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Chatter model for enabling a digital twin in machining

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Abstract

This paper presents the development of a new chatter model using measured cutting forces instead of a mathematical model with empirical nature that describes them. The utilisation of measured cutting forces enables the prediction of real-time chatter conditions and stable machining. The chatter model is validated using fast Fourier transform (FFT) analyses for detection of chatter. The key contribution of the developed chatter model is that it can be incorporated in digital twins for process monitoring and control in order to achieve greater material removal rates and improved surface quality in future industrial applications involving machining processes.

Keywords Digital twin · Chatter model · Cutting forces

1 Introduction

Chatter modelling in machining dates from the 1960s when Tlustý and Poláček [1] and Tobias [2] presented chatter models in machining. Later, Altintas and Budak [3] developed a chatter model with dynamic uncut chip thickness by solving the equation of motion analytically in the frequency domain. Further chatter models considering velocity-dependent damping and cutting forces, as well as run-out effects, have been solved in the time domain using numerical integration [4]. The challenge in all developed chatter models is that the cutting force model needs to accurately predict the actual cutting forces which depend not just on the cutting parameters but also on the cutting tool geometry, frictional conditions, kinematics of the cutting tool and workpiece material state [5]. For instance, the geometry of the cutting edge changes due to wear and the frictional conditions can change too. The workpiece material might have different properties in different locations due to differences in the material microstructure. All

these factors introduce uncertainties for the accurate prediction of the cutting forces and create challenges in using existing chatter models in process monitoring and control.

The use of process damping at low spindle speeds has been widely used in the past as well as the design of machine tools with enhanced damping capabilities [6]. Chatter avoidance has been approached by structural modification of tool-holder geometry in order to change the structural dynamics as well as tuning the mass of the tool-holder assembly [7]. Measured cutting forces, accelerations and acoustic emissions have been widely used for process monitoring and control. The most widely used methods are the conversion of measured signals from the time domain into the frequency domain for detection of chatter [8]. Other researchers used the root mean square value in the time domain to identify chatter [9]. Despite the fact that those methods are reliable, they are dimensionless indicators for chatter detection and lack the ability to quantitatively predict how conservative or aggressive the machining process is. Therefore, a new chatter model is developed and validated in this paper in order to enable the prediction of chatter-free cutting conditions based on measured cutting forces in micro-milling. The coupling of real-time measured cutting forces and physics-based predictive model for chatter-free micro-milling can be considered as a key enabler for the development of digital twins for automated process monitoring and control in micro-milling and other machining processes as well. This could be a step forward in addressing the industrial challenges in implementation of digital twin models in manufacturing operations [10].

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The paper first discusses the digital twin as a concept for automated process monitoring and control to increase process efficiency. The paper then presents a chatter model using measured cutting forces as an enabler for the digital twin. The validation of the chatter model for micro-milling is finally presented as well as its role in the digital twin.

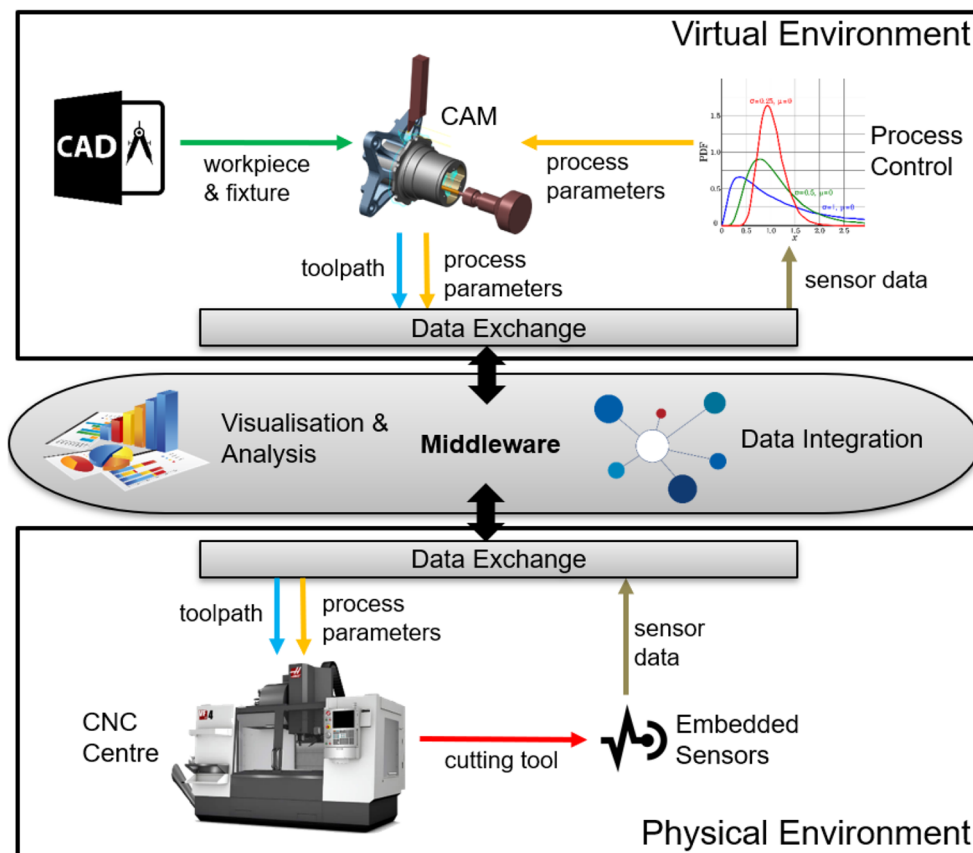
2 Digital twin for process monitoring and control: a concept

A digital twin can be described as an organised collection of physics-based methods and advanced analytics that is used to model the present state of every asset (e.g. a machine). By additionally considering the data streams of these assets and communicating with them, it can be considered as a digital counterpart to physical reality. Wherever a physical asset services a need (for example, moving people from one place to another, electricity provision, manufacturing a product), a virtual counterpart can be created to plan, optimise and control it. A wide range of digital twin applications was presented by Cimino et al. [11].

Figure 1 shows a digital twin concept for process monitoring and control in machining. The digital twin consists of a digital environment, which is a replica of the physical environment,

interfaced with a middleware that facilitates connectivity and the transfer and storage of data, information and knowledge. Considering the manufacture of a component as an asset, the first step is to design it for machining, including the design of the fixture. Once the design is completed, the computer-aided design (CAD) models for the component, fixture and cutting tools are used in a computer-aided manufacturing (CAM) system to identify the toolpath for specified process parameters. The process parameters can be selected based on knowledge of the specific cutting tool and workpiece material or based on physics-based predictive models. After the toolpath is created in the CAM system, the computer numerical control (CNC) centre is instructed how to operate through the use of G-code and initial referencing. One of the key moments in the digital twin is to identify what data needs to be collected through embedded sensors and how to use it in order to increase the material removal rate and machined surface quality through the use of adaptive process parameters and toolpath regeneration. In the proposed digital twin, measured cutting forces are used to predict chatter-free process parameters through the use of a new chatter model presented in this paper. The new chatter model is the enabler for the proposed digital twin because it can be embedded in process control systems to predict stable machining parameters and achieve increased material removal rates and improved quality of the machined components.

Fig. 1 A digital twin concept for process monitoring and control in chatter-free machining



3 Chatter methodology

Figure 2 depicts the four stages of the chatter methodology that was employed in this research to define and validate the proposed model. In stage 1, the dynamics of the tool-holder-spindle assembly is obtained. A tool-holder-spindle assembly for TiN-coated two-flute end-milling tungsten cutting tool with diameter of 500 μm and flute length of 1 mm attached to a KERN milling machine was adopted from Afazov et al. [12]. The adopted modal dynamic parameters are natural frequency (w_n) of 4035 Hz, modal damping (ζ) of 0.016 and modal dynamic stiffness (k) of 2.1415 MN/m. In stage 2, the micro-milling cutting forces are obtained. Cutting tools with the same coating and overall dimensions were used. The micro-milling cutting forces for AISI4340 with hardness of 31HRC obtained by Afazov et al. [13] and Afazov et al. [14] were used.

In stage 3, the micro-milling chatter model with a time domain solution developed by Afazov et al. [12] is modified

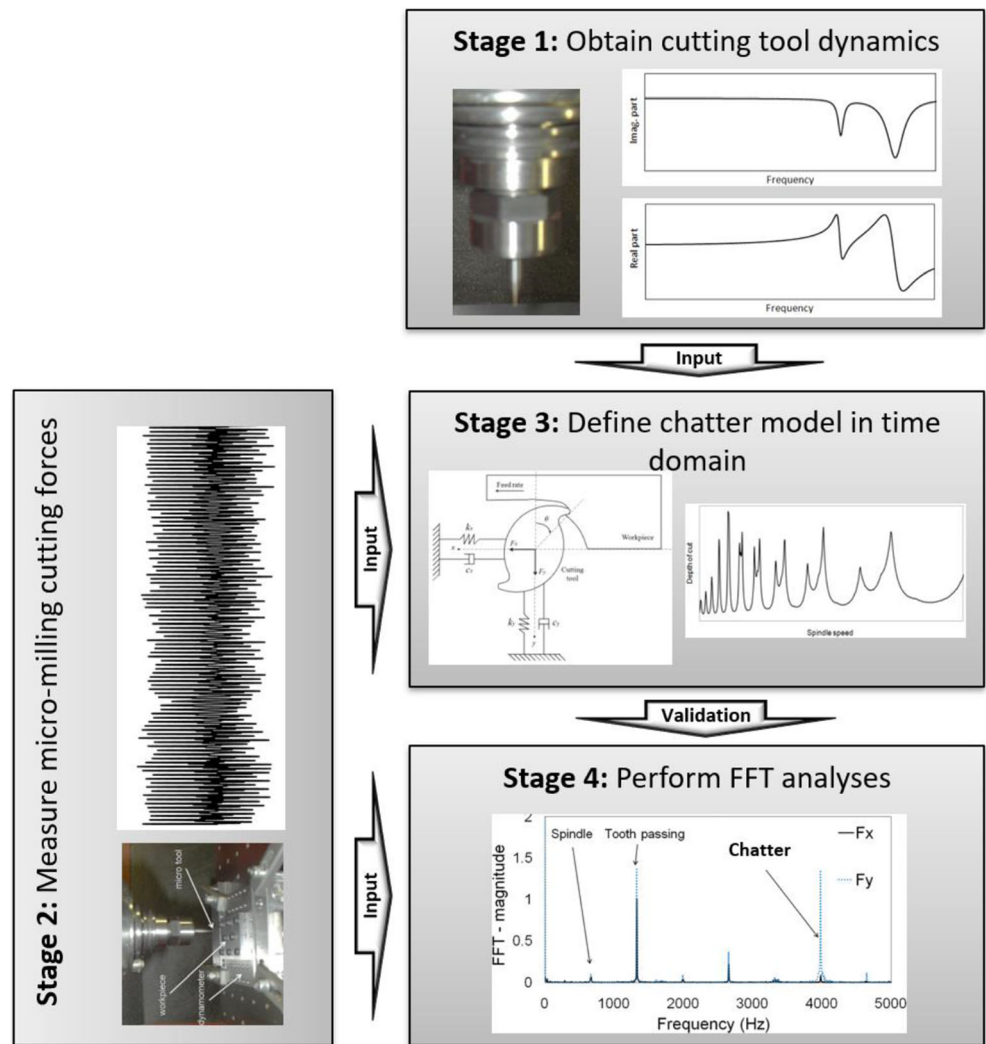
in this research to accommodate the use of measured cutting forces instead of using an empirical cutting force model. The dynamics for two degree of freedom system can be described by the equation of body motion given by Eq. (1).

$$\ddot{x}(t) = \frac{w_{n,x}^2 F_x}{k_x} - 2\zeta_x w_{n,x} \dot{x}(t) - w_{n,x}^2 x(t)$$

$$\ddot{y}(t) = \frac{w_{n,y}^2 F_y}{k_y} - 2\zeta_y w_{n,y} \dot{y}(t) - w_{n,y}^2 y(t)$$
(1)

where F_x and F_y are measured milling cutting forces in the x and the y direction respectively. The fourth order of precision Runge-Kutta numerical integration method is employed to solve Eq. (1) in the time domain solution using the same modal dynamic parameters in the x and y directions. The forces at each time increment are obtained by linear interpolation between two measured force values. After the cutting tool displacements in the x and y directions are calculated by Eq. (1), statistical variances are employed as a criterion for

Fig. 2 Chatter methodology—definition and validation



detecting the chatter phenomenon. The statistical variances are given by:

$$S_x^2 = \frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n-1}; S_y^2 = \frac{\sum_{i=1}^n (y_i - \bar{y})^2}{n-1} \quad (2)$$

where S_x^2 and S_y^2 are statistical variances in the x and y directions, x_i and y_i are the displacements at the corresponding time computed from Eq. (1), n is the number of time increments and \bar{x} and \bar{y} are the averaged displacements in the x and y directions. The micro-milling cutting is considered unstable when one of the statistical variances is greater than the value of $1 \mu\text{m}^2$ ($S_x^2 > 1 \mu\text{m}^2$ or $S_y^2 > 1 \mu\text{m}^2$).

Chatter stability is predicted for measured cutting force signals. In stage 4, the same measured cutting forces were processed using the fast Fourier transforms (FFT) to detect chatter in the cutting tool at its natural frequency of approximately 4 kHz. The results from the FFT analyses were used to validate the proposed chatter model.

4 Results

All cutting force measurements used in this research have been obtained on the 5-axis KERN machine with mounted Kistler dynamometer 9258C2 published in [13, 14]. Two sets of data were used in this study. The first set of data is produced using

TiN-coated two-flute end-milling tungsten cutting tool with diameter of 500 μm and flute length of 1 mm with measured rake angle of 0° and cutting edge radius in the range of 1.2–24 μm at different wear stages [14], referred to as cutting tool A in Table 1. The second set of data is generated for a cutting tool with the same coating and overall geometrical dimensions but with a rake angle of 8° and a cutting edge radius of 3.5 μm [13], referred to as cutting tool B in Table 1. The measured cutting forces were used to predict the existence of chatter as well as a stable depth of cut. The stable depth of cut was predicted by linearly scaling the cutting forces up when no chatter was predicted or scaling them down if chatter was predicted. It needs to be noted that the scaling up assumes linear increase of the cutting forces due to increase of the cutting depth. In the event of chatter, the measured cutting forces would capture the dynamic effects and their scaling down would still account for them, which can introduce some error in the prediction.

The results in Table 1 show agreement between predicted chatter conditions with the proposed chatter model and chatter detection using FFT analyses. Most notable is the uncertain chatter condition for cutting tool A with the FFT analyses which is a subjective decision based on the observation that a vibration is evitable at the cutting tool natural frequency but it is not entirely conclusive that the vibration is sufficient to generate chatter. For all the uncertain conditions detected with the FFT analyses, the chatter model predicted chatter with close predicted stable depths of cut to the applied depth of cut in the experimental trials (i.e. 48 μm predicted stable depth

Table 1 Process parameters and chatter results

Cutting tool	Applied spindle speed (rpm)	Applied feed rate ($\mu\text{m}/\text{tooth}$)	Applied depth of cut (μm)	Cutting edge radius (μm)	Rake angle ($^\circ$)	FFT analysis chatter?	Model prediction chatter?	Predicted stable depth of cut (μm)
A	40,000	4	70	1.2	0	Yes	Yes	17
A	40,000	4	70	3.3	0	Yes	Yes	14
A	40,000	4	70	5.6	0	Yes	Yes	19
A	40,000	4	70	14.5	0	Yes	Yes	11
A	40,000	4	70	23.6	0	Yes	Yes	15
A	24,000	8	50	1.2	0	Uncertain	Yes	44
A	24,000	8	50	3.0	0	Yes	Yes	34
A	24,000	8	50	6.6	0	Uncertain	Yes	48
A	24,000	8	50	11.1	0	Yes	Yes	44
A	24,000	8	50	14.1	0	Yes	Yes	23
B	5000	6	100	3.5	8	No	No	227
B	5000	12	100	3.5	8	No	No	114
B	25,000	6	100	3.5	8	No	No	196
B	25,000	12	100	3.5	8	No	No	120
B	25,000	24	100	3.5	8	Yes	Yes	76
B	50,000	6	100	3.5	8	No	No	192
B	50,000	12	100	3.5	8	No	No	128
B	50,000	24	100	3.5	8	No	No	125

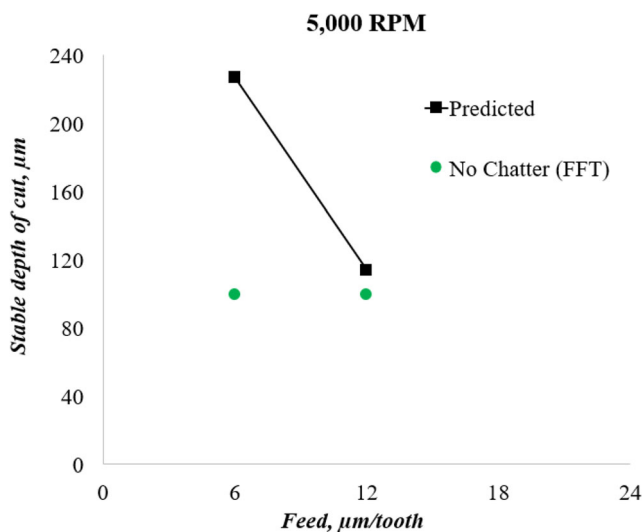


Fig. 3 Comparison of predicted and FFT stability at 5000 RPM

of cut versus uncertain condition with FFT analysis at 50 μm applied depth of cut).

Figures 3, 4 and 5 show a comparison between predicted stable depths of cut using the proposed chatter model and chatter conditions determined by the FFT for the cutting tool B. It can be seen that both approaches agree, particularly the results at 25,000 RPM in Fig. 4. It can be also seen that the stable depth of cut decreases by increasing the feed per tooth due to the increase of the cutting forces.

The advantage of this chatter model is that all geometrical changes of the cutting tool due to wear and change of frictional conditions, as well as dynamic run-out and material properties of the workpiece, can be captured in the measured cutting forces. This can enable the realisation of a digital twin for process monitoring and control where a physics-based predicted model can be incorporated to increase the material removal rate in chatter-free machining. The model can be

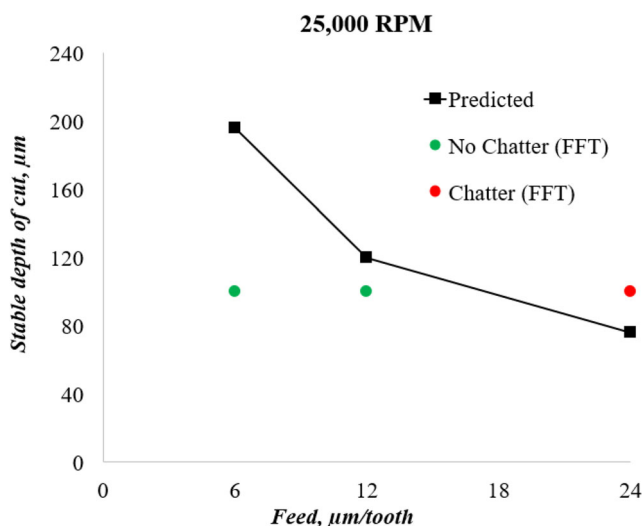


Fig. 4 Comparison of predicted and FFT stability at 25,000 RPM

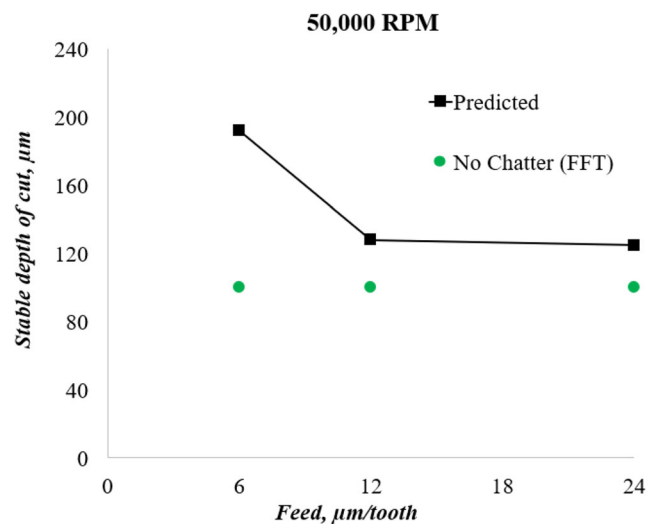


Fig. 5 Comparison of predicted and FFT stability at 50,000 RPM

applied to any material and machine tool. As most of the chatter models are more accurate for ductile materials (e.g. metals) due to the relative accuracy in the predictability of the cutting forces, this chatter model could have success in the accurate stability prediction of brittle materials (e.g. ceramics and composites) due to its use of measured cutting forces where discontinuities could be captured as well.

5 Conclusions

The following conclusions are derived from this research:

- a new chatter model using measured micro-milling cutting forces was developed and validated using FFT analyses;
- a digital twin concept for process monitoring and control was presented to illustrate how the new chatter model can enable its realisation;
- the presented digital twin concept for process monitoring and control will be demonstrated on an industrial use case in a future research;
- a comparative study between the proposed chattered model and existing chatter models will be conducted as a future research for better understanding their respective advantages and disadvantages.

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