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Improvement of surface accuracy and shop floor feed rate smoothing through open CNC monitoring system and cutting simulation

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Abstract

In the milling process of complex workpiece shapes the feed rate normally becomes instable due to the high degree of surface curvature that requires high acceleration and deceleration of the interpolated axes. This condition impacts on process time and on the surface accuracy regarding the manufactured part form and texture. The challenge to simulate the real machine and control behavior requires accurate models with a set of experiments to tune and dimension the model to the respective machine tool. The aim is to improve the HSC milling process of complex surfaces before removing any material. In this paper experiments show that the surface form accuracy and texture can be optimized through an automatic feed rate smoothing of the finishing operation directly on the machine tool. The axis positions and spindle speeds monitored through the open CNC are used as input for a geometric cutting simulation, thus enabling to predict and optimize the surface quality.

Keywords: open CNC; monitoring system; sculptured surfaces; virtual machining

1. Introduction

Tool path interpolation methods are significantly impacting machining accuracy and production time, when milling workpieces with sculptured surfaces, since the set-points generated influence the smoothness of the feed rate, which would reduce the contour error. However the virtual prediction of the feed rate behavior requires an accurate servo drive model tuned with the respective real servo drive of the machine tool.

CHENG, SU and WANG [1] proposed a feed rate regulator combined with a real time contour error estimator in a cross coupled control (CCC) motion scheme, in order to reduce the contour error in freeform curves. In this approach the maximal contour error was reduced to and maintained within a level of $c_e = 30$ µm.

The accuracy of the axis movements in a CNC machine tool is significantly affected by tracking and contour errors. Extensive research has been done in these two fields with the aim to eliminate and reduce these errors. As examples, the zero phase error tracking controller (ZPETC) and the CCC were significant contributions [2].

The inherent need to keep up the axis dynamics by the control system is the main cause of the contour error in sculptured surfaces manufacturing. Thus, the contour accuracy of a sculptured surface significantly depends of the amount of variation of axes acceleration, characterizing the challenge to achieve high and constant feed rates with smooth behavior during milling processes of complex workpiece shapes.

In this study an open CNC monitoring system is applied on the shop floor, directly on the real machine tool. In addition, the axis positions monitored through the open CNC are used as input for a geometric cutting simulation, thus enabling to predict the impact of the contour error on the surface quality.

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Nomenclature

a_f	acceleration in feed direction
a_e	cutting width
a_p	depth of cut
c_e	contour error
D	milling tool diameter
dx	CAM tolerance
f_c	cutting edge contact frequency
f_s	sample frequency
f_z	feed per tooth
n	spindle speed
v_f	feed rate
x	axis position
z_t	number of cutting teeth
α, φ	tilting angle
φ_{helix}	helix angle of milling tool

1.1. Virtual machining

The optimization of manufacturing in virtual environments has been and still is subjected by many researchers. With the increasing calculation speed of computers, extensive research and development in the field of virtual reality, simulations and virtual manufacturing are gaining more and more in importance. The benefits of optimizing processes using a virtual reality can be clearly pointed out concerning material and energy efficiency, safety and timesaving optimization of processes. KADIR, XU and HÄMMERLE give a broad technological review on virtual machining. They conclude that researchers, even though approaches since the early 1990s are considering various functions, until now are “devoted to improving the system competencies rather than expanding the system functionalities” [3].

The resent research in the field of virtual machining considers the geometric and kinematic behavior [4, 5, 6, 7, 8], the dynamic and thermal behavior of the machine tool [4, 7, 9] and CNC and tool path interpolation related errors [4, 9, 10, 11, 12]. All works include a cutting simulation, using the tool and part geometry and more or less advanced NC program interpretation. Additionally the German Federal Ministry of Education and Research (BMBF) has funded different projects such as SimCat and SindBap to enable the development of simulation tools, such as Permas, for the systematic optimization of machine tools.

Beside the difficult dimensioning of virtual machines, there are various environmental influences impacting the real machine tool behavior and the machining accuracy. Those boundary conditions are hardly to be taken into account, when simulating the machining off-process. Thus, a virtual machining system should be combined with a monitoring system, to provide a deeper understanding of each process and to ensure a promising optimization process. Nevertheless virtual machining systems are appropriate tools to estimate the process safety, the machining accuracy and part quality and therefore to get improvements by software-in-the-loop optimization.

1.2. CNC monitoring

One of the key technologies to promote the CNC monitoring in shop floor environment is the open architecture controller (OAC).

The OAC concept gained in importance in the 1990s, when the flexibility demands by the manufacturing systems and the need to implement user customized functions required a neutral interface for data access. Since then a number of communication protocols and system configurations were developed. Until today there is a gap on the application of a neutral open CNC interface in industry.

The initiatives to have a common OAC described in PRITSCHOW, et al. [13] demonstrate that all of them have similar objective in defining a standard for the open architecture controllers. The main characteristics of this standard are neutrality in relation to the manufacturers and the customization of functions through modularization and the use of application programming interface (API). However a risk to have various incompatible "vendor neutral" control systems was pointed out.

According to TETI et al. [14] the innovative sensor monitoring systems need to be robust, reconfigurable, reliable, intelligent and inexpensive in order to attend the demands of advanced manufacturing. The shop floor application of such systems requires a free "hand made" configuration and an easy use, enabling the machine tool operators to provide simple input information to the system.

There is a wide range of CNC monitoring applications depending on the openness of the machine controllers available to the industry. Still, considering the controller openness level, CNC monitoring systems need to be developed and improved.

2. Open CNC monitoring system

A data acquisition strategy was developed and applied in a commercial open CNC controller that reduces the network transmission delay, increases the sample frequency to $f_s = 250$ Hz (the same frequency of the interpolation cycle of the studied open CNC) and provides better accuracy of a monitored variable. This strategy uses an internal data acquisition procedure in an open CNC called synchronized actions that stores the monitored data continuous in a buffer and cyclically this data is transmitted to a PC where data analysis is performed.

The data of the open CNC are collected and stored in the buffer. This buffer is built using CNC intern variables called R parameters and is programmed directly in the NC program. Cyclically the data transmission and analysis process acquires and shows the monitored control values to the user.

The acquisition system was developed with the use of the LabVIEW® 8.0, National Instruments Corporation, USA. The communication of the PC with the CNC was carried out by the CP5511 card and a NC dynamic data exchange (NCDDE) server, Siemens AG [15].

3. Cutting simulation model

The workpiece surface in the 3D geometric cutting simulation, developed in Matlab©, Mathworks™, Natick, USA, consists of a x-y-resolution dependent number of discrete points. The cutting edge of the milling tool is discretized for all consecutive time steps using triangles. In order to achieve a good resolution the time step size needs to be sufficiently small. Due to the process parameter and the tool center point (TCP) location for each specific time step, points of the workpiece surface are either located inside or outside the cutting edge volume, which is defined by the surfaces generated by the cutting edge movement during one time step. In case of a point inside the cutting edge volume the point will be shifted in z-direction to the surface of the cutting edge volume (while x and y coordinate of the point remain the same).

Measured or simulated TCP deviations, for example resulting from vibrations, machine tool geometric errors and CNC actual point deviations, as well as TCP reference position can be summed up to current positions of the TCP. In case of the work presented here, the monitored actual point of the TCP is used as input for the geometric cutting simulation. The geometric simulation program is designed in such a way, that the cutting edges of the milling tool are positioned due to the TCP position for each time step. This leads to the possibility to consider tool wear due to the geometrical description of the cutting edge. The aim of developing this simulation tool was to find a correlating element between CNC monitoring data and the resulting surface quality.

To evaluate this approach a dynamically instable milling process has been conducted, in which the force and CNC monitoring system has been applied. In Figure 2 the comparison between the measured and the equivalent simulated section of the slot is shown. The topography measurements have been done using the confocal laser scanning microscope Microprof, Fries Research and Technology GmbH, Bergisch-Gladbach.

Deviations between simulated and measured surface have been mainly dedicated to result from the uncertainty of the spindle speed determination.

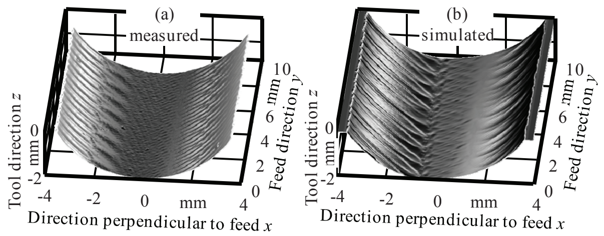

Fig. 1. Comparison of the surface topography of (a) real machined and (b) simulated surface of an instable milling process

The center line average roughness R_a and the average surface roughness R_z calculated for a set of simulations of stable and instable slot milling processes were matching the measured roughness within a relative error of 20 %.

4. Experimental procedure and Simulation

For the finish milling of complex surfaces, the machine tool behaviors impact on TCP deviations must be taken into consideration, especially in HSC processes, in which high dynamics can be expected. Thus a freeform surface with steep und shallow curves has been used on the basis of non uniform rational basis splines (NURBS) [16], which leads to a significant variation of the axis acceleration and load. Aim of the experiments is to analyze the impact of the axis movement on the machining accuracy concerning the deviation of actual point to the set point of the corresponding axis.

4.1. Experimental set-up

To investigate the influence of feed rate smoothing on the contour error direct on the machine tool, the developed monitoring system was applied. Cutting experiments considering two feed rate values and two types of interpolation methods [16], were performed on the HSC milling center LPZ 500, MAP Werkzeugmaschinen GmbH, Nienburg, Germany, with an open CNC controller. For the experiments a TiAlN coated ball nose milling tool with a diameter of D = 8 mm and a cutting tooth number of $z_t = 2$ is used.

The workpiece material is the aluminum alloy EN-AW 7075. The applied feed rates are $v_f = 2500$ mm/min and $v_f = 6000$ mm/min, while the tool path interpolation methods tested are linear and NURBS with a CAM tolerance of dx = 0.005 mm. The monitored variables are the set position, the actual position and the actual feed rate of each axis.

4.2. Simulation parameters

The monitored CNC-data is then used as input for the geometric cutting simulations programmed in Matlab. To avoid difficulties concerning the interpolation of the monitored CNC-data, the appropriate sections of the set freeform surface are fitted between the monitored positions. The time step size for the simulations is $dt = 10^{-4}$ s.

5. Analysis of results

5.1. CNC data analysis

For a comprehensive analysis the acceleration a_f, whose amount of variation in the following is understood as smoothness, are used, since the acceleration can be understood as indicator for the axis load. The acceleration signal is derived from the monitored actual feed rate. The acceleration signal drawn in Figure 3 shows, that the machine tool structure is more dynamically stressed using linear interpolation in comparison to the movement with NURBS interpolation. The acceleration signal shown in Figure 4 is clearly smaller. Thus, the actual feed rate using NURBS is considered as smooth.

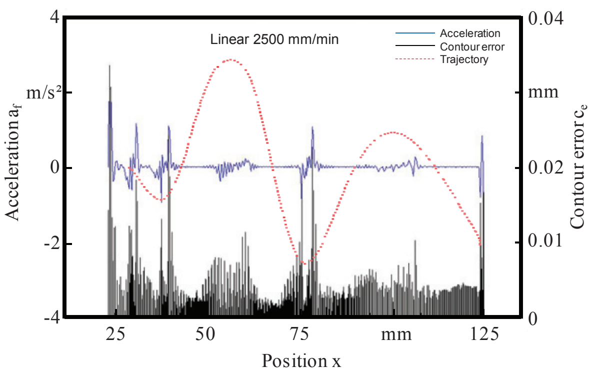

Fig. 2. Monitored contour error and axis acceleration for linear interpolation with $v_f = 2500$ mm/min

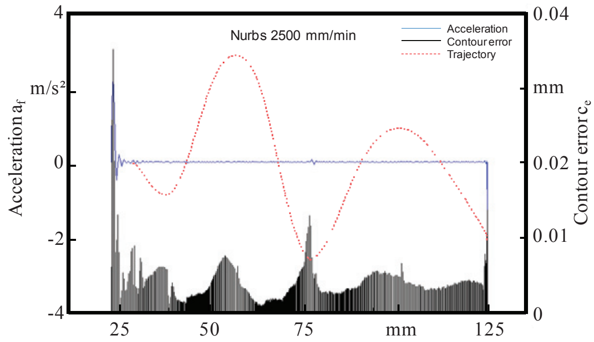

Fig. 3. Monitored contour error and axis acceleration for NURBS interpolation with $v_f = 2500$ mm/min

High amplitudes in the acceleration signal show a tendency to increase the contour error in the according stressed tool path regions. They also may indicate a decrease of the surface accuracy. The box plot presented in Figure 5 shows the contour error distribution for the feed rate $v_f = 2500$ mm/min. Although the median line for the contour error is almost the same for both cases, the distribution for the linear interpolated tool path is less symmetric and contains a big number of outliers with maximum values of nearly $c_e = 0.025$ mm, that characterize an instable dispersion. The distribution for NURBS interpolated tool paths is almost symmetrical and has less outliers with maximum values below $c_e = 0.015$ mm.

Table 1 shows the maximum contour error with the variation of the feed rate. The increased contour error results from non constant actual feed rates at the set feed rate $v_f = 6000$ mm/min for both interpolation methods. The median and maximum contour error is higher for NURBS than for linear interpolated tool paths with the feed rate $v_f = 6000$ mm/min.

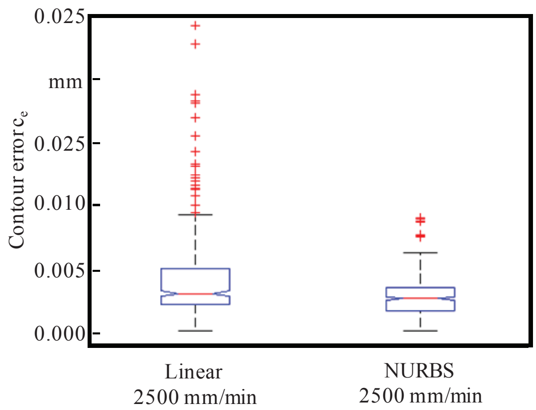

Fig. 4. Box plot of monitored contour errors

At feed rates of $v_f = 2500$ mm/min the maximum contour error for NURBS interpolated tool paths is only half the maximum contour error for linear interpolation. Of course the manufacturing time will rise with the lower feed rate and a conflict between quality and time is stated.

Table 1. Median and maximum contour error

Interpolation Method	Median error (mm)	Maximum error (mm)
Linear 2500 mm/min	0.003	0.024
NURBS 2500 mm/min	0.003	0.014
Linear 6000 mm/min	0.005	0.042
NURBS 6000 mm/min	0.009	0.058

5.2. Simulation result analysis

The extension of the NC monitoring system by a cutting simulation was mainly targeting the analysis of the machining accuracy due to control and contour errors. For the analysis of the simulation results the mean values of the surface height z_{mean} have been calculated over all machined points perpendicular to the feed direction. The mean values of the simulated surface heights have then been directly compared to the set freeform curve. The results are shown in Figure 7 and 8. It can be clearly seen, that there are similar curve errors at specific regions of the freeform curve. At x = 30 mm and x = 130 mm a big error can be observed. This error is rising, when increasing the feed rate. While the error at x = 30 mm is mainly due to the inertia of the axis, the error at x = 130 mm results from a corner with a radius smaller then the milling tool radius.

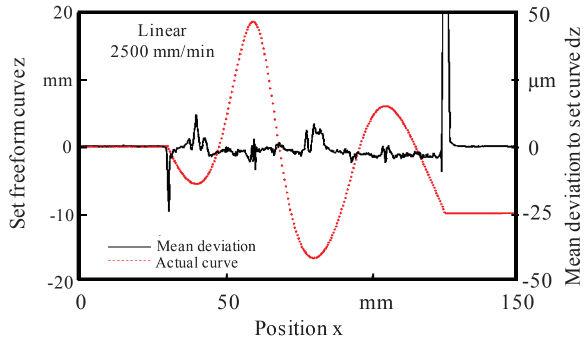

Fig. 5. Mean simulated machining error for linear interpolation with $v_f = 2500$ mm/min

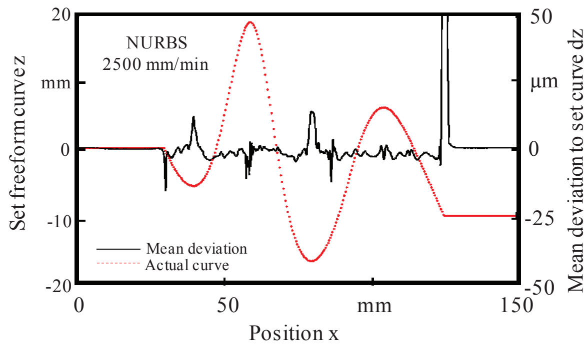

Fig. 6. Mean simulated machining error for NURBS interpolation with $v_f = 2500$ mm/min

Furthermore there are distinctive errors at the local minima and maxima of the freeform curve. At both minima the mean deviation is maximal, which means the actual height is greater than the set height. At the local maximum of the freeform curve at x = 55 mm, there is a high roughness, but the mean deviation is comparably small. At the local maximum at x = 105 mm the deviation is not significant. In the NURBS interpolated curve a waviness in the deviation occurs over the whole curve, which is missing in the linear interpolated curve. In Table 2 the median and the maximum simulated machining errors are listed.

Table 2. Median and maximum simulated machining error

Interpolation Method	Median error (mm)	Maximum error (mm)
Linear 2500 mm/min	-0.002	0.012
NURBS 2500 mm/min	-0.001	0.012
Linear 6000 mm/min	-0.005	0.040
NURBS 6000 mm/min	-0.006	0.047

Because the freeform machining behavior is of interest, the errors at x = 30 mm and at x = 130 mm are neglected there. The machining error considering a feed rate of $v_f = 2500$ mm/min is equal for both interpolation methods. But the machining error at $v_f = 6000$ mm/min is slightly higher for NURBS interpolated tool paths.

5.3. Comparison of CNC data and virtually machined surface topography

The results of the NC monitoring and the cutting simulation were partly controversial. The maximum values of the contour error, listed in Table 1, let assume, that NURBS interpolation of the tool path especially at the lower feed rate $v_f = 2500$ mm/min has a positive impact on the machining accuracy. In difference to the contour error, the simulation results summarized in Table 2 suggest almost the same machining error, when using NURBS or linear interpolation. Considering the higher feed rate $v_f = 6000$ mm/min the results of contour error and machining error analysis show the same tendency, as both errors are bigger for NURBS interpolated tool paths.

Neglecting other error sources, the machining error is smaller than the contour error and may show differing tendencies. A reasonable explanation could be, that the contour error is considering a one dimensional tool, while the cutting simulation takes account of a full tool with a diameter of D = 8 mm. That means, if there temporarily is a big deviation of set and actual point, the tool may still cut material in the according area even though the TCP has already left the according region.

The observation, that the machining error at higher feed rates is bigger for NURBS interpolated tool paths can be explained by the fact, that for $v_f = 6000$ mm/min the feed rate using linear interpolation is about 25 % smaller at areas with high curvature, while using NURBS interpolation the feed rate remains almost at $v_f = 6000$ mm/min for all positions. As stated, an increase of feed rate leads to an increase of contouring error. The machining error seems to be increased too.

6. Conclusion

Experiments have been done to show the open CNC monitoring application on the feed rate smoothing and to analyze the associated contour error. The impact of contour errors on the surface quality has been determined using virtual cutting simulations.

The system results state that shop floor feed rate smoothing reduces the contour error on the milling of sculptured surfaces. But even though the contour error was smaller using NURBS instead of linear tool path interpolation for low feed rates, the cutting simulation did not fully approve, that a lower contour error accounts for a higher surface quality. At higher feed rates contour error and simulated machining error are showing a better consistency.

Further studies in this field will focus the combination of the monitoring and cutting simulation systems with a simplified CNC servo drive model. In addition the cutting simulation model will be extended by models of different error sources impacting the TCP position. In this way the impact of each error source can be quantified before and in the cutting process to improve the overall behavior and the productivity of the process.

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