HOLISTIC OPTIMIZATION OF SCULPTURED SURFACES MANUFACTURING (HoliMan)

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Abstract. *The mould and die industry is characterized by permanently rising competitive pressure. Competitiveness has to be increased with higher productivity through reduction of machining times and costs as well as by the same or higher quality of the products to be machined. A key technology to succeed these objectives is the 5-axes HSC machining of sculptured surfaces, whose potentials are currently used, but not bailed out. Therefore, the main objective of the BRAGECRIM project "Holistic Optimization of Sculptured Surface Manufacturing" (HoliMan) is to identify and to exploit the production accuracy and efficiency increasing potential. Within this project Brazilian and German researchers are working together on the holistic optimization of sculptured surface manufacturing by considering the significant impacts of the manufacturing process on the workpiece quality. Experiments have been done to dimension and to evaluate simulation models and to show the influence of different interpolation methods on the dynamic behavior of the machine tool while driving a sculptured surface path. The results shows the challenge to model the process dynamic behavior and the influence of the interpolation methods on the tool path dynamics.*

Keywords*: machine tools, dynamic behavior, sculptured surface, interpolation methods*

1. INTRODUCTION

In recent years the pressure on the worldwide mould and die industry has been continuously increasing due to the constant growth of the Asian industry. In order to remain competitive, the leading industries must therefore increase its productivity by reducing machining time and costs, while at the same time the product quality has to be increased. High speed cutting (HSC) has significantly higher potential than is currently being taken advantage of by the manufacturing industry. For example, it was estimated by Canter (2007) that productivity increases of up to 500% could be achieved if the full potential of HSC would be utilized.

The need for HSC technology has been demonstrated by factory suppliers and end-users in the automotive, aerospace, electrical and optical industries, with various technological roadmaps and market studies evaluating the implementation of adaptive and intelligent production processes as a first priority. For those sectors of industry, the development of high performance applications was found to be of high priority, with a relevance ratio of 45% to 55%. It was also reported by Westkämper (2007) that 86.4% of surveyed enterprises intend to establish adaptive, intelligent and high performance processes in their production. The challenge in the milling of sculptured surfaces lies in the enhancement of surface quality as well as the reduction of production time and costs (Enselmann, 1999).

The dynamic behavior of machine tools influences the machining accuracy and the stability of the machining process. Therefore, an area of conflict between possible product quality and productivity is given. In consideration of the process stability and accuracy anyhow the maximum material removal rate should be realized during high speed cutting. To increase the material removal rate, a detailed knowledge about the machine tool behavior of high speed milling machines while machining is essential (Mewis and Meister, 2010).

So, it is necessary to have an integrated optimization regarding all possible process influences. Therefore, process and machine structure analysis and their interaction must be determined for the optimization of machine tool operations. Hence, it is necessary to model the dynamic machine tool behavior and the regarded machining process. At the Institute for Machine Tools and Factory Management (IWF) models have been developed to simulate the dynamic behavior of grinding and milling processes, which allow a simple integration into a process simulation. Furthermore, these models only need the set point given by the computerized numerical control (CNC), to simulate the impact of the dynamic behavior of the machine tool on the cutting process (Uhlmann, *et al.,* 2010).

Altintas (2000) declare the regenerative effect as significant reason for milling processes to become instable. Instable processes result for example in a worse surface quality because the alternating and varying cutting forces initiate self excited vibrations, which lead to an additional relative displacement between cutting tool and workpiece.

The motion accuracy is one of the most important factors to ensure the part quality in CNC machine tools. The drives responsible for accelerating and moving the machine axes and the control system respectively play an important role regarding the motion error in high feed rate values, too. Motion accuracy in CNC machine tools is degraded due to unavoidable uncertainties occurring in the current, velocity and position loops. Uncertainties like current measurement error, friction, loads, external cutting forces and the dynamic behavior of the machine tool structure have a significant impact on the motion accuracy (Huang, 2010).

Brecher *et al.* (2011) had developed a surface roughness monitoring that uses cutting parameters and the numerical control (NC) data to predict the machined surface roughness in real time. One challenge appointed is that the system requires several prior cutting tests related to the machine tool and combination of material, cutting tool and tool holder in order to tuning the neural artificial network parameters.

Del Conte and Schützer (2007) developed and implemented a new data acquisition strategy for monitoring the open CNC data, where a buffer module reduces the network delay influence and increase the sample frequency, resulting in better monitored data accuracy. In previous studies the performance of high speed machining (HSM) processes were monitored with the use of this strategy. The actual feed rate, the axis acceleration and the manufacturing time were monitored during the movements of a sculptured surface trajectory with two conditions of tool path interpolation methods (linear and spline). This led to the identification of the optimum condition within the tested range of parameters. The software user interface developed in LabVIEW (National Instruments Corporation, USA) samples the feed rate and acceleration behavior during the milling process with the corresponding median values and the optimized tool path time (Del Conte *et al.*, 2009).

Thus, the objectives of the studies displayed in this paper are on one hand to use a simulation model describing the dynamic behavior of the machine tool to obtain an appliance to correlate the process forces with the surface topography and on the other hand the experimental investigation into the interaction among computer aided manufacturing (CAM), CNC and machine tool dynamics showing the influence of different interpolation methods on the dynamic behavior of the machine tool while driving a sculptured surface path. In context of HoliMan these objectives address the dynamic related aspects of the holistic optimization approach of sculptured surfaces manufacturing.

2. EXPERIMENTAL PROCEDURE

The BRAGECRIM project "Holistic Optimization of Sculptured Surfaces Manufacturing" aims on a holistic improvement of 5-axes freeform manufacturing considering all manufacturing process factors influencing the quality of the manufactured product. For the experiments the high speed machining (HSM) center LPZ500, MAP Werkzeugmaschinen GmbH, Nienburg, Germany, with a maximal feed rate of v_f = 120 mm/min and an acceleration of a_f = 25m/s^2 is being used. The optimization includes the determination of the machining strategy in the CAM system, the description of the tool path and its interpolation by the CNC of the machine when executing the machining program. In particular the static and dynamic machine tool properties and its impact on the freeform surface manufacturing are considered and modeled. The experimental procedures to investigate the dynamic behavior of the machine tool and the CAM/CNC/machine dynamics are presented in the two following sections.

2.1. Dynamic behavior

As described in the introduction, one of the goals of the research project HoliMan is the identification of the machine tool dynamics' impact on the manufacturing accuracy and the prediction of the process stability. For an efficient monitoring of the dynamic machine tool behavior simulation models of the structural machine tool dynamics need to be developed and dimensioned. The cutting tests have been done on the 5-axis HSM machining centre LPZ500. In the experiments a ball nose milling tool with a diameter of d = 8 mm, 2 cutting teeth and a helix angle of φ = 30 ° was used. The work piece material is the aluminum alloy AlZnMgCu1.5 (EN-AW 7075). The cutting tests consisted of face milling processes with a feed rate per tooth of f_z = 0.1 mm, a cutting depth of a_p = 2 mm, a spindle speed of n = 19,600 rpm and a cutting width of a_e = 6.928 mm. The machine tool table was swiveled by an angle between α = 0 and α = 30 ° in feed direction y. The experimental set up has been outlined in Fig. 1. In the tests the work piece has been mounted on a Kistler 3-component dynamometer 9257A to measure the cutting forces. The surface topographies of the milled slots have been measured using the confocal laser scanning microscope MicroProf®, FRT GmbH, Bergisch Gladbach, Germany.

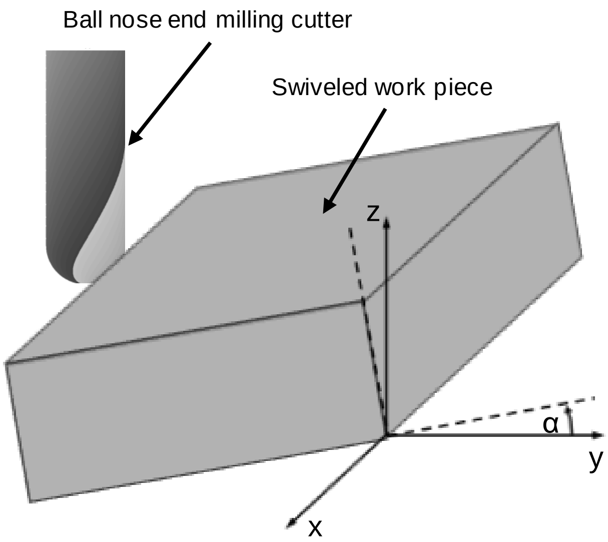

Figure 1. Experimental set up for milling of slots using a ball nose end milling cutter

2.2. CAM/CNC/Machine Dynamics

To investigate the influence of CAM/CNC interpolation methods on machine dynamics driving a sculptured surface, the signal of a tri-axial-accelerometer placed on the tool center point (TCP) of the LPZ500 and the CNC drive signals were simultaneously monitored. Figure 2 shows the measurement set up with the tri-axial accelerometer sensor Kistler 8692C10M1 with measurement range of a_s = +/- 10 g and a frequency range of f_s = 20 Hz to f_s = 20,000 Hz assembled on the TCP. The interpretation of the measurement results has been limited to the z-axis direction, considering that the z-axis dynamics are dominant in the movement due to the high degree of curvature and reversion of movements in this direction.

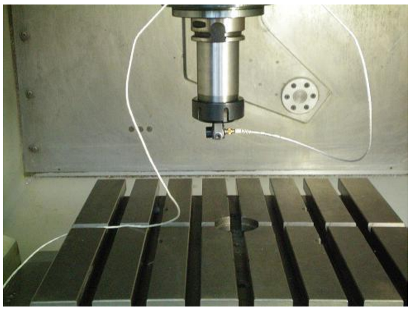

Figure 2. Measurement set up with a tri-axial acceleration sensor at the TCP

The experiments have been done using two different tool path interpolation methods, linear and spline with a CAM tolerance of dx = 0.050 mm. A feed rate of v_f = 2,500 mm/min has been used and the movements were executed without the cutting process. The NC programs of the finishing operation of a sculptured surface used for the experiments are according to the study part of Helleno (2008) presented in Fig. 3.

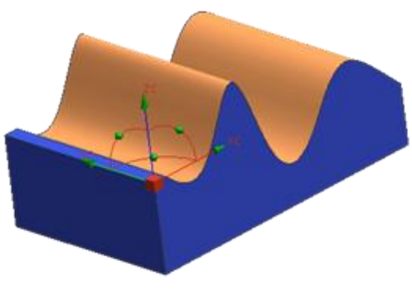

Figure 3. Sculptured surface CAD-model (Helleno, 2008)

The reference of part illustrated in Fig. 3 was changed in the NC program in such a way, that the part was rotated $\gamma = 45$ ° around the z-axis. In this way the three linear axes were moved simultaneously. The spindle was locked, so the deviations and accelerations measured only result from the linear axes movement.

3. ANALYSIS OF RESULTS

According to the experimental procedure, the analysis of results is structured in the two following sections, which respectively show the results of combining the dynamic behavior of the machine tool with a cutting force monitoring system and the results of the measurement concerning the interaction of CAM, CNC and machine dynamics.

3.1. Dynamic behavior

Figures 4 (a) and (b) show the topography measurement results of the cutting test with a swiveling angle of $\alpha = 10$ °. In Figure 4 (b) a section of the groove's surface topography can be seen. Chatter marks can be clearly identified in the area below $x = -1.0$ mm and the area above $x = 1.0$ mm, which result from an instable cutting process. The chatter shows in a waviness with a maximum amplitude of $dz = 75$ µm around $x = -2.5$ mm, while the area between $x = -1$ mm and $x = 1$ mm exhibits an amplitude of $dz = 9$ µm, respectively a center line average roughness of $R_a = 1.4$ µm. In Figure 4 (a) the spectrum of the surface topography in tool path direction y, considering a constant feed rate of $f_z = 0.1$ mm, is shown. The waviness on the left side of the groove appears at frequencies around $f = 60$ Hz and $f = 120$ Hz, while the topography at the right side of the groove is dominated by a waviness at frequencies around $f = 60$ Hz, $f = 144$ Hz and $f = 202$ Hz.

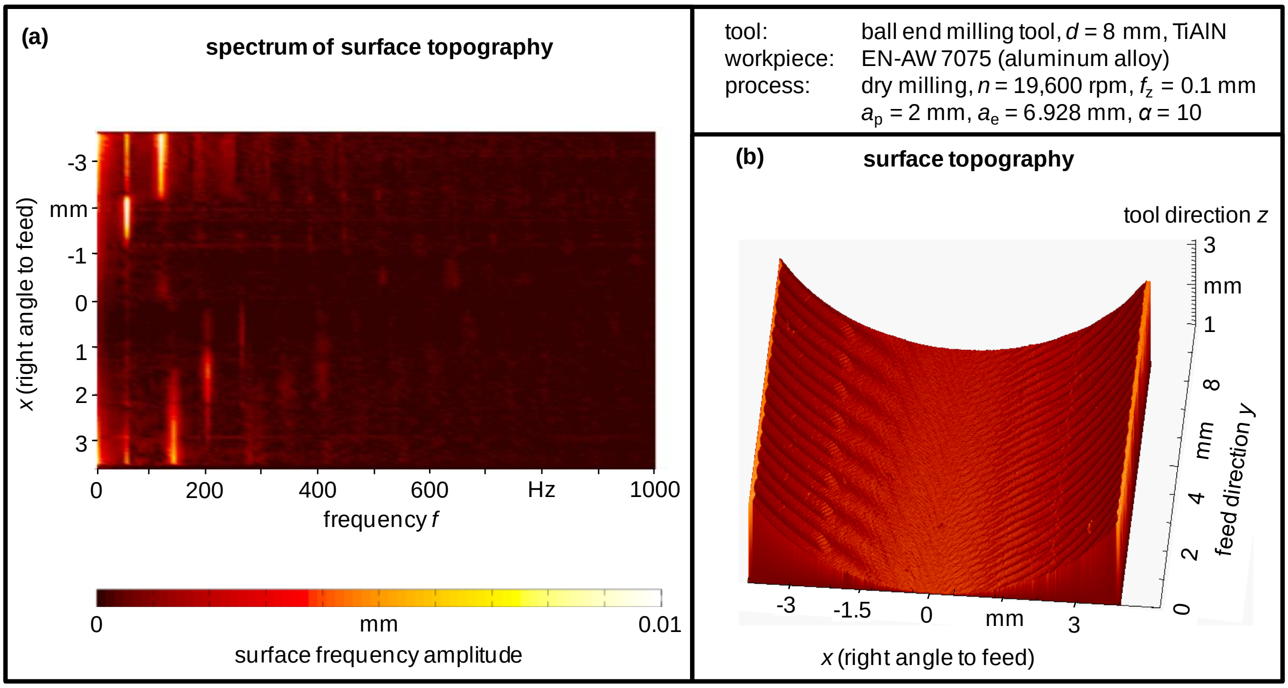

Figure 4. (a) Spectrum of surface topography and (b) surface topography of milled slot

In Figure 5 the spectrum of the process forces in dependency of the process time is shown. The excitation frequency $f_1 = 653$ Hz and harmonics of this frequency can be identified. The surface waviness at f_1 is very low and does not contribute to the error pattern of the surface topography shown in Fig. 4 (b). The surface topography spectrum does not show a significant waviness above $f = 300$ Hz, while the cutting force amplitude spectrum below $f = 300$ Hz does not include significant rates. A special distinction in the spectrum of the cutting force deserves the amplitude around the frequency $f_2 = 4{,}200$ Hz, because it is increasing during the process, which is a hint for the instability of the process in terms of chatter.

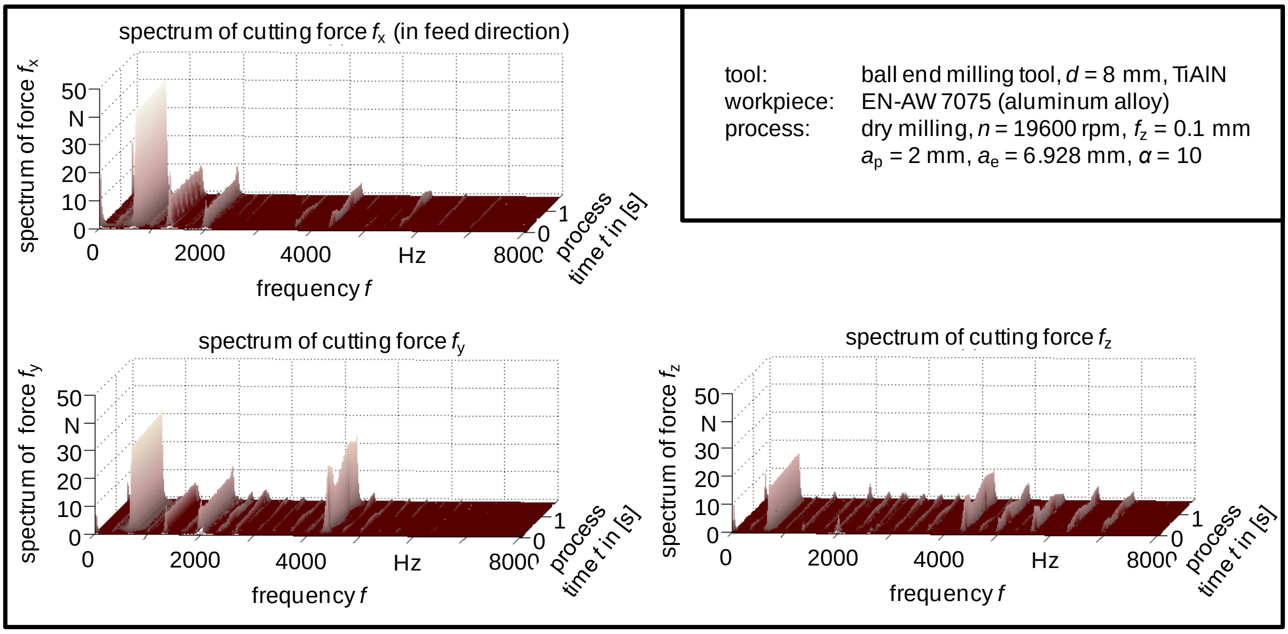

Figure 5. Diagrams of the spectra of the cutting force components

As stated, the spectra of the measured process forces do not show a correlation to the spectra of the measured surface topography. There is an indication to a vibration at the excitation frequency f_1 between x = 0 mm and x = -1 mm, but the amplitude at this frequency is very small compared to the dominant parts. To develop a correlation between force monitoring and machined surface topography, a finite element (FE) model of the machine tool LPZ500 has been developed to simulate its dynamic behavior. The model, shown in Fig. 6, is used to simulate the TCP deviations in correspondence to the measured forces, which are used as boundary conditions for the simulation. The TCP deviations are then included into a geometric cutting simulation, considering a constant milling tool geometry, constant spindle speed and given cutting parameter. The result is a simulated surface topography, which can be evaluated and compared with the experimental results.

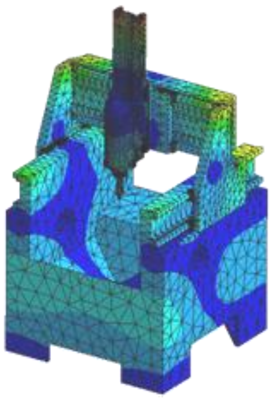

Figure 6. FE model of the milling centre LPZ500

The FE-model has been dimensioned with respect to the material and the geometry of the components of the LPZ500. The explicit dynamic simulations have been done with the simulation program ANSYS workbench 12.1, Ansys Inc., Canonsburg, USA. The measured forces have been included as boundary conditions at the TCP. The simulation of a cutting process with a duration of t = 0.1 s took around 60 minutes of calculation time. The TCP deviations have been saved for each set of measured forces. To visualize the impact of the simulated TCP deviations on the surface topography a geometric simulation program for five-axis milling with a ball nose milling tool has been developed and implemented in Matlab®, Mathworks®, Nattick, Massachusetts, USA. The results of the process simulation with a swiveling angle of α = 10 ° can be observed in Fig. 7. The amplitude of the slots' simulated surface waviness, which lies between 1 µm at around x = 0 mm and 7 µm towards the sides of the groove, is in about 10 times smaller than the measured waviness, shown in Fig. 4 (b).

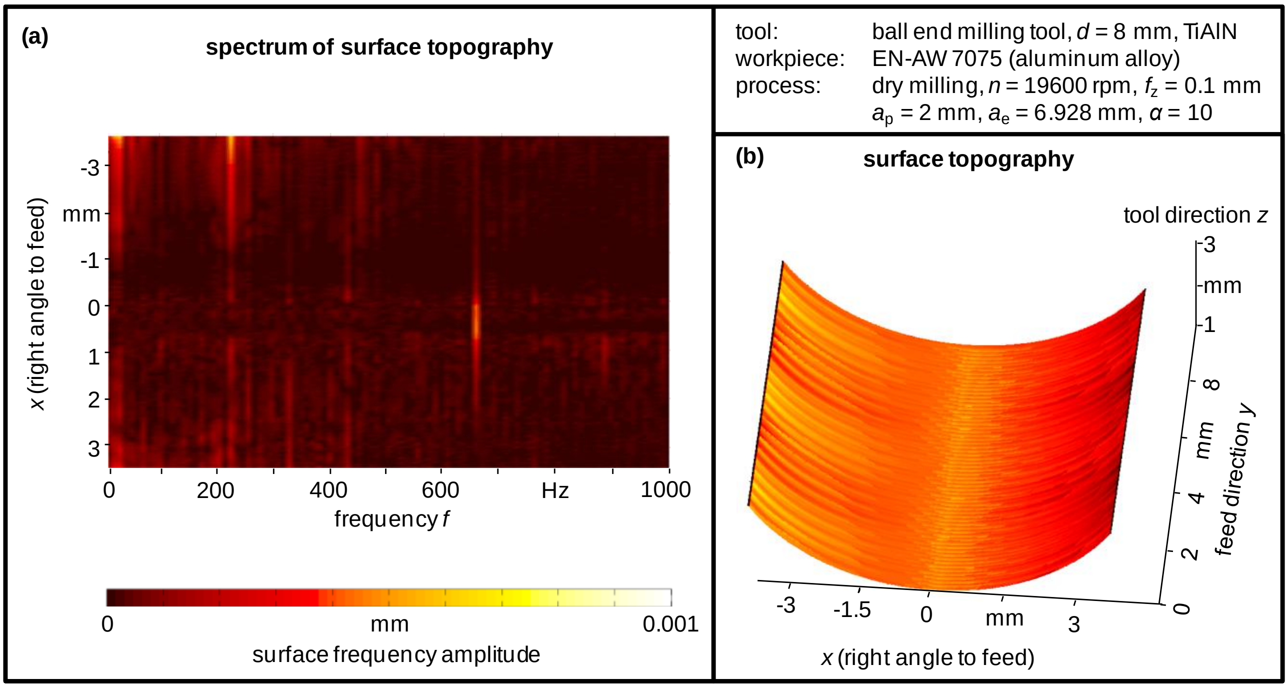

Figure 7. (a) Spectrum of simulated surface topography and (b) simulated surface topography of milled groove

The topography displayed in Fig. 7 (b) does not show a tendency to instability. The spectrum of the waviness, which can be seen in Fig. 7 (a) is different to the spectrum shown in Fig. 4 (a). The dominant frequencies observed are around $f = 20$ Hz, $f = 220$ Hz and $f = 653$ Hz. The excitation frequency $f_1 = 653$ Hz can be clearly identified. The amplitude at the excitation frequency is slightly higher, than the amplitude at f_1 observed in Fig. 4 (a). The differences in the other regions can be explained by the fact, that the restrictions, which had to be considered due to calculation resources, when creating the FE-model, change the dynamic of the machine tool behavior by the simulation in such a way, that the dynamic behavior of the FE-model is not precise enough to efficiently describe the instability behavior of the machine tool. The solutions of the geometric simulations show, that the stiffness of the FE model is much higher than the stiffness of the real machine. The behavior of the connections of the different machine tool components should be included into the FE-model to get better results. However, without having measured the compliance of the real machine to dimension the simulation model, a precise simulation of the dynamic behavior of a machine tool seems barely possible.

3.2. CAM/CNC/Machine dynamics

According to the experimental procedure described in topic 2.2, Tab. 1 shows the dominant frequencies, which have been identified and summarized for the linear and the spline interpolated movements.

Table 1. Experimental results for linear and spline interpolation methods with $v_f = 2500$ mm/min.

Response variables	Linear	Spline
Dominant frequency f_1 (Hz)	20	19
Dominant frequency f_2 (Hz)	781	770
Dominant frequency f_3 (Hz)	1925	1925
Actual averaged feed rates v_f (mm/min)	2213	2368
Tool path time t (s)	4,192	3,876

In Figures 8 and 9 the acceleration spectra development over the time are illustrated. It can be seen, that the acceleration amplitude at $f = 781$ Hz and $f = 770$ Hz tops the other amplitudes significantly, supposedly due to an eigenmode of the machine tool structure at this frequency.

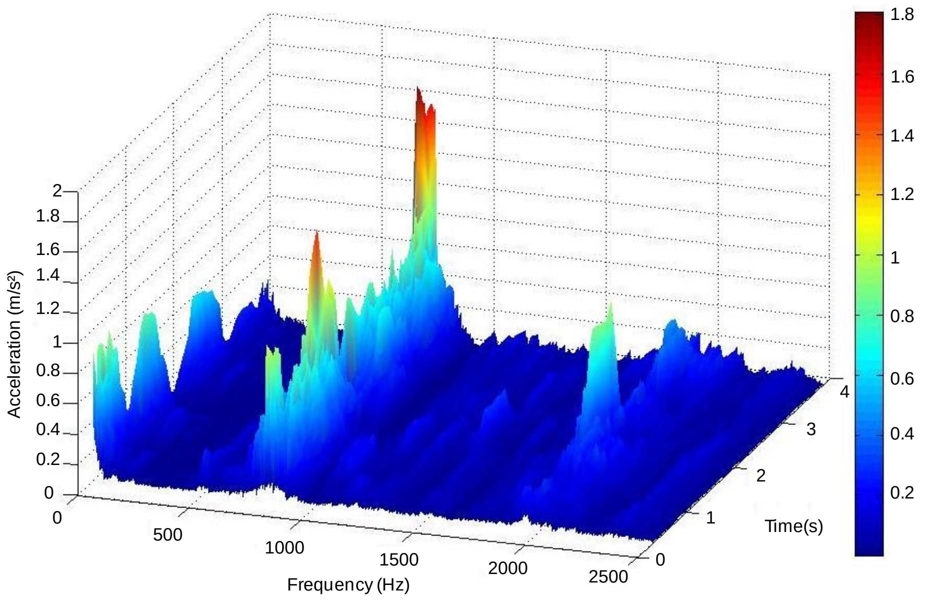

Figure 8. Development of spectra of z-axis-acceleration using linear interpolation

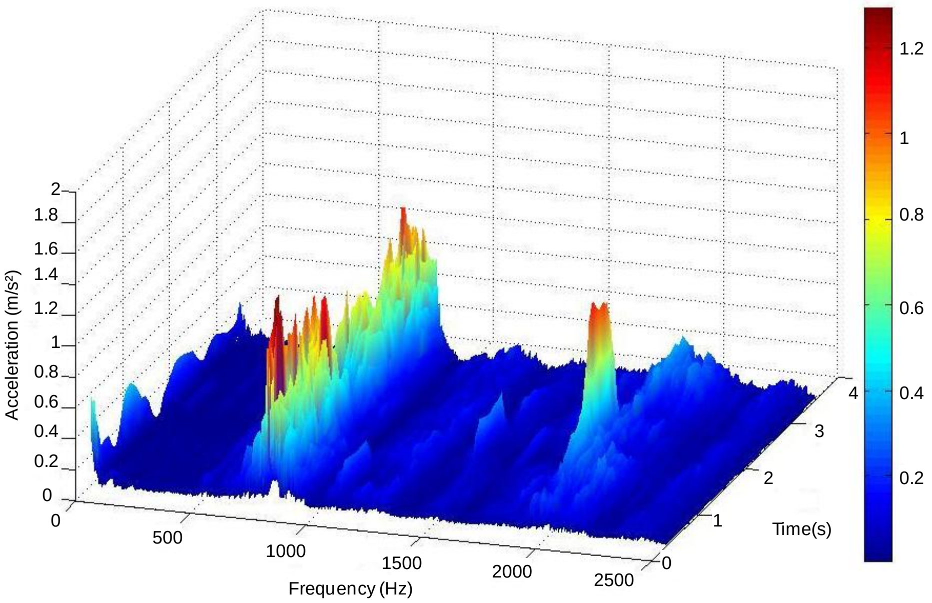

Figure 9. Development of spectra of z-axis-acceleration using spline interpolation

The dominant frequencies for the two interpolation methods are close to each other, but as shown in the spectra of the acceleration signals the amplitudes are varying differently along the tool path. The tool path time for the spline interpolation is smaller due to the stable feed rate behavior, which can be observed in Fig. 10. The difference in the acceleration amplitudes along the tool path could be explained by the small segments length generated by the linear interpolation method. This influence can also be identified in Fig. 10, in which the feed rates along the tool path are shown. The increase of the acceleration amplitude at the end of the tool path shown in Fig. 8 could be explained by the high velocity variation at the end of the movement using linear interpolation. This behavior can as well be identified considering the feed rate diagram in Fig. 10 and its' deviations at the end of the movement.

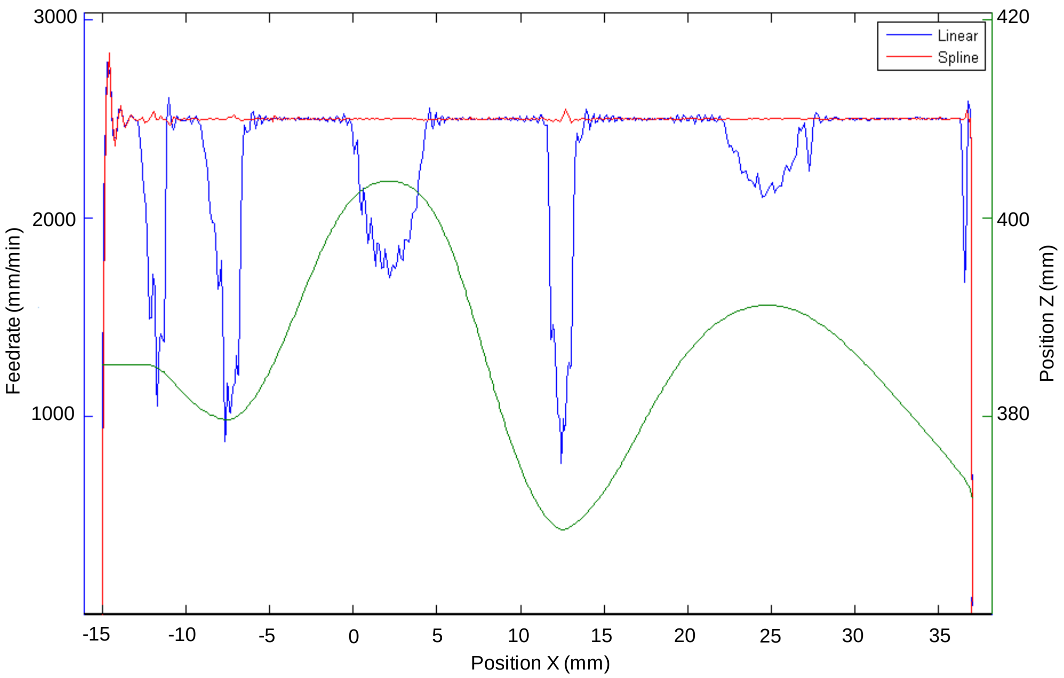

Figure 10. Actual feed rate for linear and spline interpolation methods during the tool path

The actual feed rates using the spline interpolation method can be considered as stable. Since the feed rates of the movement using linear interpolation methods for the tool path generation are in part much smaller than the desired feed rate the tool path time, shown in Tab. 1 is greater with this interpolation method. Furthermore Fig. 8 and 9 illustrate, that the machine tool structure is more dynamically stressed using linear interpolation in comparison to the movement based on the spline interpolation.

4. CONCLUSIONS

Various experiments have been done to dimension and to evaluate simulation models and to show the influence of different interpolation methods on the dynamic behavior of the machine tool and the deviation of the feed rates while driving a sculptured surface path.

The measured forces of the first set of experiments and the corresponding surface topography do not show any direct correlation. In order to find an indirect correlation two simulation models have been developed and tested. The simulation models have been extended by a geometric simulation model for a ball nose milling tool. Various applications are planned to be tested with this model. For instance, it can be used to directly test a sequence of set points given by the CNC due to a NC program. It is furthermore capable to estimate the tool wear and to simulate the deviations of the TCP regarding the calculated tool wear, if the wear can be estimated as a function of the uncut chip thickness.

The FE model was not capable to show the instability of the cutting process, which has been observed by the analysis of the measurement data. This was due to the restrictions, which have been made when creating the FE model. An approach to achieve a better correlation of the dynamic behavior of the FE model and real machine tool would be a combination of the FE model with a multi body system (MBS). Such a model is currently being developed at the IWF. The calculation time, which is needed for simulations with the FE model is much too long for a monitoring application. Nevertheless, a well dimensioned FE model combined with an MBS model should be capable to optimize a cutting strategy, to help avoiding instabilities in cutting processes or to help optimizing the measurement strategy for characterization of the manufacturing accuracy.

Regarding the CAM, CNC and machine dynamics the identification of dynamically critical tool path regions were achieved, showing that the CAM strategies relating to the tool path interpolation methods can strong influence on the path dynamics. One main possible reason to the high variation on velocity and acceleration due linear tool path method are the short segments length and in some regions the association of this condition to the high degree of curvature of the investigated sculptured surface causes high variation on z-axis acceleration, that could degrade the superficial integrity of the manufactured part in this regions.

5. ACKNOWLEDGEMENTS

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