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Apparent unbalance caused by torque ripple due to encoder eccentricity

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Abstract
Although spindle balancing is a mature subject with exhaustive documentation in the literature, the consequences of torque ripple on unbalance are relatively unknown. This effect is significant for applications sensitive to unbalance-induced error motion such as direct machining of optical quality surfaces with nanometer- level form requirements. This paper demonstrates the torque ripple caused by encoder eccentricity error and the implications on balancing.

Keywords: Spindle metrology, encoder accuracy, unbalance, torque ripple

1. Introduction

Vibration of the machine structure resulting from a rotating unbalance force or moment may lead to fundamental (once-per-revolution) axial motion, higher order harmonic motion, and poor dimensional control with changes in speed [1-4]. Furthermore, for high dynamic response servo systems, torque ripple due to encoder eccentricity can be misinterpreted as unbalance. Attempts to eliminate the vibration due to torque ripple at one speed can lead to increased unbalance at other speeds. In this work, vibration caused by torque ripple as a result of encoder eccentricity is investigated and potential improvements are suggested.

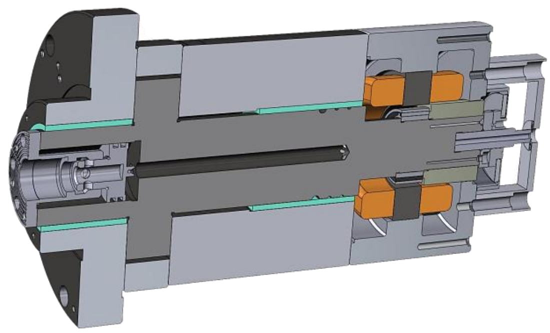


Figure 2. Captured thrust air bearing spindle with integral brushless servo motor and 4096 line count encoder.

2. Methodology

The block diagram in Figure 1 shows the servo loop for the system under test which incorporates a standard PID controller via linear amplifier (Aerotech Ensemble HLE20). An air bearing spindle (PI ISO 3R in Figure 2) with integral brushless servo motor and encoder is used to demonstrate the unbalance disturbance. A higher bandwidth, higher stiffness loop tuning (unity gain crossover frequency, fc = 175 Hz) is compared to a lower bandwidth, lower stiffness servo loop (fc = 11 Hz). Torque disturbances are introduced at the spindle speed via encoder eccentricity and unbalance. The magnitude and phase of the encoder-related disturbance is dictated by the loop transmissions shown in Figure 3. The unbalance torque disturbance magnitude is proportional to the square of the speed and the phase is dictated by plant dynamics.

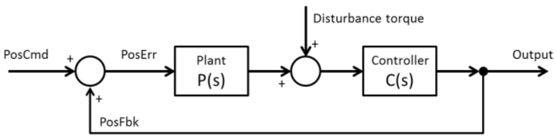
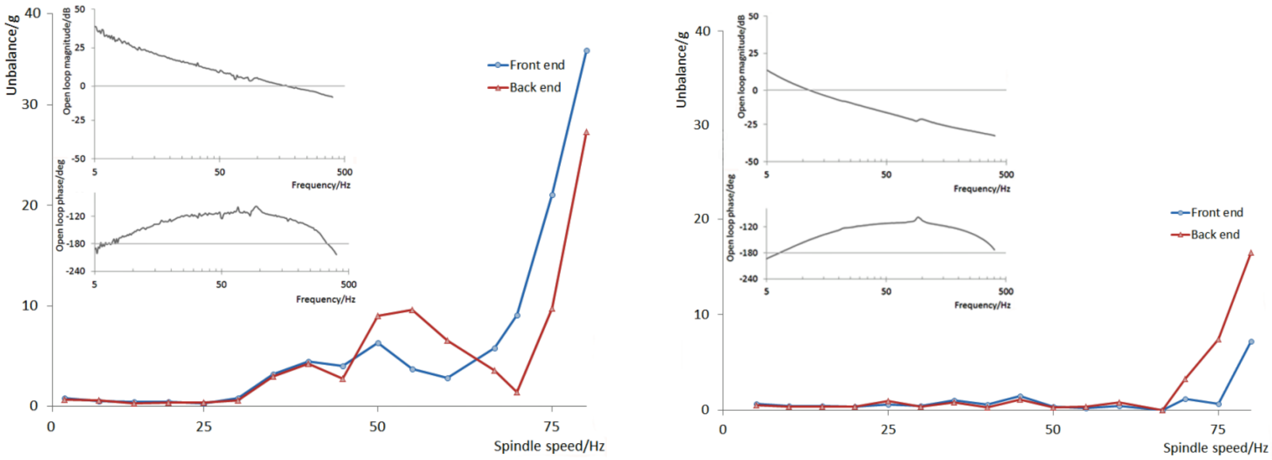


Figure 1. Servo loop block diagram with the PID controller C(s) and the air bearing spindle plant P(s).

High resolution balancing at 66 Hz is achieved using sensitive accelerometers (Kistler K-shear 25 g) mounted at the two spindle correction planes and balancing on compliant foam. Balancing software (Benstone Instruments Rotolab) calculates corrections using the encoder index to determine phase relationship. Use of the encoder index eliminates the need for reflective tape that introduces balance errors. Final balance corrections are on the microgram-level using a buffing wheel to remove material from setscrews.

3. Results

For the high-bandwidth system, vibration levels are below accepted levels at the balancing speed of 66 Hz. However, unacceptable unbalance vibration exists at speeds above and below the 66 Hz balance speed as shown in Figure 3a. A particular concern is the unexpected increase in vibration below the balancing speed from 30-65 Hz. This is presumed to be caused by magnitude and phase mismatch of the torque ripple compared to the 66 Hz torque disturbance. The corresponding peak-to-peak torque ripple shown in Figure 4 is ten times higher for the high bandwidth system. The servo loop is tracking the sinusoidal disturbance due to eccentricity of the encoder.



a) b)

Figure 3. Tenfold improvement in vibration levels between the a) high bandwidth servo (fc = 175 Hz) and b) low bandwidth servo (fc = 11 Hz). Open loop transmission magnitude and phase shown inset for each. Balancing is performed at 66 Hz.

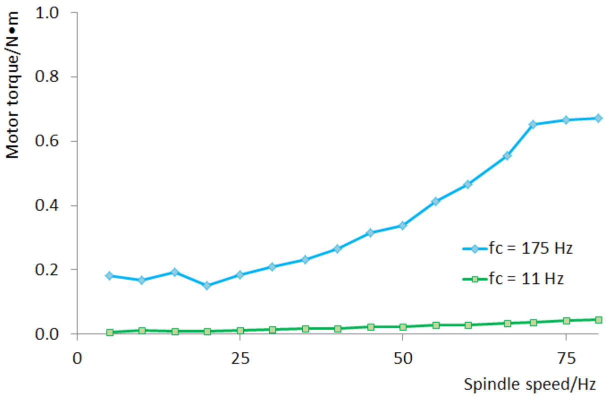


Figure 4. Peak to peak torque ripple caused by encoder eccentricity for the high and low bandwidth servo systems. The torque ripple is ten times greater for the high bandwidth servo.

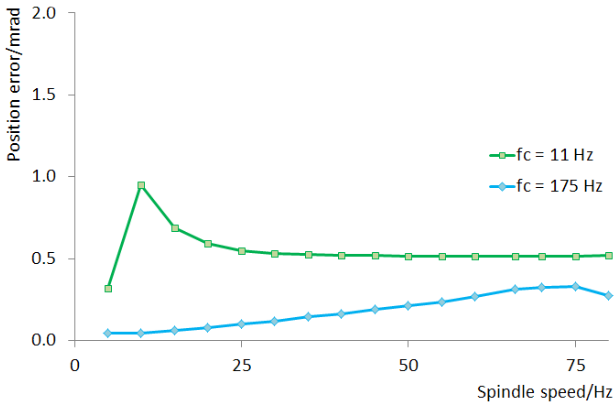


Figure 5. Position error caused by encoder eccentricity for the high and low bandwidth servo systems. The position error for the low bandwidth system converges to 0.5 mrad at speeds much greater than the crossover frequency.

In the case of the low-bandwidth system, the balance condition below 66 Hz is improved tenfold because the torque disturbance is minimal. The servo loop is not able to track the sinusoidal disturbance. Above the balancing speed, the unbalance for the low-bandwidth servo is half as much as the high-bandwidth system. However, the obvious disadvantage of the low-bandwidth servo is the inability to track the desired trajectory resulting in an increased position error.

4. Summary

In this work, unbalance of high precision spindles is examined with an eye towards understanding the cause of vibration using a deterministic approach. The approach requires identification of a disturbance that is masked as unbalance. In this study, the magnitude of the vibration due to torque ripple caused by encoder eccentricity is an order of magnitude higher without this error. Therefore, an incorrect diagnosis of the cause of vibration could result in significant errors attempting to eliminate the “apparent” unbalance.

5. Conclusion

Precision balancing over a wide speed range can only be accomplished by eliminating the torque ripple caused by encoder eccentricity. This is critical to processes sensitive to vibration of the machine structure such as optical surfaces with nanometer-level form tolerances or parts requiring tight dimensional control with changes in speed.

6. Future work

In cases where high bandwidth is required, the torque disturbance must be eliminated. In future work, we will demonstrate a two-pronged approach to eliminate encoder eccentricity torque ripple. The first step is a brute force improvement to the assembly process using the encoder readhead output to minimize centering error. The encoder position is adjusted mechanically until the phase between the output of two readheads diametrically opposed is constant. The second step uses compensation with a high-bandwidth servo to eliminate the residual encoder error using error mapping of a low bandwidth system running at a speed well-above the crossover frequency. This multistep approach provides precision balance and superb positioning error.

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