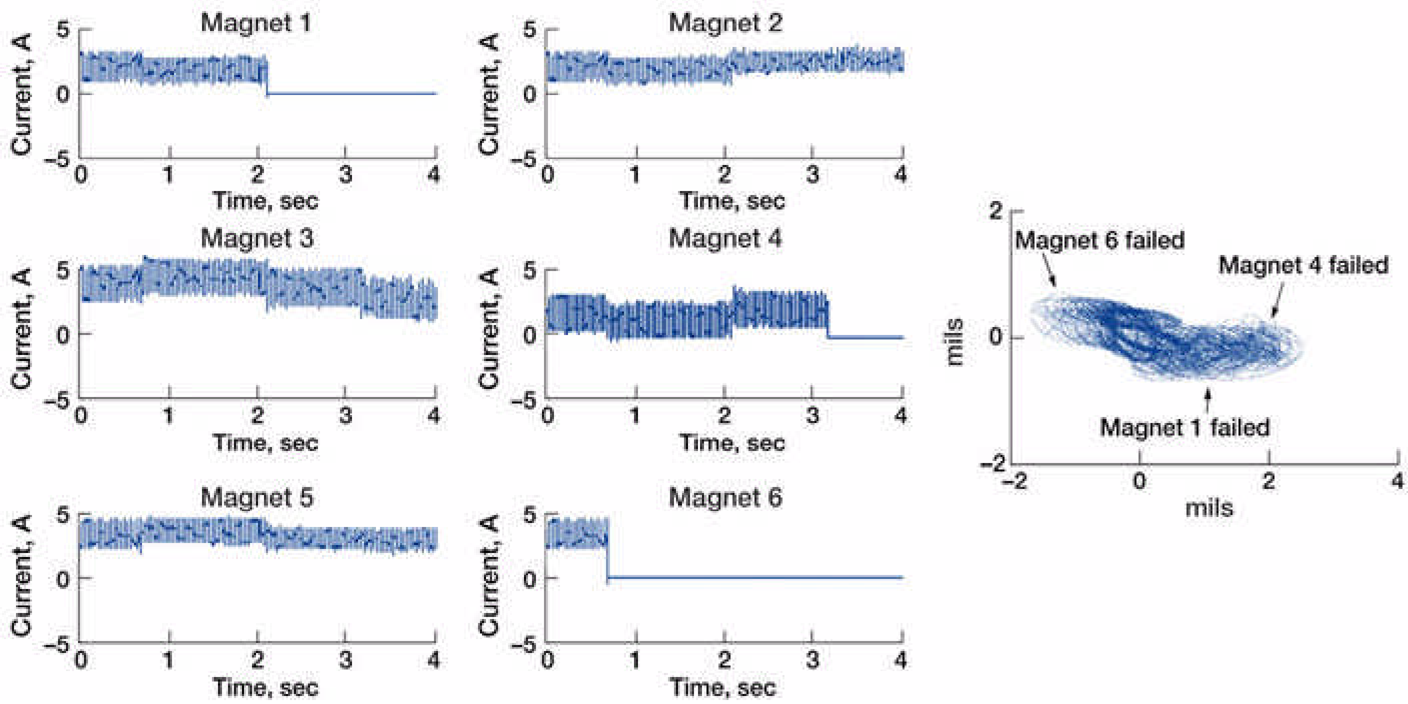
Fail-Safe Operation of a High-Temperature Magnetic Bearing Investigated for Gas Turbine Engine Applications

The Structural Mechanics and Dynamics Branch at the NASA Glenn Research Center has developed a three-axis high-temperature magnetic bearing suspension rig to enhance the safety of the bearing system up to 1000 °F. This test rig can accommodate thrust and radial bearings up to a 22.84 cm (9 in.) diameter with a maximum axial loading of 22.25 kN (5000 lb) and a maximum radial loading up to 4.45 kN (1000 lb). The test facility was set up to test magnetic bearings under high-temperature (1100 °F) and high-speed (20,000 rpm) conditions.

The magnetic bearing is located at the center of gravity of the rotor between two high-temperature grease-packed mechanical ball bearings. The drive-end duplex angular contact ball bearing, which is in full contact, acts as a moment release and provides axial stability. The outboard end ball bearing has a 0.015-in. radial clearance between the rotor to act as a backup bearing and to compensate for axial thermal expansion. There is a 0.020-in. radial air gap between the stator pole and the rotor. The stator was wrapped with three 1-kW band heaters to create a localized hot section; the mechanical ball bearings were outside this section. Eight threaded rods supported the stator. These incorporated a plunger and Bellville washers to compensate for radial thermal expansion and provide rotor-to-stator alignment. The stator was instrumented with thermocouples and a current sensor for each coil. Eight air-cooled position sensors were mounted outside the hot section to monitor the rotor. Another sensor monitored this rotation of the outboard backup bearing. Ground fault circuit interrupts were incorporated into all power amplifier loops for personnel safety. All instrumentation was monitored and recorded on a LabView-based data acquisition system. Currently, this 12-pole heteropolar magnetic bearing has 13 thermal cycles and over 26 hr of operation at 1000 °F.

For a fail-safe operation of this rig in temperature extremes, a proportional-integral-derivative (PID) controller that does not require a fault detection mechanism was tested in a passive way where the initial bias current and control gains for all six independent magnets were not changed for the remaining active magnets in the fault situations. The action of the integral term in the controller generated autonomous corrective actions for the magnet failures to return the rotor to the set point after the failure transient. The passive fault tolerance was successfully demonstrated up to the rig's maximum achievable speed of 15,000 rpm by using as few as three active magnets out of the six independent C-core magnets. Current data that were input to the power amplifiers for normal operation were also measured in terms of the rotor speed and temperature to investigate the change of actuator gain.



Left: Control command signals to compensate for the consecutive failure of magnets 6, 1, and 4 during operation at 12,500 rpm. Right: Transient rotor orbit plot.

In comparison to a conventional active fault tolerance approach, which can handle a single magnet failure, this approach demonstrated that three active magnets out of six C-core magnets (multiple failure cases) levitated the rotor and spun it up to 15,000 rpm at 900 °F. It also showed that a passive approach could be applied to a heavily loaded magnetic bearing. This extremely valuable demonstration could help to ease the safety concerns of using high-temperature magnetic suspension technology for advanced high-speed rotating turbomachinery at temperature extremes caused by the possibility of system faults in the main bearing components.

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