Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 55 (2016) 83 – 88

www.elsevier.com/locate/procedia

5th CIRP Global Web Conference Research and Innovation for Future Production

Elaborated analysis of force model parameters in milling simulations with respect to tool state variations

Stefan Hess[a,*], Felix Finkeldey[a], Petra Wiederkehr[a]

[a] *Institute of Machining Technology, TU Dortmund University, Baroper Str. 303, 44227 Dortmund, Germany*

[*] Tel.: +49-231-755-2364; fax: +49-231-755-5141. *E-mail address:* hess@isf.de

---

Abstract

Geometric physically-based simulation systems for milling processes can provide the possibility to analyze and predict characteristically behaviors of a certain process. The parametrization of the simulation models is a crucial task when optimizing the quality of the simulation prediction. In order to determine tool load, process forces have to be calculated. Thus, the parametrization of the cutting force model that is mainly subject to the processed material and tool characteristics has a versatile impact on the simulation results. However, the tool state is expected to be constant within common milling simulations and therefore tool state variations like several tool wear effects are not represented. The tool state is defined through the geometric constitution of the cutting edges of the tool. This paper aims to analyze tool wear effects by re-calibrating the parameter values of the force model within the simulation system. To validate the simulation system, several milling experiments were conducted. In order to induce a fast change of the tool state within the process and to provoke high tool loads, the powder metallurgic high speed steel 1.3344 was machined. Advanced surrogate modeling techniques from the design and analysis of computer experiments (DACE) were applied to analyze the contribution of the force model parameter values. The fitting of the surrogate model is performed by means of sequential design of experiments. This allows the retrieval of sets of fitting parameter combinations for each tool state with a relatively small amount of simulation runs compared to genetic algorithms or gradients based methods. The surrogate models are exploited to analyze the behavior of the force model parameter values over the varying tool states. Approaches for further research are recommended and potential practical applications are discussed.

Peer-review under responsibility of the scientific committee of the 5th CIRP Global Web Conference Research and Innovation for Future Production

Keywords: Milling; Geometric modelling; Surrogate models

---

1. Introduction

In industrial applications, the layout and optimization of machining processes is often time consuming and costly. Simulation systems allow to predict important process characteristics, such as forces and dynamic effects, for a given process layout. As a consequence, simulations can reduce the number of real experiments and therefore time and costs. Altintas et al. provide a comprehensive survey of recent capabilities of machining process simulations [1]. In this paper, a geometric physically-based simulation system, developed at the Institute of Machining Technology (ISF), is used. This tool enables the prediction of the material removal process, the resulting cutting forces and resulting effects like chatter vibrations [2]. A description of the system is given in section 2.

A main requirement for the simulation system is an accurate calculation of the process forces. To achieve this, an empirical force model is used [3], whose parameters have to be calibrated by physical experiments. This is usually done a priori to the actual milling process using the same tool and material as in the process. However, tool wear during the milling process causes a change of the process forces. Research of tool wear effects is already known in literature, e.g., for simulation systems based on the finite element method (FEM) [4,5]. Further investigations were made regarding an extension of an analytical cutting force model to represent tool wear and to predict the remaining tool life [6]. The calibration of the force model was done through a genetic algorithm and the idea of an online adaptive control system using a time series analysis was proposed. The modeling of tool wear using regression models or artificial neuronal networks is also possible [7]. Kolar et al. developed a force model, which is highly dependand on tool wear effects and the basic tool geometry [8]. The averaged flank wear value was measured in advance in order to integrate the characteristics of tool wear into the force model. To provoke wear effects, C45 carbon steel was machined using a coated carbide tool.

In geometric physically-based simulation systems, however, a geometric representation of the tool wear within the simula-

Peer-review under responsibility of the scientific committee of the 5th CIRP Global Web Conference Research and Innovation for Future Production
doi:10.1016/j.procir.2016.08.044

tion system would significantly increase the computation time. In addition, the measurement of tool wear for each regarded tool state is inefficient and only represents the tool wear effects for the discrete measured states. Therefore, this paper discusses the implicit modeling of the tool wear effects by adapting the calibration parameters. For this purpose, simulated forces are fitted to the measured forces of different states of tool wear over the time and the resulting information about the calibration parameters is compared.

Since the evaluation of simulation runs with different calibration parameter values can be time consuming, mathematical or statical methods are generally utilized to determine fitting calibration parameter values from all possible calibration parameter combinations, the so called parameter space. In existing studies, the best solution for these calibration parameter values is found straightforward by optimization algorithms [9–12]. This procedure is appropriate when optimizing isolated single problems. However, regarding the force calibration task, it will be shown that there are several parameter value combinations which lead to equally good results. The existence of entire regions of optimal solutions makes the comparison of single points from the parameter space over different tool wear states therefore inappropriate. Moreover, for a model-based interpolation of the tool wear states, the information from all calibration parameter combinations is required. Since optimizers are not able to provide more than single (best) points from this parameter space, they are not sufficient to tackle this task. Models from the Design and Analysis of Computer Experiments (DACE), however, can be used to gather information about the whole space of force coefficients based on a small set of simulation experiments. Thus, it is possible to analyze and visualize the progression of suitable calibration parameter values with increasing tool wear.

However, before the information of these models can be exploited, their approximation and prediction quality has to be validated to guarantee a sufficient fit over the considered parameter space. Therefore, a cross validation of the models is performed. To finally prove that the regions of good parameter values found by the models are actually optima, they will be compared to the solution found by an established optimization algorithm. The surrogate models and the calibration procedure are presented in section 3. Section 4 gives a brief overview of the experiments. The model validation and the results of the comparison of the calibration parameter values is presented in section 5. The paper ends with a conclusion in section 6, which also discusses potential practical applications and how the models can be used to interpolate the optimum force coefficients between the tool states.

2. Simulation system

Using a geometric physically-based milling simulation system, the material removal process and resulting effects, e.g., tool vibrations and heat input, can be predicted. The geometric model of the used simulation system is based on the Constructive Solid Geometry technique (CSG) [13] to model the geometry of the tool and the workpiece. To achieve a representative tool model, basic shapes like spheres, cylinders and tori can be combined. As initial workpiece model for the stock material typically a cuboid is used [14]. The calculation of the process forces is based on the undeformed chip thickness of the milling process at discrete points in time. To represent the irregular shape of the undeformed chip, the cutting edge of the tool model is approximated by rays, whose origin lie on the center axis of the tool model (Fig. 1). These rays are distributed along the cutting edge. Furthermore, a time-related discretization is used to represent the envelope of the tool and the feed movements. The sum of the lengths of the ray intersections with the workpiece model represents the undeformed chip thickness. The computed thickness and the width of the chip can be fed into an appropriate force model to predict the process forces. This force model [3] is described by the equation

$$F_i = b \cdot k_i \cdot d_0 \cdot \left(\frac{d}{d_0}\right)^{1-m_i}, i \in \{c, n, t\}, \tag{1}$$

where d is the thickness and b is the width of the undeformed chip, which results from the Euclidean distance between the first and the last endpoint of the intersected rays. Furthermore, $d_0 = 1$ mm and F_c, F_n, F_t are the resulting forces in the cutting, normal and tangential direction.

3. Empirical surrogate modeling

3.1. DACE models and correlation functions

The functional relationship between input and output parameters of complex nonlinear systems can be approximated by empirical surrogate models. The most popular choice of a surrogate model is a polynomial regression model [16]. In this modeling approach, a set of N observations with d input variables $X = (x_1, \dots, x_d)$ is generated by methods of design of experiments. The evaluation of the design on the complex system leads to N observation pairs $(X^{(i)}, y^{(i)})$, $i = 1, \dots, N$ of input parameters and corresponding response values. Polynomial regression models assume the functional relationship $y(X) = f(X) + \boldsymbol{\varepsilon}$, where the vector of residuals $\boldsymbol{\varepsilon}$ is assumed to be a random noise variable with a mean of zero and an unknown standard deviation σ. The function f represents a predefined functional term of the input parameters. Polynomial regression models are efficient, if the actual underlying problem function is close to linear or quadratic [16]. However, if the investigated system is highly nonlinear, this model tends to a poor fit or local overfitting [17]. DACE models [18], also called Kriging or Gaussian process models, enhance the polynomial regression

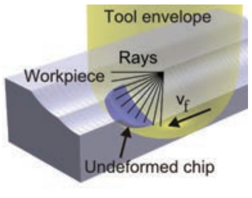

Fig. 1: The undeformed chip results from an intersection operation with the current workpiece and tool model. The undeformed chip thickness is approximated using rays, which originates from the axis of the tool model [15].