Ultra precision oil hydrostatic spindle design and metrology

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Hydrostatic spindles with conical surfaces provide high load capacity in compact, low-profile packages. This work describes the design and testing of an oil hydrostatic spindle consisting of two conical bearing surfaces (bi-conic) using step compensation rather than restrictor compensation with pockets. This spindle features a combination of nanometer level error motions, high load capacity, good dynamics and high crash resistance.

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1. Introduction

Hydrostatic spindles featuring conical surfaces have been shown to be very effective in providing precision rotation and high load capacity in a compact, low-profile package [1]. This work describes the design and testing of an oil hydrostatic spindle consisting of two conical bearing surfaces (bi-conic) using step compensation rather than restrictor compensation with pockets [2]. This spindle features a combination of nanometer level error motions, high load capacity, excellent dynamics and high crash resistance.

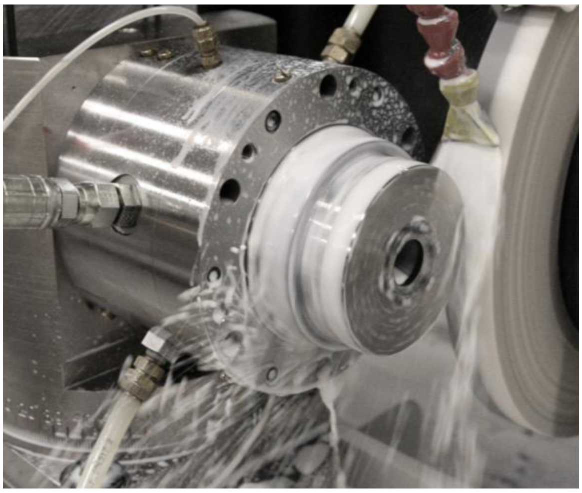

Fig. 1 A bi-conic oil hydrostatic spindle is ideal for the rigorous demands of precision machining and grinding. The 4R bi-conic oil hydrostatic features crash resistance.

2. Motivation

The motivation for a step-compensated bi-conic spindle is derived from several potential advantages of the bi-conic design including:

- High bearing efficiency (load capacity for a given volume)
- High structural stiffness (enabling the use of higher bearing pressures)
- Higher oil film pressure than restrictor design
- Balance of radial, axial and tilt load capacities
- Design simplicity (reduced complexity)

This step-compensated design has several advantages over a pocketed design with restrictor-compensation:

- Increased bearing area
- No pocket "print-through" to error motion
- Higher-pressure bearing films
- Improved bearing stability
- No complicated up-stream restrictors

Fig. 2 Stator and rotor components of the 4R bi-conic.

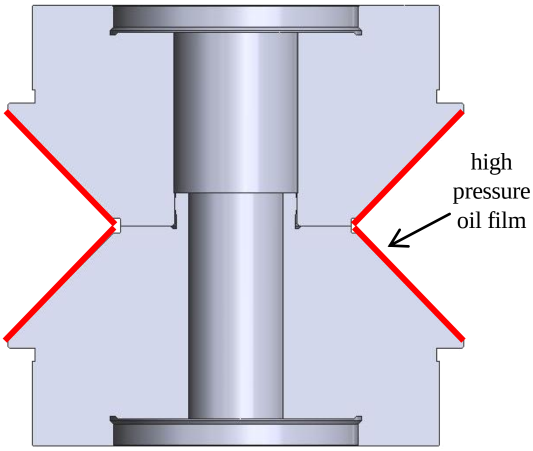

Fig. 3 Cross-sectional view of the bi-conic rotor. The compact and stiff design permits the use of high pressure oil with minimum rotor expansion.

3. Design

The bi-conic design uses conical bearing surfaces to provide axial, radial, and tilt load capacity. The stator and the rotor halves are manufactured from 416 series stainless steel for corrosion resistance, hardenability, and thermal expansion coefficient similar to that of steel. Structural stiffness of the rotor improves static and dynamic performance. The bi-conic rotor is stiff enough to permit use of oil pressure up to 8 MPa (1,200 psi) without significant distortion. This results in higher load capacity and stiffness along with amazing film damping characteristics. In addition, squeeze film effects help to prevent damage to the bearing surfaces during an overload.

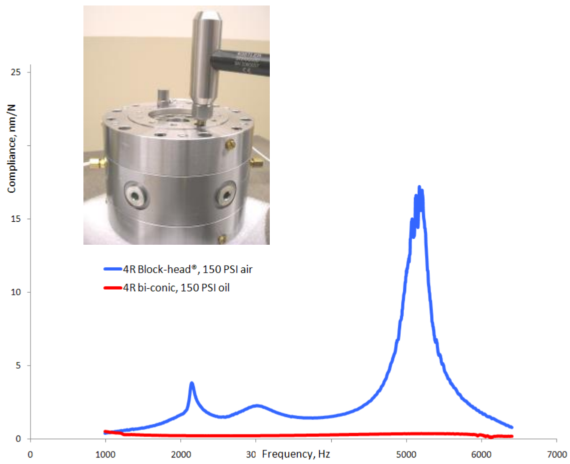

Fig. 4 Compliance frequency response function illustrates the superior dynamic response of the oil hydrostatic bi-conic as compared to an “H-style” air bearing. A modal impact hammer (Kistler 2000 N) was used to excite the rotor while measuring the response with an accelerometer (Kistler K-Shear® 50g). The frequency response function was acquired with a dynamic signal analyzer (HP 35670A).

The bi-conic rotor's mechanical structure is noticeably stiffer in the axial direction than an “H-style” thrust plate, resulting in improved dynamic performance. The cone angle can be optimized for a given load condition or to minimize thermal sensitivity. A variation in the design featuring convergence of the cones at a common apex could result in a completely thermally in-sensitive spindle. The photo in Fig. 5 shows a pair of high-precision non-contact air seals that prevent oil leakage. The seals are non-contact in order to minimize their influence on spindle error motion.

Fig. 5 Non-contact air seals prevent leakage of oil and minimize friction and errors associated with contact seals.

4. Spindle Metrology

The reversal techniques described by Donaldson and Estler theoretically provide the simplest method for separating spindle error motion from artifact form error [3, 4]. However, in a production environment, measurement accuracy of these techniques suffers from the difficulty of exact artifact reversal. Particular care must be taken to accurately remount the artifact exactly 180° without influencing form error, which can be difficult when testing at high speed. Any change in the artifact between the tests, for example a fingerprint or dust, is split evenly between the spindle and artifact. In addition, the probe must be positioned along an identical artifact measurement track after indexing.

Previous work has described the multiprobe error separation procedure using a high resolution capacitive sensor [5]. This implementation of the multiprobe method assesses a single component of synchronous error motion from three asymmetrically orientated measurements. The sensor is moved from 0° to 99.844° and 202.5° without indexing the artifact. While this method does not perfectly separate all of the components of spindle and artifact error, the chosen orientation angles minimize harmonic distortion.

	Axial	Radial	Tilt
Stiffness	350 N/μm	130 N/μm	1.1 N•m/μrad
Load capacity	9,000 N	3,000 N	300 N•m

Table. 1 Measurements of stiffness and load capacity of oil hydrostatic 4R bi-conic spindle with 4 MPa (600 psi) oil. These values are approximately linear with oil pressure.

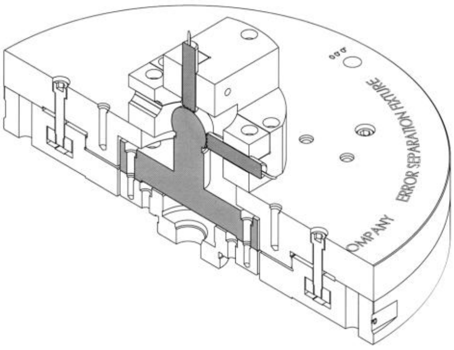

Fig. 2 Sectioned view of the multiprobe error separation tooling. This tooling was designed to allow separation of artifact and spindle errors with multiprobe separation and Donaldson's reversal. Multiprobe separation is used with the sensors located at 0°, 99.844° and 202.5°.

To measure error motion, the bi-conic spindle was fitted with a brushless DC motor and a 1024-count rotary encoder. The capacitive sensor (Lion Precision C23-C, 0.5 nm/mV) targets an Ø25 mm lapped sphere. The amplifier incorporates a 15 kHz first-order, low-pass analog filter with linear phase response. Data acquisition (Lion Precision SEA V8.2), is triggered by the encoder. A low-pass digital filter with a 150 UPR cut-off is applied to the axial and radial error motion plots shown. Spindle error motion components are defined by ASME B89.3.4 [6].

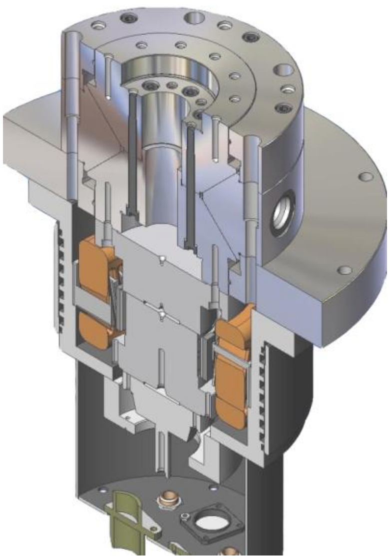

Fig. 6 Sectioned view of the bi-conic spindle with optional brushless motor and encoder.

Typical synchronous radial error motion results after separation are shown in Figure 8. Measurements recorded at the three orientation angles are a combination of spindle error motion and artifact form error. A mathematical manipulation of the three measurements enables the separation, showing better than 6 nanometers of total radial spindle error in this case.

The axial component of spindle error does not require error separation since artifact imperfections do not influence the axial measurements except by second-order effects. Total axial error motion including fundamental, residual synchronous, and asynchronous is better than 7 nanometers as shown in Figure 8.

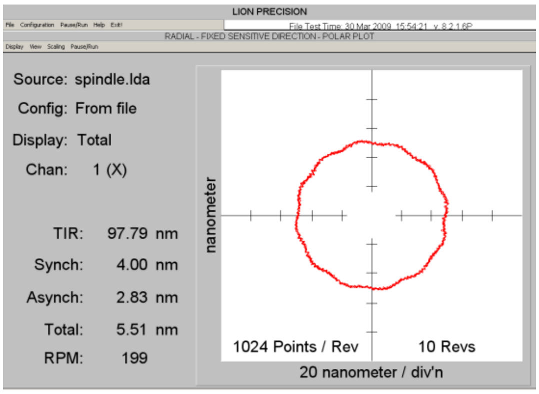

Fig. 7 Radial error motion after multiprobe error separation. The total radial error is less than 6 nanometers with 150 UPR filter cutoff.

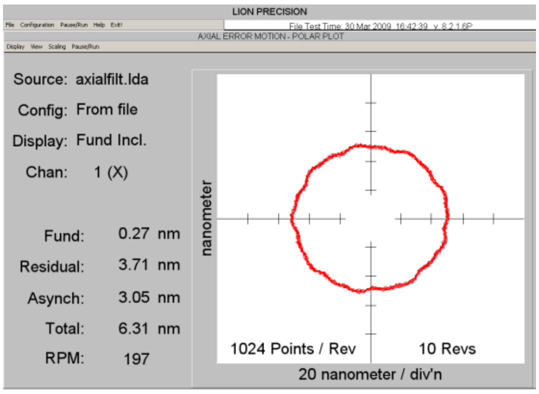

Fig. 8 Total axial error motion is less than 7 nanometers with 150 UPR filter cutoff.

4. Machining Results

The compact size and simple construction of the bi-conic allows for this spindle to be used in a variety of situations. It is ideally suited to be retrofitted into existing machines. Test grinds were conducted on a CNC cylindrical grinder (Parker Liberty) retrofitted with a 4R bi-conic oil hydrostatic work head shown in Figure 1. Three inch diameter workpieces of hardened 440C stainless steel were mounted to the precision workhead and ground. The typical out-of-roundness of the workpieces is shown in Figure 9. The oil hydrostatic spindle reliably grinds parts to better than 0.25 micrometer (10 microinches) out-of-roundness.

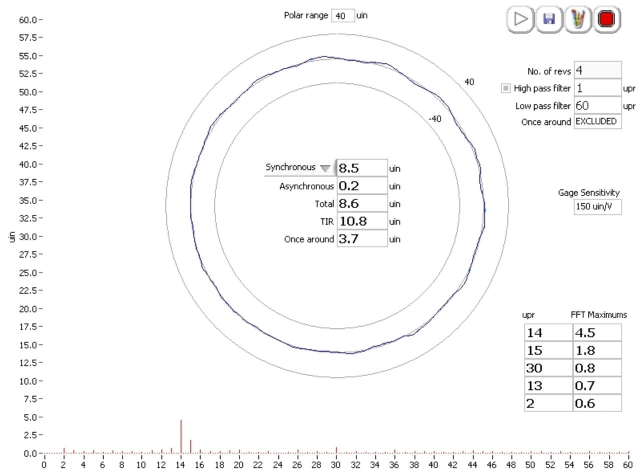

Fig. 9 Typical roundness polar plot of a 440C stainless steel part ground using the 4R bi-conic oil hydrostatic work head. Out-of-roundness is less than 0.25 micrometers.

5. Conclusion

In industrial machining and grinding applications, air bearing spindles may lack the load capacity necessary to withstand sudden overloads. This high pressure oil hydrostatic bearing is a logical alternative due to its high load capacity with nanometer-level error motions. Squeeze film effects and lubricating properties of the oil help to prevent damage to the bearing surfaces during an overload. This oil hydrostatic spindle features nanometer-level error motions, high load capacity, excellent dynamics, and high crash resistance.

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