Ultra-precision, High Speed Micro-machining Spindle

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Abstract

Deterministic micro-cutting processes such as diamond micro-milling, raster fly-cutting and micro-grinding are used to efficiently manufacture optical quality freeform surfaces like the one in Figure 1a) [1]. High stiffness spindles with low synchronous and asynchronous error motions improve the micro-machining process. This paper describes design and testing of a 50,000 RPM ultra-precision micro-machining air bearing spindle capable of producing optical quality surfaces.

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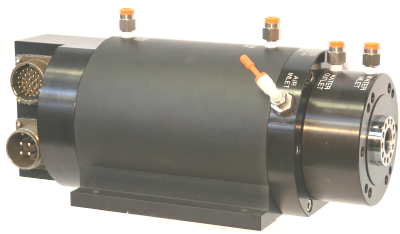
b) 

Figure 1: a) Micro-milling a lens array mold with the spindle discussed in this paper (photo courtesy of Moore Nanotechnology Systems), this mold was machined using the spindle discussed here and b) ISO 50K air bearing micro-milling spindle.

1 Design

The spindle in Figure 1b) incorporates a “captured thrust” groove compensated air bearing between two radial groove compensated air bearing journals. Air is ported through the stator to annular manifolds that distribute it to radial and thrust

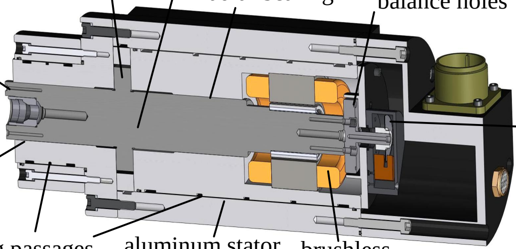


Figure 2: Sectioned view of the ISO 50K.

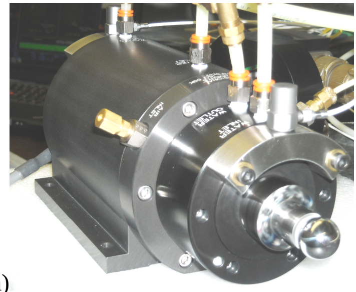
bearings. Wide journal bearing spacing provides tilt capacity and stiffness, enabling the use of a smaller diameter thrust and reducing heat generation of the air-films. Typically, a trade-off exists between a high speed and a high stiffness spindle design. Tighter clearances will provide higher stiffness but create more heat due to drag and additional motor heat. In this spindle, axial and radial air films are 7 µm and spindle temperature is controlled using integrated water-cooling. A stainless steel rotor is combined with an aluminum stator as shown in Figure 2. The spindle features a 100-line count rotary encoder with integral hall effect sensors, a DC brushless permanent magnet motor and provision for balancing front and rear planes.

2 Testing

This paper demonstrates a comprehensive approach to balancing and error motion measurement—two issues that influence surfaces machined with high speed spindles. Balance is critical in deterministic micro-cutting processes such as micro-grinding, raster fly-cutting, and diamond micro-milling. Several negative consequences can be attributed to unbalance in micro-cutting at high speeds including vibration of the machine structure and increased fundamental axial motion. Furthermore, the negative effect of spindle asynchronous errors in single point machining are well-documented, and they are critically important for raster fly-cutting [2, 3].

2.1 Balancing

A setup for balancing the 50K spindle is shown in Figure 3a). The spindle rests on a compliant surface for high resolution measurement of residual unbalance. Accelerometers are mounted in two planes to measure dynamic unbalance while the spindle encoder provides phase orientation. Microgram unbalance corrections are adjusted by removing material from M3 setscrews at each balance plane.



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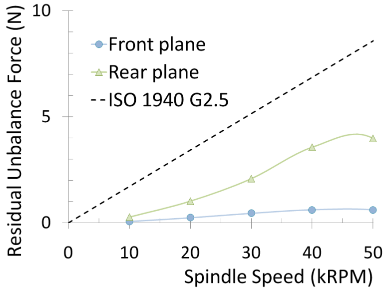
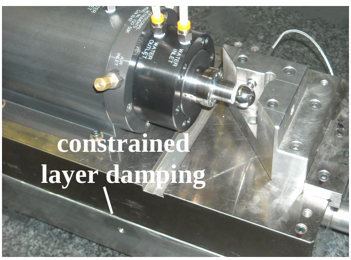


b)

Figure 3: a) Accelerometers measure residual spindle unbalance on compliant foam, and b) residual unbalance force after balancing compared to ISO 1940 G2.5 [4].

2.2 Error motion measurement

This spindle is designed to run up to 50,000 RPM with less than 25 nm total axial and radial error motions. Such demanding performance requires rigid test hardware and isolation of external disturbances. Error motion tooling shown in Figure 4a) features a large granite base with passive air isolation, stiff steel structure and rigid sensor mounts. Originally, the test fixture was a solid piece of steel 190 mm wide by 350 mm long and 64 mm thick. As shown in Figure 4b), adding a constrained layer of viscoelastic damping material provided a dramatic improvement in the dynamics [5].



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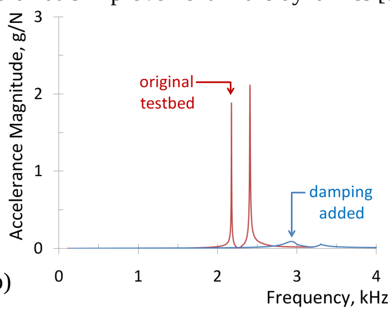

b)

Figure 4: a) Tooling for error motion measurement, and b) accelerance frequency response function of test fixture before and after damping improvement.

A capacitive sensor targets a 19 mm diameter lapped spherical artifact in the radial and axial directions. The sensor amplifier incorporates a 15 kHz low-pass analog filter. The Lion Precision SEA data acquisition system is triggered by the encoder data channel, providing exact partitioning of synchronous and asynchronous errors.

Total axial and radial error motion results are shown in Figure 5a) as a function of spindle speed. Maximum asynchronous error is 12 nm over all tests.

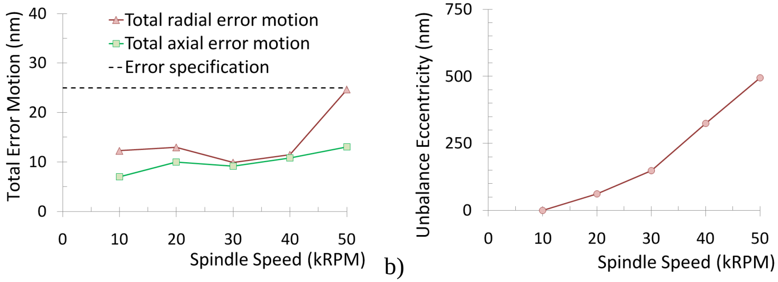

Figure 5: a) Total axial and radial error motions are less than 25 nm at all speeds, and b) unbalance induced eccentricity is less than 0.5 μm at all speeds.

Conclusion

Balancing and error motion testing techniques and apparatus required for an ultra-precision high speed micro-milling spindle are described. At speeds from 10,000 RPM through 50,000 RPM, the unbalance induced eccentricity for this spindle is shown to be below 0.5 μm as a result of precision balancing and high stiffness. Total axial error motion and total radial error motions for this spindle are less than 25 nm at these speeds. Axial and radial asynchronous errors, critically important for optical quality surfaces, are less than 12 nm at these speeds.

References:

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