Experiences in Testing Large Ultra-Precise Air Bearing Spindles

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Background

This talk covers our experiences in testing large, air-bearing spindles we build for a manufacturer of ultra-precision, diamond-turning lathes. Specifically I will talk about how our testing evolved as our customer's requirements became ever more stringent. Making the spindle wasn't a giant technical leap for us but testing it turned out to be more difficult. Our whole toolbox of spindle testing equipment was not up to the task and new tools had to be built from the ground up for the testing of these specific spindles. I'll be going through a few of our tries at testing and will conclude with a look at future plans for using error separation techniques at high speeds that should allow us to get the last few nanometers of measurement error out of our tests.

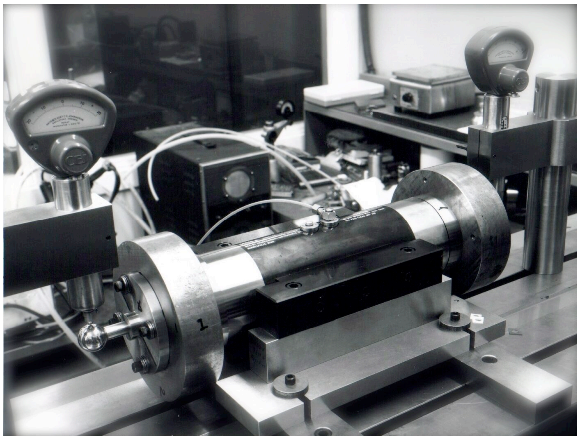


FIGURE 1. Early spindle test of a sub-micro-inch spindle

Spindle testing

Professional Instruments has a 45 year history of making sub-micro-inch air bearing spindles. Our spindles are used in a variety of applications from the mundane to the exotic. Traditionally we tested spindles at relatively low speeds before installing the motorization. We used spherical artifacts, and relatively flimsy indicator mounts. At low speeds you can get away with general-purpose indicator mounts and how you mount your spherical target isn't critical. However the customer in this case requested tests up to 6,000 rpm, and we soon started running into ball mounting and probe-holder vibration problems. This challenging testing requirement had to do with real issues our customer has because of motor-pole print through. These errors, which sometimes only show up at relatively high speeds, show up in their end products, and even though they are only a few nanometers in magnitude, they are unacceptable.

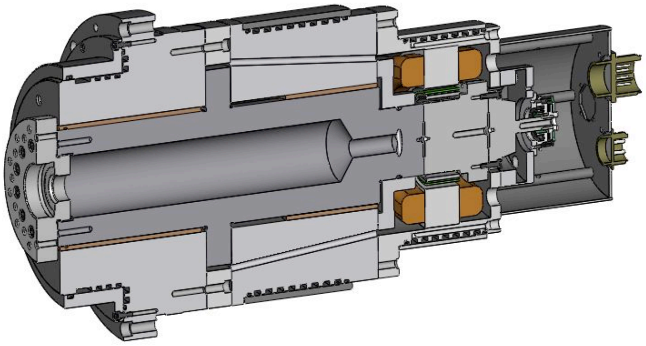


FIGURE 2. The 5.5 ISO is designed for maximum accuracy in a compact package. Its captured thrust between large radial bearings provides high tilt stiffness in a spindle that can be operated high speeds.

Design Considerations

There are many considerations to take into account when designing precision air-bearing spindles. In the case of the 5.5 the requirements included being able to carry 200 pounds at the spindle nose, go 6,000 rpm, be accurate to less than 2 micro-inches over the speed range, and have minimal thermal growth.

These requirements drove us towards a captured thrust design because of the relative ease of implementing cooling jackets and the fact that the bigger the thrust diameter, the more heat will be generated by the air-films. Even so the ISO 5.5 generates 125 watts of heat at 6,000 rpm.

Things got more interesting when our customer changed the 2 micro-inch accuracy requirement to less than 1 micro-inch.

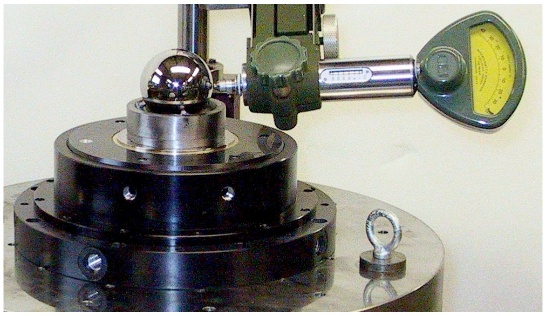


FIGURE 3. testing a 5.5 spindle with a spherical artifact and a 1 micro-inch resolution Mikrokator.

Testing Realities

We slowly came to realize how difficult this whole process of testing would be when we finished the 1st spindle and went to test it. First, (as shown in figure 3), we tested the spindle without the motor at low speed. Our customer, however, wanted polar charts at a variety of speeds.

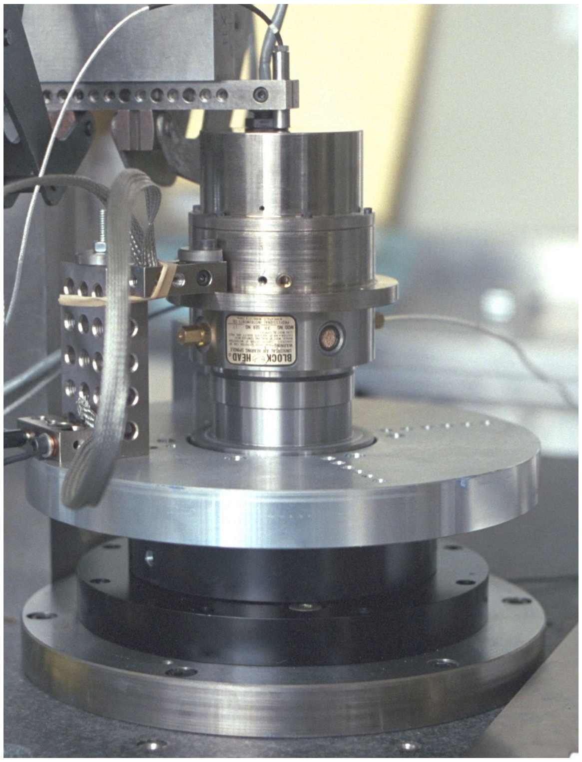
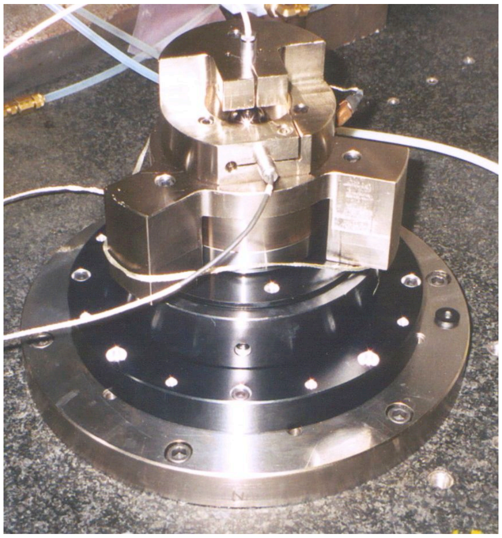
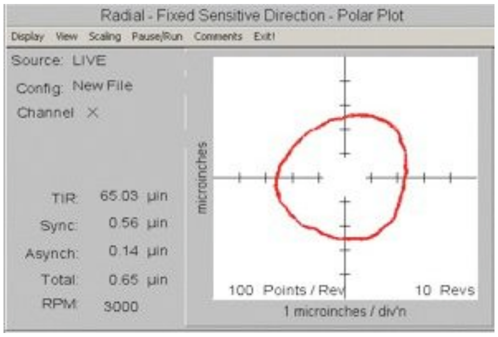


FIGURE 4. *Master-axis spindle test using a model 3R spindle as a test artifact. The advantage is that a master-axis spindle can be very accurate; the problem is that it would be quite dangerous in the event of a spindle crash, with hoses whipping around at high speed!*

As shown in figure 4, we decided to try a technique where one spindle is checked using a master spindle. Using this technique we achieved impressive results, but abandoned this path after we thought about the consequences of having a crash during a high-speed test.

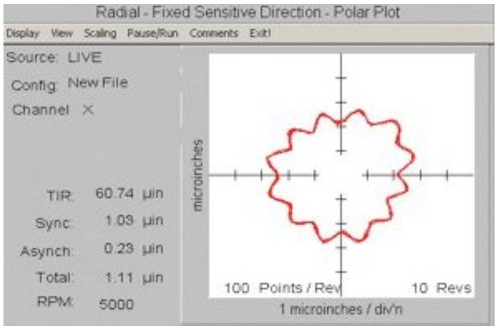
We then made up a new test rig that seemed very robust and ran tests on many subsequent spindles, (see figure 5).





Radial - Fixed Sensitive Direction - Polar Plot

Source: LIVE
Config: New File
Channel: X
TIR: 65.03 µin
Sync: 0.56 µin
Asynch: 0.14 µin
Total: 0.65 µin
RPM: 3000

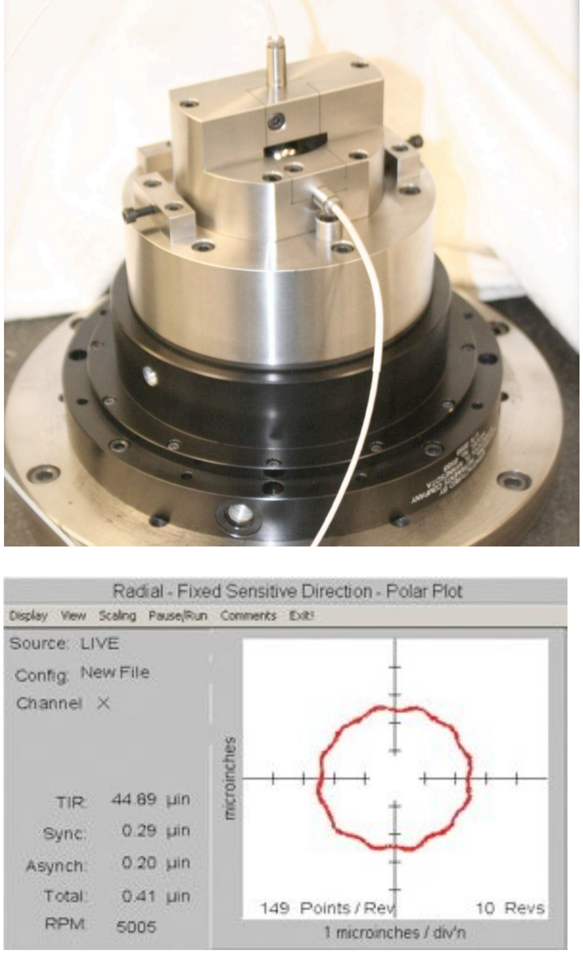


Radial - Fixed Sensitive Direction - Polar Plot

Source: LIVE
Config: New File
Channel: X
TIR: 60.74 µin
Sync: 1.03 µin
Asynch: 0.23 µin
Total: 1.11 µin
RPM: 5000

FIGURE 5. *Test rig, seemingly robust, and results of test at 3000 and 5,000 RPM.*

The new test set-up seemed to work well and gave what we felt were impressive results, but there is a clear 12-pole component, very prominent at 5,000 RPM. Interesting that went almost completely away when we retested the very same spindle with a new set of test hardware, (see figure 6).



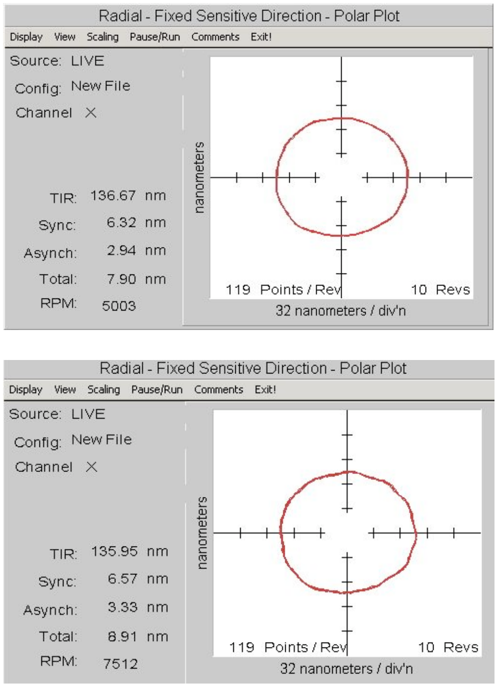
Source: LIVE
Config: New File
Channel X
TIR: 44.89 µin
Sync: 0.29 µin
Asynch: 0.20 µin
Total: 0.41 µin
RPM: 5005
149 Points / Rev
10 Revs
1 microinches / div'n

FIGURE 6. *New test rig and results, which include a new one piece, flange-mounted test artifact and a "ring-paradigm" probe mount.*

In figure 6 we still see some motor pole print through, but it is a much smaller magnitude. Comparing the 5,000 rpm tests of the same spindle we conclude that the probe mount was itself vibrating and even though there is a definite 12 pole error present, it is only 1/3 of a micro-inch in magnitude. The lesson here is: "make your probe mounts as robust as possible". And: "don't assume that your tests only show spindle error", because they also show what is wrong with your test.

Current state of the art

Having been pushed by our customer to make better spindles than ever before, we found ourselves at the limits of what we could achieve by better test rigs. But to our customer, *any* motor pole print through was too much, so we decided to look into different motors.



Source: LIVE
Config: New File
Channel X
TIR: 136.67 nm
Sync: 6.32 nm
Asynch: 2.94 nm
Total: 7.90 nm
RPM: 5003
119 Points / Rev
10 Revs
32 nanometers / div'n

Source: LIVE
Config: New File
Channel X
TIR: 135.95 nm
Sync: 6.57 nm
Asynch: 3.33 nm
Total: 8.91 nm
RPM: 7512
119 Points / Rev
10 Revs
32 nanometers / div'n

FIGURE 7. *Typical test result from one of our ISO 5.5 motorized spindles. Synchronous radial error of less than 7 nanometers at 7,500 rpm. This includes the roundness of the test artifact!*

Future work

We seem to be limited only by how good we can make our test artifact, which we can reliably produce to better than 5 nanometers roundness at the equator. This seemingly insignificant amount of error however is problematic as it limits our confidence in our testing and can unfairly attribute errors to our spindle, or could in some instances actually subtract from our stated spindle error. The problem with most error separation techniques is the complicated structures they require, and the fact that you have to index the ball during the testing. (We do use the *Donaldson Reversal* technique in the measuring of our test-balls but there we have the advantage of doing our tests at low speed where the dynamics of the structure are not critical). We feel for this type of high-speed testing the *Multi-Probe* technique is more promising and we are currently building tooling to test spindles in that fashion. The only novelty will be that we will be moving the radial probe on a precision indexing plate instead of testing with 3 probes simultaneously.

The beauty of the multi-probe technique is that it allows you to separate spindle errors from artifact errors, without having to index the artifact.

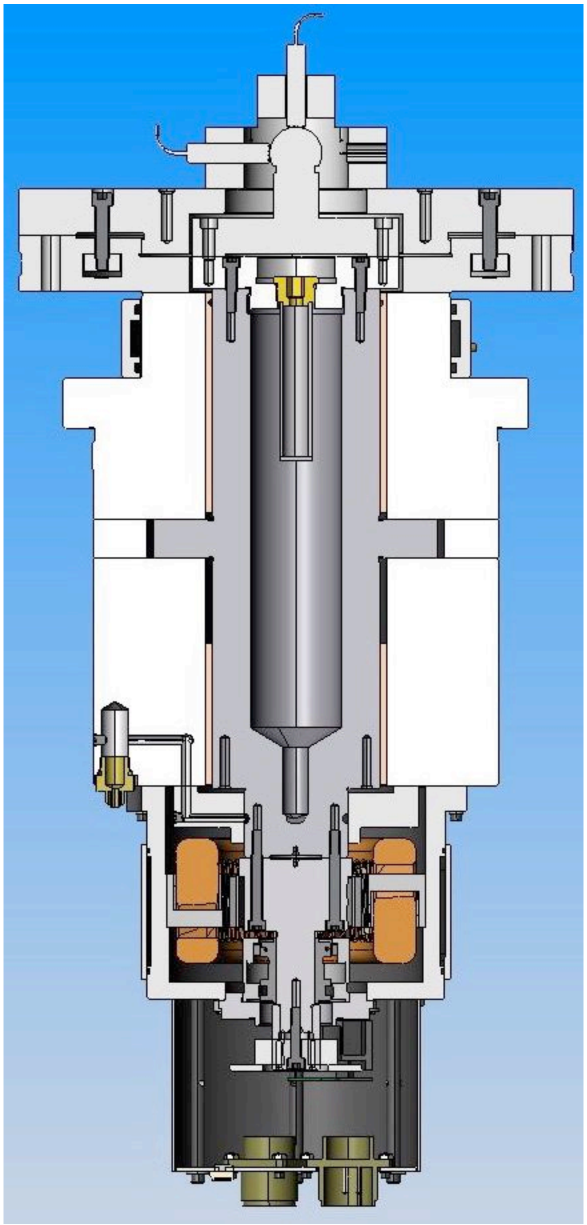


FIGURE 8. *Future concept, showing a moving probe/multi-probe setup on our 5.5 ISO spindle. This will allow us to separate target error from spindle error, even at high speeds.*

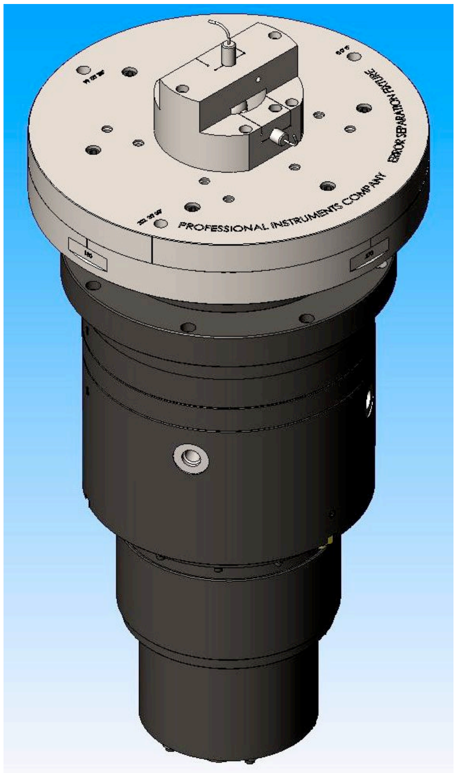


FIGURE 9. *Future concept, top view, showing the 3 index points, (O, 99.844, and 202.5 degrees, calculated by Dr. Eric Marsh).*

Conclusion

State of the art spindles require that as much effort go into the testing hardware as goes to the building of the spindle. It is not enough to build a nearly perfect spindle, you need to have a way to test it, and that means designing hardware specifically for the task. Analytical tools like the Lion SEA allow you to measure spindle accuracy with far more precision than ever before, but that level of precision also requires the spindle metrologist to be much more diligent in their testing methods.

A spindle test is always more than simply a test of the spindle…it is a test of the spindle plus the artifact plus the probe mounts. The challenge is in reducing the contribution of the last two to the point of being insignificant.