2) applications, further described in [1]. Briefly described for reference figure 1 shows the existing sCO2 Brayton loop test skid which already operated within the demanding (high temperature/high pressure) conditions typical of sCO2 turbomachinery.

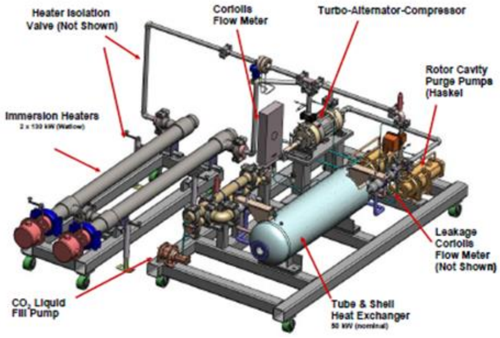
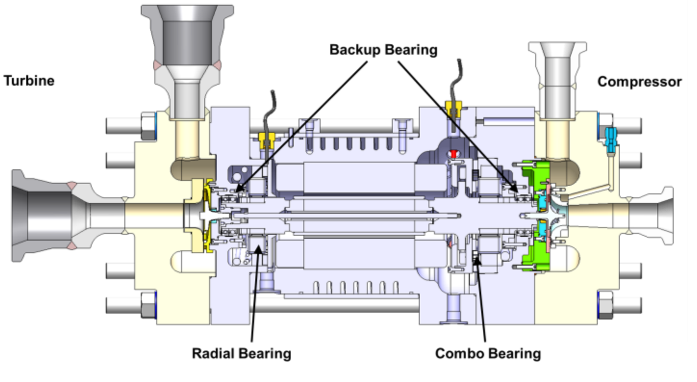


Fig 1. Overview of existing sCO2 Brayton loop test skid.

In addition to evaluating the thermal performance and material compatibility of the AMBs, the test rig serves the secondary purpose of assessing the cross-coupled stiffness coefficients of the sCO2 turbomachine. These stiffness coefficients are crucial for understanding the dynamic behavior of the system, especially in relation to cross-coupled forces, or "Alford" forces, which can destabilize the rotor at high speeds. Measuring these forces at various pressures and temperatures can provide valuable data on the operational limits of the AMB-supported turbocompressor. While AMBs have already been successfully adopted in high-speed, high-power turbomachinery applications, this retrofit is focused on confirming their viability in sCO2 systems, particularly in the context of thermal and dynamic behavior.

The AMBs used in the retrofit were sourced from a previous CO2 blower application and required significant modifications to accommodate the AMBs. Figure 2 and 3 presents a cross-section of the AMB system and the highlighted major components of the AMBs after the retrofit, illustrating the design and configuration of the bearings integrated into the modified setup. The bearings are a permanent magnetic (PM) bias, homopolar topology, typical of most recent (2012+) Calnetix AMB systems. Table 1 summarizes the major design characteristics of the AMBs. Although these bearings were originally designed for a CO2 environment, they were not initially intended for high-temperature operations. As such, there was (is) a need to reassess the materials used in the bearings to ensure their suitability for the higher thermal conditions of the current setup. The retrofit system is currently limited by the backup bearing ring material, which restricts the maximum operating temperature to 80°C. However, beyond this, there are several other potential pain points in terms of temperature limitations, including: actuator/sensor varnish, lamination stack adhesives, and backup bearing lubrication. These limitations underscore the need for further research into high-temperature materials that can maintain the performance and reliability of the AMBs in the extreme conditions of sCO2 turbomachinery.



. Fig 2. Cross section view of machine retro fitted with an AMB system

Table1. Magnetic Bearing Design Parameters

Parameter	Radial Brg1	Radial Brg2	Axial
Load capacity N (lbf)	266 (60)	355 (80)	1067 (240)
Neg. stiffness N/mm (lbf/in)	753 (4300)	683 (3900)	718 (4100)

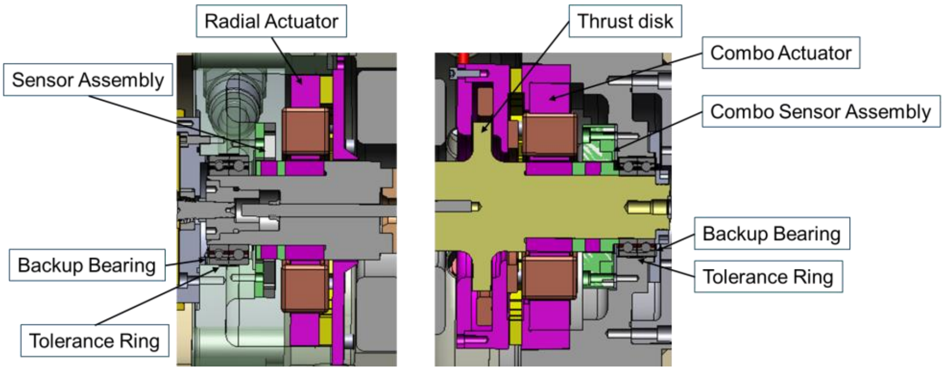


Fig 3. Major components of AMB design

3. Material Compatibility for Active Magnetic Bearings in High-Temperature sCO2 Applications

AMBs intended for high-temperature sCO2 environments present unique material selection challenges. Unlike traditional AMB systems, sCO2 applications require sustained performance at elevated temperatures, often exceeding 300°C, and occasionally approaching transient fault conditions beyond 500°C. These conditions impose strict demands on the thermal, mechanical, and dielectric properties of all AMB components, necessitating a thorough evaluation of material compatibility.

Permanent Magnets

Permanent magnets used in high-temperature AMB actuators must retain magnetic strength while operating near or above 300°C. Recent developments in ultra-high-temperature samarium cobalt (SmCo) magnets suggest that operating temperatures up to 550°C are achievable with appropriate circuit design to maintain a steep load line. SmCo magnets remain the preferred choice for high-temperature AMB applications due to their superior thermal stability compared to neodymium-based magnets, which demagnetize rapidly above 200°C.

Magnet Wire

Magnet wire selection is among the most restrictive factors in high-temperature AMB design. Conventional organic wire insulation is limited to a maximum temperature of approximately 250°C. Inorganic ceramic-insulated magnet wires can withstand temperatures beyond 500°C but introduce significant trade-offs. Ceramic wires typically require large minimum bending radii, severely constraining actuator coil geometries, and exhibit low dielectric breakdown voltages, sometimes as low as 50V. This necessitates careful voltage management and may require parallel conductor arrangements to achieve acceptable current densities within low-voltage constraints. Fiberglass and mica-insulated wires offer higher voltage ratings but result in thicker insulation layers, reducing slot fill factors and potentially increasing actuator size.

Soft Magnetic Laminations

For high-temperature operation, laminated stator materials must offer acceptable magnetic performance with minimized eddy current losses. Fe-Co alloy laminations are a proven solution for elevated temperatures and have been successfully deployed in both AMB and electric motor applications. Silicon steel remains a lower-cost alternative but may exhibit increased losses at high temperatures and should be carefully evaluated during design trade studies.

Lamination Bonding and Assembly

Standard lamination bonding adhesives typically degrade at temperatures above 200°C. Alternative strategies include mechanical clamping or spot welding, though both approaches introduce potential drawbacks. Mechanical clamping can increase the radial envelope of the stator and adversely affect rotordynamic margins, while spot welding can result in increased eddy current losses due to local shorting between laminations. A potential solution is the use of high-temperature adhesives in combination with light mechanical clamping to maintain structural integrity without sacrificing electrical isolation.

Coil Impregnation and Slot Insulation

High-temperature coil impregnation is critical to prevent conductor movement and to mitigate partial discharge effects. Ceramic cements have been successfully used as impregnation materials in high-temperature electric machines and are likely applicable to AMBs as well. For slot insulation, mica and ceramic sheet insulators are commonly used in high-temperature motor designs and can be adopted for AMB actuators, especially when external coil winding on bobbins is feasible.

Lead Wires and Splice Insulation

Flexible lead wires with mica or fiberglass insulation are commercially available for high-temperature environments and are suitable for AMB applications. Splice insulation can be achieved using high-temperature fiberglass sleeves or mica tapes, with additional impregnation to ensure dielectric strength.

4. Test Results

Figure 4 and 5 shows the plant sensitivity transfer function of bearings 1 and 2 at 0 rpm. There is little response at the bending modes making the control system robust and insensitive to sudden impact loads or other irregularities. The system can achieve full speed of 40 krpm in either air or nitrogen; however, when sCO2 is used there is a significant pressure different which could subject the system to cross-coupled stiffness forces, also called "Alford" forces, which are rotordynamically de-stabilizing [2] limiting the maximum speed to 20 krpm.

Fig 6. shows the transfer function taken at 10 krpm in air, nitrogen, and sCO2. 10 krpm was chosen since the system is stable enough at this speed for all three fluids to take transfer functions. At this speed there is enough stability for the system to run safely. The nitrogen doesn't create an instability since the pressure differential is lower than when sCO2 is used. However, when the nitrogen differential pressure is increased, the rotor drops at full speed. Further testing is required, in particular cross coupled transfer functions need to be taken to identify the destabilizing force.

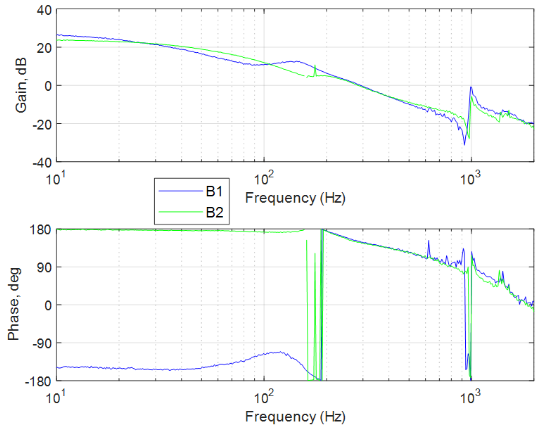


Fig 4. Plant transfer function of bearing 1 and 2 at 0 rpm.

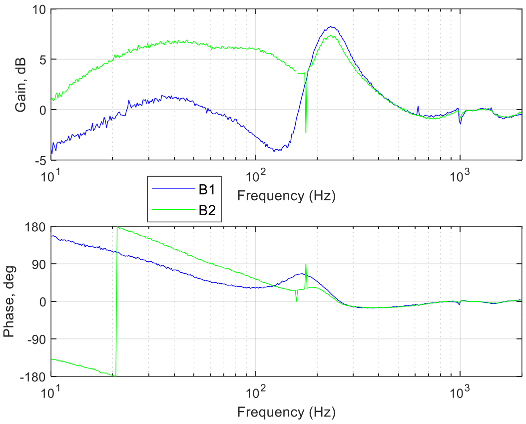


Fig 5. Sensitivity transfer functions of bearing 1 and 2 at 0 rpm

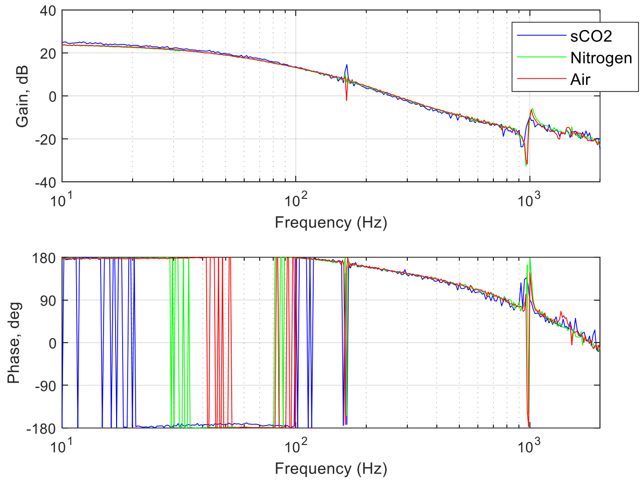


Fig 6. Transfer functions of the unit spinning in air, nitrogen, and sCO2 at 10 krpm

5. Conclusion

Design of a turbine-alternator-compressor retrofitted with AMBs is presented along with the discussion of material selection and manufacturing for high temperature operation. Although the retrofit is currently temperature limited due to the backup bearing material, the machine can operate in sCO2; however, there's seal cross-couple instabilities that were not present during the initial commissioning of the system in air. A follow-up paper will provide a more in-depth review of the seal cross-couple effect on the system.

References`

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