Reconfigurable Machine-Tool for Micro Machining

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Abstract

This paper concerns the development of a reconfigurable CNC machine tool for micro machining with a work volume of 200 X 200 X 100 mm, a positioning accuracy of 0,1 μm to be extended to work with 3, 4 or 5 synchronized axes, in operations of milling, drilling, grinding and turning. The development aspects from the conceptual design up to its implementation are presented.

1 Introduction

The origins of machine-tools for the fabrication of small parts can be traced to the 19th century clock makers. The current need of miniaturized systems for parts with small dimensions and high aspect ratios brought the machine-tool designer to a new era of micro machine-tool developments. Functional micro-structures are parts with dimensions varying from a few micrometers up to few millimetres, usually with a high aspect ratio. Micro parts are key elements for many micro-systems, transducers and actuators, and their demand is continuously increasing.

The high costs associated with the manufacturing of micro parts and micro assemblies, have been seen as one of the major factors for the development of micro system technology. The possibility of manufacturing some micro parts by means of conventional micro machining can result in competitive costs for micro system technologies.

Machine-tools for micro machining have specific design concerns, usually incorporating most of the requirements and design solutions of ultra-precision ones.

A reconfigurable machine-tool has additional requirements in order to perform different machining processes, and enough degrees of freedom to produce complex part geometries.
2 Design Development

The design process started following the recommendations from VDI 2221, 2222, 2224, Pahl & Beitz [1], Krause [2] and Rozenfeld [3]. The main issues are shown in Table 1.

Table 1: Design requirements, specification and solution

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Demands</th>
<th>Design Solution</th>
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<tbody>
<tr>
<td>Able to perform different machining process</td>
<td>Process reconfigurability</td>
<td>Standard fixture interfaces</td>
</tr>
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<td>Able to perform complex geometry parts</td>
<td>Geometrical reconfigurability</td>
<td>5 axis simultaneously synchronized movement</td>
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<tr>
<td>Positioning accuracy</td>
<td>0.1 μm</td>
<td>Control loop combined with mechanical solutions</td>
</tr>
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<td>Movements without stick-slip, and frictional hysteresis</td>
<td>- - -</td>
<td>Air bearing guides</td>
</tr>
<tr>
<td>Reliability</td>
<td>1 fail / 6 months</td>
<td>Manufacture and assembly concerns</td>
</tr>
<tr>
<td>Thermal stability</td>
<td>Maximised</td>
<td>Materials, geometrical symmetry, cooled environment</td>
</tr>
<tr>
<td>Dynamic stability</td>
<td>Critical freq. $\omega_c &lt; 5$ Hz</td>
<td>Dynamic damped structure</td>
</tr>
</tbody>
</table>

The machine was divided into eight different sub-systems: one for the structure and vibration isolation systems, one for bearings and guides, one for motion and measurement systems, one for the spindle, one for the tool holder, one for the cooling system and chip removal, one for systems integration, and one for the control system and electronics.

2.1 Conceptual Design

The functional design, part of the development process, set a minimum motion course of 150 mm for the Z, X and 100 mm for the Y axes. A steel structure with passive vibration dampers was chosen to support a granite base. The base was selected to provide thermal and dynamic stability, and to set an assembly reference for the guides. Air bearing guides were developed for the X and Z axes, with the Y axis supported by linear guides. The option for air bearing guides brought limitations to the inertia and load of the moveable parts. Two options for the motion system were presented, one based on linear motors, and another based on the classical ball screw with a brushless rotary motor. The option for linear motors
allows a compact design, with an easy assembly, with the disadvantage of being a source of heat and high frequency vibrations. The solution based on a ball screw with brushless motor was chosen, for being a low heat source, in spite of the disadvantage of a more complex manufacture and assembly. The rotations around X axis ($a$) and around Z axis ($c$) were also supported by air bearings and driven by brushless motors, and had full continuous rotation capacity. The measurement systems were based on rotary encoders for $a$ and $c$ axes, and linear encoder for $X$, $Z$ and $Y$ ones. A commercial air bearing spindle was selected with a fixture for diamond blades and grinders or a 6 mm clamp system for micro mills and drills. A tool holder for turning tools was developed using a monolithic spring system, driven by micrometric screws for adjusting the tool edge position. A component fixture system was developed with modular interfaces to allow compatibility between each configuration, which can be adapted according to the geometry. All part fixture systems incorporated a force measurement and/or acoustic emission system for an in process control-loop.

The CNC control system was implemented using open and free platform Linux CNC, that can control up to 9 axes simultaneously and supports a variety of interfaces [4].

### 2.2 Detailed Design

The detailed design allows 5 configurations: a) 3-Axis machine, able to perform micro grinding with diamond blades and turning; b) 4-Axis, with active C-axis that allows free form micro-end-milling and drilling, turning and grinding with diamond blades and CVD-pencils; c) 3-Axis for end-milling; d) 5-Axis micro-milling; and e) 4-Axis, with active $c$-axis for micro-end-milling (Figure 1). The machine can also be reconfigured as a micro scratch test device. Static, dynamic and thermal analyses using Finite Element allowed corrections to the design in order to improve stiffness, damping and critical frequencies, and thermal stability. The air bearing guides were cylindrical, with a 30-mm diameter. The air bearings have a 1,5 Length/Diameter ratio, with a 10 μm radial clearance and orifice type flow restrictors, which gives a maximum load capacity of 190 N, at 90% of clearance. The guide axes have a semi-
active internal damping system. An Colibri/IBAG® with 60,000 rpm and maximum output of 1,2 kW was selected.

Figure 1 – Reconfigurability of the micro-machine-tool developed.

3 Qualification and Conclusions

Metrological analysis and qualification pose a new challenge, since the directives from the ISO 230 series standard, entitled Test code for machine tools, does not contain small displacement machine-tools. The qualification of the machine was conducted using a finished test piece according to ISO 10791-7 standard [5] and metrological test based on ISO 230. Test parts with the same geometry were machined using micro-end-mills and micro-grinding process. A free form turning part was developed and dimensional and geometrical analyses were conducted using a coordinate measuring machine (CMM). Position accuracy of 0,1 ± 0,02 μm was obtained for Z and X axes, and 0,5 ± 0,02 μm for the Y axis. Machine-tools for micro machining have a closer design relation with ultra-precision ones, incorporating most of their requirements and design solutions, but with different levels of concern.

References: