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# Industrial tool holding for ultra-precision machining

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**Abstract**
Efficient and cost effective automated tool changing and tool setting are industry standards for CNC machine tools. However, the ultra-precision machining industry still lacks in this area and further development has the potential to significantly increase productivity. One major reason for this is that the tool and work-holding spindles used for CNC machining don't have ultra-precision capabilities. Conversely, ultra-precision spindles historically have not had the flexibility to incorporate automated tool changing.
With new generation aerostatic spindles that combine industrial taper clamping with ultra-precision and new tool holder technologies, this circumstance is changing. First the reader is given a basis for how advanced spindle dynamics are used to guarantee resonance-free operation and minimal dynamic tool run-out over the entire speed range of the spindle. Then the distinct benefits of using automated taper clamping systems with repeatability of less than 0.2 microns are discussed.
Having an ultra-precise spindle is only half the battle, one must also have ultra-precise tool holding. The reader is given an inside view of how to machine and balance taper based tool holders to give the machine user static tool run-outs of below 0.6 micron and balance qualities of better 0.3 mm/s at 60.000 rpm. A machining example with pre-set tools and in-process tool change finally proves that there are ultra-precision solutions capable of automated tool change using HSK tooling and aerostatic tool spindles.

keywords: Ultra-precision machining; aerostatic tool spindles; automated tool change; HSK; dynamic balancing

## 1. Tool holding for ultra-precision and CNC machining

Taper based tool clamping systems are state of the art for CNC machine tools and enable safe, fully automated tool changing and setting. Changing and setting a tool for ultra-precision machining, on the other hand, requires a skilled operator and significantly longer time. Automated tool changing for ultra-precision has not yet been considered for two main reasons. First there weren't industrial tool spindles with ultra-precision qualities and second there wasn't a tool-holding technology that allowed machining parts with optical surfaces. However wrapped around an optimized ultra-precise aerostatic bearing system there are spindle solutions offering industrial and automated HSK taper clamping capable of ultra-precision machining. Considering this it becomes clear that tool holding is the limiting factor and can't be covered by standard solutions. Tool-holders with ultra-precision qualities need to be part of a solution for ultra-precision machining.

## 2. Spindle dynamics for ultra-precision machining

Considering a rigid shaft system supported by two radial and two axial aerostatic bearings with speed-depending stiffness leads to cylindrical and conical rigid-mode resonances around the centre of gravity with speed according to Fig.1.

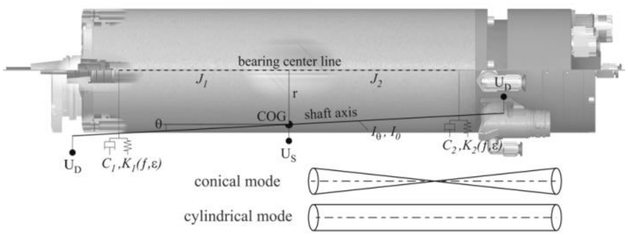


**Figure 1.** Rigid mode shaft dynamics model and resonances

The cylindrical and conical resonances with speed can be developed to

(1)

$$\omega_r(f,\varepsilon)^2 = \frac{K_1(f,\varepsilon) + K_2(f,\varepsilon)}{M}$$

(2) [1,2,3]

$$\omega_\theta(f,\varepsilon)^2 = \frac{K_1(f,\varepsilon)\cdot {J_1}^2 + K_2(f,\varepsilon)\cdot {J_2}^2}{(I_\theta - I_0)}$$

and lead to the resonance speed map shown in Fig. 2 that has been confirmed to be valid within -5/+7% accuracy [1].

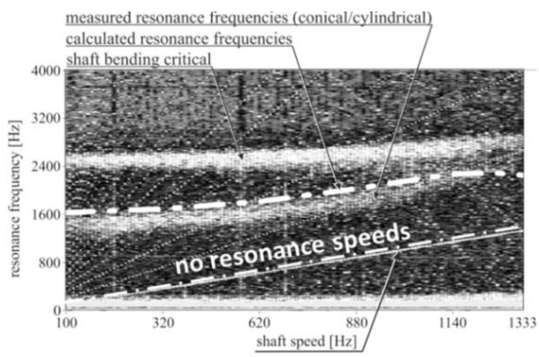


**Figure 2.** Measured rigid-mode shaft dynamic resonances [1]

If the spindle speed is close or equal to a system resonance this would result in high vibrations and excessive tool run-out. As it can be seen this is not the case for the spindle system considered and guarantees a resonance-free.

## 3. Ultra-precision HSK taper clamping system

For an HSK tooling system the taper and the axial contact face define the radial (R), axial (Z), and angular position (ψ) of the tool-holder to the shaft according to Fig.3.

The shaft taper is required to be a few microns smaller than the taper of the tool holder. This makes it necessary to deform the tool holder taper for correct clamping where both of the axial faces need to seat solidly on each other. Although this sounds rough, it allows much larger machining tolerances than other clamping systems.

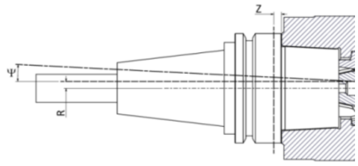


**Figure 3.** HSK tooling system alignment error budget

Grinding the taper and the axial face is the most important and last machining step in shaft production. Due to the compensation effect of aerostatic bearings, where the shaft allows errors in motion much smaller than the sum of all shape errors, the shaft taper can be ground in an air bearing to get taper run-outs below 30 nm. The same applies to the axial face.

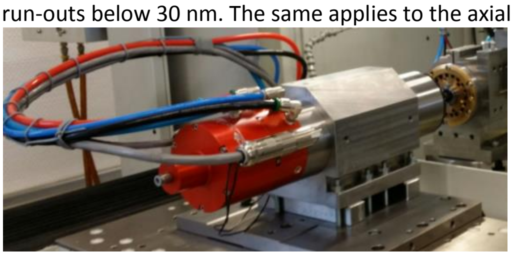

**Figure 4.** Insito shaft taper grinding in/with aerostatic tool spindles

## 3. Ultra-precision HSK tool-holders

With 3 micron static tool run-out [7,8] and a balance quality of 2.5 mm/s at 25.000 rpm [5,7,8], standard HSK tool holders don't have the accuracy required for ultra-precision machining.

However using the aerostatic tool spindle and machining technology from Section 2., tool holders with better 0.6 micron static tool run-out, a repeatability of less than 0.2 micron, and balance grades of < G0.3 at 60.000 rpm [6] are manufacturable.

**Table 1** – Tool holder comparison

| * at 25.000 rpm ** [7,8] | Conve., specif** | Conventional, measured (avg.) | UTS-x, measured |
|---|---|---|---|
| **Tool run-out (mic)** | 3 | 5 | 0.6 |
| **Balance quality (mm/s)*** | 2.5 | 8 | 0.15 |
| **Taper shape error (µm)** | | 1.2 | < 0.05 |
| **Axial face square. (mic)** | | 1.7 | < 0.2 |
| **Repeatability (mic)** | | 2 | < 0.2 |

### *3.2. Tool-holder balancing and tool clamp repeatability*

To balance tool-holders low speed balancing machines operated at below 2.000 rpm and roller bearing supported fixtures are widely used. The lack of alignment, high synchronous and asynchronous errors, and low spinning speeds lead to residual imbalances that are much higher than specified. But similar to the grinding process the aerostatic tool spindle from Section 2. can be used to clamp the tool holder and run it to up to 100.000 rpm for balancing. The clamping in particular combined with the shaft taper quality not only guarantees an excellent tool holder alignment, but also a situation equal to its real use.

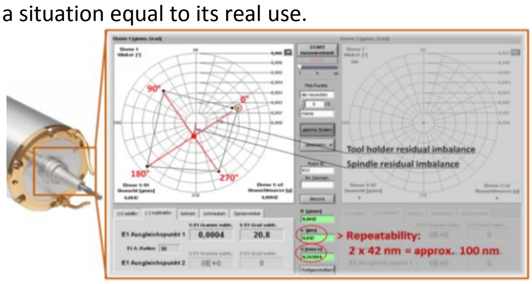


**Figure 5.** 3 x 90° reversal tool-holder balancing

By supporting the spindle in flexible hinges to avoid resonances and using accelerometers and custom hard- and software, residual imbalances of less than 0.05 mg can reliably be compensated for. Knowing the shaft mass and its moment of inertia also allows determining the tool clamp repeatability and the residual imbalance of the spindle shaft by a 3x90° measurement where the tool is rotated against the shaft.

## 4. Ultra-precision machining with in-process tool change

This example of a complex optical "freeform peanut shape" LED mold with in-process tool change confirms the measurements during spindle and tool holder manufacture. It would not have been possible without a tool clamp repeatability of < 0.1 micron in axial and radial directions [9].

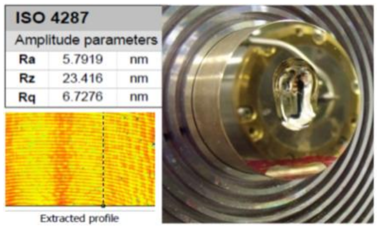


**Figure 6.** Ultra-precision "peanut shape" mold machining with in-process tool change [9]

In order to prove the repeatability of the HSK tool holder multiple tool changes were made and a test sphere was machined after each change. The resulting form accuracies are below 0.12 mic. This gave us the confidence to use one carbide roughing and one diamond finishing tool to make the peanut without setting the tools during the machining process.

**Table 2** – Form accuracies with in-process tool change [9]

| | Initial | Recut #1 | Recut #2 |
|---|---|---|---|
| **Form accuracy (mic)** | 0.18 | 0.1 | 0.12 |

## 5. Conclusions

Resonance-free shaft dynamics and aerostatic spindle based machining allow the creation of an aerostatic tool spindle with errors in motion of less than 30 nm and automated tool change. The same machining technology applied to tool-holders proved that HSK tool holders are available that give ultra-precision quality. Together with the ultra-precision tool spindle a tool run-out of below 0.6 micron, a repeatability of better 0.2 micron, as well as tool holder balance grades of under 0.3 mm/s at 60 krpm are commercially available. Machining trials with ultra-precision machine tools proved the productivity, repeatability, and ultra-precision quality.

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