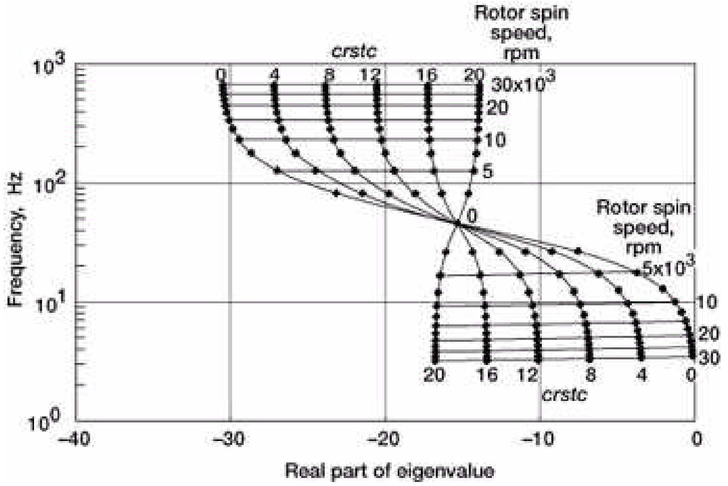
Stability of the Tilt Modes of an Actively Controlled Flywheel Analyzed

Applications of strongly gyroscopic rotors are becoming important, including flywheels for terrestrial and space energy storage and various attitude control devices for spacecraft. Some of these applications, especially the higher speed ones for energy storage, will have actively controlled magnetic bearings. These bearings will be required where speeds are too high for conventional bearings, where adequate lubrication is undesirable or impossible, or where bearing losses must be minimized for efficient energy storage.

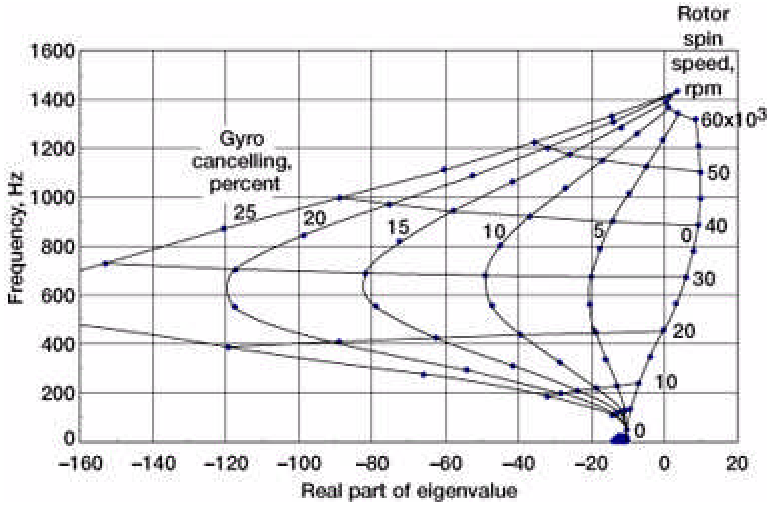
Flywheel rotors are highly gyroscopic, and above some speed that depends on the bandwidth of the feedback system, they always become unstable in an actively controlled magnetic bearing system. To assess ways to prevent instability until speeds well above the desired operating range, researchers at the NASA Lewis Research Center used a commercial controls code to calculate the eigenvalues of the tilt modes of a rigid gyroscopic rotor supported by active magnetic bearings. The real part of the eigenvalue is the negative of the damping of the mode, and the imaginary part is approximately equal to the mode’s frequency.

A modal controller was presumed in which the pure translation and pure tilt modes were separated. We addressed only the tilt modes. The controller included simple proportional-derivative (PD) gains for each tilt angle and proportional and derivative cross-coupling gains. Bandwidths were imposed in the control loop to represent the various phase lags of a magnetic bearing system. The effects of bandwidths, cross-axis proportional gain, and cross-axis derivative gain (gyroscopic canceling) were considered individually and in combination to show the qualitative and quantitative effects of each. Both cross-axis gains were "scheduled" by being multiplied by the rotor spin speed Ω since they were needed only to counteract the effects of gyroscopic torques.

The tilt mode of a nonspinning rotor becomes two modes under rotation: one mode (called the forward whirl mode) goes up in frequency with the rotor speed; the other (called the backward whirl mode) goes down. We found that cross-axis proportional gain, *crstc*, increases the damping of the backward whirl mode, which is otherwise a poorly damped, low-frequency mode at high rotor spin speed (see the top figure, which was calculated with high bandwidth). The point common to all curves is for zero rpm. Damping increases toward the left. This gain (*crstc*) decreases the damping of the forward whirl mode, which is otherwise better damped, but which could be subject to strong forcing by rotor unbalance as rotor speed increases (see the top figure). Cross-axis derivative gain (also called gyroscopic cancelling) can improve the forward whirl mode damping but has little effect on the backward whirl mode. An appropriate combination of these cross-axis gains can result in a closed-loop system that is stable over a wide speed range without additional gain scheduling, as shown in the bottom figure, which was calculated with more realistic bandwidths. Again, the point common to all curves is for zero rpm. Modes to the right of the vertical axis are unstable; modes to the left are progressively more stable as damping increases. Note that with 10-percent gyroscopic canceling, for example, the flywheel would be stable to nearly 60 000 rpm.



Effect of position cross coupling with W factor; five corners at 50 kHz.



Effect of small-percent gyro canceling with position cross coupling; five corners at 2 kHz; crstc, 12.

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