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# Static stiffness and dynamics testing on a spindle for ultra-precision diamond turning

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**Abstract**

Ultra-precision machining for high end optics requires thorough testing of the precision spindles involved. Spindles for high end optics not only need to be extremely accurate, they also need to be incredibly stiff and have excellent dynamics. Test methods and results are demonstrated that determine spindle static stiffness and dynamics are sufficient to perform in demanding ultra-precision machining applications. The static stiffness for axial and radial bearings of the spindle is linear through the full deflection of the spindle at 151 N/µm and 700 N/µm respectively. The spindle dynamics demonstrate that the first modes (or resonances) for axial and radial directions occur well above the required 1500 Hz (~1700 Hz and 2300 Hz, respectively).

Air bearings, diamond turning, ultra-precision, modal testing

## 1. Introduction

Increasing demand for advanced optics requires continuous improvement of ultra-precision diamond turning machines. Thorough testing of air bearing spindles for use in the most demanding precision applications is increasingly important. In particular, spindles with nanometer error motions and high stiffness is critical. High static stiffness and excellent dynamic properties are required as diamond turning and optical surfaces continue to develop.

This paper describes the testing used to determine the static stiffness and dynamic properties of the Professional Instruments ISO 5.5 PG air bearing spindle.

## 2. Background

The subject of these tests is a bespoke spindle designed for use in diamond turning and grinding applications. Capable of operating up to 10,000 RPM, it is driven by an integrated, frameless brushless permanent magnet motor. Two encoders are mounted directly to the rotor: a 1,024 line-count incremental encoder for motor commutation and high speed operation and a 9,000 analog line-count encoder for positioning and low speed operation. Integrated water-cooling channels maintain the front and rear radial bearings as well as the motor. A vacuum chuck can be operated and the vacuum is supplied through an integrated annular seal non-contact rotary union.

**Figure 1.** Professional Instruments ISO 5.5 PG air bearing spindle

## 2. Stiffness testing

Ultra-precision machining applications require the spindle to have high static stiffness. Of particular importance is central stiffness which in this context describes the responsiveness of the spindle to small increases of force. These small changes in force can result from drive influence, unbalance, or interrupted cutting forces.

Indicators mounted in short, stiff structural loops are used to accurately measure the stator-to-rotor displacement. These measurements are taken under multiple increasing loads to capture the low to high displacements and verify spindle stiffness linearity. The linearity of the spindle stiffness better indicates the performance of the spindle than a single measurement of the total deflection.

Diamond-tipped Mikrokators are used to measure the displacement. These are taut-band, frictionless instruments capable of sub-micrometer displacements. Force is applied using air bearing pistons which are ideal because of their low friction and low hysteresis. They also make setup easier and allow for testing through the full range of displacement. Spindle stiffness linearity is measured in radial and axial directions by measuring at multiple loads. The setup for radial static stiffness test is shown in Figure 2 and is similar to the axial static stiffness test, except the piston acts in the axial direction with the force applied collinear with the spindle axis.

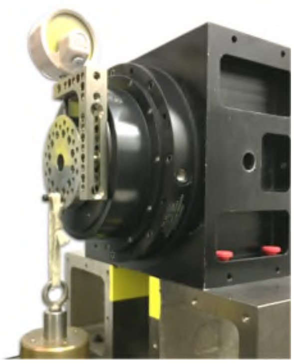

**Figure 2.** Setup for radial static stiffness test

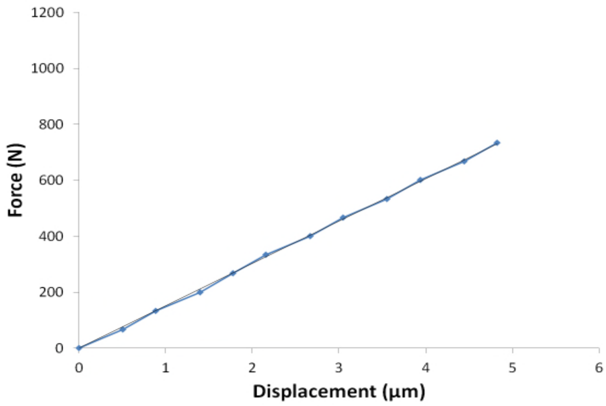


**Figure 2.** Radial Stiffness results are linear at 150 N/µm

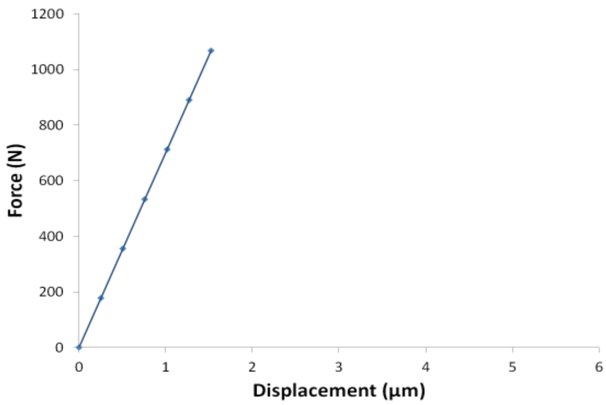


**Figure 3.** Axial stiffness results are linear at 700 N/µm

### 3. Dynamics testing

Modal impact tests examine the air bearing in axial and radial directions shown respectively in Figure 5 and Figure 6. A Kistler 500 N instrumented hammer excites the structure in the appropriate direction (radial and axial) a Kistler K-Shear 25g accelerometer measures the response. Compliant foam supports the spindle and serves to minimize boundary condition influences. The most important value in the dynamic response is the location of the first harmonic or first mode of the spindle, for the most demanding optics machining applications, location of the first mode of the spindle must be above 1500 Hz. These tests are conducted at the normal operating air pressure of 0.7 MPa. Resulting dynamics for the radial and axial directions are shown in Figures 6 and 7, respectively. Dynamics show extremely high first modes with high damping. The low frequency peak is due to the mounting condition of the spindle on the foam.

**Figure 4.** Modal impact test in the axial direction

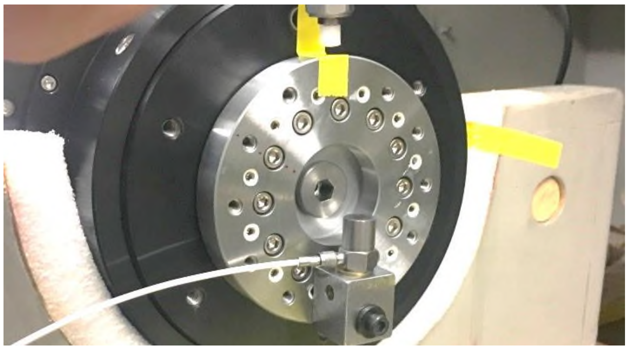

**Figure 5.** Modal impact test in the radial direction

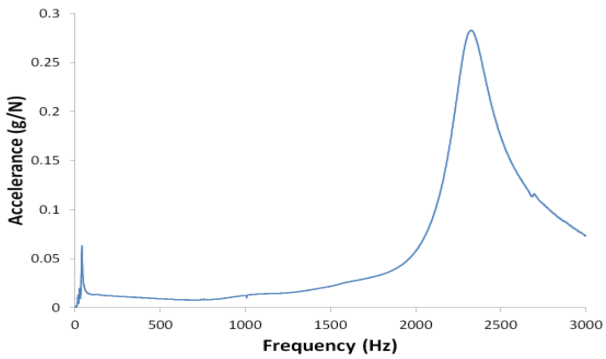


**Figure 6.** Radial frequency response function shows first resonance at above 2300 Hz

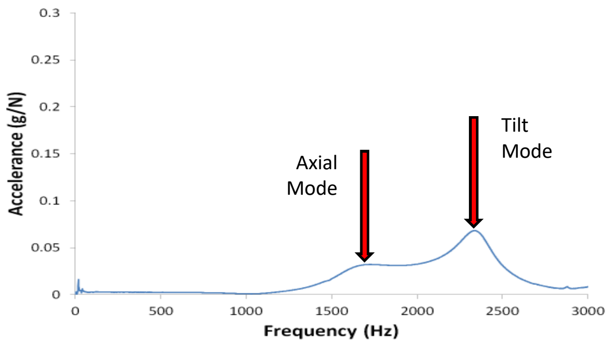


**Figure 7.** Axial frequency response function shows first resonance at above 1700 Hz

### 3. Conclusion

Methods and results of ultra-precision spindle stiffness and dynamics testing are described. These results are for spindle SN 1018 tested in December 2017. There have been 170 of these spindles made and tested since their introduction in early 2013. Results demonstrate static stiffness for axial and radial of the ISO 5.5 PG spindle are linear at 150 N/µm and 700 N/µm respectively. Dynamics tests reveal damped first spindle modes in the axial and radial directions to be well above 1500 Hz ( ~1700 Hz and ~2300 Hz respectively). These tests along with stringent axial and radial error motion tests conclude that the spindle is qualified for use in ultra-precision diamond turning and grinding machines.

### References

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