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# Active Vibration Isolation of an Unbalanced Machine Spindle

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## **Abstract**

Proper configurations of controls, sensors, and metrology technologies have enabled precision turning machines to achieve nanometer positioning. However, at this level of positioning resolution, vibration sources can become a limiting factor. One of the largest sources of vibration in a turning machine may be an unbalanced rotating spindle. In this paper, a system is implemented to actively cancel spindle unbalance forces. Specifically, to attenuate the spindle housing vibration using an active vibration control system to prevent the unbalance force from disturbing the rest of the machine systems e.g., the slide servo system or the machine metrology frame. The system controls three degrees of motion.

An unbalanced spindle creates a rotating force vector with a once per revolution period. The cause and size of this force is a function of the spindle, the part, the part fixturing, the part setup and the spindle speed. In addition, certain spindle speeds coupled with the size of the unbalance force may contain other harmonics that can excite machine structural resonances. The magnitude of the unbalance force increases as the square of the spindle speed.

The control algorithm of this system is fully implemented on a commercially available machine tool controller and is sensitive only to unbalance induced motion. The paper describes in detail the control algorithm and how it is implemented. The system has demonstrated the ability to adapt in real time to remove the fundamental component of the unbalance force to nanometer levels. However, higher-order structural resonance components of the test bed have been observed when the system is active. The control system is stable and the voice coil (VC) excitation is harmonically clean but the high Q of the mechanical test system is apparently excited by energy leakage. Our results indicate the need to carefully examine the dynamics of any spindle system that would take advantage of this active system.

## **Introduction**

Spindle unbalance forces in a precision machine can impart energy into the machine base and provide a forcing function to the machine slides and the machine metrology frame and may cause undesirable slide motion. This motion can be rejected to some extent by the control system loop gain but the loop gain decreases with increasing frequency. This is exactly opposite of what is desired as the unbalance spindle forces increase with spindle speed (frequency) further compounding the problem. Force disturbance of the metrology frame can cause non-rigid body motion of the frame and distort the measured tool position. Eliminating or canceling the spindle unbalance force reduces these error sources.

The ideal solution is to cancel the unbalance force at the source or rotor of the spindle. This is difficult since the spindle must hold the part and any apparatus that would be used to cancel the rotor unbalance. Our approach is to cancel the vibration forces that radiate from the spindle housing so that these forces do not induce motion into sensitive machine systems.

The basic concept of the system is to measure the force-induced spindle-housing motion and exactly cancel this motion with a controlled moving inertial mass. Essentially, the spindle housing motion is measured with a displacement sensor referenced to the machine base. The measured displacement is sinusoidal and corresponds to the motion profile required of the VC motor creating the opposing force. The displacement measurement, along with the spindle angle (measured with an encoder), is fed to a controller running a specific algorithm. The algorithm computes the required signal and the controller actuates a voice-coil (VC) motor, canceling the original force-induced motion. The amount of force required to cancel the unbalance is a function of frequency (spindle speed), the amount of mass the VC is moving, and the range of VC travel. The equation that relates these variables and describe the motion profile is;  $F = (W/g) [-A\omega^2 \sin(\omega t)]$ . Where F is the force, W is the weight the voice coil is moving, g is

acceleration due to gravity so  $W/g$  is the moving mass. The term  $[-Aw^2 \sin(\omega t)]$  is the acceleration due to the motion profile and is derived from the second derivative of the VC displacement profile.  $A$  represents the maximum peak amplitude of the measured displacement and  $\omega$  is  $2\pi f$  where  $f$  is the spindle RPM divided by 60.

### The System

The test bed and a simple block diagram of the control system are shown in Figure 1. The test bed structure is designed to be compliant and vertically holds a four inch air-bearing spindle. A bolt can be screwed into the spindle face-plate to unbalance the spindle. The control algorithm is fully implemented on a commercially available controller and is sensitive only to unbalance force induced motion. (The controller performs synchronous demodulation of the capacitance gauge signal so only signals synchronous to the once per revolution of the spindle are processed and used by the controller.) The VC motors are mounted on the opposite side of the spindle housing directly in-line with the corresponding displacement sensor. The voice coil motors are moving an inertia mass and do not act against a reference structure. We have addressed three degrees of freedom of spindle housing motion of the test bed system, the X direction, (the single VC motor) the Y direction, (the two Y VC motors acting together) and rotationally, the yaw motion (the two Y VC motors acting oppositely).

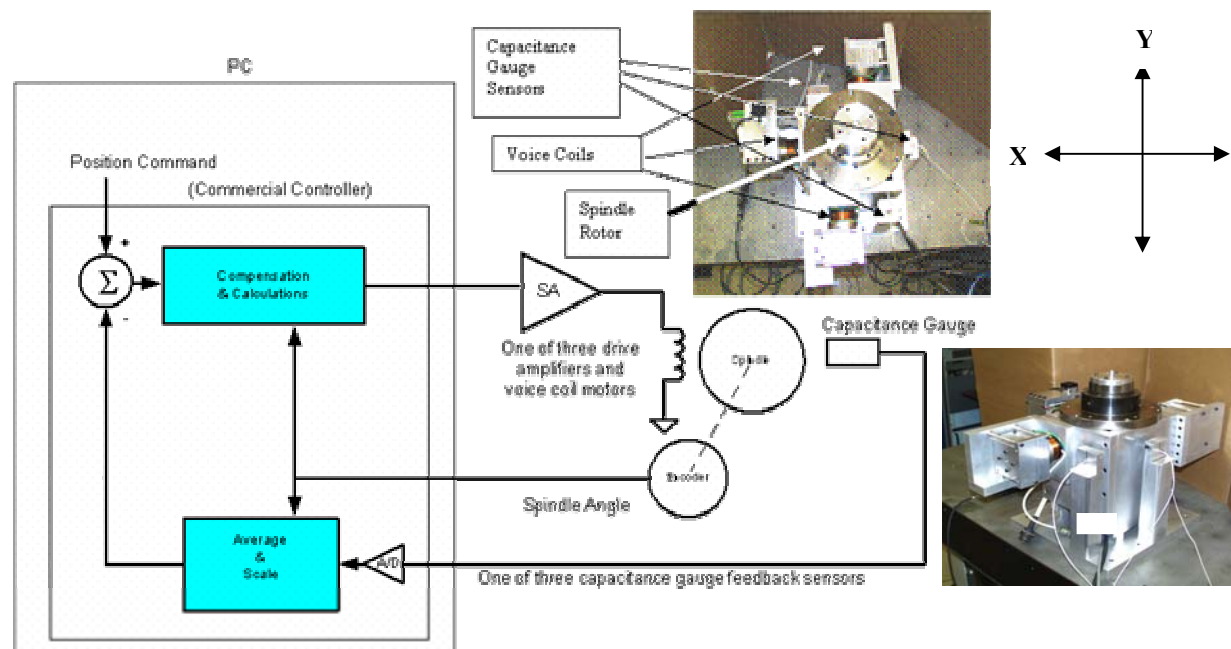


Figure 1: Simple control system block diagram and top and side view of the physical test bed system.

### Control Algorithm

When a machine tool controller commutates a brushless motor, it uses a sensor (typically an encoder) to sense the location of the motor rotor and modulates the servo output signals delivered to the torque amplifier (motor current command) for each motor phase. The signals of the two output phases (the PID output or 2<sup>nd</sup> order filter output– Actuator Excitation - see Figure 2) are modulated (commutated) in many modern day machine tool controllers with a sinusoid, the value of which depends on the angular position of the encoder. The two outputs typically have a commutation angle offset of either 90 degrees or 120 degrees (as in Figure 2) depending on whether the motor is a two phase or three phase device respectively. (In the case of a three phase motor, the torque amplifier typically generates the third phase internal to the amplifier.) If ninety degrees is chosen as the phase offset, e.g., for a two phase brushless motor, the torque command is modulated by the sine and the cosine of the motor rotor angle.

Figure 2 is the typical configuration of a single axis of the 32 possible axes available in the machine tool controller used in this paper. The controller allows configuring a typical servo axis in several ways. The

interpolated position command can be set to zero. The PID terms are all adjustable as are the coefficients of the second order filter allowing the filter to be set to a gain of one. The commutation function can be enabled or disabled if the motor is self commutating. The sensor feedback input, normally an encoder, can be used to commutate a motor and also interpolated to create higher resolution position information for the servo axis feedback (Processed Position Feedback). This is the usual case for many applications; however, it is possible to have the commutation feedback for a particular axis be derived from the feedback input of another axis, i.e. the commutation feedback and the processed position feedback do not have to come from the same sensor. Also, the sensor feedback can be derived from any type of device. It is these last two key features that provide a very powerful capability and when coupled with the other capabilities listed, the controller requires no additional components to provide the adaptation algorithm discussed in this paper.

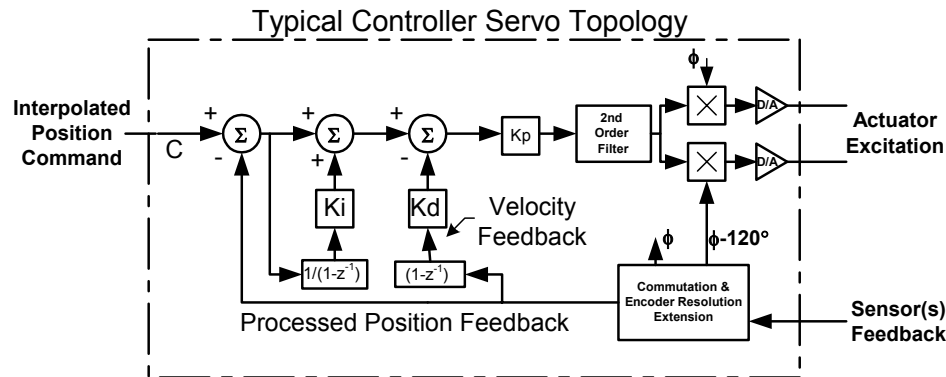


Figure 2: Typical configuration of a single axis of the machine tool controller configured to commutate a three phase brushless motor

In this system, the sensor feedback for one of the axes is an analog signal derived from a capacitance gauge sensor measuring the displacement of the spindle housing caused by the rotational force of an unbalance spindle. When commutation is enabled for this axis and the axis is commutated from the spindle rotary encoder derived from another axis and the terms of the servo axis are set to a gain of one, the analog displacement signal will be synchronously demodulated at the two outputs of the axis with respect to the angular location of the encoder. This provides a harmonically clean measurement of displacement caused by the unbalance occurring at once per revolution of the spindle. If the sensor signal was not processed in this way, it could be contaminated with other synchronous and non-synchronous displacement noise. By picking 90 degrees as the phase offset between the two output phases of commutation, the output signals (Actuator Excitation) will be the Fourier transform of the measured displacement signal. (Sine of the encoder angle times the sensor input signal is available at the first output and the cosine of the encoder angle times the sensor input signal is available at the other output.) Once these signals are low pass filtered (integrated), a coefficient for each of these two outputs is available that represents only the synchronous value of the sensor signal. Because of the Fourier transform, any input signal not related to the once per revolution of the rotor are rejected by the transform (It is a selective filter.) The process can be thought of as a two phase synchronous demodulator. When these signals are used as part of a control system that adjust the reference phase (relative to the zero point of the encoder), the sine modulated output represents the magnitude of the input signal and the cosine modulated output represent the amount of phase adjustment needed to obtain the maximum signal gain for the sine output at the maximum location of the unbalance. This is the key to the adaptation aspects of this system. The control system tries to adjust the cosine signal term to a minimum or zero and when this occurs, the sine signal term should be at a maximum or gain of one.

To be more specific, assume a displacement sensor is observing motion caused by an unbalance force acting on the structure as the spindle rotates. Initially, the maximum amplitude of the displacement signal may not necessarily correlate to the peak of the sine and or the zero of the cosine of the commutation cycle due to the angular position of the encoder versus the angular position of the unbalance. Because of the dual synchronous demodulation, it is possible to find the maximum unbalance signal and the location

of this signal relative to the encoder zero. When there is an offset between the encoder commutation angle and the peak of the unbalance signal the sine modulated output will have less than a signal gain of one and the cosine modulated output will have more than a zero or minimum output. If the cosine term is used in a control system loop to adjust a simulated encoder reference or virtual encoder, the adjustment continues until the cosine signal magnitude is zero. At this point, the maximum synchronously demodulated signal is obtained at the first output or sine modulated output. Once this signal is low passed filtered, a DC value is obtained representing the peak of the displacement signal at the maximum unbalanced location. This signal can now be used as an amplitude command to actuate a second motor axis that is also commutating in sync with the virtual encoder. This signal is a sine wave that is used to drive the VC motor actuator canceling the synchronous motion detected by the displacement sensor.

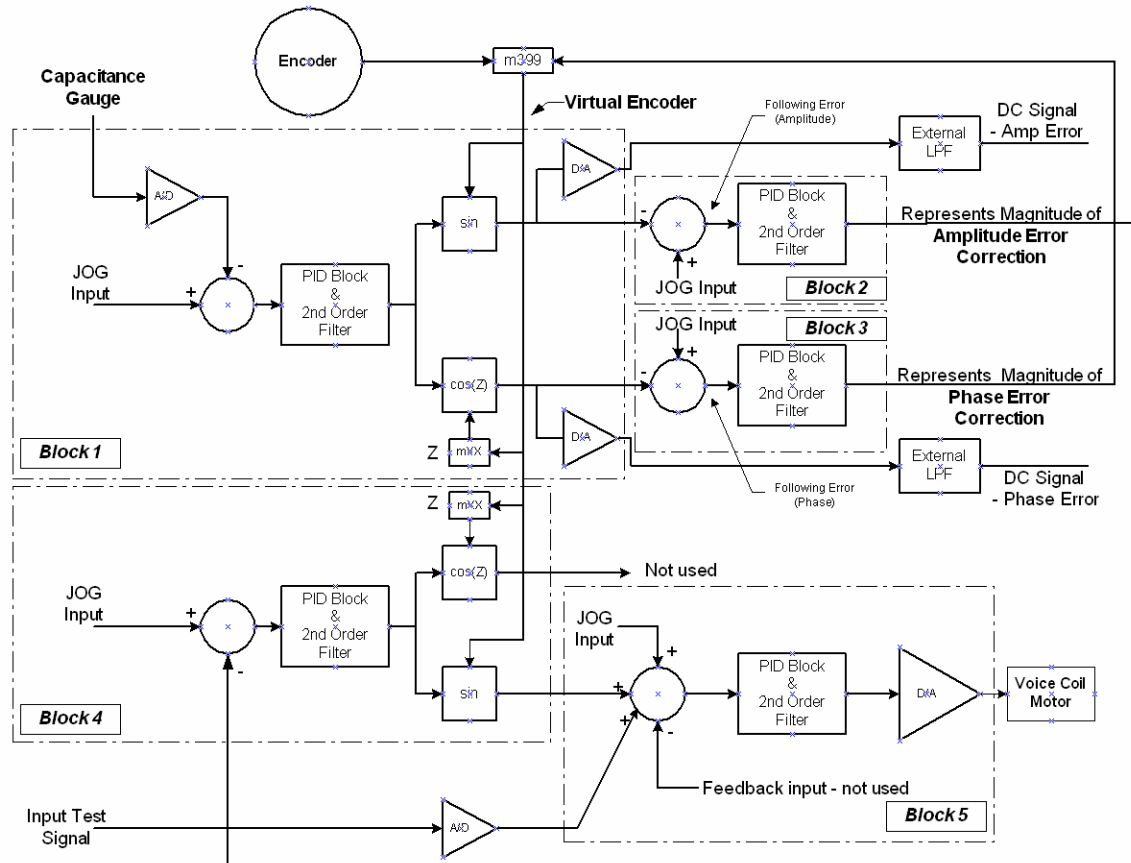


Figure 3: The complete control algorithm using dual synchronous demodulation and adaptive feedback control of the reference phase for the virtual encoder with the force cancellation device

The complete control algorithm is shown in Figure 3. Each dotted outline represents a Block or axis of the machine controller as shown in Figure 2. Blocks 1 and 4 have commutation enabled. Blocks 2, 3 and 5 have commutation disabled. The capacitance gauge sensor input signal is an analog signal representing displacement. Block 1 does the dual synchronous demodulation of this signal as previously described. The mXX register in Blocks 1 and 4 is the phase angle offset between the two commutation outputs and is set to 90 degrees to provide the sine and cosine multiplying values for the commutation (synchronous demodulation) of the displacement signal. The two outputs of Block 1 are filtered (not shown) by a controller filter function built into Block 2 and 3 (The sensor input is filtered before becoming the processed feedback input – See figure 2.). Blocks 2 and 3 respectively provide the servo compensation for the two control loops. The JOG input of Block 2 and 3 are normally set to zero and can be thought of as a DC offset to the filtered signals. If the following error is zero for the cosine path, the phase of the imbalance has been properly determined. If the following error of the sine path is zero, the imbalance has been effectively canceled by the voice coil forcer shown at the output of Block 5. The D/As near Block 2

and Block 3 are available as output analog signals which can be viewed with an oscilloscope or passed through external low pass filters to verify the correct values of the demodulation process. Block 4 uses the sine output to generate a sinusoidal command signal to Block 5 based on the amplitude of the error correction output of Block 2. Block 1 and 4 uses the virtual encoder (offset register label m399) developed from the sum of the actual encoder count and a count value derived from the output magnitude of Block 3. This is part of a feedback loop that adjusts the offset phase register m399. This adjustment continues until the following error at Block 3 reaches zero. When this occurs, the virtual encoder phase is lined up with the maximum angular location of the unbalance. The filtered sine output is now at a maximum and through feedback, the value of this signal is now used by Block 4 to generate a harmonically clean sine signal whose amplitude will force the VC motor motion to produce zero at the filtered sine path input of Block 2. When this happens, the unbalanced displacement is exactly canceled by the voice coil actuator.

## Results

Figure 4 shows data plots of the displacement signals before and after activation of the control algorithm. It also shows the voice coil excitation command required to achieve the cancellation. The unbalance spindle produces approximately 50 nm of peak to peak motion at 200RPM. It can be seen that the fundamental component of unbalance is very well suppressed; however, higher frequency displacement signals now dominate the response.

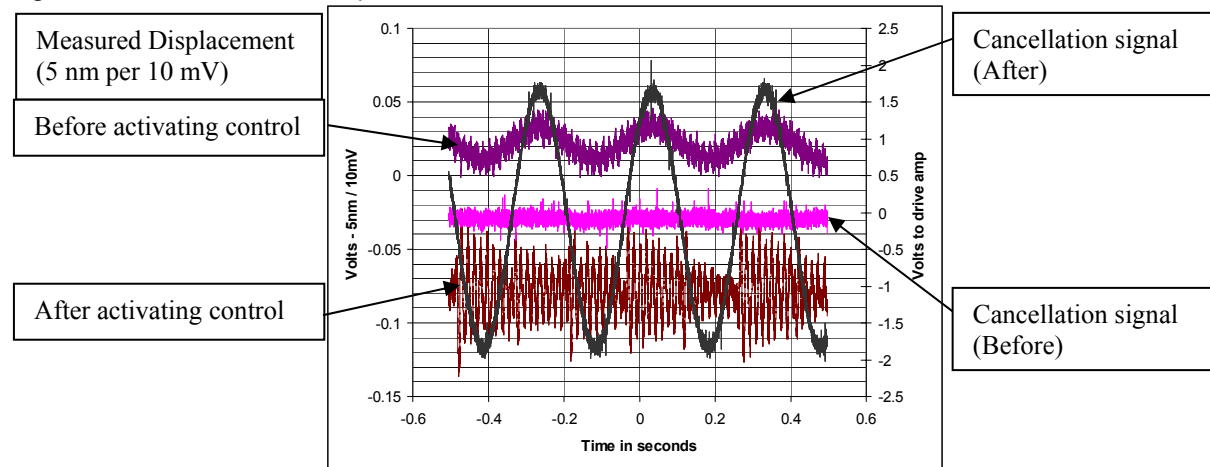


Figure 4 Data Plots (Some plots are offset for easy of viewing)

## Conclusion

The control algorithm of this test system has demonstrated the ability to adapt in real time to remove the fundamental component of the unbalance rotational force vector to nanometer levels due to an unbalanced spindle. However, higher order structural resonance components of the test bed have been observed when the system is active. The control system is stable and the voice coil excitation is harmonically clean but the high Q (measured) of the mechanical system is apparently excited by energy leakage. The test bed was purposely designed to be mechanically compliant and potential resonances were not modeled. The test bed does not represent a well designed machine spindle, however, the results indicate the need to carefully examine the dynamics of any spindle system that would take advantage of this active system. Future work would concentrate on testing the control system on a real machine tool spindle or developing a more damped and better modeled mechanical test bed.

## Reference

David J. Hopkins, Timm A. Wulff, George F. Weinert, "A Machine Tool Controller using Cascaded Servo Loops and Multiple Feedback Sensors per Axis", Proceedings ASPE Spring Topical Meeting Control of Precision Systems, April 2004.

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