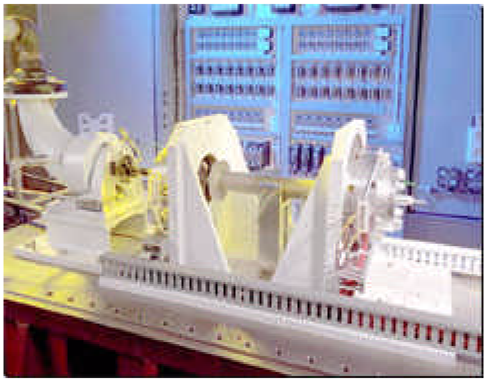
Observer-Based Magnetic Bearing Controller Developed for Aerospace Flywheels

A prototype of a versatile, observer-based magnetic bearing controller for aerospace flywheels was successfully developed and demonstrated on a magnetic bearing test rig (see the photograph) and an actual flywheel module.

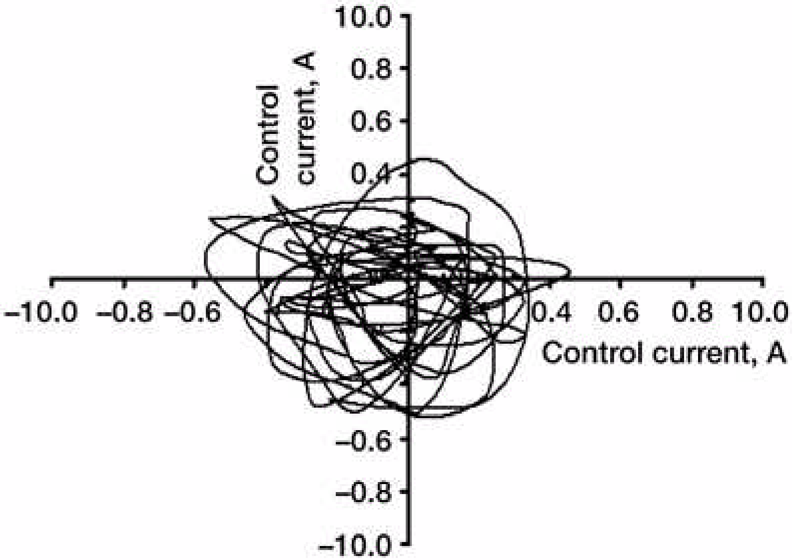
The objective of this development included a fast, yet low risk, control development process, and a robust, high-performance controller for a large variety of flywheels. This required a good system model, an efficient development procedure, and a model-based controller that addressed the key problems associated with flywheel and bearing imbalance, sensor error, and vibration. The model used in this control development and tuning procedure included the flexible rotor dynamics and motor-induced vibrations. Such a model was essential for low-risk scheduling of speed-dependent control parameters and for reliable evaluation of novel control strategies. The successfully tested control prototype utilized an extended Kalman filter to estimate the true rotor principal-axis motion from the raw sensor position feedback. For control refinement, the extended Kalman filter also estimated and eliminated the combined effects of mass-imbalance and sensor runouts from the input data.

A key advantage of the design based on the extended Kalman filter is its ability to accurately estimate both the rotor's principal-axis position and gyroscopic rates with the least amount of phase lag. This is important for control parameter scheduling to dampen the gyroscopic motions. Because of large uncertainties in the magnetic bearing and imbalance characteristics, this state-estimation scheme alone is insufficient for containing the rotor motion within the desired 1-mil excursion radius. A nonlinear gain adjustment based on an estimation of the principal-axis orbit size was needed to provide a coarse (nonoptimal), but robust, control of the orbit growth. Control current minimization was achieved with a (steepest gradient) search of synchronous errors in the principal-axis position input data.



Simple test rig used to develop the observer-based controller.

Structure of a table-mounted frame containing the flywheel test hardware and magnetic-bearing system with racks of electronic control equipment in the background.



Test results of the observer-based controller on an actual flywheel module. Speed at 26,000 rpm; imbalance compensation, 0.83 of estimated total errors.

Graph of the x- and y-axis electrical control currents in amperes. The locus of the currents over many cycles of rotation of the flywheel forms a series of randomly shaped loops in the center of the graph (Lissajous pattern). This pattern, called an orbit pattern, indicates that the controller can operate the levitated flywheel safely over the revolutions-per-minute operating range required.

Actual flywheel tests of this observer-based controller (developed entirely in-house) at the NASA Glenn Research Center showed that the model correctly predicted the rotor orbit growth as a function of rotational speed, and it demonstrated the capability of gain adjustments to arrest this growth. Data from these tests on an actual flywheel module spun to 26,000 rpm proved that the controller was able to contain the shaft motion to within much less than 0.5 mils of radial excursion with axis currents less than 300 mA in root-mean-square estimate (see the graph). The test speed range was limited because of thermal expansion concerns for this particular flywheel unit, not because of any deficiency in the controller. Simulations for this unit indicated that the controller should be robust up to its top operating speed of 60,000 rpm. Aside from these important achievements, and most significantly, it took less than 1 week to adapt this controller from the simple test rig to the actual flywheel and to demonstrate full five-axis levitation and control. This demonstration showed that both the controller and the model-based development and tuning framework are easily adaptable to a wide range of rotors and bearing configurations and, hence, are capable of reducing design risks and costs for many future flywheel technology developments.

Bibliography

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Glenn contacts: Dr. Dzu K. Le, 216-433-5640, Dzu.K.Le@grc.nasa.gov; and Andrew J. Provenza, 216-433-6025, Andrew.J.Provenza@grc.nasa.gov
Author: Dr. Dzu K. Le and Andrew J. Provenza
Headquarters program office: OAT
Programs/Projects: AFTP, SRF