CLOSING REPORT OF NKFI-PD 137673

Guaranteed stability of controlled dynamical systems with delay

Principal investigator (PI): David Hajdu

1. ABOUT THE PROJECT

Time-delays are present in many fields of science, such as biology, chemistry, physics, economics, engineering, and in our everyday life also, where the finite time of information propagation plays an important role in the processes. Inclusion of delay in the governing equation changes qualitatively the picture of the dynamical behavior of the system and highly complicates the investigation. Stability can easily be lost if time-delays are present, which are difficult to compensate and can lead to bad performance. Unstable operations are typically identified by the unwanted harmful oscillations, which are usually irregular, unacceptable, or can even be dangerous. Machine tool vibration is a typical engineering application, where the delay comes from some cutting periodicity of the process (turning, milling, etc.). The harmful vibrations (called chatter) lead to unacceptable surface finish, poor quality, tool breakage and reduced lifetime of the machine components. The undesired phenomena can be avoided by using stability charts (passive methods), or by adopting vibration dampers (active methods) that mitigate chatter. The real applicability of both offline passive methods and controlled active systems highly depend on the reliability of the models, in other words, on the robustness of the models.

The aim of the project was to uncover the key uncertainties and modeling errors that lead to inaccurate stability predictions in machining operations, where time-delay is a nonnegligible parameter in the governing equations. By “guaranteed stability” we refer to stability properties that remain the same (robustly stable) even in the absence of the complete knowledge of the system’s behavior. Another goal of the project was to combine such modeling and design tools with active vibration control techniques to achieve the best and still reliable performance of the actuator.

To reach the goals of the project, numerous measurements and tests have been performed during the years. Experiments reflect the real uncertainty regions along the stability boundaries that are needed for reliable validation. I have analyzed the accuracy of cutting force measurements, effect of empirical force models, and reliability of dynamical models. All these “ingredients” were needed to find the most critical parts of the model that has the largest effect on the stability. When the project started, I though that model parameter uncertainties have the key impact on the stability, but the research has highlighted that the classic dynamical model itself lacks the ability to completely describe the process. These minor effects – such as the uncertain clamping of the tool – changes the cutting process dynamics. Tests revealed that discrepancies were not predictable by standard robust tools but were actually captured by the new developed models. This new model is recently being developed and extensions are left for the future work.

The experimental studies I have performed in the laboratory highlighted many conceptual difficulties, that delayed the work and made it harder to reach aim. However, these problems were mostly successfully solved, which are found to be scientifically relevant issues. Although these were not planned initially in the project (improvement of force measurement, runout modeling, etc.), I could not step over them because these were fundamental problems in machine tool dynamics research. These obstacles and difficulties are detailed later.

All in all, the gains of the projects are valuable and useful for the related machining society and industry. It initiated some collaborative works, and we intend to continue this research direction to exploit the potential and develop our models furthers.

2. MAIN RESULTS IN DETAILS

Experiments and model validation of machine tool chatter is always complicated. To make the process simpler and exclude some difficulties, I have designed a test rig for milling operations, which mimics the dynamics of a single-degree-of-freedom system. Similar designs have been used many times in the literature, and it was found to be a good experimental device for initial laboratory validations. This test rig was used to test the robustness of the dynamical models, automatic chatter detection, and also for different other experimental configurations. In-process impulse-based dynamical characterization of milling operations have been developed and the results were published in a journal paper [1]. This paper highlights the actual robustness of the stability charts by means of automatic chatter detection versus offline stability prediction (see Figure 1). The method makes us able to compare not only stable/unstable classified points (two states only), but also the distance from instability on a continuous scale. The method is still recently being developed further for more realistic industrial applications.

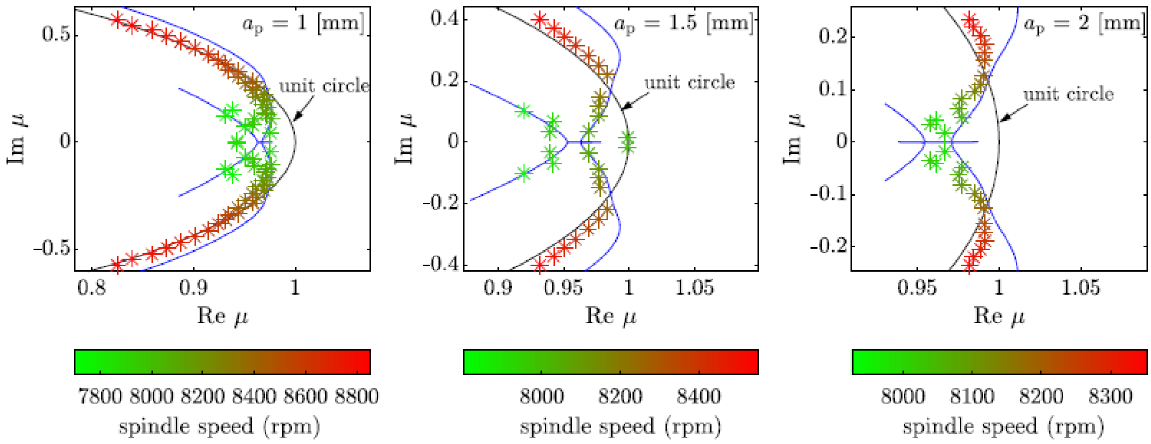

Figure 1. Identification of the critical characteristic multipliers near the stability limit (blue is the theoretical model and colored stars are the measured multipliers) [1].

The dynamical equation of milling requires the accurate representation of the cutting force characteristics, and also the dynamics of the machine. The cutting force characterization is critical, because a slight deviation in the nonlinear empirical force model has a huge effect on the linear stability charts. A new general geometric model has been developed, called curved uncut chip thickness model, which extends cutting force predictions to various cutting edge geometries. This model is used to model nose radius, which highly complicates the geometrical representations, although, all inserts used for indexable cutters have a measurable nose radius. Experiments have been performed on different setups, and it showed that different models provide significantly different cutting forces at extreme technological parameters (see Figure 2). The results have been published in the International Journal of Machine Tools and Manufacture (IJMTM) entitle '*The curved uncut chip thickness model: A general geometric model for mechanistic cutting force predictions*' [2] with foreign collaborators. The choice of models provides different cutting parameters, which can be represented as parametric uncertainties. These uncertainties shift the stability charts and are responsible for inaccurate predictions. However, better representation can be reached with the advanced models, as the study suggests.

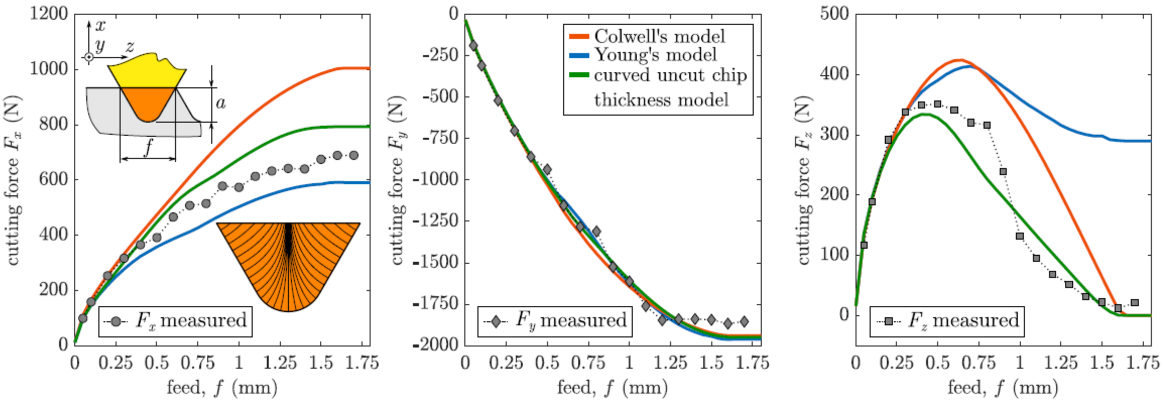

Figure 2. The curved uncut chip thickness model for improved cutting force prediction [2].

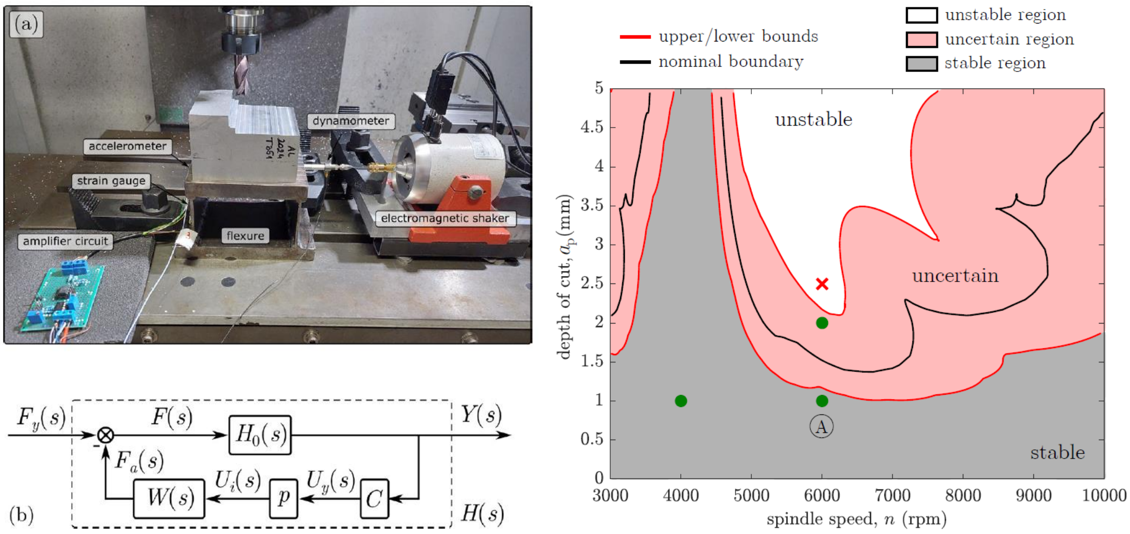

Figure 3. Active vibration controller on a test rig [3]*: (a) experimental configuration with an electromagnetic shaker, (b) schematic of the controller loop, (c) robust stability chart with measurements (green circle is stable, red cross is unstable).*

Robustness of control loops in machining operations have been studied on the test rig using an electromagnetic shaker (see Figure 3). The experimental setup is planned to be extended with piezoelectric stack actuators, but the experiments showed that the purchased amplifier is limited in power and the design should be reconsidered. Moreover, the published model is based on a mathematical simplification (time-averaged model), which can be extended to time-periodic systems (milling operations). Theoretical robustness of the stability chart has been presented successfully, however, the model remained at the level of a laboratory setup. It is possible to build an actuator onto the housing of the machine column close to the spindle (there exists such published designs), but it was found to be too complicated for the project. For safety reasons and technical issues, I was not capable to realize it alone. The results were published at a conference [3].

The experiments, such as the ones presented in [1] and [3], triggered the extensions of the dynamical model considering the radial runout of the tool. The first idea was that runout changes the cutter-workpiece engagement (CWE), and when the cutting force characteristics are identified, a false assumption is used for the CWE and it results in parameter uncertainties. When the kinematic model was updated, it turned out that the dynamical equations are actually so much altered, that the mathematical equations are not correct anymore. This led to the research on cutter runout, which became the deepest theoretical problem I faced in these years. This previously “unmodelled dynamics” finally explained why the measurements deviated so much from the experiments, see Figure 4. The validity of the model is proved by laboratory test and industrial validations also. The industrial validations are performed on a heavy-duty milling machine at our industrial collaborators, which finally explained a long-ago unsolved problem with the milling machine. It was shown that some cutting edges of a multi-teeth milling cutter can lose the contact with the workpiece, and the tool machines with lower number of edges. The forced vibrations change the CWE, and the delay pattern that affect the stability of the process, which is fully the consequence of a few micron runout. The real cutting forces and the machine surface qualities are predicted well only by our updated model. This case study was a strong motivation to continue the research. We believe that such observations are especially important for the machining community, and we intend to publish these results in a high-quality journal (IJMTM). The results will be presented in the form of a collaborative work with industrial partners and scientific colleagues. The study is almost ready for submission (Figure 4 is taken from the unsubmitted manuscript), but it was not finalized by end of the closing of the project, unfortunately. Some results have already been presented for the community at conferences [4], [5].

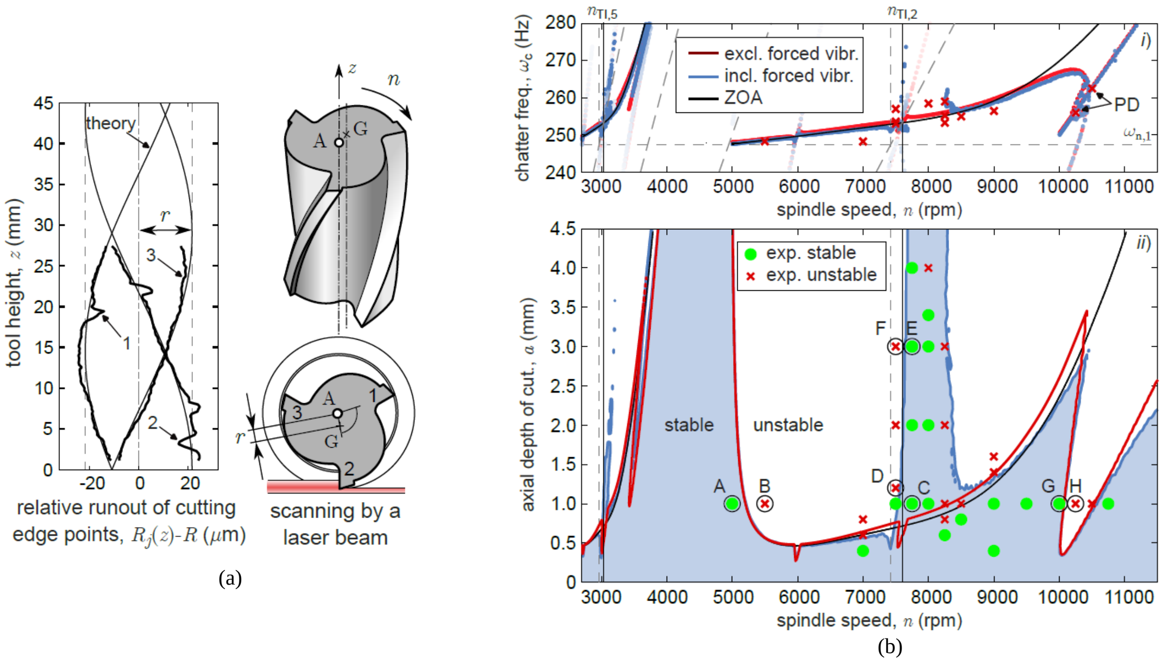

Figure 4. UNPUBLISHED RESULTS: Improved dynamical model with the runout of the tool: (a) experimental configuration for runout measurement, (b) classical stability chart (red) and new stability chart (blue).

3. UNEXPECTED OBSTACLES AND DIFFICULTIES

The aim of the project was not only to improve the mathematical models, but also to test and implement them in practice. Laboratory experiments were designed that explained many issues regarding the controller's problem. Although the laboratory tests were successful on a test rig, the implementation in real-life applications remained unsolved. Piezoelectric stack actuators and drives have been purchased for this purpose, but the practical applications remained limited because of the limitations of the configuration. The timescale of the project was shorter than the needed time to extend the application further, moreover, the costs of ready-to-use equipment was beyond the limit of the budget. Therefore, this goal was not reached, yet.

Even the first tests with the simple labor devices showed that measurements are hard, and many uncertainties are present on the signal processing's side. Therefore, more accurate measurements were planned, and the signal processing techniques have been improved. These extensions, e.g., dynamic compensation of the dynamometer, and cutting force identification took a significant amount of time, which delayed the progress of the project.

The dynamic measurements showed that the tool runout (due to eccentric clamping in the collet) effects both the cutting force identification and the dynamical model. However, the dynamical model needed not only some extensions, but a completely new formulation. The model requires nonlinear periodic solution continuation techniques, which needed significant improvements in the calculation methods. These new models have been successfully developed and implemented numerically, but the manuscript is yet not submitted for publication (the results are yet only presented at a conference [5]).

The active controller I have created is built up by analog elements to reach a delay-free closed loop design. It was planned to construct a more sophisticated digital controller, but the models suggested that if the artificial delay in the feedback does not match perfectly the tooth-passing time of the milling process, than a similar effect will arise as with runout. Therefore, the improvement of the dynamical model mentioned before remained a superior problem to be solved first. Once that model is completely understood, it can be generalized further. Otherwise, the models at this point would contain too many critical assumptions, and the actual implementation is far from simulations.

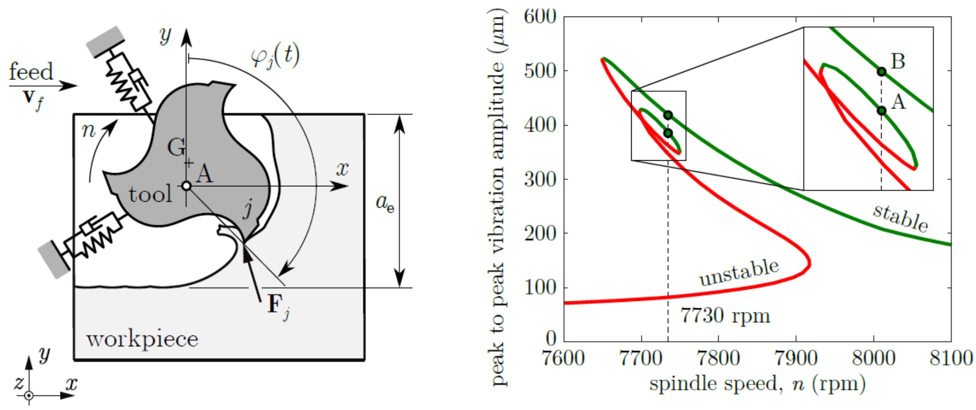

Figure 5. Continuation of the periodic solutions of the nonlinear milling model [4]. *New multiple stable/unstable solution branches are found (points A and B), which are planned to be experimentally validated in the future.*

4. Future research

During the research years of the project, some relevant models have been developed. I have extended a dynamic compensation technique for milling operations, developed a runout model, and a general milling model for various tools combining the effect of forced vibrations. These new nonlinear models required a complex mathematical framework that needed more time (e.g., continuation of periodic solutions, see Figure 5), than the timespan of the project. However, the first validations of the models are performed, and a journal paper will be submitted soon on the topic. The model is being developed, and the continuation of this project will be funded by a Bolyai research grant that starts after the closing of this recent project.

5. Closure

The project supported the investigation of machining operations in terms of robustness to parameter uncertainties and unmodelled dynamics. The research successfully developed new robust computation methods with frequency response function uncertainties and active vibration control. The improved dynamic measurement techniques, cutting force characterizations made it possible to get a deeper insight into the sources of measurement inaccuracies and into the effect of the uncertainties. As a consequence of the detailed investigations, radial tool runout was identified as a key issue that leads to altered stability diagrams and changes in the cutting process dynamics. The investigation triggered further problems to be solved. The results are relevant for practical applications, which are confirmed by the foreign collaborators and industrial colleagues we are working with.

6. Relevant publications

[1] A. K. Kiss, D. Hajdu, D. Bachrathy, G. Stepan, Z. Dombovari, *In-process impulse response of milling to identify stability properties by signal processing*, Journal of Sound and Vibration 527:116849, 2022, 10.1016/j.jsv.2022.116849

[2] D. Hajdu, A. Astarloa, I. Kovacs, Z. Dombovari, *The curved uncut chip thickness model: A general geometric model for mechanistic cutting force predictions*, International Journal of Machine Tools and Manufacture, 2023, 10.1016/j.ijmachtools.2023.104019

[3] D. Hajdu, D. Bachrathy, *Active vibration control for milling operations including frequency response function uncertainties*, 19th CIRP Conference on Modeling of Machining Operations, Procedia CIRP 117:181-186, 2023, 10.1016/j.procir.2023.03.032

[4] D. Hajdu, Z. Dombóvári, *Nonlinear effects in time-periodic cutting operations induced by various edge engagements*, 11th European Nonlinear Dynamics Conference (ENOC), Delft, Netherlands, 2024. (conference abstract)

[5] D. Hajdu L. Balogh, Z. Dombóvári, *Experimental study and numerical simulation of symmetry breaking effect in milling operations*, 17th IFAC Workshop on Time Delay Systems, Montreal, Canada, 2022. (conference abstract)