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Miniaturized parallel kinematic machine tool for the machining of small workpieces

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Abstract

Machining small workpieces with large scale machine tools has several disadvantages such as high costs, low efficiency and higher sensitivity to errors. Miniaturizing the machine to workpiece scale is a suitable approach to overcome certain limitations. However, this measure also leads to significant changes in machine properties even if the kinematic structure remains unchanged. On the basis of a parallel kinematic machine tool the paper investigates size effects and machine characteristics during dimensioning and design process. Static stiffness of joint bearings and overall dynamic behaviour are analysed to derive and prove certain design measures. Furthermore the influence of miniaturization on structure synthesis and feed drive dimensioning is shown. The paper concludes with final design and specifications of the developed parallel kinematic machine tool.

Parallel kinematic machine tool; miniaturization; micro machining

1. Introduction

During the last decade the trend to miniaturize technical systems affects almost every industrial sector [1]. In this context the machining of small workpieces with high accuracy and complex geometric design is a key enabler to drive this development. Currently machining of small workpieces, with part and/or geometry dimensions up to 10 mm [2], is realized by common precision machines. This leads to disproportions between machine size, work space, energy consumption and costs towards the small sized workpiece.

Size-adjustment of the machine tool to part scale is an approach to solve these deficits [3]. In addition, using a parallel kinematic structure such as presented in [4] offers advantages related to high motion dynamics, slight machine complexity and less sensitivity towards geometric errors.

Aim of the research is to develop a miniaturized machine tool with pentapod kinematics based on downscaling a large prototype by a scaling factor *S* of 0.2.

2. Preliminary dimensioning through size effects

Size effects in miniaturization [2,5] cause changes in all domains of machine properties which have to be identified early during the machines development process [6].

The goal of preliminary design studies was to analyse the principle sensitivity of overall static and dynamic machine behaviour towards down-sizing and certain design measures. Therefore the FE-model of the existing 5-axis-PKM was scaled and selected stiffness parameters where adapted accordingly.

The static behaviour of machine tools is determined by rigidity *r* respectively the stiffness matrix ***K*** of the mechanical structure. Regarding the scaling of a simple structure from size A to B in Eq. (1) shows the related scaling law [5].

$$r_B = S \cdot r_A \quad (1)$$

Concerning static behaviour of parallel kinematics properties of joints are decisive. Figure 1 shows a linear trend of rigidity over the scaled joint bearings conform towards the scaling law.

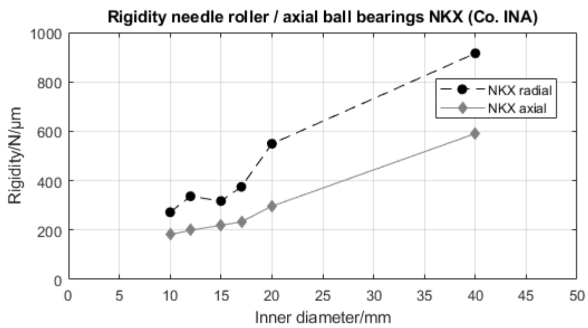

Figure 1. Rigidity of joint bearings over the inner diameter

For dynamic behaviour eigenfrequencies f show a linear relation to the scaling factor Eq. (2) [5]:

$$f_B = S \cdot f_A \quad (2)$$

Aiming to predict the general shift of eigenfrequencies FE-analysis was carried out under changing model properties representing certain design measures. For example the influence of different spindle or feed drive types was represented by adding discrete masses to the existing setup. Geometry variation of structural components such as the struts was implemented by modifying density and E-modulus. Results of the study are represented in Table 1.

Table 1 Results of modal and sensitivity analysis; first 13 modes

	Mode number / Frequency(-range)	
Machine setup	***Local eigenmodes not affecting TCP***	***Global eigenmodes affecting TCP***
Large Scale PKM	1-10 / 21-29 Hz 13 / 53 Hz	11-12 / 32-49 Hz
Miniaturized PKM		
Basic	1-10 / 97-117 Hz	11-13 / 225-258 Hz
Feed drive mass +1kg	1-10 / 59-93 Hz	11-13 / 216-247 Hz
Spindle mass +2kg	1-10 / 97-117 Hz	11 / 156 Hz
Strut diameter x1,4	1-10 / 136-177 Hz	11-13 / 225-263 Hz

The local eigenmodes are mainly characterizes by the struts bending motion around the DOFs of their according joints. Global eigenmodes show complex deformation and have direct impact on machining performance.

Results show that miniaturisation has positive effects, leading to significantly higher eigenfrequecies similar to the trends related to scaling law. Also, spindle mass is a crucial factor regarding dynamic properties whereas strut diameter and feed drive weight predominantly affect only local eigenmodes.

3. Development of the miniaturized machine tool

The development process of parallel kinematics is slightly different compared to seriell kinematics [7]. In general, this concerns the iterating execution and optimazation of structure synthesis, dimensioning and design.

Kinematic structure and work space are defined by kinematic parameters especially number *i* and degrees of freedom (DoFs) of mechanisms, joint locations $\boldsymbol{A}_i$, $\boldsymbol{B}_i$ and vectors of the struts traveling range $\boldsymbol{l}_i$. The work space can be determined using the loop equation LE_i Eq. (3) [7] and various collision conditions:

$$LE_i = \|\boldsymbol{l}_i{}^2\| - \|(\boldsymbol{A}_i - \boldsymbol{B}_i)^2\| = 0 \tag{3}$$

Refering to the miniaturization, linear scaling of kinematic parameters is an effiecient method to maintain the optimized transmission behaviour expressed by Jacobian Matrix $\boldsymbol{J}$ (Eq. (4)) with $\boldsymbol{X}$ for global coordinates and $\boldsymbol{L}$ for drive coordinates:

$$\boldsymbol{J} = \frac{\partial \boldsymbol{X}_i}{\partial \boldsymbol{L}_i} \tag{4}$$

Regarding the work space ***WS,*** defined as the summary of all possible Tool Centre Point (TCP) locations for a fixed spindle orientation, scaling leads to a linear influence Eq.(5):

$$\boldsymbol{WS}_B = S \cdot \boldsymbol{WS}_A \tag{5}$$

The calculated work space for the considered machine is about (300 x 300 x 300) mm³, shown in figure 2. Compared to the frame width of 550 mm, the proportion between machine size and workspace is excellent. Additionaly, the work space for full 5-axis machining, meaning spindle orientation 0° - 90°, is about (100 x 100 x 100) mm³.

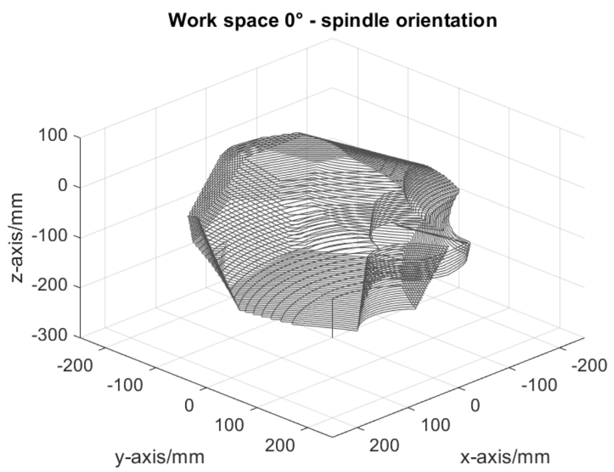

Figure 2. Work space of the miniaturized PKM in 0° spindle orientation

4. Design and configurations

The modular design enables various configrations. Figure 3 shows the final design of the miniaturized parallel kinematic machine tool in desktop configuration. Table 3 lists selected technical data. Furthermore, installation to a full maching center and other options can be realized.

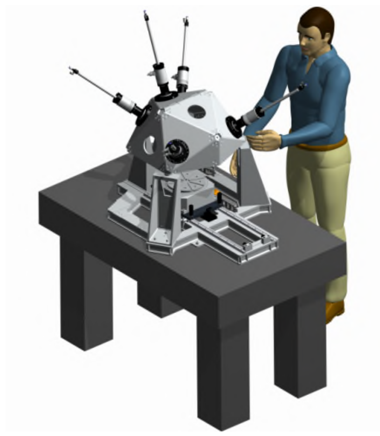

Figure 3. Miniaturized PKM in desktop configuration

Table 3 Specifications of machine tool in desktop configuration

Parallel kinematic modul – frame width / mass	550 mm / ≈ 70 kg
Machine tool – footprint	(850 x 1025) mm²
Machine tool - mass	≈ 200 kg
Max. velocity (depent on position)	> 17.5 m/min
Max. acceleration (depent on position)	> 9 m/s²
Max. prozess force	200 N

5. Conclusions

Miniaturization of machine tools for machining of small workpieces aims to achieve enhenced machine properties. This paper presents a parallel kinematic machine tool downscaled by factor 0.2 from a large counterpart. Therefore an analysis of size effects used to predict machine properties and prove design measures during development process was carried out.

Size effects contain physical phenomena described by equations based on the theory of similarity. These scaling laws are usefull to predict machine properties based on existing modells and know-how. Concerning rigidity of joint bearings and eigenfrequencies the results are conform to scaling laws. Either structure synthesis is more efficient while using scaling laws. Additional size effects occur in micro range can be neglected due to the dimension of the considered machine.

Results presented in this paper and especially the influence of friction and damping needs further experimental characterization.

Acknowledgements

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