Elements for the Design of Next Generation, High Stiffness and High Accuracy Precision Machines

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Abstract

Next generation precision machines will require ever more rigid elements to achieve the required machining tolerances [1]. The presented work focuses on the application of ultra stiff servo-controllable kinematic couplings, hydrostatic bearings, and magnetic bearings to minimize the structural loop of multi-axis precision grinding machines while reducing complexity.

The fundamental importance of these ultra stiff, adjustable machine elements is demonstrated in the design of a grinding machine for 450mm diameter silicon wafers. A new generation of silicon wafer grinding machines is needed to back-grind large (450mm diameter) wafers from the production thickness of up to 1mm down to less than 50µm so as to reduce the cost of Si-wafer based components. The grinding process needs to be done in about 90sec (fine-grinding, e.g. -200micron) to 160sec (coarse grinding, e.g. -600micron). After completion of the fine grinding process the wafer must be flat to 0.1µm/□45mm and parallel to 0.6µm/450mm diameter. The surface roughness must be less than Rymax 0.1µm and Ra 0.01µm.

Even though the required machining forces are <10N, the machine must be extremely rigid in order to achieve the necessary surface quality with a reasonable grinding feed-rate. Assuming a feed-rate of 5m/min and a total allowable error motion of 5nm, a stiffness of >1N/nm is required, which is many times stiffer than a typical machine tool (0.1 to 0.3N/nm).

In cooperation with industry, this work had the aim of creating a new machine design philosophy, with an example application that focuses on nano-adjustable kinematic couplings and feedback controlled water hydrostatic bearing technology. This new design philosophy is needed to enable the design of a relatively small footprint, compact precision machines.

In particular, a ball screw preloaded height adjustable kinematic coupling and a magnetically preloaded hydrostatic work spindle thrust bearing as well as a magnetically levitated wheel spindle with self centering, hydrostatic radial bearings were designed and built.

The adjustable kinematic coupling allows for up to 8mm of vertical height adjust and 7N/nm stiffness at 26kN preload. By varying the preload on the coupling by +/- 10%, in-process nm to micron height and tilt adjustment at >95% of the nominal stiffness is possible [2].

Under the assumption of a constant flow supply, the hydrostatic bearing achieves a theoretical stiffness of 1N/nm at a 20micron bearing gap and 7000N combined gravitational and magnetic preload. In practice, the stiffness is limited by the pressure flow characteristics of the supplying pumps. To increase the bearing stiffness to a required 4N/ nm, various control loops have been developed and tested [3], although we find that there is much room for more advanced pump/control system development.

The wheel spindle with axial magnetic bearing and hydrostatic radial bearings achieves a minimum dynamic stiffness of 340N/µm at 120 Hz and a radial bearing stiffness of nearly 600 N/µm at 1.8 MPa water pressure, which corresponds to 160 N/µm radial stiffness at the front end of the shaft.

1 Introduction

Increasing machining productivity often creates higher machining forces. Consequently, according to Hook's law maintaining or improving accuracy, without decreasing machining speed, generally requires increased machine stiffness.

In the case of wafer grinding the required machine stiffness is proportional to:

$$k_m \propto \left(\frac{a_n}{\delta} - 1\right)\frac{{d_w}^2}{d_s}$$

k_m - required machine stiffness

a_n - nominal depth of cut per revolution of wafer

δ - depth of cut error

d_w - wafer diameter

d_s - grinding wheel diameter

2 Machine Design Philosophy

In order to maximize stiffness, the number of components and associated stiffnesses along the structural loop must be minimized and the component stiffness must be maximized while also reducing the length of the structural loop. However, compactness can conflict with machine handling or maintenance aspects such as tool changing. The machine, shown in Figure 1, needs to have two configurations:

- machining configuration: minimum structural loop, maximum stiffness
- work preparation configuration: sufficient space for part handling and tool exchange, no critical stiffness

In addition to a stiff structure and high stiffness bearings, a structural interface element is needed to switch between the two configurations with high repeatability, while maximizing stiffness in the machining configuration.

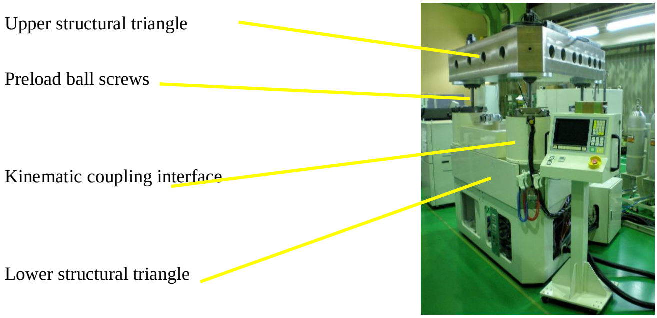

Figure 1: Prototype wafer grinding machine, wheel spindle not mounted/shown yet (would be in center of upper triangle), no grinding tests available yet

2. 1 Height Adjustable Kinematic Couplings

A height adjustable, controlled preload three-V-groove canoe-ball kinematic coupling allows for repeatable opening and closing of the coupling interface as well as nano-, micro- and macro- height and tilt adjustability.

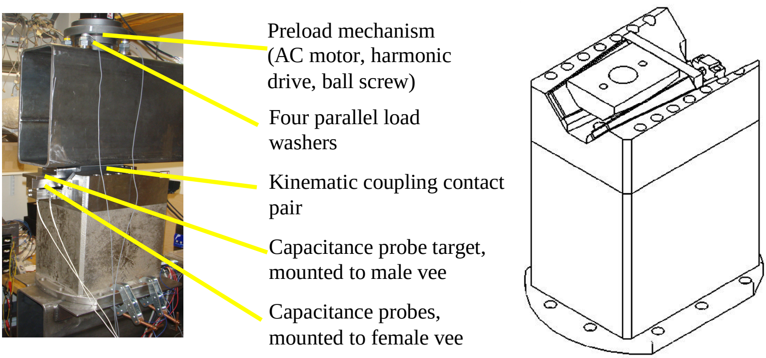

Figure 2: Adjustable height wedge-based ballscrew preloaded kinematic coupling

Preload is achieved using ballscrews that pass through the center of the coupling V-grooves, and load washers enable servo control of the preload. The adjustable kinematic coupling mechanism achieves a stiffness >7kN/µm at 26kN preload per contact pair while achieving +/-1micron height adjustment resolution (currently limited by friction effects).

2.2 Feedback Controlled Hydrostatic Bearings

By supplementing a hydrostatic bearing with a feedback control loop almost infinite stiffness can be achieved over a limited range of pressures (load forces). The basic thought of infinite stiffness control is to make the flow out of the bearing proportional to the pressure in the bearing pocket. This can either be achieved by direct measurement and control of the bearing gap or the ratio of bearing flow and pressure. 450mm silicon wafer grinding requires extremely stiff thrust bearings on the order of 3 to 4kN/µm for the work spindle thrust bearings. To achieve this stiffness at a bearing gap of ≥10µm either a minimum preload of 10kN or a lower preload in combination with feedback control of the bearing gap is needed.

2.3 Magnetically Levitated Wheel Spindle with Hydrostatic Radial Bearings

The main building blocks of the water cooled, rotary-axial spindle [4], as shown in Figure 3 are: two hydrostatic-bushings [5] in the front for radial and tilt support, a 13 kW brushless direct-drive motor in the middle for rotary motion (grinding), and an active magnetic thrust bearing/actuator in the back for axial support and in-feed actuation.

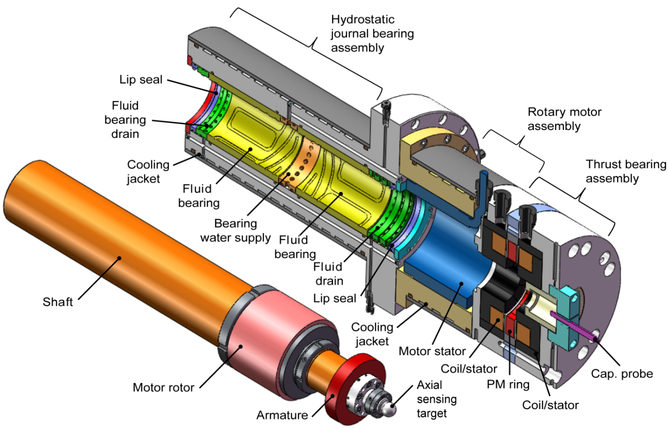

Figure 3: Exploded view of rotary-axial spindle assembly

Figure 4 shows a detailed view of the axial actuator. The actuator is comprised of four main components: a stator core which is made of powdered iron to limit eddy current generation, a ring shaped biasing, radially magnetized permanent magnet, two excitation coils and an armature.

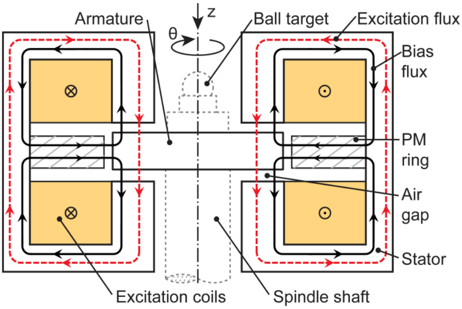

Figure 4: Axial actuator working principle

Compared to conventional horseshoe magnetic bearings, this design can achieve 16 times higher force-to-power ratio and 8 times more load capacity, given identical armature size, coil winding, and stroke requirements. The axial thrust bearing is controlled via a 1.5mm stroke capacitive probe. The rotary motor Hall-effect sensors are used for spindle position and velocity control.

The overall length of the spindle is 1 m, with a 120 mm diameter shaft and total shaft assembly weight of 78 kg without tool attachment. Figures 5, 6, and 7 show the key performance measures of the presented spindle design, such as stiffness of the hydrostatic radial bearings, axial spindle force.-displacement curves at different current levels as well as dynamic stiffness of the closed loop controlled spindle shaft.

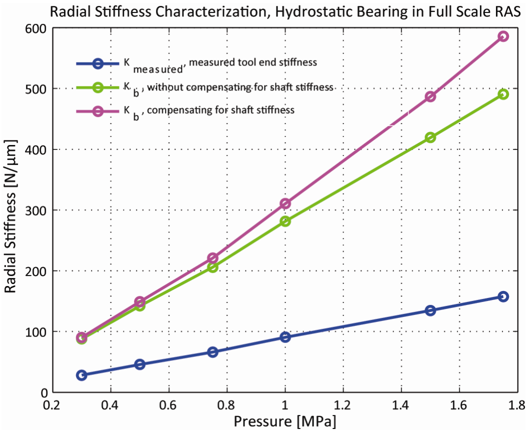

Figure 5: Tool Spindle Radial Stiffness Test Results

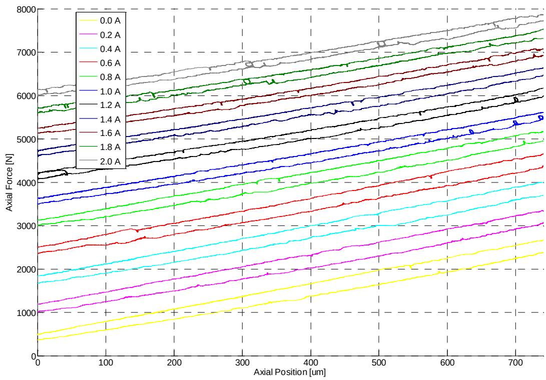

Figure 6: Spindle axial actuating force measurement at various axial positions and currents.

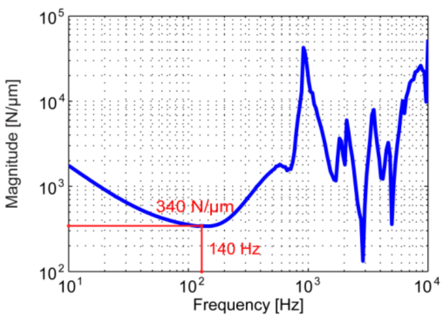

Figure 7: The axial dynamic stiffness of the spindle shaft under closed-loop control.

3 Conclusion

Adjustable kinematic couplings are the key element to achieve increased stiffness over a larger, open structural loop machine tool with multiple stacked axes each moving by a small amount. Feedback control of the coupling preload is necessary to fully use the positioning capabilities of such a coupling and maximize accuracy. Friction turned out to be a limiting factor to the positioning resolution. Feedback control can also further increase the stiffness of hydrostatic bearings and also allow for micro and nano positioning by varying the bearing gap. Furthermore high bandwidth feedback control in combination with strong and fast power amplifiers is the enabler to the proposed magnetic bearing spindle with axial positioning capability. Feedback controlled, adjustable machine elements in combination with a compact machine design will be the enablers to the design of increased stiffness and consequently increased accuracy, future machine tools such as 450mm Si-wafer grinding machines.

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