Abstract
For precision milling manufacturing machine tools with high stiffness $K$ and high masses $m$ are state of the art. Usually this will be achieved due to heavy and large machine beds and frames. Hence, a new approach based on the compensation of the dynamic dislocation was investigated. The aim of this new approach was to develop a high dynamic machine tool with a compliant machine frame. Therefore, a novel compliant three-axes machine tool for high precision milling based on an Ethercat Technology® and the open source ethercat master etherlab machine is developed by the Technische Universität Berlin and the Fraunhofer Institute for Production Systems and Design Technology. For the dynamic dislocation a Kalman-filter is integrated in the machine control which calculates the tool body with respect to the tool-center-point TCP and its velocity $v$. For the verification milling structures are manufactured with the compliant machine tool. Various setups were investigated, braced, compliant without compensation and compliant with compensation. Further the feed speed $v_f$ and the gain factor of the control system $K_v$ were modified. To measure the average diameter $D_{av}$ and the concentricity $C_6$ of the milling structures, the coordinate measurement machine O-INSPECT of the company CARL ZEISS IMT was used. As a result the compliant machine tool can be used for high precision milling processes. Finally, the compliant machine tool is compared with the WISSNER GAMMA 303 HIGH PERFORMANCE, WISSNER GmbH, GÖPPINGEN, GERMANY.

Keywords: compliant machine tool, high precision milling, machine control

1. Introduction
The development of improved cutting tools and machine tools are major aspects of current research in production technology. Machine tools with high stiffness $K$ and high masses $m$ are state of the art to meet the requirements of precision and ultra-precision technology. These systems are typically limited regarding axes dynamics [1]. Therefore, novel machine tool concepts aim at lightweight system design. The presented machine tool design allows high feed drive dynamics and is based on real-time displacement compensation.

The developed control- and design concepts are described in the following and subsequently, the results of an experimental validation are presented. These results are validated by comparison with workpieces manufactured by a micro milling machine tool WISSNER GAMMA 303 HIGH PERFORMANCE.

2. Control- and design-concept
The used control system is based on a Linux real time kernel. Controller input data are CNC setpoints and real time calculated system shift data, whereas corrected setpoints are transferred to the machine control. The used control-loop is based on a Kalman-Bucy filter. In contrast to established control methods, using system acceleration $a_D$ as input parameter, a velocity $v_D$ based control system using an order-reduced FE-Model was implemented. Figure 1 shows the control scheme by example of the position-loop for the X-axis [2]. The control-concept was integrated in a three-axes test stand at the PRODUCTION TECHNOLOGY CENTRE PTC Berlin (Figure 2).

The system design is based on integrated leaf springs to apply determined dynamic weak points.
3. Validation and Verification

With the realized three-axes test stand milling experiments in rigid foam material were carried out. Experimental parameters as well as results are presented in figure 3. The experiments were carried out with a cemented carbide milling tool with a diameter $d = 1$ mm.

A compliant and compensated machine tool frame with a feed rate $v_f = 2$ m/min and a gain factor for the velocity $K_v = 200$ was used for the experimental evaluation. The geometric features roundness and inner diameter are illustrated in figure 3 (top). Machining forces and workpiece-tool interactions could be excluded by using rigid foam as workpiece material.

A concentricity of $c_b = 13$ µm and a mean diameter of $d_{m} = 4.01$ mm ± 1 µm could be achieved with this setup. The results were measured with a tactile coordinate measurement machine tool O-INSPECT, CARI ZEISS IMT, OBERKochen, Germany.

In addition, the results of the compliant machine concept were compared with the machining by two different setups (table 1) of a micro milling machine tool WISSNER GAMMA 303 HIGH PERFORMANCE, that is representative for commercial state of the art high-precision-machine tools.

<table>
<thead>
<tr>
<th>Setup</th>
<th>Depth of cut $a_p$</th>
<th>Width of cut $a_v$</th>
<th>Spindle speed n</th>
<th>Feed speed $v_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.1 mm</td>
<td>0.1 mm</td>
<td>25000 1/min</td>
<td>2 m/min</td>
</tr>
<tr>
<td>B</td>
<td>0.1 mm</td>
<td>0.1 mm</td>
<td>25000 1/min</td>
<td>4 m/min</td>
</tr>
</tbody>
</table>

The results of the comparison are presented in table 2.

<table>
<thead>
<tr>
<th>Feed rate $v_f$</th>
<th>Mean diameter $d_m$</th>
<th>Concentricity $c_b$</th>
<th>Standard deviation $s_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 m/min</td>
<td>3.94 mm</td>
<td>14 µm</td>
<td>1.6 µm</td>
</tr>
<tr>
<td>4 m/min</td>
<td>3.90 mm</td>
<td>33 µm</td>
<td>2.5 µm</td>
</tr>
</tbody>
</table>

The geometry features were also measured with the tactile coordinate measurement machine O-INSPECT described above. With increased feed speed $v_f$, the concentricity of the cylinder $c_b$ increases. The compliant and compensated machine tool achieves a comparable concentricity $c_b = 14$ µm to the WISSNER GAMMA 303 HP. The important difference is that the dynamics of the feed-axes in conventional high precision machine tools are limited [1, 2], whereas this is not with the compliant machine tool frame.

4. Conclusions

The paper shows the ability of compliant machine tools to produce micro structures within specification. Here a suitable control-loop for the feed axis system is used to fulfill the needed requirements. The verification of the compliant machine tool was performed by experimental validation. The measurement results of machined structures in rigid foam workpiece material illustrate the high potential for this machine tool design.

However, in comparison to a conventional machine tool design, axis dynamics have a significant influence on machining result. Thus, lightweight machine tools with high dynamic feed axes can lead to increased efficiency in micro production.

References
