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Procedia CIRP 14 (2014) 339 – 344

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6th CIRP International Conference on High Performance Cutting, HPC2014

Highly integrated high precision fluidic feed axis

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Abstract

Current machine tools for micro manufacturing feature unfavorable ratios of installation space to work space as well as moving masses compared to the work piece mass. Therefore, these machines show potential for optimization [1]. Machine tool components leading to these drawbacks are the currently used feed axes. The required features of such feed axes for micro manufacturing comprise high functional integration, high damping and high precision. Compared to electromechanically build up feed axes incorporating high installation space as well as small damping ratios due to linear guide rails, hydraulic feed axes feature the potential of a high force density and high damping ratios. However, a drawback is the poor precision. At the wbk Institute of Production Science Karlsruhe a novel approach has been realized: A highly integrated hydraulic feed axis with high compactness due to the hydraulic force density. Additionally, it features high functional integration by piezoelectric seat valves built into the piston rod and an integrated hydrostatic guidance system. Within this paper, the approach as well as the measurement results of the prototype of the feed axis by the Institute of Production Science are shown. Furthermore, it addresses the feed axis's properties such as positioning errors, performance and inaccuracies. In the end, an outlook will be given on further ongoing research activities regarding an upgrade enabling an intelligent, active manipulation within the hydrostatic guidance system to compensate the errors of the feed axis.

Selection and peer-review under responsibility of the International Scientific Committee of the 6th CIRP International Conference on High Performance Cutting

Keywords: Micro-machining; Conceptual design; Hydraulic;

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1. Introduction

Micro technology is still growing in double-digit numbers. Applications for micro products can be found for example in automotive, telecommunication, medical, and life science as well as in consumer and lifestyle products [2]. The further predicted growth requires adapted machine tools for production of small components.

The currently used machine tools feature a distinct disproportion in size compared to the size of the machined work pieces. This leads to unfavorable drawbacks such as energy and resource consumptions as well as to economic and technical disadvantages. These disadvantages comprise high investments and high life-cycle costs as well as high cooling efforts due to the thermal expansion of the machine tool. Other technical drawbacks are the contours of the machine tool components interfering with each other and leading to a reduced work piece complexity [1].

Processes used in fabrication of micro parts range from cutting and shaping processes to technologies used for example in the manufacturing of electronic parts e.g. LIGA [3]. Within the manufacturing processes, cutting processes can be used in a wide variety of materials (see Fig. 1) [3]. Their usage is economically ideal in small batch series. Additionally, cutting technologies are applied when manufacturing molds e.g. for MetalInjectionMolding (MIM) [4]. Bulk processes in comparison are economically suitable for high quantities and small structures. Therefore, they are mostly used for production of sensors e.g. in automotive industries.

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doi:10.1016/j.procir.2014.03.084

● Good ◑ Medium ○ Poor			Attributes			Materials				Lot sizes		
			Resolution	Image	Geometry	Metal	Plastics	Ceramic	Silicium	Small series	High volume	Mass production
Tool	Cutting/ Ablation	Micro cutting	◑	●	●	●	●	◑	●	●	◑	◑
		Micro grindig	◑	●	◑	◑	○	●	●	●	○	○
		Micro-EDM	●	◑	◑	●	○	◑	◑	●	○	○
		Laser ablating	●	●	◑	◑	●	●	●	●	◑	◑
	Casting/ Reshaping	Micro injection molding	◑	●	●	◑	●	◑	○	○	●	○
		Micro casting	◑	●	●	◑	●	◑	○	○	●	○
		Micro embossing	●	●	●	○	●	○	○	○	●	○
Mask		Bulk Micro-machining	●	●	○	○	○	○	●	○	○	●
		Surface Micro-machining	●	●	○	○	○	◑	●	◑	◑	●
		LIGA	●	●	○	◑	◑	○	○	○	◑	○

Fig. 1: Manufacturing processes in micro technology [3]

In summary, it can be stated that cutting is a very flexible manufacturing process which can be used for manufacturing small parts and as a basic technology for fabricating molds [5] for large scale production. The used machine tools, however, feature technical and economical drawbacks. One of those drawbacks is the large installation space of such machine tools due to the used feed axis. Within this paper, an approach for a highly integrated high precision fluidic axis will be presented.

2. State of the art

2.1. Machine tools for micro machining

Machine tools for machining small parts can be divided into research activities and into industrial applications.

Machine tools in industrial applications are numerous and feature high installation and floor space in comparison to the work piece's size [6]. This prevents the adaption to the dedicated processes and leads to higher energy consumption as well as investment costs.

In the field of research on the other hand, several approaches are known regarding research work for highly dedicated processes in adapted machine tools with improved installation space to workspace ratio. These machines stemming from research projects feature several drawbacks such as the stiffness of the bearings, the structural stiffness and the reduced power [6].

2.2. Feed axes in machine tools for micro machining

Currently used feed axes in machine tools feature a wide variety of technical principles. They range from linear drives to ball screws and to hydrostatic ball screws. Aerostatic and hydrostatic guides as well as roller-based guides are used [6]. If higher accuracy, stiffness and damping ratios are required, hydrostatic guides are employed due to their better characteristics in comparison to roller guides [7]. Aerostatic guides are also used for high accuracy but they require a large installation space for the necessary stiffness and load.

Since the feed axis is one of the components that determines the required installation space and workspace of a machine tool, it requires further consideration. Compact and highly functional integrated feed axes can contribute to small and adaptable machine tools. Therefore, the feed axes are one issue addressed as part of the collaborative research program SPP 1476 [8].

2.3. Requirements for the feed axis

In [6], process requirements for a compact five-axis milling machine and for the feed axes are derived as shown in table 1.

Table 1. Process requirements for a five-axis milling machine tool (extract) [6]

Process	Feature
Work piece geometry	Obliques and undercuts (<90°) at the entire circumference of the work piece
Work piece size	≤ 70 x 70 x 70 mm
Workpiece accuracy	≤ 5 µm
Process force	1 – 10 N
Cutting speed	50 – 200 m/min
Feed rate	500 – 6.000 mm/min

It can be summarized that the required feed axes for a compact machine tool must feature high compactness, high dynamics and high precision.

3. Approach

In [9], the basic approach was presented and first measurement results regarding stick-slip effect and stiffness were shown. In [10], the design process, the positioning error as well as the control behavior of the prototypically realized first concept were discussed.

Within this paper, the final design and the latest prototypical realization featuring a significant decrease in size (80 % to [9] and [10]) and the integration of the piezoelectric seat valves [11] will be shown. The major measurement results of this prototype will be addressed in the following.

The hydraulic feed axis comprises a compact setup due to the following design characteristics: The common principle of a fixed piston housing is inverted to obtain short oil columns for improved control behavior and high system compactness. As shown in Fig. 2, the moving part is the piston housing designated as moving carriage resulting in small moving masses. This enables the application of a fixed piston rod. The piezoelectric seat valves are integrated into this piston rod resulting in short oil columns. The control principle of this feed axis can be described as a two metering edges control [9]. The required orifices for propulsion and the necessary back-pressure valves are integrated into the moving carriage. This also contributes to having short oil columns and enables a better control behavior.

Next to the moving carriage, eight hydrostatic pockets are implemented resting on two bronze prisms realizing a hydrostatic guidance system with high damping ratios and an adequate stiffness. The constant orifices of the hydrostatic guidance system are located in the top part of the moving carriage. They can be replaced according to the required stiffness of the guidance system.

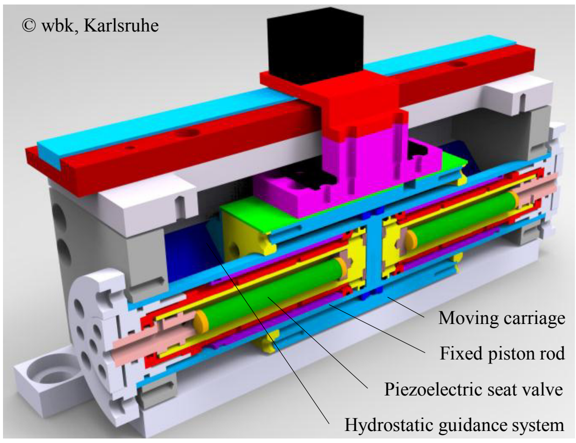

Fig. 2. Cross section of the hydraulic feed axis [10]

The piezoelectric seat valves are directly propelled by the internal piezo and are specifically designed and adapted to the requirements for the hydraulic feed axis [11].

The detection of the feed axis's position in x direction is realized with a glass scale (Heidenhain LIP 401R) having a resolution of 0.4 µm. The glass scale is located besides the stationary housing. The main drawback of this setup is the pivot length between the moving carriage and the position sensor. However, due to the hydraulic fluid, this alignment is essential to keep the glass scale clean of oil for securing high measurement accuracy. To reduce the influence of the long pivot length, there are no further loads on the link between the sensor and the moving carriage.

The control of the feed axis is realized by a PID controller with anti-windup measures to control the integrator [10].

4. Results

4.1. Prototype

The above described concept was implemented in a prototype at the Institute of Production Science in Karlsruhe. The prototype features the external dimensions of 208 mm x 101 mm x 94 mm (see Fig. 3). It is embedded within a test stand for determining the prototype's static, dynamic and thermal behavior. Therefore, length gauges, temperature sensors and pneumatic cylinders with a load cell can be positioned as well as adjusted according to the measured value.

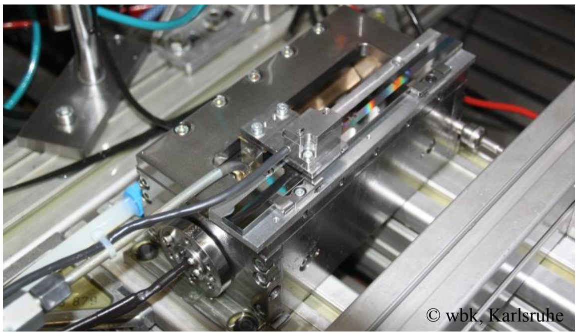

Fig. 3. Highly integrated high precision fluidic feed axis

The prototype in comparison to the already in [9] and [10] presented version is 80 % smaller due to the integral design and the specifically manufactured parts.

4.2. Measurement equipment and approach

For characterizing the geometrical behavior of the feed axis, a test setup was developed and first used to characterize the prototypic realization of the feed axis presented in [9] and [10]. For measuring the linear deviations in y and z direction as well as the rotations around y (Fig. 4, b)), z (Fig. 4, c)) and x (Fig. 4, d)) direction, length gauges (Heidenhain MT1281, accuracy +/- 0.2 µm) and a reference standard were used (see Fig. 4).

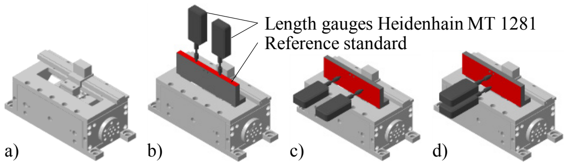

Fig. 4. (a) Hydraulic feed axis; (b) Offset in Z and Rotation Y; (c) Offset in Y and Rotation Z; (d) Rotation X

For determining the dynamic behavior as well as the control behavior of the feed axis, procedures similar to [12] were applied. Additionally, further investigations were conducted regarding the minimum and maximum velocity, the maximum acceleration as well as the minimum step size. All measurements were performed by using the internal glass scale of the feed axis.

The thermal behavior was determined by measuring the temperature at three locations and by detecting the offset on top of the moving carriage.

Since stiffness is an important parameter it was determined in linear direction as well as in two rotational degrees of freedom. In order to determine the linear stiffness, a length gauge as well as a pneumatic cylinder were adjusted coaxially in each direction. The pneumatic cylinder was equipped with a load cell (Kistler Type 9011 A) enabling the determination of the applied force [9].

4.3. Dynamic characterization of the feed axis

The hydraulic feed axis was characterized regarding the dynamic behavior. Therefore, the maximum feed rate of the feed axis as well as the acceleration was determined. The measurement was conducted by applying a set point for the opening of the specific valve. The measurement was evaluated by deriving the position signal of the glass scale mathematically. The maximum feed rate was determined with 4,700 mm/min. This is considered to be sufficient in a parallel kinematic setup as proposed in [11]. The acceleration was deduced by the mathematical derivation of the feed rate signal. The feed axis features a maximum acceleration of 10 m/s².

Feed rate and acceleration are major characteristics but also the positioning error of the feed axis is important. Therefore, nine set points were approached from positive and negative feed direction. The evaluation was conducted as proposed in [12]. The measurement value was taken after standstill, 0.5 seconds before the next step was set (time for each step - 13 seconds). All set points were approached 5 times from each direction. The position value was measured with the internal glass scale (Heidenhain LIP 401R with EXE 602, accuracy +/- 0.4 µm). The evaluation showed a bi-directional positioning accuracy of 1.3 µm. As can be seen in Fig. 5, the median bi-directional repeatability (X_i) ranges between -0.08 and 0.03 µm.

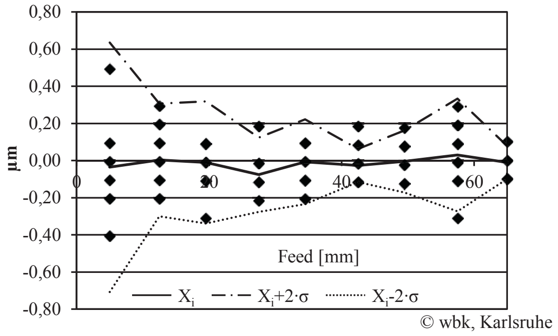

Fig. 5. Positioning error (of the PID controller) measured with internal measurement system)

Further investigations regarding the dynamic behavior were conducted to determine the minimum step size, the response time constant and the stationary accuracy of the feed axis. All of these measurements were conducted by setting step points into the PID Control. The controller itself was implemented in an industrial dSPACE system. The measurement frequency of the system is limited to 1,000 Hz.

The result of the minimal step size can be seen in Fig. 6. A step of 1 µm was set. The measured oscillation can be subjected to noise.

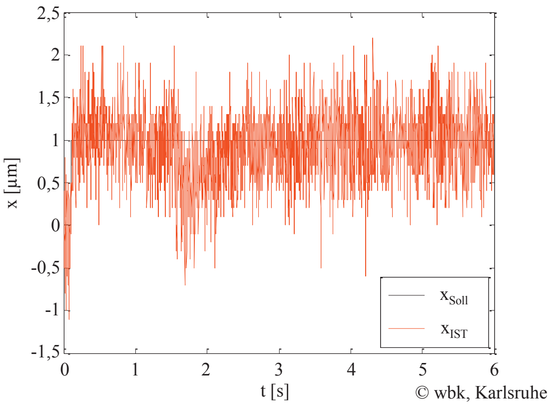

Fig. 6. Minimum increment of the feed axis (step size 1 µm)

The stationary accuracy of the feed axis was determined with 0.58 µm (median 5 sec. to 6 sec. in Fig.7). Fig. 7 shows the step response. The feed axis's response time constant was evaluated from a step response. It can be calculated with the point where 63% of the speed is reached. The response time constant is 10 ms.

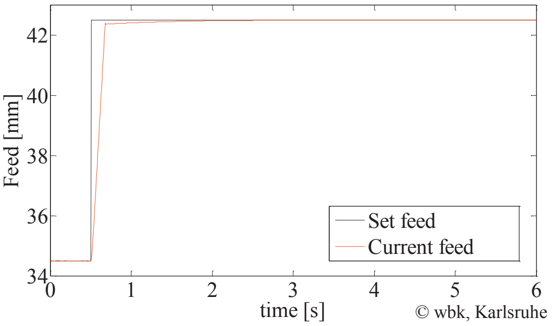

Fig. 7. Step response

4.4. Static characterization of the feed axis

The static characterization of the feed axis was performed by determining the stiffness as well as the deviations in five degrees of freedom.

For determining the stiffness, several measurements were executed along the entire feed axis. In order to determine the feed axis's stiffness, 3 positions (5 mm, 35 mm and 65 mm) were approached. While in control mode, a force ranging from 20 N to 120 N was applied. The deviation was measured with a length gauge. As can be seen in Fig. 9, the feed axis features linear stiffness ranging from 15 N/µm to 30 N/µm in the y and z direction. The stiffness can be adjusted or increased by adjusting the orifices of the hydrostatic guide.

For characterizing the stiffness in feed direction, a different approach was conducted: Since a load in feed direction on the top of the moving carriage would result in a momentum around its center, a fork shaped (Fig. 8) device was used to create the load on the moving carriage.

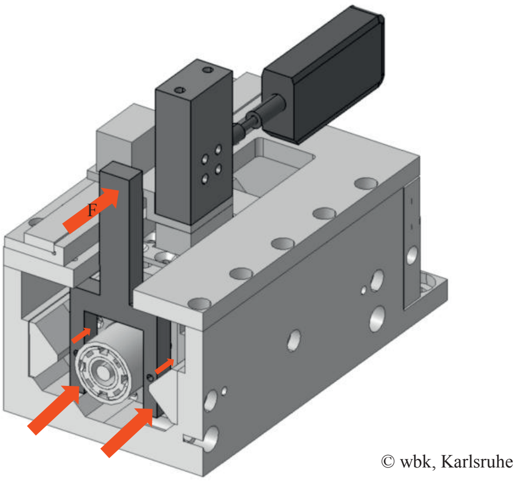

Fig. 8: Test setup for stiffness and force in x direction

This device features a long lever on which the load can be applied. The other ends were hold in place at the bottom of the feed axis's housing. At the height of the center of the feed axis two bolts applied the force directly to the moving carriage with no momentum around the moving housing. The measurement was only possible at one specified location. The stiffness in feed direction was measured with a maximum of 28.99 N/µm. There was a slight difference when the feed axis was in control mode or the control was switched off (see Fig. 9).

The same test setup was used to determine the feed axis's force in feed direction. The maximum force was determined with 192.5 N. This allows accelerating almost 20 kg with the maximum acceleration.

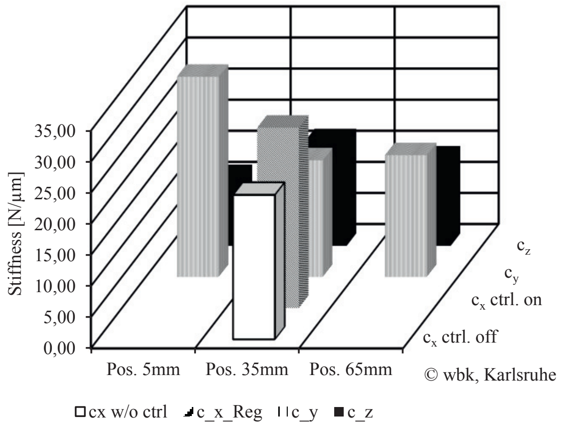

Fig. 9. Stiffness of the feed axis in x, y and z direction

Further investigations regarded the rotational stiffness of the feed axis. Therefore, a lever was designed allowing the loading of a momentum around a single axis. Measurements of the stiffness round the x and y direction were conducted. The measurement was repeated in the same position as described with the linear stiffness. As result, a rotational stiffness around the x direction of 0.67 Nm/(µm/m) – 0.88 Nm/(µm/m) and the y direction of 0.54 Nm/(µm/m) – 5.67 Nm/(µm/m) depending on the applied force and position of the moving carriage was measured. Due to the setup, the investigation of the stiffness around the z direction was not possible.

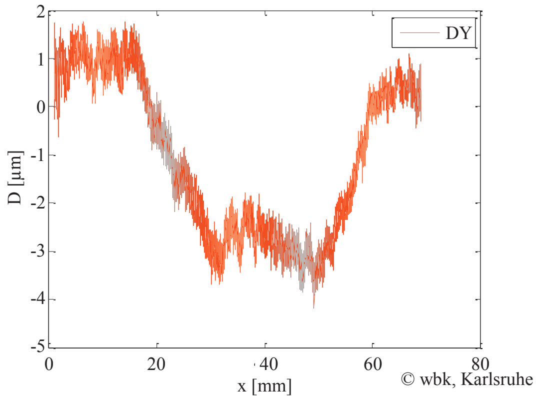

Fig. 10. Offset in Y-direction of the feed axis

To determine the geometrical deviations of the feed axis, the above described approach consisting of length gauges and a reference standard was used. The reference standard was grinded, it thus features high smoothness and geometrical accuracy. The measurement was conducted while the moving carriage passed the length gauge at low speed.

Fig 10. shows the offset in y direction. The moving carriage shows a deviation in that direction of 5 µm. The z direction exhibits the same deviations. The offset resulting from the mounting of the reference standard was compensated mathematically.

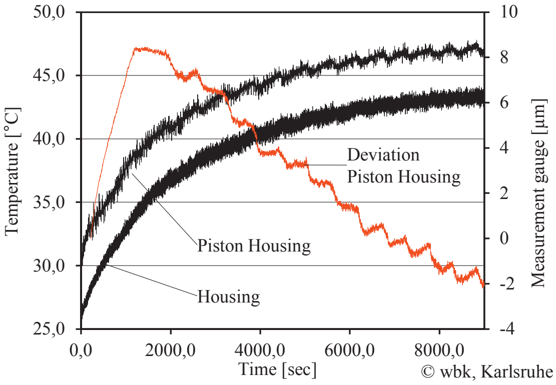

Fig. 11. Temperature profile of the feed axis and deviation in z direction

The temperature of the feed axis during the measurements was held around 40 °C and 45° C respectively. As seen in Fig. 11, it requires more than 2 hours to raise the temperature to an almost static state. The moving carriage undergoes a deviation of 10 µm due to the temperature influence. Within this deviation also the thermal expansion of the feed axis housing as well as the test setup is measured. For decreasing the thermal expansion the oil temperature can be controlled. First heating leads to a shorter time to reach the feed axis's operating temperature. Second a constant temperature would lead to smaller deviations.

5. Conclusion and Outlook

In conclusion, it can be stated that the proposed approach can be used in machine tools for micro machining. In future works, the feed axis presented here will be refined. The work will regard the reduction of the deviations in geometrical behavior. Therefore, the parts will undergo improvements such as lapping and straightening of the prisms and the moving carriage's surfaces. Further adjustments will be conducted on the stiffness of the system.

The future approach will contain the compensation of errors due to manufacturing by implementing an active hydrostatic guide. Therefore, active orifices will be implemented for each pressure pocket of the hydrostatic guide. This enables a shift of the moving carriage according to its position. It is expected to reduce the manufacturing errors significantly. The compensation approach for internal errors is planned by a repeating algorithm which will stepwise decrease the feed axis's geometrical errors by measurement and compensation cycles.

Additionally, it is envisioned to provide an extra range for compensation of geometrical errors of other modules attached to the hydraulic feed axis. For achieving that goal, a simulation approach will be developed for calculating the set points of the hydrostatic guide in dependence of its position. In combination with the active module and the above described prototype a serial build up X-Y positioning stage is envisioned, which can be used for micromachining.

Acknowledgements

This paper is based on investigations of the collaborative research program SPP1476 which is kindly supported by the German Research Foundation (DFG).

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