CLOSING REPORT

High Performance Computing of Complex Cutting Models

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1 BACKGROUND & GOALS

The literature on methods analysing the vibrations occurring during cutting processes has a past of more than 100 years. Nevertheless, we can only meet the industrial application of these methods in very few cases. The mathematical descriptions of commonly used cutting models use deterministic constant parameters. An imperfect correlation between repeated measurements of these parameters is denoted to non-appropriate setups, while the deviation of resulting signals is thought to be due to poor measurements (noise). Hence only the average values are used in the models.

Nevertheless, it is simple to see that these variables have uncertain average values and change randomly. This can either have its roots in material inhomogeneities or in unmodelled dynamical properties of the systems. Thus the probabilistic and stochastic description of the variables is an essential tool for the appropriate characterisation of the system.

2 ACHIEVED GOALS

Our main goal was to explore how the stochastic effects influence delayed dynamical systems. With the help of the proposed methods, we can predict resulting surface quality, measured forces and vibration signals for milling with their average values and deviations, too.

Secondly, we investigated how the changing dynamical properties, which depend on the tool position and the removed material, modify the stability properties and how the robust stability limit can be determined, which is insensitive to these changes and the changes in the technological parameters.

2.1 Robust stability calculations

Parameter uncertainty is a main challenge in industrial applications partly because there is no sufficient apparatus and experts to identify the parameters precisely and because they can change slightly in time and for different environmental conditions. The uncertainty of the modal properties are captured in [22,23] through the inaccurate measurement of the FRF, from which the nominal and the robust stability limit of the corresponding milling process is determined based on pseudospectral method and Multi-frequency Solution with Structured Singular Values (Fig. 1).

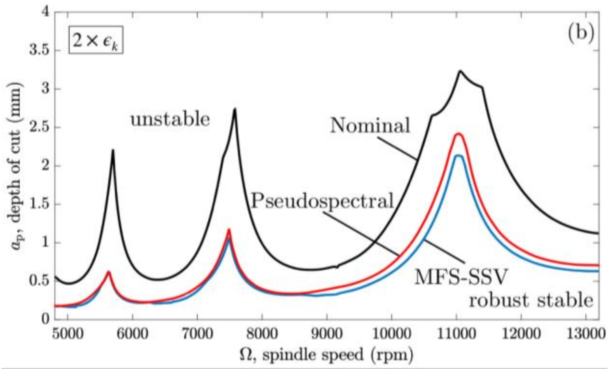
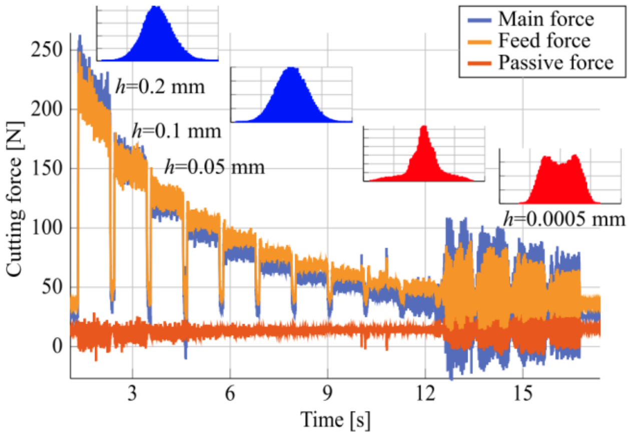


Figure 1. Comparison of the pseudospectral method and the Multi-frequency Solution with Structured Singular Value.

2.2 Stability of Stochastic Systems

We determined the stochastic nature of the cutting force signal through a series of cutting force measurements. We modelled the cutting force by coloured and white noises [7,17] (Fig. 2).
It is shown that the cutting force is inherently a stochastic process and can be modelled as a multiplicative noise component with an overall relative noise intensity of ~1%. This small amount of noise in the cutting force does not influence the stability properties of the milling process but the stationary vibrations due to the noise-induced resonance. These stationary vibrations can cause unacceptable surface quality, make it harder to detect chatter, or even cause a transition to chatter in bi-stable zones near the stability borders.

Figure 2. Example of raw measured force signal for exponentially decreasing chip thicknesses *h* with the usually occurring force distributions (blue: Gaussian, red: not Gaussian)



We investigated different algorithms and stability definitions to analyse the stochastic delay differential equations of the proposed milling models [5,6,12,21]. It is found that for engineering purposes, the moment stability is the best choice; however, there was no available efficient method for these type of stochastic delayed differential equations. We established and implemented the Stochastic semidiscretization method [13,14,19]. It is shown that it can reach higher-order convergence, while its computation complexity is $\sim$ O(p4.752), which is high, but still the best available. Currently, a collocation based method is under investigation.

We determine the stability borders of the milling processes with the Stochastic semidiscretization method and find almost negligible difference compared to the deterministic models. However, we managed to show the stochastic resonance effect close to the stability borders, which presents a hyperbolically increasing random vibration approaching the boundary. With the help of this new stochastic model of milling processes, the formulation of a chatter peak in the FFT of the signal in the stable machining parameter domains is explained as the manifestation of the noise-induced resonance near the stability borders. This properly explains the practical problems of chatter detection, which have high practical importance. We performed multiple measurements in a milling tool to show this phenomenon which is presented in [15,24,25] (see Fig. 3). This method is also used efficiently in collaborative work in a control problem, which is presented in [20].

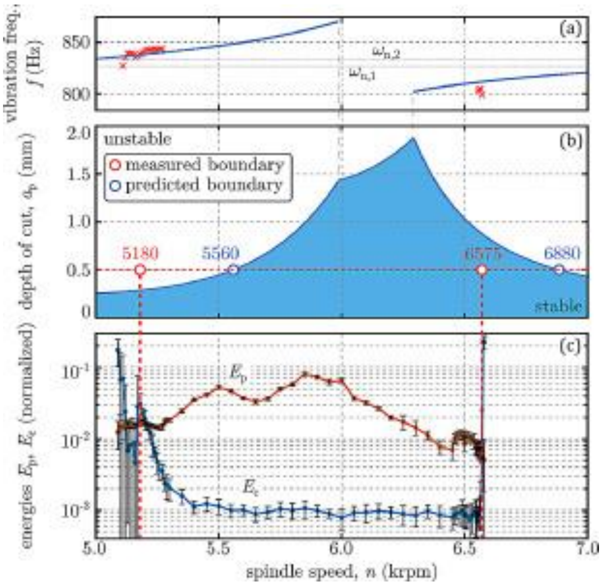
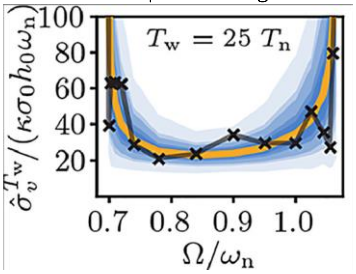


Figure 3. Predicted (left) and the measured (right) stochastic resonance effect in milling along the spindle speed. Left: Shaded blue region shows the probability distribution of a single measurement outcome. Right: top: chatter frequency, middle: stability chart, bottom: mean (red) and the variation (blue) of the measured periodic signal.



2.3 Effect of changing dynamical properties

In the analysis of changing dynamics, first, the turning process is investigated, in which the effect of the decreasing diameter of a long beam is analysed due to the material removal. It is shown by different analytical models and FEA how will the natural frequencies will change [9,10].

The mechanical models are extended to describe the changing properties during the milling processes [16]. By the applied in-process measurement by means of the BallShooter device, the changing natural frequencies were followed during the milling process (see Fig. 4).

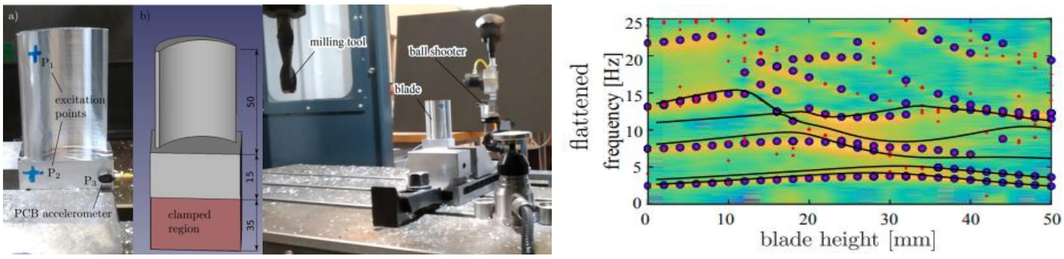


Figure 4. left: Photo and the CAD model of the machined final blade profile, middle: the in process measurement setup with the ball shooter, right: natural frequencies of the FE model with the artificial elastic layer (black lines) and the measured averaged Frequency Response Function in the function of the blade height presented as a waterfall diagram.

To follow the uncertain parameters during the machining, a precise measurement of the spindle speed fluctuation were performed [3], and a contact sensor was created [4]. This way, we could collect input data for the uncertainty analysis and the robustness calculations.

We needed precise chatter detection during machining to validate the robust stability prediction. In [8], we performed a quantitative identification of chatter based on Floquet multipliers in milling operation. A series of measurements were performed, from which we could predict the stability boundaries based on the measurements only in the stable domain.

In [18], we applied the impulse dynamic subspace description method for periodic signals in the milling measurement for precise parameter identification. With the proposed method [26,27,29], we were able to characterise the stability not only by qualitative values (stable/marginal/chatter) but quantitative ones (Floquet multipliers), which can be used for direct comparison to the result of the mathematical models (see Fig 5).

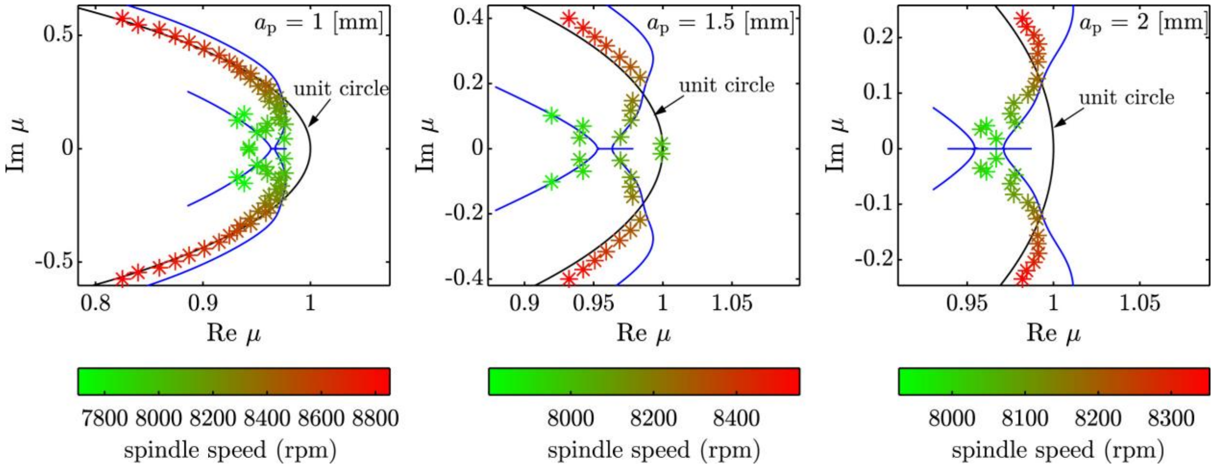


Figure 5. Measurement-based identified Floquet multipliers for different spindle speeds (denoted by stars) in the complex plane compared to the path of the theoretical ones (continuous blue line) for different axial depth of cuts (1, 1.5, 2mm).

2.4 Virtual environment, accurate CWE

To combine all the mentioned numerical methods and to be able to compute the complex Cutter-Workpice-Engagement even for a complex toolpath, a virtual environment is developed for milling processes (see Fig 6.).

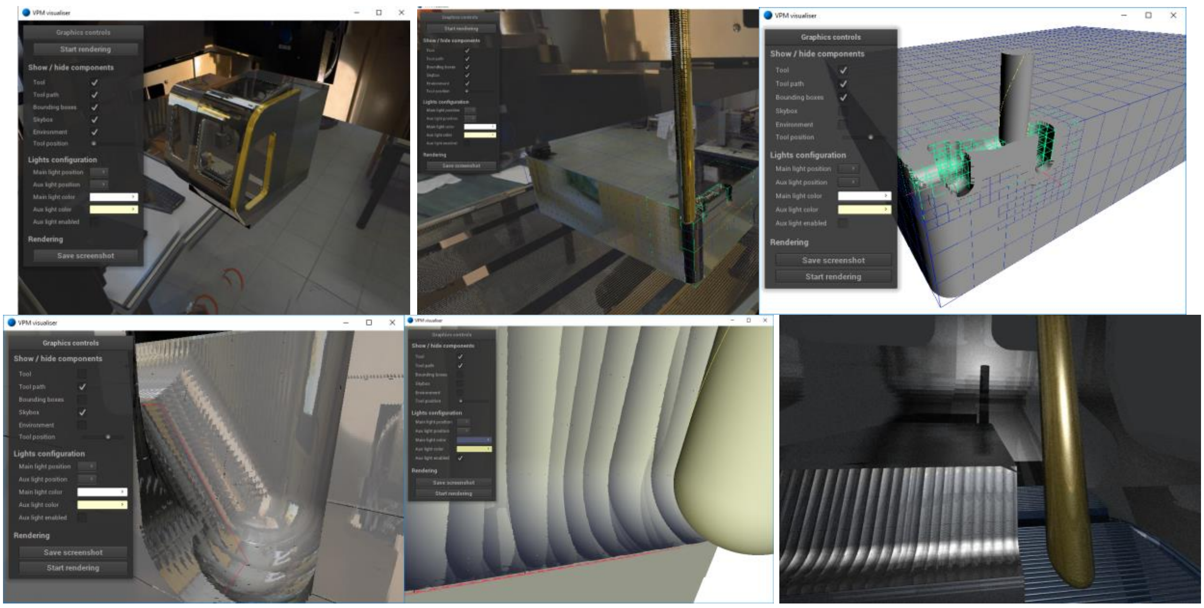


Figure 6. Screenshots from the implemented virtual milling environment

3 IMPLEMENTED ALGORITHMS

During the project, multiple algorithms were implemented and upgraded in Julia program language, which are available for free as a Package of the language.

1. Stochastic differential equation solver - *StochasticDelayDiffEq.jl*
2. First and second moments of stochastic linear delay differential equations - *StochasticSemiDiscretizationMethod.jl*
3. Multi-Dimensional Bisection Method - *MDBM.jl*

4 SIDE RESULT

During the evaluation of the main research directions, many associated problems must have been solved. Most of them are related to the stability measurement of the milling process. Many of them represent a complete and independent research direction.

• We precisely measured the surface properties using a laser sensor. Furthermore, based on the detected waviness, we could determine the frequency of the chatter vibration [1].

• In some measurements, we used a test rig to have a well-defined mechanical property (natural frequency and damping ratio). In this way, we could measure the vibrations precisely, and using the measured acceleration signals, we could determine the cutting force and detect some force characteristics [2].

• We also found out that for precise modal analysis, it is not enough to measure the longitudinal (main) excitation force of the traditional modal hammer. The lateral (slight) components would also be needed. Thus, we started to develop a triaxial model hammer.

• To create an efficient milling tool geometry optimisation, the previously developed HIL environment is upgraded to analyse highly interrupted-milling processes. Furthermore, the measurement efficiency is greatly improved by the Multi-Dimensional Bisection Method [30].

5 CONCLUSON

Overall, it can be said that the targeted, efficient algorithms have been developed and have been successfully applied to machining processes. In the research, we developed several numerical algorithms suitable for studying complex delayed stochastic differential equations. Free implementations are available in the Julia program environment.

The algorithms have been successfully applied to models of cutting processes. The stochastic description was used to predict the uncertainties experienced in the measurement of cutting processes. The phenomenon of stochastic resonance has been quantified, i.e. that the stationer high-amplitude noise process can lead to erroneous identification (stable/unstable) when measured close to the stability limit. With the developed mechanical material removal model, we successfully described the change of the natural frequencies of workpieces with variable geometry and found robustly stable technological parameters.

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