Cross-Axis Proportional Gains Used to Control Gyroscopic Effects in a Magnetic-Bearing-Supported Flywheel

For magnetic-bearing-supported high-speed machines with significant gyroscopic effects, it is necessary to stabilize both forward and backward tilt whirling modes. Instability or the low damping of these modes can prevent the attainment of desired shaft speeds. Previous work elsewhere showed that cross-axis derivative gain in the magnetic bearing control law can improve the stability of the forward whirl mode, but it is commonly recognized that derivative gains amplify high-frequency noise and increase the required control effort. At the NASA Glenn Research Center, it has been shown previously that a simple cross-axis proportional gain can add stability (without adding noise) to either forward whirl or backward whirl, depending on the sign of the gain, but that such a gain destabilizes the other mode.

It has been predicted by Glenn analysis that both modes can be stabilized by cross-axis proportional gains by utilizing the large-frequency separation of the two modes at speeds where the gyroscopic effects are significant. We use a modal controller that decouples the tilt and center-of-mass-translation modes. Only the tilt modes exhibit speed-dependent gyroscopic effects. The key to controlling them by the present method is to stabilize the backward whirl tilt mode with the appropriate sign of cross-axis proportional gain in the control law, but to include a low-pass filter on that gain term to restrict its effect only to the low-frequency backward-whirl mode. A second cross-axis term with the opposite sign and a high-pass filter stabilizes the forward whirl, which can have a frequency one or two orders of magnitude higher than the backward whirl, permitting very independent action of the two terms. Because the physical gyroscopic torques are proportional to the spinning speed of the shaft, it is convenient to gain-schedule the cross-axis control terms by making them proportional to shaft speed. This has the added benefit of avoiding a somewhat awkward zero-speed splitting of the tilt-mode eigenvalues.

Phase lags in the closed loop do place a limit on the speed at which this simple method is effective, but if the phase lags are known, a modification of the method can extend the benefits to extremely high speeds. The action of the cross-axis gain is really to provide phase lead in the control to counteract phase lags in the rest of the closed loop. The displacement of one axis leads or lags the other by 90° and can be used with an appropriate gain to provide up to that amount of phase lead. However, at a shaft speed such that the forward whirl frequency reaches a value where the system phase lag reaches 90°, the method, as outlined so far, fails. But a linear combination of the two tilt displacements can have any desired phase (up to 360°) with respect to one of the displacements. An appropriate linear combination can be formed for any forward whirl mode frequency at which the external system phase lag is known, and that combination can provide adequate phase lead for forward whirl stability at any shaft speed. Implementation would require knowledge of the system transfer function and gain scheduling with respect to rotor speed. This extension of the method has been verified by eigenvalue analysis but not tested experimentally.

The basic method was experimentally demonstrated on the "DEV1" energy storage flywheel unit at Glenn at speeds up to 20,000 rpm. At that speed, the forward-whirl mode frequency was about 240 Hz and the backward-whirl frequency was about 15 Hz. Spectral density measurements of the shaft displacements confirmed that the two gain terms acted independently on the two modes. Each gain could be increased to reduce the affected spectral density peak to insignificance or, by using a small gain of the opposite sign, the modal damping could be reduced in order to sharpen the spectral density peak for accurate frequency measurement.

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