Development of a dynamic high precision miniature milling machine

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Abstract

One of the main focuses in many research fields is the miniaturisation of work pieces and components. Micro fluidic, micro mechanic, micro electronic and micro optical functional groups are integrated into smallest space to microsystems for medical, information technology or automotive purposes. Directly opposed to the miniaturisation trend of these products are the machine tools used for the production becoming bigger and bigger, with the result that the proportion between the machining space and the needed floor space is more and more inefficient. To meet the process requirements as well as the requirements of the machine users of flexible and small high performance machine tools the Fraunhofer IPT developed and designed a compact high precision milling machine. The paper describes current trends in the field of compact machine tools under special consideration of the mechanical setup and the development of a small and high precise as well as high dynamic micro milling machine.

Keywords: compact machine tool, high precision, mould and die making

1. Introduction

There is a continuing drive towards miniaturisation of work pieces in the field of micro fluidics, micro mechanics, micro electronics and micro optics which has left its prototype state and the integration of these components into functional groups of microsystems is state of the art [1]. But for a final breakthrough of standard Micro-Electro-Mechanical Systems (MEMS) and mass-customized optical components, cost efficient production technologies are essentially needed [2,3]. To obtain a cost efficient production one has to differ in mass production of standard parts and mass customized production of individual products for example in medical purposes. High precision moulds for die casting are essential for an efficient mass production of MEMS parts like miniature gear wheels. To achieve long lifecycles the moulds are mostly made out of wear resistant hot forming tool steel, which results in special challenges on the process technology [4].

The paper focuses on the development of a compact micro milling machine tool. Unlike the state of the art machine tools used for this purpose the described machine tool offers common travel ranges in combination with very high accuracies and an outstanding minimized floor space of one square meter.

Depending on the special purpose there are design key points like maximum travel range at smallest space, highest accuracy and unique attributes like extreme dynamics, which will be pointed out subsequently.

2. General aspects of the design process

2.1. State of the art machine tools

Taking a look on the market of high precision machine tools one finds a wide assortment of different machine tools, but the proportion between the machining space and the needed floor space is quite inefficient. But to optimize the flexibility and efficiency compact machine tools are needed to use the full capacity of existing special climate shop floors necessary for ultra precision machining. Nevertheless the large size of a machine tool does not increase its precision.

Because of faster and faster changing product life cycles the mobility of machine tools will become more important in the future, so the aim of compact machine tool design also contains the integration of the periphery in the structure. A closer look on conventional high precision machine tools points out the existing dilemma. At a horizontal travel range of 250 x 250 mm\textsuperscript{2} normally seven square meters of space are necessary. Compared to the novel machine design, described in this paper, the same travel range can be realized at a needed floor space of 1 m\textsuperscript{2} contributed with a big step towards the required direction.

2.2. Key components of the miniature milling machine

Next to the aspect of the size of a machine tool the technical data like accuracy, travel range and path feed are important aspects not to forget the price. To keep the price of small machine tools acceptable it is necessary to use standard high precision components in an optimized design. Subsequently different basic components will be shortly analysed and characterized for the use in compact machine tools.

2.2.1 Drive system selection

Depending on the process and the needed path feed, different drive technology can be used. To gain the necessary position accuracy the influence of friction has to be minimized. In many ultra precision machine tools the use of linear direct drives are state of the art. The theoretical stiffness of these drives is infinite, as long the force is below its maximum force. The abandoning of mechanical transmission elements supports high dynamics, especially high jerks and KV-factors, which characterises the ability of high precision at high speeds [5].

The KV-factor is the speed amplification factor of the position control where \((v)\) is the path speed and \((\delta)\) is the contouring error. Possible KV-factors of linear drives are up to 25 m/ (min*mm) because of the lack of mechanical transmission elements. Standard lead screw drive systems reach only up to 3.5 m/ (min*mm).
\[ K_v = \frac{v}{\delta} \] (1)

Intensive investigation on direct drive in combination with air bearings proved possible step response of 20 nm and below depending on the control. In combination with ultra precision scales resolutions down to 0.001 µm can be realized, either with iron core and ironless drives [6]. Using iron core linear drives, the machine structure and guidance system has to resist the magnetic force, but on the other hand this technology offers a slim design and installed cooling facilities.

2.2.2 Guidance system selection

Depending on the drive system, the machining process and the work piece requests several guidance systems can be used in high precision machines. Using for example an iron core linear motor the guidance system will be preloaded with a magnetic force up to 1000 N even at small iron core direct drives.

The developed compact milling machine is equipped with high precision grade guidances, reaching a linearity below 1.5 µm/300 mm, what can be reached with non recirculating bearings. This allows the integration of these components in high precision machine tools [7]. In combination with needle bearings very high stiffness at low construction space can be achieved. This property allows the integration of ball bearings in compact machine tools with high process forces like the presented milling machine. The characteristic small size is a key factor for compact axis systems to minimize Abbé errors.

2.2.3 Machine base material selection

To provide the best attributes for high and ultra precision machining one can find an overall trend according to the machine base materials. Because of the characteristically low cutting forces (< 100 N) and the aim of highest form accuracy and surface quality even at long machining time, the machine base material has to be thermally very stable. This feature is expressed in a low thermal expansion coefficient and a low specific heat capacity. To improve the surface quality good damping properties of the base material, expressed in a high logarithmic decrement, are needed. These attributes are best fulfilled using granite or mineral casting as material. Mostly granite or other hard rocks are used because of its very low thermal expansion coefficient of 6.5 exp-6 mm/K, 2.5 times less than mineral casting. Additionally, granite can be lapped to very high accuracies of 1 µm deviation per meter, what is essential to guarantee highest precision of the linear guidances [8].

Due to its unique material properties the subsequent introduced miniature milling machine is equipped with a granite machine base machined in precision with less than one micrometer deviation in the ultra precise mounting areas.

3. Design of the high dynamic miniature milling machine - MiniMill

3.1. Requirements of the micro milling Process

The field of application addressed by the MiniMill machine is the high precision machining of hot work steel used mostly for plastic casting. General process requirements are listed below:

- Workpiece size: 100 x 100 x 50 mm³
- Accuracy: 2 µm (@ work piece)
- Acceleration: 15 m/s²
- Tool diameter: 0.1 – 5 mm
- Spindle speed: 10.000 – 160.000 rpm
- Material: Hot work steel 60 HRC

The SEM pictures in Fig. 1 point out the dimensions of the used tools and work pieces. To enable the conventional use even of a small sized milling machine the structure and drive system has to be designed to provide ideal process parameters like path speeds of 1000 mm/min and accelerations of more than 1 g also for cutting forces above 150 N [9].

![Miniature endmill 0.1 mm and mould with freeform geometries for plastic casting.](image)

Fig. 1. Miniature endmill 0.1 mm and mould with freeform geometries for plastic casting.

The biggest impact on the process time while machining freeform surfaces of complex work pieces has the jerk of the slides. To reach the best accuracies at high path speed at multi axis machining the KV-factor of all axes have to be equal and as high as possible. As described in chapter 2.2.1 this claim can be mostly fulfilled using linear direct drives. The combination of a light weight construction with high performance direct drives enables theoretical accelerations of 200 m/s² and more at long stroke movements in test benches [10]. To machine smallest complex geometries with freeform shapes the axes have to be accelerated and decelerated at smallest strokes like 0.05 mm, to keep the path speed up and minimize form deviations of the mould.

Looking at small axis movements the jerk as the derivation of the acceleration has a large influence on the process time and parameters. Analyzing Fig. 2 it is obvious that the moving time of a 500 µm set point ramp can be shortened by 30 percent using a three times higher jerk. The ideal path speed of the micro milling process is 1000 mm/min, what can only be reached at high jerks [9]. The increased jerk makes micro milling much more efficient. A tool path examination of a workpiece with freeform surface is given in Fig. 1 (right) shows that most machining steps are far below 1 mm, usually about 20 µm. Conventional machine tools, independently of the used drive system, require a jerk limitation of the drives, to avoid a stimulation of the machine base at the eigenfrequency. The jerk limitation is needed to obtain the asked work piece precision decreasing the path speed at multi axis machining significantly.
Fig. 2. Dynamic behavior of a linear axis at a 500 µm set point ramp with limited jerk.

3.2. Drive system and impulse decoupling strategies

To minimize the machine base impact without heavy jerk limitation at the nc-control mechanical impulse decoupling strategy is one solution to maximize the possible jerk of the axis simultaneously. Focussing on the micro milling process, high accelerations and jerks are inevitable to provide nearly ideal process parameters. As described in chapter 2.2.1 high precision at high path speeds demand high KV-factors of the drive system. Regarding this specification the drive systems chosen for the milling machine are linear direct drives. Next to other possible impulse decoupling strategies a system using an elastically supported magnet track is integrated in all axes of the miniature-milling machine MiniMill.

Using the impulse decoupling system shown in Fig. 3 offers many advantages regarding the application in a miniaturized milling machine. Because of its small size and low costs compared to other systems, this solution demands only an additional guidance system for the magnet track and a metrology system to maintain the commutation of the linear motor. The connection between the magnet track and the base is designed as a special spring-damper-system what minimizes the impact on the machine base especially at the range of the natural frequency. On test benches at the Fraunhofer IPT and the WZL the impact on the machine structure could be decreased about 60 percent and the possible jerk could be raised up to the factor 10, compared to standard settings without decoupling systems [11], [12]. The mass of the damping slide is normally about five to ten times higher than the moving slide system. This property makes the integration of an impulse decoupling system into stacked axes very complex. Without changing the relation between the slide and the damping mass, the heavy weight would equal dynamic behavior for stacked axes.

3.3. Machine design

To achieve highest accuracies different arrangement of axes have been analysed under the consideration of the chosen impulse decoupling system and the process requirements. Due to the design of a three-axis machine, at least two axes have to be stacked either on the tool or on the work piece side. Examining conventional high precision machine tools, the slowest axis is the vertical z-axis, which is normally equipped with a self-locking lead screw. To provide the same dynamics of 1.5 g in all three axes the z-axis is mounted separately on the tool side. Passive magnetic actors are integrated in the z-axis as weight compensation to supply the same acceleration in positive and negative z-direction. The design of the z-axis impulse decoupling system is similar to the system shown in Fig. 3, but additionally the damping mass spring is preloaded by gravity. The impulse decoupled horizontal x- and y-axis are stacked and integrated in a compact and lightweight cross table design. To minimize Abbé errors the drives and guidance systems integrated into the cross table have to be arranged as close as possible. As the application of this machine tool is the milling of non optical moulds the integration of ball bearings is allowing for a very compact design.

Fig. 4. Miniature milling machine - MiniMill.

For a complete impulse decoupling setup in all axes the decoupling system had to be integrated into the cross table. To minimize the weight of the moved
mass different direct drives have been analysed and an iron core motor was chosen to be integrated in the x-axis. Especially the motor characteristics of a high continuous force at low weight is necessary to accept the process force and additionally provide enough maximum force to assure high accelerations and jerks even in process. This offers some important advantages, compared to an ironless drive in the upper axis. The total weight iron core drives (coil incl. magnet track) is lower than iron less drives because only one magnet track is needed. Compared to ironless motors the slim configuration allows a compact design and minimized vertical distances between the x- and y-axis guidence, what helps to minimize stacking errors. Another advantage is the integrated precision cooling unit to keep heat away from the structure.

To avoid heat sinks in the closed cross table, the magnet track of the x-axis is also equipped with water cooling channels. Keeping the stacked weight on the carrying y-axis low, the mass of the damping slide is only a bit higher than the x-axis slide. Therefore harder damping and spring coefficients of the damping elements are needed to achieve efficient damping properties at short strokes of the magnet track. A detailed design demonstration is given in Fig. 5.

The requirements of the y-axis drives are quite different to the x-axis. As the friction force is only about 4 N and the process force up to 150 N, the main drive performance is needed to accelerate the cross table including the x-axis with 1.5 g. With a total cross table weight of 60 kg, 900 N peak force is needed for the acceleration. Under this circumstances the use of an ironless drive is favourable because these drives offer up to ten times higher peak forces compared to the continuous force. With an integration of the magnet track on the machine base this design was chosen. Fig. 5 shows the two chosen ironless drives of the y-axis. They supply more than 2000 N totally as peak force and a continuous force of 400 N. To avoid thermal influences the coils and magnet tracks are water cooled.

This unique design will provide much better process conditions and will speed up the machining time approximately about 20 percent, at less tool wear and better surface qualities, due to better process conditions. The dimensions of the machine base showing Fig. 4 are 800 x 800 mm² and the total machine will use about 1 m² floor space including periphery.

4. Summary

This paper presents the latest developments of the Fraunhofer IPT in the field of compact machine tools. After a short introduction of important machine components like drives and bearings a unique developed compact milling machine of only 1 m² floor space is described. The machine tool represent novel design and control approaches in the field of micro milling to provide highest accuracy and optimized process parameters. Regarding the demands of micro milling of free-form surfaces, a design with integrated impulse decoupling units in all axes was presented, providing highest jerks for continuous optimized path speeds. The overall effect on the machining of die casting moulds, prototypes and EDM electrodes, will be significantly decreased primary processing times at less tool wear and better surface qualities without a cutback of precision.

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