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ESTIMATION OF THE POSE-DEPENDENT STABILITY LOBE DIAGRAM FOR A NEW 5-AXIS MACHINING CONCEPT

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Abstract: In this paper, the dynamic behavior of a lightweight 5-axis milling concept is analyzed using finite element simulation. It has a pose-dependent dynamic behavior with structural Eigen modes between 28 Hz and 50 Hz. Based on these results, the stability lobe diagrams (SLD) for the milling module at different axis-positions are derived. The milling module shows a changing process stability with a maximum critical cutting depth of 7.2 mm at “best case” position and 2.3 mm at “worst case” position. With a material removal simulation, the SLDs can be used to predict the process stability for unknown NC-programs.
Keywords: 5-axis machining concept, Pose-dependent process stability, Finite element analysis

1. INTRODUCTION

An increasing demand for customized products forces the manufacturing industry to move from series production to individual production. Thus, production has to be very flexible to ensure a short set-up and lead-time. The delivery time can be further reduced by using a distributed local production instead of central production facilities. The European Project “CassaMobile” tackles this challenge by introducing a localized mini-factory in a container [1]. The “CassaMobile” container consist of different exchangeable process modules, which are chosen according to the specific application of the container. There are process modules for additive manufacturing, milling, micro assembly, cleaning and packaging. Depending on the process chain of the use-case the process module are arranged and linked with an automatic transport system or by manual transportation.

This article focuses on the development of the milling module for the CassaMobile container. As there are several modules and the space in a container is very limited, the area for each module is restricted. This makes an efficient use of the available area necessary. The milling module is mainly for post-processing of the parts produced with additive manufacturing, and should ensure high accuracy and good surface quality.

One of the limiting factors of the milling performance is the appearance of chatter vibrations. Chatter vibrations are caused by the interaction of the tool and the work piece. The self-excitation of the flexible machine tool structure results from the interaction of the wavy surface left by the last cutting edge and the current cutting edge. Thus, this effect can be described as a differential equation with time delay [2]. The spindle speed, the machine dynamics, the tool, the material and the depth of cut are mainly influencing the stability behaviour of the process [3]. As the spindle speed is defining the time delay, the critical depth of cut acr is different for different spindle speeds. This can be graphically illustrated in a so called stability lobe diagram (SLD), which shows the critical depth of cut for all spindle speeds [4]. With the dynamic behaviour of the machine tool, the critical depth of cut and the stability lobe diagram can be calculated [5,6].

The static and dynamic behaviour of machine tools can be analysed using finite element analysis methods, before the machine is built. The finite element analysis is a numerical approximation procedure and is widely used in mechanical engineering and during the machine tool design process [7]. It is suitable to predict the elastic compliance and the Eigen frequencies of the system. For the simulation the software Meshparts [8] was used, which allows a component based simulation with Ansys.

In this paper the development of a new 5-axis machining concept is described. The machine tool is analysed using a finite element model and the dynamic and static behaviour is derived. Based on this analysis the stability lobe diagrams at different axes positions are calculated to predict the milling capabilities of the machine tool.

In the next section the kinematic and the results of the finite element analysis are presented and evaluated. In section 3 the results are used to investigate the effects of the pose-dependent dynamic on the stability of the milling process. Finally, a conclusion of the results and an outlook on future research topics is given.

2. MACHINE CONCEPT

In "CassaMobile", there are some restrictions and specifications, which the milling module has to meet. All process modules have to fit in the container. Therefore, the area for each module is limited to 700 mm x 1000 mm. Moreover, a standardized automatic transport system moves the work piece on a generic work piece carrier. Thus, all 5 axes of the milling module must be integrated in the spindle head, as the transport system and the work piece carrier do not allow any movement of the work piece during the production process.

The machining concept is based on a parallel kinematic, moving a base in the X-Y-plane, and a parallel kinematic consisting of three hollow shaft motors (HSM) on this base for the Z, B and C axis. A CAD-model of the kinematic including the coordinate system and the analysis positions is given in Figure 1.

The concept of the kinematic of the spindle head with the two rotation axes C and B is shown in detail in Figure 2. It can be seen that the movements of the three HSM are coupled to generate the Z-position and the B-and C-rotation. The position of the TCP in Z-direction z is generated via a ball screw drive with the spindle pitch h_z and the relative positioning between M_1 and M_2. Additional, the fixed dimensions given in Figure 3and the positioning of the position of the B-axis β influence z. The rotation in B β is realized using a worm gear with the ratio i and the relative positioning of M_1 and M_3. The rotation in C γ correlates with the position of M_3. The position of the TCP in X-direction x and Y-direction y is generated by M_5 and M_4.The calculation of the TCP positions given in equation (1) to (5).

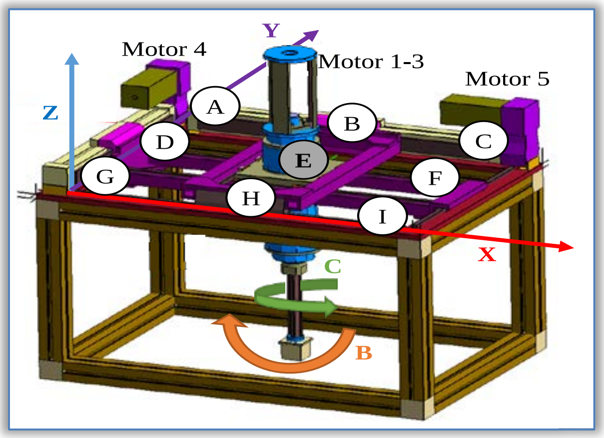


Figure 1–Kinematic concept with the nine axis positions (A-I) for the analysis

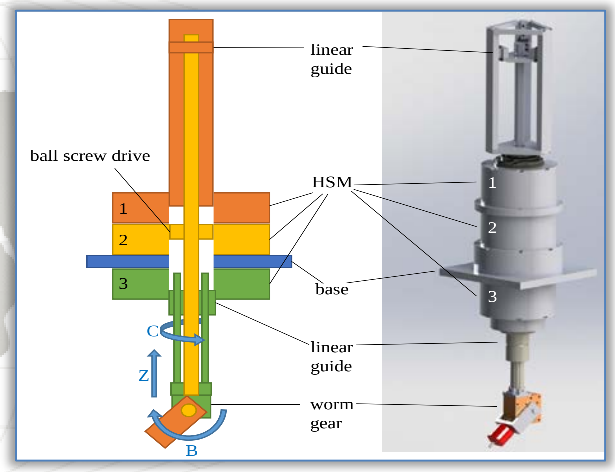


Figure 2– Schema of the spindle head (left) and CAD model (right)

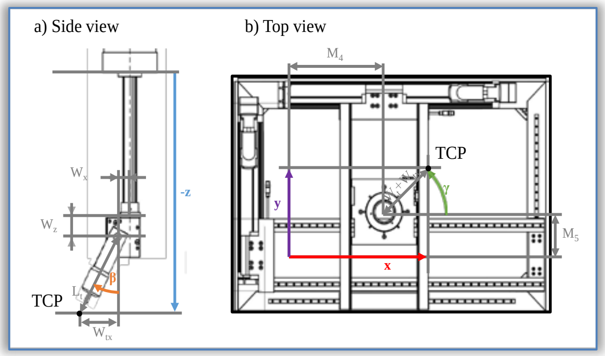


Figure 3– Dimensions of the milling module

$$x = M_4 + (W_x + W_{tx})\cos\gamma + L_t \cos\gamma \sin\beta \quad (1)$$

$$y = M_5 + (W_x + W_{tx})\sin\gamma + L_t \sin\gamma \sin\beta \quad (2)$$

$$z = -W_z - (M_1 - M_2)\cdot h_z - L_t \cos\beta \quad (3)$$

$$\beta = (M_3 - M_1)/i \quad (4)$$

$$\gamma = M_3 \quad (5)$$

With this kinematic a very compact module can be realized. The footprint of the module is an area of 1000 mm x 700 mm, with the presented kinematic an area of 500 mm x 300 mm can be processed. This leads to a compactness of 50% for the X-axis and 43% for the Y-axis, which is very good in comparison to standard machines with a mean compactness of 33% [9].
A critical part for the static and dynamic behaviour is the linear guide for the Z movement. As this guide goes through the hollow shaft the dimension and the stiffness is limited. To find the optimal design for this linear guide, this part is analysed in detail. To save computation time and avoid influences from other parts of the machine tool structure only this part is modelled and analysed. There are two different approaches possible, one with a hollow shaft and small linear drives (Figure 4 A), and the other approach with a ball spline with hollow shaft (see Figure 4 B).
For both approaches the first Eigen frequency and the static deformation with 100 N is calculated. According to the results given in Table 1 the ball spline approach is more suitable. The tension is similar in both approaches, while the ball spline has a higher Eigen frequency and a smaller deformation.

Table 1– Simulation results for the different Z-axis approaches

	Eigen frequency	Deformation	Tension
A: Linear guide	267,6 Hz	0.24 mm	36.6 N/m^2
B: Ball spline	545,6 Hz	0.098 mm	37.1 N/m^2

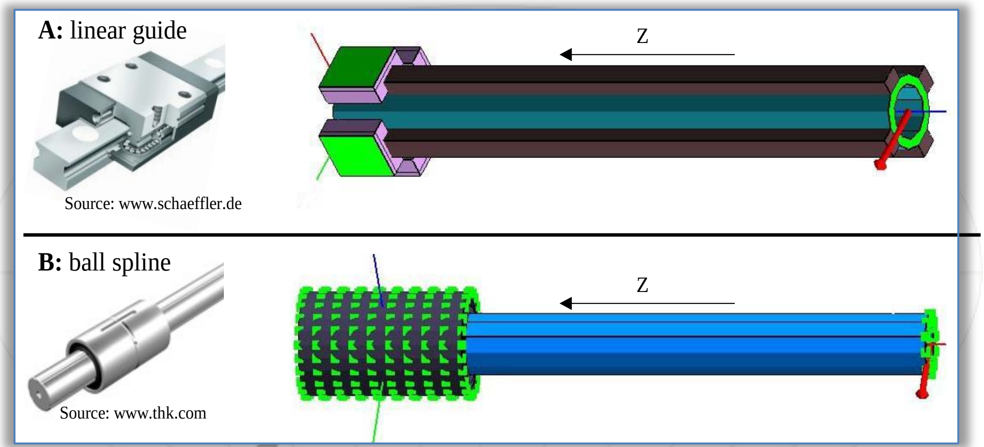
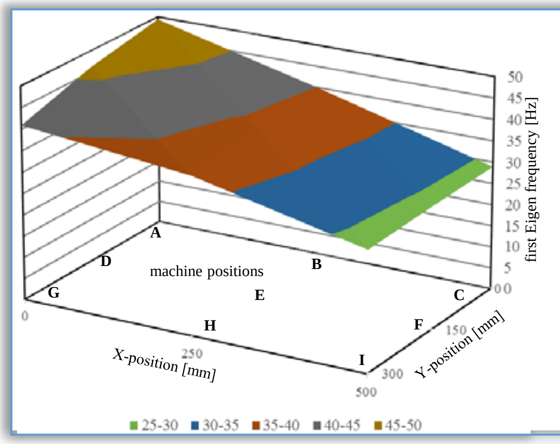


Figure 4– Different approaches for the Z-axis

With this result a complete model of the machine tool was generated and analysed at different axes positions, to investigate the pose dependency of the static and dynamic behaviour of the machine tool. The model is analysed in Position A to I (see Figure 2) and the Eigen frequencies at these positions are illustrated in Figure 5.
The Eigen frequency decreases for an increasing distance between the spindle head and the drives (position A: small distance, position I: large distance). At position A the first Eigen frequency is 49 Hz, while it is just 28 Hz at position I. This significant change of the Eigen frequency with the position has an important influence on the process stability. As the dynamic is one of the main influencing parameters for the process stability.



Position	Frequency
A	49.4 Hz
B	39,7 Hz
C	28.9 Hz
D	46.2 Hz
E	38.6 Hz
F	28.7 Hz
G	40.9 Hz
H	37.0 Hz
I	28.2 Hz

Figure 5– Eigen frequency at different axis positions

3. PROCESS STABILITY

The first Eigen frequency is derived for different positions, the effect of the pose-dependant dynamic on the stability of the milling process is investigated in this chapter. For this investigation, the one degree-of-freedom dynamic model as given in equation (6) is used [6].

$$\ddot{x}(t) + 2\zeta\omega_n \dot{x}(t) + \omega_n^2 x(t) = -\frac{ah(t)}{m}(x(t) - x(t-T)) \quad (6)$$

The parameters are the relative damping ζ, the natural frequency ω_n, the modal mass m and the depth of cut a. The time delay T is defined by the tooth passing period 60/(NΩ), with the number of cutting edges N and the spindle turning speed Ω in rpm. The specific cutting force coefficient h(t) is calculated using the tangential and normal linearized cutting force coefficients K_t and K_n as given in equation (7).

$$h(t) = \sum g(\Phi_j(t))\sin(\Phi_j(t))\left[K_t \cos(\Phi_j(t)) + K_n \sin(\Phi_j(t))\right] \quad (7)$$

The angular position $\phi_j(t)$ of the jth tooth is calculated with equation (8).

$$\Phi_j(t) = (2\pi\Omega/60)t + (j-1)2\pi/N \quad (8)$$

The function $g(\phi_j(t))$ indicates, if the tooth j is in the material or not and is defined in equation (9).

$$g(\Phi_j(t)) = \begin{cases} 1 & \text{if } \Phi_{st} < \Phi_j < \Phi_{ex} \\ 0 & \text{otherwise} \end{cases} \quad (9)$$

For down-milling, what is considered in this analysis, the start angle ϕ_{st} and the exit angle ϕ_{ex}, where the cutting edge enters and leaves the material, can be calculated according to equation (10) an (11).

$$\Phi_{st} = \arccos(2b/D - 1) \quad (10)$$

$$\Phi_{ex} = \pi \quad (11)$$

The radial immersion ratio b/D defines the width of cut depending on the tool diameter D. For the calculation of the stability diagram the full discretization method described in [6] is used. The cutting force coefficients for Aluminium Alloy 2014-T351 and a 6 mm cutter with two teeth are used as derived in [10].

The calculation of the stability lobe diagrams is done for all positions A to I as shown in Figure 1. There is an important pose-dependency of the process stability. At position A the critical depth of cut acr is 7.2 mm at 1490 rpm, while at position I only 2.3 mm at 860 rpm are possible. The SLDs for all positions A to I are shown inFigure 7.

There are two important facts, following fromFigure 7. First, the maximum depth of cut is varying in wide range within the working envelope. Second, the spindle speed with the maximum stable depth of cut is changing with the position. Thus, the NC program for new parts must be analysed to predict the occurring cutting depth based on a material removal simulation. An example of the result of the material removal simulation is given inFigure 6. The cutting depth is colour coded along the tool path (0 mm: blue; 10 mm: red) [11]. Additional to the optical representation, a detailed table with all important process parameters (cutting depth, cutting width, spindle speed) is generated and can be analysed automatically. Moreover, the positioning of the raw part in the working envelope is important, as the stability changes with the position. The spindle speed has to be selected suitable for the process stability and for the technological parameters of the process and the tool.

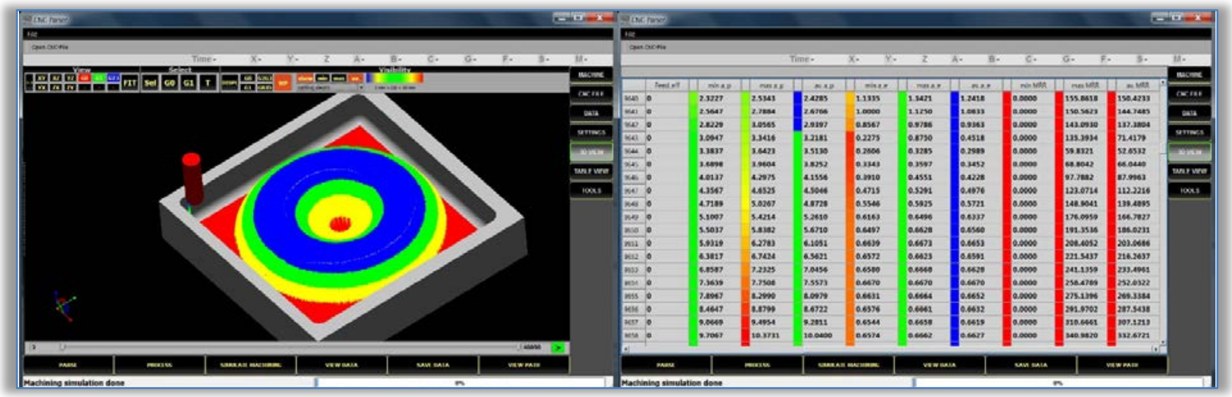


Figure 6–Material removal simulation with color coded depth of cut

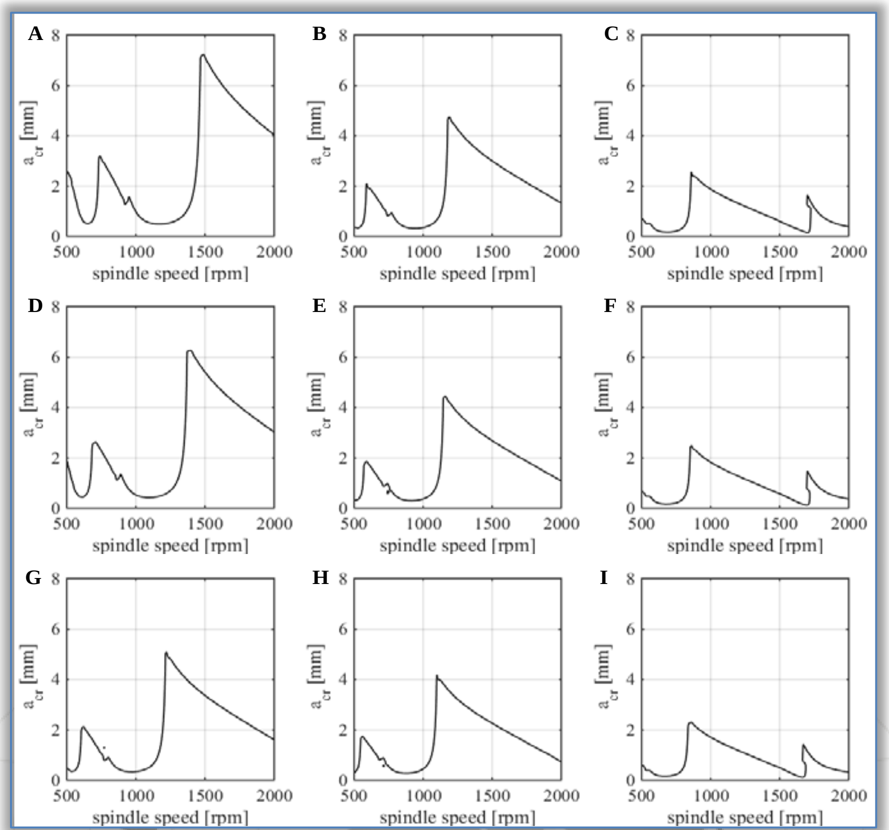


Figure 7–Stability lobe diagram at different axis positions

4. CONCLUSION AND OUTLOOK

In this paper, a new lightweight concept for a 5-axis milling module for a localized production is presented and analysed. All five axes are integrated in the spindle head, which allows the use of a standardized work piece carrier with an automatic transportation system. The compactness of the module is higher than in standard machine tools that allows the production of bigger parts with a smaller footprint.

The module is analysed using finite element simulation. Even with the compact realization, the dynamic behaviour of the machine is suitable for the application in the "CassaMobile" container. However, the lightweight construction, leads to a pose-dependent dynamic behaviour with Eigen frequencies between 28 Hz and 49 Hz. The process stability in terms of the stability lobe diagram is calculated for different positions of the axes. The critical depth of cut varies from 2.3 mm to 7.2 mm. Moreover, the spindle speed of the maximum stable depth of cut is changing with the position. Therefore, the NC program of a new part has to be analysed using material removal simulation to extract the cutting depth and the spindle speed. Based on this analysis and the positioning of the part, the resulting process stability and the part quality can be predicted based on the SLDs.

In future research the predicted SLDs can be compared to measured and experimentally derived SLDs. Furthermore, a closed loop optimization should be realised, which analyses the NC program and optimises the part positioning and the process parameters according to the SLD. Moreover, an update of the SLD based on vibration measurements during machining would be useful.

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Note

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