Synchronous Control Effort Minimized for Magnetic-Bearing-Supported Shaft

Various disturbances that are synchronous with the shaft speed can complicate radial magnetic bearing control. These include position sensor target irregularities (runout) and shaft imbalance. The method presented here allows the controller to ignore all synchronous harmonics of the shaft position input (within the closed-loop bandwidth) and to respond only to asynchronous motions. The result is reduced control effort.

A previous article in this report outlined a method for automatic centering of a shaft in radial magnetic bearings, which achieves zero average control current. That was done by adding a very slowly building integral of the control current to the control output. (Using an integral of the controller output command rather than measured current can be a simpler alternative.) The method for rejecting synchronous disturbances is an extension of that method. We presume that the shaft's angular (spin) position θ is always known (from a once-per-revolution pulse, for example). For each actuator degree of freedom, an array of integrals of control output O is calculated and stored. Each integral $I(n)$ is approximated by a sum that receives a new contribution n samples after each one-per-revolution pulse:

$$I(n) = (1 - f\,Ig)\,[I(n) + \alpha\, I(n - 1) + \alpha\, I(n + 1)] + (1 - 2\alpha)Ig\,O(n)$$

where Ig is a small gain (such as 0.02) and $f\,Ig$ is a "forgetter" factor. The terms containing α are discussed in the last paragraph of this article. Thus at a given speed, we are integrating the control effort required whenever the shaft has a particular angular position and are storing that in one element of the array. Adding that element in the array to the control output whenever the shaft angle is θ results eventually in the magnetic bearing producing no synchronous control force at that shaft angle. The output for the nth sample after the one-per-revolution is

$$O(n) = PD\_\mathrm{control\_etc}(n) + I(n) + \{cg\,[I(n + 1) - I(n - 1)]\}/\Delta t$$

where PD_control_etc(n) is the control output for whatever control law is used, Δt is the time between samples, and the presence of the term containing Δt is explained in the last paragraph of this article. The $I(n)$ array acts like a feed-forward function. Spurious synchronous sensor runout signals come into the controller and contribute to PD_control_etc(n) but are cancelled out by $I(n)$. Furthermore, the shaft is allowed to revolve about its principle inertia axis rather than about its geometrical centerline, reducing the control effort due to imbalance as well as reducing the forces transmitted to the housing. The shaft runs like a supercritical shaft at all speeds

The method was demonstrated on a magnetic-bearing-supported energy-storage flywheel (DEV1) at the NASA Glenn Research Center. The runout of the radial sensors was very serious, amounting to 15 to 20 percent of the backup bearing gap of 8 mils (0.2 mm). The sensor runout produced apparent (but spurious) displacements at least an order of magnitude higher than the real shaft dynamics. Moving notch filters had previously been needed to keep the sensor runout from causing power amplifier saturation at high shaft speeds. Spectral density measurements of the sensor signals showed that the present method reduced synchronous harmonic content by factors of 3 to 10 at shaft speeds up to 20,000 rpm.

If explicit synchronous feed-forward signals are introduced to deal with unbalance, the array $I(n)$ converges to the difference between its former values and the feed-forward function.

Several implementation details were developed on an ad hoc basis. The required size of the array is equal to the number of samples in one shaft revolution at the lowest speed at which the method will be used. We used arrays of 1500 to 2000 elements with a controller sample rate of 60 μsec and could introduce the integrals at shaft speeds somewhat below 1000 rpm. Note that the number of active elements in the array becomes much smaller at high speeds; there are only 50 samples per revolution at 20,000 rpm. We do not need to change the array dimension with speed; rather the code automatically uses only as many elements as required in one revolution. The array was continually smoothed by a degree of averaging of adjacent elements. This was affected by the terms containing α, which was arbitrarily set somewhere between 0 and 0.25. This aids in letting the array adapt to changing speeds. Furthermore, each element was gradually eroded to remove contributions of the distant past by using a forgetter factor ($1 - f\,Ig$), which is very slightly less than one, where f was of order 1. Each element is, thus, a geometric average of the control effort exerted for *n* σαμπλεσ αφτερ τηε ονε–περ–ρεϖολυτιον πυλσε, σμοοτηεδ σομεωηατ ιν τιμε. Φιναλλψ, το αϖοιδ αν ινσταβιλιτψ τηατ ωουλδ οτηερωισε δεϖελοπ ιν τηε αρραψ, α δεριϖατιϖε οφ τηε αρραψ ωιτη ρεσπεχτ το θ was added to the control output, with an empirically determined gain *cg* of the order of 0.005.

If the shaft speed is set low, the actual sensor runout, which is difficult to measure otherwise, can be obtained by allowing the synchronous rejection to converge and then recording the sensor output. This measurement is relatively uncontaminated by closed-loop effects that would otherwise prevent direct measurement of runout on the levitated shaft.

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