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Magnetic Bearings for Supercritical CO_2 Turbomachinery

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ABSTRACT

For supercritical CO2 applications, magnetic bearings present several advantages over conventional bearings: suitability across a wide range of operating and environmental conditions; consistent stiffness and damping coefficients; and measurement of static and dynamics forces to perform diagnostics and improve predictive capabilities.

In general, clearances in magnetic bearings are much larger than those in conventional bearings. Therefore, large swings in operating temperatures, as experienced in supercritical CO2 service, have minimal effect on the rotordynamic coefficients of the bearing.

Magnetic bearings maintain consistent stiffness and damping coefficients not only over temperature swings but over a wide range of rotating speeds and pressures. Supercritical CO2 fluid forces within turbomachinery may constantly excite subsynchronous vibrations and stability problems, and magnetic bearings can consistently provide significant magnitudes of damping to keep subsynchronous modes stable.

Finally, the diagnostic, monitoring, and force measurement capability of magnetic bearings is a key advantage in this new field of technology. By monitoring the bearing currents and position sensor outputs, both static and dynamic loads can be measured with the magnetic bearing system. This is an important capability for the development of turbo machines for supercritical CO2 service, as it is especially difficult to calculate the thrust load generated by the machines over the complete operating envelope.

This paper will describe the permissible operating speed, and temperature envelopes for magnetic bearings in SCO2 environments, and how magnetic bearings maintain stability over the wide range of operating conditions, before discussing the measurement capabilities and specific load capacity of magnetic bearings. Design features of a magnetic bearing system applied to a SCO2 turbine will also be described.

INTRODUCTION

Supercritical CO_2 Brayton cycles are being investigated for their potential to significantly improve thermodynamic efficiencies for electric power generation. A wide range of turbomachinery and rotating equipment technology is being reviewed, developed and considered to implement this promising thermodynamic cycle. Among the machine architectures under consideration are turbines with overhung impeller designs, which present some key design input challenges for the bearings. Those challenges include high thrust loads at startup conditions, high speeds, high fluid density, extreme temperature ranges, and

For more than 30 years, active magnetic bearing (AMB) technology has been used in turbomachinery and rotating equipment to address such challenges. In the pursuit of efficient electric power generation, it is useful to compare the requirements for bearing systems in supercritical CO2 equipment with the capabilities of AMB systems.

HIGH THRUST LOAD AT STARTUP

Certain SCO2 turbine designs have high thrust loads at the startup conditions. These thrust loads are caused by the shutoff pressure surrounding the impeller acting on the shaft cross sectional area at the shaft seal. This thrust load can be a maximum at zero speed and then moderates at the 100% speed design condition.

Magnetic bearing systems provide a fully levitated rotor at zero speed conditions; no shaft rotation is required for the bearing to ‘lift off’. Hence, the AMB system can provide the maximum steady state load capacity at zero speed and at maximum speed. This magnetic bearing attribute is in contrast to many conventional bearings that require velocity to develop a fluid film to generate load capacity.

With the bearing’s maximum thrust load capacity available at all speeds, there is no time limit for operation at intermediate speeds during the startup transient for the system. This eliminates the need for special controls that would otherwise be needed for extreme run up curves [1]. This operational flexibility can also be beneficial for startups where thermodynamic cycles need time to stabilize at intermediate speeds.

The typical SCO2 turbines require high rotational speeds to achieve efficiency targets. Axial magnetic bearing load capacity for high-speed machines has recently increased due to the availability of new alloys for the axial magnetic bearing collar. This ‘thrust collar’ rotates with the shaft of the machine and provides part of the magnetic flux circuit for the actuator. Therefore, the material must have high strength and have reasonable magnetic properties. The force, F, applied by an electromagnet is given by the equation,

$$F = \frac{B^2 . S}{2 . \mu_0}$$

Where B is the magnetic flux density, S is the total pole projected area, and μ_0 is the permeability of free space.

The magnetic flux density of the most commonly used thrust collar materials becomes saturated between 1.3 Tesla and 1.4 Tesla. Hence, the peak load capacity of the thrust bearing is heavily dependent on the total pole projected areas. Magnetic alloys containing cobalt can be pushed to flux densities of 2.0 Tesla, but these alloys have relatively low strength, so cannot be used for high-speed applications. For high-speed applications, 'ultra-high strength' ferrous alloys have been identified with satisfactory magnetic properties. Prior to the availability of ultra-high strength alloys, the maximum peripheral speed of the magnetic bearing thrust collar was approximately 450 m/s. With the ultra-high strength alloys, together with special mechanical design considerations, the maximum peripheral speed capability of the magnetic bearing thrust collar is now 675 m/s.

Further design options are also available to meet high thrust load capacity requirements for high-speed applications. The axial magnetic bearing actuator can be configured with a dual thrust disk design. The axial magnetic bearing air gaps are large enough that two adjacent actuators can be placed in an environment with highly changeable temperatures and still function properly. The axial magnet air gaps range from 1 mm to 2 mm depending on the overall diameter of the bearing. Temperature changes within the operating envelope of the machine will cause the gaps of the axial actuators to change, but these thermal changes are small relative to the bearing air gaps, so two adjacent actuators can be placed in the environment and still function properly.

HIGH SPEED CAPABILITY AND ROTORDYNAMICS

SCO2 turbines require high rotational speeds to meet efficiency targets. Magnetic bearings are a proven technology for high speed applications. Magnetic bearings are able to maintain consistent stiffness and damping coefficients over the large speed ranges that SCO2 machines may face. Synchronous control algorithms allow reliable operation at high speeds with high levels of imbalance, and the stiffness and damping coefficients of magnetic bearings remain consistent over wide speed ranges.

Many SCO2 turbomachine designs have a high temperature gradient along the length of the rotor. These gradients can easily lead to relatively high levels of rotating unbalance due to thermal distortion. Synchronous control algorithms allow the rotor to rotate around its inertial axis, which drastically decreases the transmitted force to the housings, enabling reliable operation. Conventional bearings do not have this capability. Conventional bearings are simply not active devices and cannot actively adjust their characteristics.

High fluid density is another characteristic of SCO2 machines providing increased cycle efficiency. Destabilizing cross coupled stiffness from seals increases with increasing fluid density. The bearings must provide high levels of damping to stabilize the seal effects at low speeds to traverse the rigid body modes with low vibration levels and also at high speeds to avoid subsynchronous instabilities of the rigid body modes. For magnetic bearings, the stiffness and damping coefficients at the rigid body mode frequencies will not vary with rotating speed. This provides a very consistent stability condition over the operating speed range. Most conventional bearings have stiffness and damping coefficients that vary widely with speed, which can lead to stability problems.

For very high speed machines (>20,000 rpm) equipped with magnetic bearings, it is preferable to have a subcritical rotordynamic design. Subcritical designs place the first bending mode frequency of the rotor above the operating speed range. Increasing the shaft diameter to increase the bending stiffness of the rotor is essential to meeting subcritical requirements.

Auxiliary bearings are included with magnetic bearings systems to land the rotor in cases of input power loss or overload events. The typical auxiliary bearing system is based on rolling element type bearings. The limiting performance parameter for these auxiliary bearings is a DN number of 2 million. The DN number is the product of the bearing bore diameter in mm and the rotational speed in rpm. Bushing type auxiliary bearings have proven a viable technology for DN numbers up to 3 million. The increased allowable DN number allows a larger shaft diameter for a given speed, increasing the bending stiffness of the shaft and resulting in an increased first bending mode frequency.

EXTREME TEMPERATURE CAPABILITIES

Supercritical CO2 Brayton cycles use high temperatures to increase efficiency. The bearing compartments in certain SCO2 machines can easily reach 400C. Cooling of the bearing compartments may decrease efficiency when process gas is used for cooling. Magnetic bearing systems are able to operate over a wide range of temperatures. AMB systems have been applied in environments with operating temperatures ranging from -196º C (liquid nitrogen) to 450º C (gas turbine exhaust). Conventional bearings have difficulties with extreme temperatures. Obviously, any bearing requiring liquid lubricants will not be capable of operating in excess of 400 C.

In addition to challenging the maximum temperature rating of bearing components, the high temperatures in SCO2 equipment also cause high thermal dimensional expansion of housings and shafts. In conventional bearing designs, this can lead to misalignment and clearance variation between rotor and stator components. Magnetic bearings provide robustness against these variations in alignments and clearances due to the relatively large clearances used. Air gaps may range from 0.75mm to 2 mm, accommodating the effects of thermal expansion. Conventional bearings have gaps on the order of 0.050 mm.

Temperature variation is another case of magnetic bearings maintaining consistent stiffness and damping coefficients compared to conventional bearings, because the ratio of bearing gap over thermal expansion is much greater with magnetic bearings.

SCALABLE TECHNOLOGY

Supercritical CO2 Brayton cycle projects are mostly in the demonstration phase at this time, using relatively low-power, scaled machines compared to the full-size power equipment that will be required in the future. Magnetic bearings are an easily scalable technology, both in the size of the mechanical bearing components and in the capabilities of the control electronics; with the ability to adapt to small and large machines. High speed magnetic bearing applications have ranged from rotor masses of a few kilograms up to rotor masses of 10 tons. In terms of radial magnetic bearing rotor outside diameter for these applications, the diameters ranged from 25 mm to 550 mm.

As size and/or speed of machines increase, so must the dynamic load capability of the magnetic bearings. The dynamic load capacity is generated by slewing the current to the windings of the magnetic bearing actuator. This dynamic current capacity is dependent on the voltage of the power amplifier. The maximum dynamic current, ΔI, is indirectly proportional to the coil inductance and frequency and directly proportional to the voltage rating of the power amplifier:

$$Maximum\ \Delta I\ at\ frequency\ (f) = \frac{V}{2\pi.f.L}$$

Where V is the voltage rating, f is the frequency in Hz, and L is the bearing magnet inductance.

The power ratings of state-of-the-art magnetic bearing system power amplifiers range from 120 volts/4 amps up to 600 volt/60 amps, giving magnetic bearing technology the ability to be applied to rotor masses ranging from a few kilograms up to several tons.

CANNED BEARING TECHNOLOGY

There are supercritical CO2 applications where water content in the process fluid is negligible and some where water content is significant.(Ref 2) Magnetic bearings can operate immersed in either environment. If water is present, the environment may be quite corrosive. Canned magnetic bearings would provide a robust selection for this corrosive environment. Canned magnetic bearings have a thin corrosion resistant lining that hermetically seals the bearing stators and sensors from the process fluid.

For supercritical CO2 applications where water content is negligible, uncanned magnetic bearings may be operated while immersed in the process fluid.

PROCESS FORCE MEASUREMENT CAPABILITIES

Supercritical CO2 Brayton cycle projects are mostly in the demonstration phase at this time, and the understanding of the aerodynamic forces generated with the supercritical CO2 working fluid are not well understood. Calculation methods for these forces will need to be developed in order to design the larger machines for the full size plants. These calculation methods must be benchmarked against actual measured quantities, and the measurements can only be done while the machine is in operation.

Magnetic bearings have the ability to measure the forces reacted by the bearings, including the steady state forces and the dynamic forces. Also, the magnetic bearings can be used to measure to transfer function of the rotor/bearing system to measure the destabilizing forces due to aerodynamic effects.

The forces can be measured along the axes of control for the bearings. The most common magnetic bearing configuration has five axes of control: four radial axes and one axial axis. A pair of perpendicular radial axes at each end correspond to the radial AMBs. The forces reacted by the bearings can be related to measurable bearing parameters of current and displacement using the following relationships;

$$B = \frac{\mu_0 . N . I}{\epsilon} \; ; F = \frac{B^2 . S}{2 . \mu_0}$$

Where N is the number of turns, ϵ is the magnitude of the air gap, and I is the current flowing through the coil.

Magnetic bearing systems are able to measure the transfer function characteristic of the rotor-bearing system through the injection of a disturbance into the servo control loop and the measurement of the resulting signals. Similarly, offsets may be entered into the servo control loop reference signals to offset the bearing position. These excitation and offset functions have been used in a variety of experimental test rigs to assess hydrodynamic or aerodynamic performance of other elements affecting the rotor-bearing system, such as seals or impellers.

Conventional bearings, of course, are unable to measure forces or dynamic characteristics. The use of magnetic bearings to measure forces and dynamic characteristics within supercritical CO2 machines will provide a vital tool for designing the full size machines for the final power plant implementations of the technology.

SUMMARY

Supercritical CO2 turbines require bearings with high thrust load capacity at zero speed and at high speeds. Magnetic bearing systems provide a fully levitated rotor at zero speed conditions; no shaft rotation is required for the bearing to 'lift off'. Hence, the AMB system can provide the maximum steady state load capacity at zero speed and at maximum speed. This magnetic bearing attribute is in contrast to many conventional bearings that require velocity to develop a fluid film to generate load capacity.

To address the demand for higher thrust loads at higher speeds, new alloys and designs have been developed for active magnetic thrust bearings. With the ultra-high strength alloys, together with special mechanical design considerations, the maximum peripheral speed capability of the magnetic bearing thrust collar is now 675 m/s.

Supercritical CO2 turbines produce very large temperature gradients and large changes in temperature in bearing compartments, over the course of normal operation cycles. For magnetic bearings, the stiffness and damping coefficients versus frequency characteristic has a very small variation due to temperature change, thermal expansion effects, and rotating speed change.

The supercritical CO2 Brayton cycle technology will move from scaled demonstration units to larger, grid scale power generation units. The bearing technology utilized will also progress from small demonstration sizes to larger sizes. Magnetic bearings are an easily scalable technology, both in the size of the mechanical bearing components and in the capabilities of the control electronics; with the ability to adapt to small and large machines. High speed magnetic bearing applications have ranged from rotor masses of a few kilograms up to rotor masses of 10 tons.

Supercritical CO2 machines may have corrosive or non-corrosive environments. Canned and conventional magnetic bearing designs will provide robust service in corrosive or non-corrosive supercritical CO2 environments.

The use of magnetic bearings to measure forces and dynamic characteristics within supercritical CO2 machines will provide a vital tool for designing the full size machines for the final power plant implementations of the technology.

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