CLOSING REPORT

Suppression of self-excited vibration in manufacturing processes

Researcher: Zoltan Dombovari, PhD

1 BACKGROUND

The main aim of the project was to develop new mathematical and numerical tools dealing with manufacturing processes such as metal cutting and forming. In both type of processes rotary parts or tools, or both produce the so-called surface regeneration. Machine tools are typically not rigid structures, consequently, those react on the process force sometimes quite violently. Since the geometry of the machined surface is the result of the relative motion of the tool and the workpiece, any vibratory behaviour leaves its mark on the surface. This pattern then fed back to the process due to the rotation of the workpiece (turning), of the tool (milling) or both (axles rolling). This pattern eventually establishes a feedback mechanism, in which the already machined surface excites the system again. This already machined surface carries the past vibratory state of the system, consequently, having dependency from its own delayed states. Moreover, active vibration attenuation techniques introduce sampling and computation lag in the system by their digitalized nature. The project general goal was to improve the mechanical models and numerical tools for predicting their production capabilities of the above-mentioned processes. All of these processes subjected to some form of non-smooth effect like edge fly-over, sampling, saturation or elastic-plastic relay. It is important to mention that this young researcher FK 124361 project was the twin-project of postdoctoral PD 124362 project. Also, both FK and PD projects were extended due to the COVID 19 pandemic, since both were affected and causing serious delays for the PI and in PI's collaboration network.

2 ACHIEVED GOALS

The PI and his group during the project have achieved all major milestones, however,m some results have not reached the expected maturity level due to some modelling constrains. These expected to be corrected after the finish of the project NKFI FK 124361. In both projects three main manufacturing process were dealt with, the time independent turning and the time periodic milling processes where the general aim is to implement parameter optimization and semi-active or active control. The third process was the axles rolling or burnishing cold forming process, which machines contains force control by its nature. Since the PI has long experience in the cutting processes it was not a problem to extend turning and milling models to deal with nonsmooth problems, however in the axles rolling case the underlying mechanics (plasticity) in the process still causes modelling problems.

In turning we had introduced a general actuator close to the tip of the so-called boring tool [1], with which significant improvement can be achieved on the stability properties shown in Fig. 1 *a b*). We have showed, in velocity feedback control the turning process can be unstable in quite unexpected regions [2] presented in Fig. 1 *c*). In the case of use of passive dampers, it is important to increase the mass ratio between the moving mass and the so-called reflected mass of the e.g. boring bar. Due to the limited availability of high-density materials the highest possible volume is needed, which eventually leads to small gaps between the moving mass and the cover. This gap has an essential role operating as a physical "saturation", which limits the overall power of the applied solution. We showed for turning process this can significantly affect the effectivity of any passive solution so as active ones in [3, 4] (Fig. 1 *d*). Semi-active type of piezoelectric circuit solution was theoretically investigated, where we had showed that effectivity of completely passive so-called shunt type of circuits can be improved by using gyrators, which requires power input, however it does not need control law. Thus, in control point of view this system behaves completely as a shunt passive circuits. In this feasibility analysis we had demonstrated improvement on stability of boring (turning) operation [5] (Fig. 1 *e*). We had created an industrial model of robotic manufacturing where the robot control is given and acceleration feedback is applied. For borehole extension it is possible to apply robotic solutions for turning operations, on which we showed that for a given industrial sampling frequency there is optimal rotary speeds, which should be used for the operation achieving higher productivity [6] (Fig. 1 *f*).

Turning is an important process because it is easier to describe mathematically, consequently it is easier to apply control schemes, however, it is well known that measurements, in turning, are most of the times poisoned by still unknown effects. This is why we turn our attention in most cases to milling (Fig. 2 *a*), in which higher rotation speed can be achieved resulting in better environment for model validation. During the project the effect of slowly varying parameters (typically natural frequencies) were dealt with in [7], where we showed that the expected stability limit can shift in the parameter domain and this shift has mathematical reason. In Fig. 2 *b*) the dashed line shows the original "static-parameter" stability limit, while the process escapes seemingly around the predicted continuous black line. In this regard we were able to construct a simple mathematical model where this effect can be derived analytically by applying integration by parts leading to an exact iterative form. This is important because it is extremely hard to perform time-domain simulation regarding to solution escape (stability) in a time-dependent system. Apart from this example, this means, essentially there is no way to know if the solution is a real solution or only a numerical artifact. The presented example serves as a unique benchmark solution for a slowly varying dynamics [8] (Fig. 2 *c*).

We showed that by using pitch angle optimization higher material removal rate can be achieved in [9]. By solving this nonsmooth optimisation problem new stabilization technique is possible for milling cutters Fig. 2 *d*). We also presented a new mathematical formalism for determining grinding tool path for manufacturing harmonically varying milling tool in [10] (Fig. 2 *e f*). In connection to thin-walled workpieces we had presented the analytical dependency of the so-called directional factors, with which the milling operation can be planned approximately [11] (Fig. 3 *a*). We have extended the milling model to the nonlinear domain in [12] (Fig. 3 *b*), where we showed experimentally the appearance of the so-called bistable/unsafe zone. For this, we have developed a general quasi-periodic solver that is capable of dealing with delayed states and additional conditions. We have presented a tunable clamping device, in which we achieved higher stability for flexible workpieces [13] (Fig. 3 *c d*). We also presented an automatic iterative tuning mechanism for the tunable table in [14] (Fig. 3 *e f*). The PI made a proof of concept investigation about the direct derivation of stability limits using impulse response functions in [15], while the same concept was used for setting Kalman filter for a force sensor in [16] (Fig. 4 *a*). We also implemented a general control scheme for milling process resulting in piecewise smooth sampled hybrid system shown in [18, 17] (Fig. 4 *b*).

Describing the axles rolling process we have presented the general nonsmooth model of this process in [19] (Fig. 5 *a*), with which we were able to show this nonsmooth regenerative effect alone can cause instability in the process shown in (Fig. 5 *b*). Moreover, it is important to mention in [19] we used force models originated from the literature, however, recently development is carried out by finding an apropriate force model for axles rolling. To achieve that two different finite element model was developed in MARC and in ANSYS framework. The MARC environment [20] (Fig. 5 *c*) we simulate the process with complete time integration, while in the ANSYS model we perform quasi-static cases (Fig. 5 *d*).

Regarding to the experimental validation of the axles rolling process, there was a fruitfull and quite intense industrial collaboration. The Hungarian side had provided all the design skills and manufacturing including the high load force cell (Fig. 6 *a*), while the industrial partners had provided the linear roller guide system (Fig. 6 *b*). This linear roller guide system was bayond the reach of the project not only in terms of cost, in terms of order-ability as well. Also our industrial partner had provided the exact industrial roller assembly and the train shaft workpiece as well. We had developed an online data acquisition system (Fig. 6 *c*), with which the operation was possible to be measured synchronously with the rolling force, feed motion and indentation. A surface scanning methodology was designed to scan the surface before and after the operation (Fig. 6 *d*). Regarding to the results, by using the FEM models, we had showed that both the residual stresses and the rolling force depends on the feed. In fact there is an achievable feed at which the rolling force drops significantly. Time domain simulation (Fig. 6 *e*) showed that by increasing feed dynamic stability actually increases, so this creates a desired situation when process force drops and the process becomes even more stable. By using the retrofitted high load rolling machine we were able to show this effect however it is hard to compare with the FEM results (Fig. 7 *a*). The reason for this is that the FEM solution is indentation driven, while the experiment is force driven, this means during the experiment we essentially measue the inverse of the FEM results (Fig. 7 *b*). This creates a serious problem in the post processing phase, which had significantly increased the publication time a bit over the closing date of the project. In (Fig. 7 *a b*) one can recognise the local minimum and maximums on the indentation driven FEM and force driven experimental results. In the experiment we had used a much more reliable novel ditch-measurement what we had developed by performing huge amount of measurements (Fig. 7 *d*). It is important to emphasize in the retrofitted rolling measurement test rig (Fig. 7 *c*) we had developped a necessary turning capability to prepare the surface for the rolling process. The preparation was a half day long preparation to achieve flawless turned surface to perform five consecutive passes for axles rolling processes in couple of minutes.

3 ONGOING RESEARCH

The force characterization of the axles rolling process has been finished, however we suffer on some evaluation problem regarding to comparability of the FEM, plasticity modelling issues in the time domain simulation and the actual experimental results. In the FEM results the interpolation between calculation points pose a problem, for which we used the so/called latin hypercube sampling. In the time domain simulation, the volume preserving property of the plastic deformation gives hard time in modelling. In the experimental result the preparation surface property is a huge issue, since the surface waviness and roughness can be figured out after the measurement analyzing the scanning data. Consequently, it happened quite often the surface preparation was not adequate but it was realized after the complete batch of measurement was already performed. Therefore, this overcoming of the previously mentioned problems are still going on and hopefully will be solved in the end to achieve a publishable form of our findings.

4 EXPLOITATIVE RESULTS

The design of the tunable table was submitted to the Hungarian Patent Office and the decision of the acceptance was received recently in an official decree [21]. The patent is going to defend the general idea behind the tuneable table, which can be used for thin wall machining as a mountable clamping device or as part of the machine table. We expect some success on this patent regarding to the general roadmap of the Industry 4.0 concept, which idealizes an automated self-reliant manufacturing cell solution, in which tuneable embedded clamping devices might play an important role in the future.

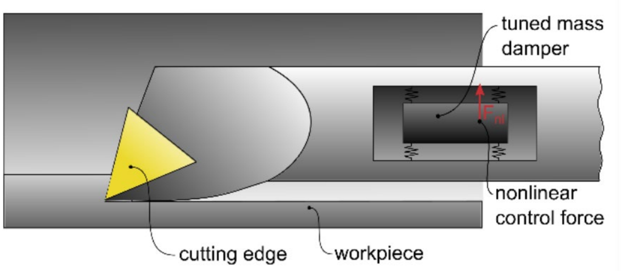
5 DISSEMINATION

In publication point of view the project can present some quite prestigious scientific dissemination of some of the results. The experimental validation of the bistable zone in milling is presented in the Transactions of the Royal Society A [12], while the tunable table design was presented in the CIRP Annals Manufacturing Technology [13]. This result has a accepted (Hungarian) patented also in [21]. A journal paper [17] about the effect of sampling was accepted by the ASME Journal of Computational and Nonlinear Dynamics. Regarding to the limitations of passive dampers our manuscript was accepted by the Journal of Sound and Vibration [4]. The effect of acceleration feedback control on robotic machining was accepted by International Journal of Non-linear Mechanics [22]. In conference-wise the project participated in prestigious conferences like ASME [6, 18, 23, 24, 25, 26], IFAC TDS [19], CIRP HPC [7], HSM [1] and in the most respected dynamics conference the ISMA [8, 27]. The project and the PI are represented themselves in the most important Turkish manufacturing conference in the UTIS [20] and in the Hungarian Mechanical Conference [28, 29]. In the end of the twin project, as a closure, the PI expects to have a summary paper in the prestigious CIRP Annals Manufacturing Technology about axles rolling experiments. The results of the project can be openly followed in the webpage (https://www.mm.bme.hu/sci/nkfifk124361/news.html)

6 COLLABORATION AND IMPACT ON PI'S RESEARCH

The PI was able further grow his collaboration network by having important research with Giovanni Totis from University of Udine (Italy), who is a research director in LAMA. The PI continued the fruitful collaboration with Ideko, which is a Spanish (Basque) Research Centre. This is an important connection, where the PI can earn ideas for future seed projects, since their main interest to solve problems for their mother company who is a World leading machine tool builder the DanobatGroup. As it can be seen in the publications, further collaboration is going on related to varying dynamic modelling with Rachel Kuske from GeorgiaTech (USA). Furthermore, the PI has very good relationship with Irino Naruhiro, who is the science director of the World leading DMGMori (Japan).

a) damped boring bar control development [1]



b) advanced stability of boring bars [1]

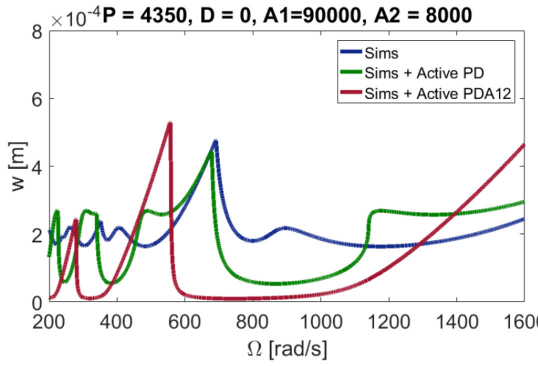
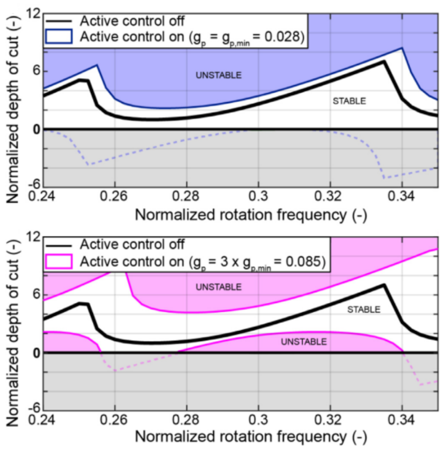
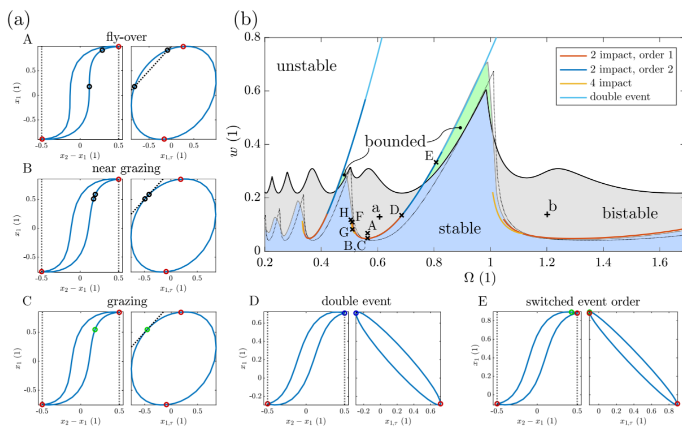


Fig. 8: The effect of PD and PDA12 control on the boring process.

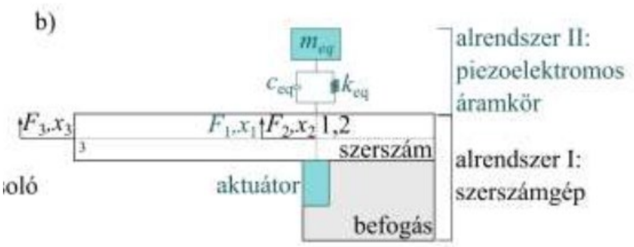
c) unstable control at 0 depth of cut [2]



d) tphe effect of gap limitation on passive dampers [4]



e) piezoelectric semi-active boring tool holder [5]



f) borehole extension (turning) with industrial robot [6]

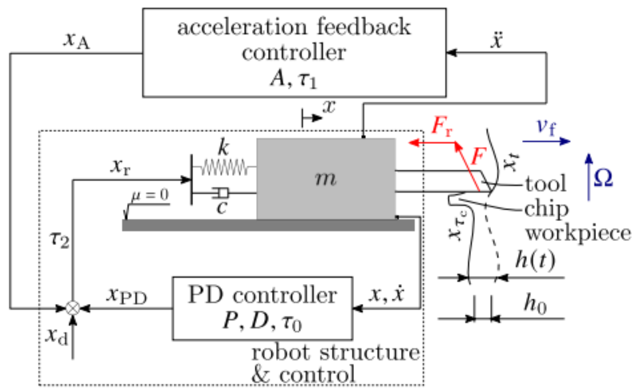


Fig. 1. Montage of the results achieved in NKFI PD 124361 project related to turning processes.

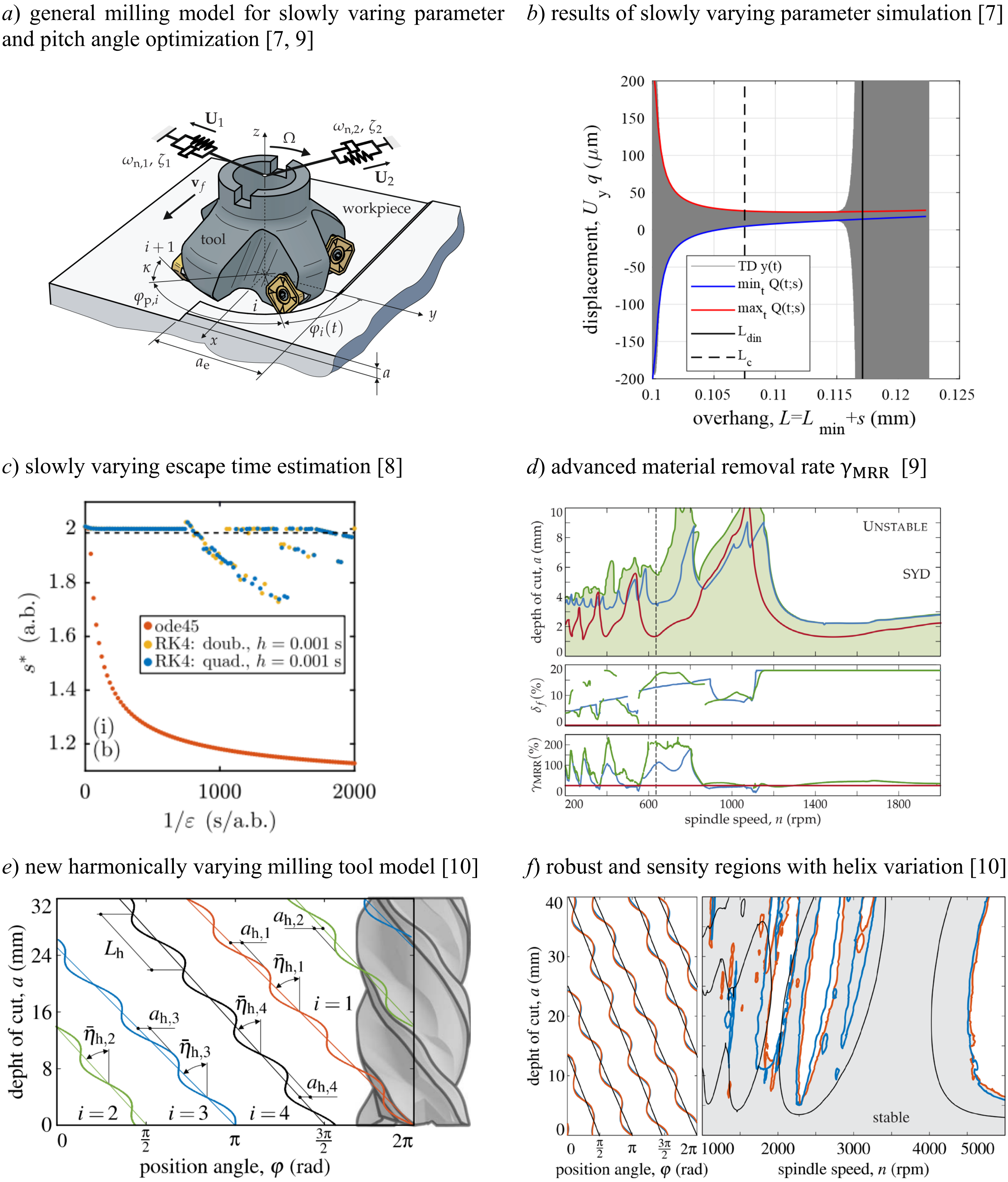


Fig. 2. Montage of the results achieved in NKFI PD 124361 project related to milling processes.

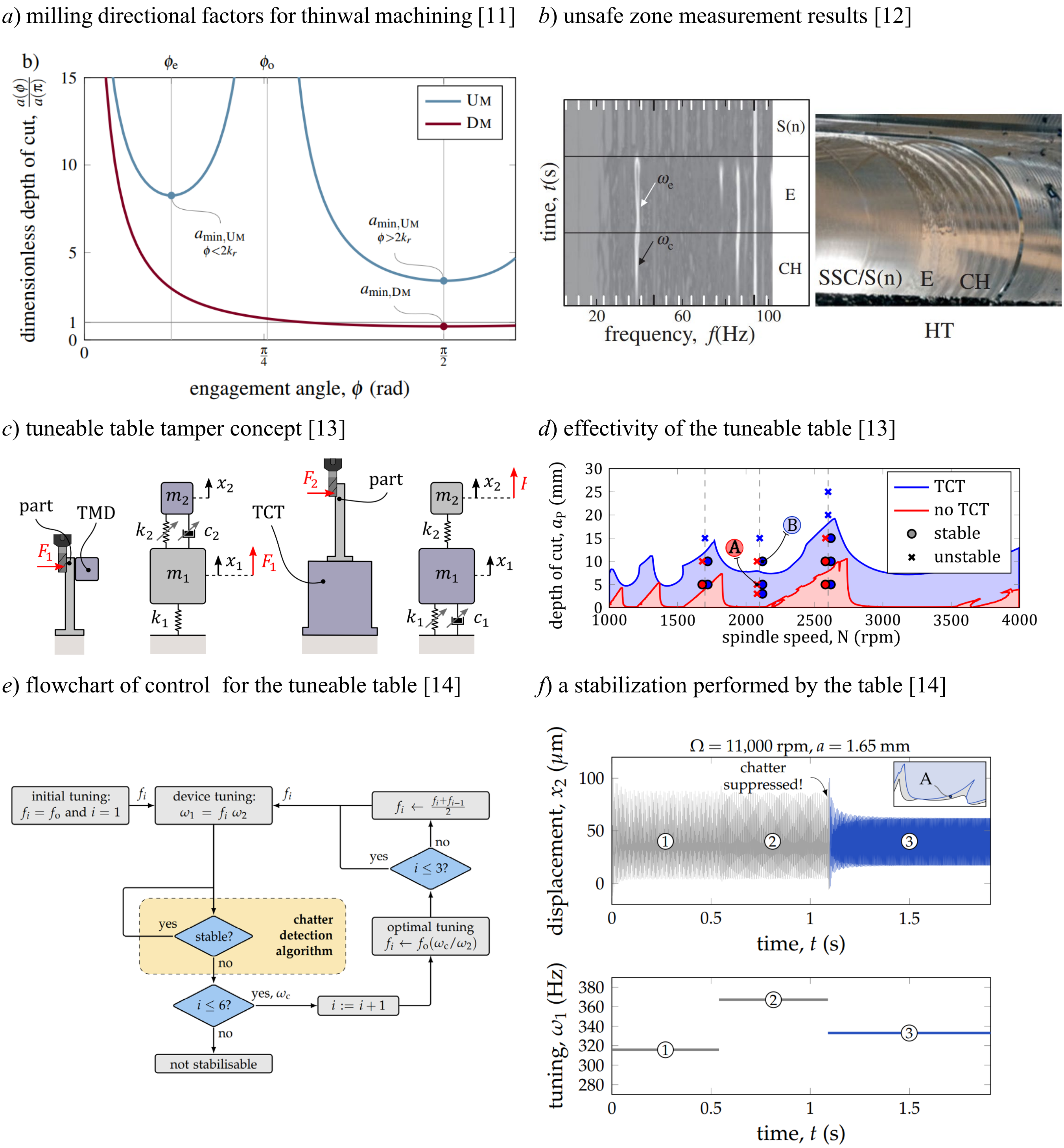
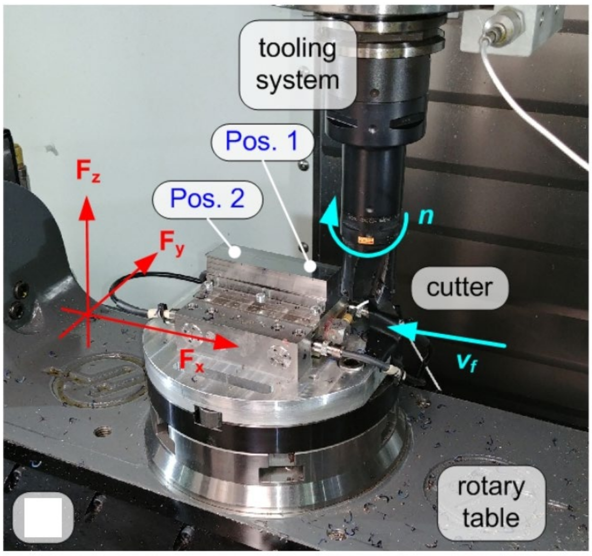


Fig. 3. Montage of the results achieved in NKFI PD 124361 project related to milling processes.

a) special load cell measurement [16]



b) model of general active milling process [18, 17]

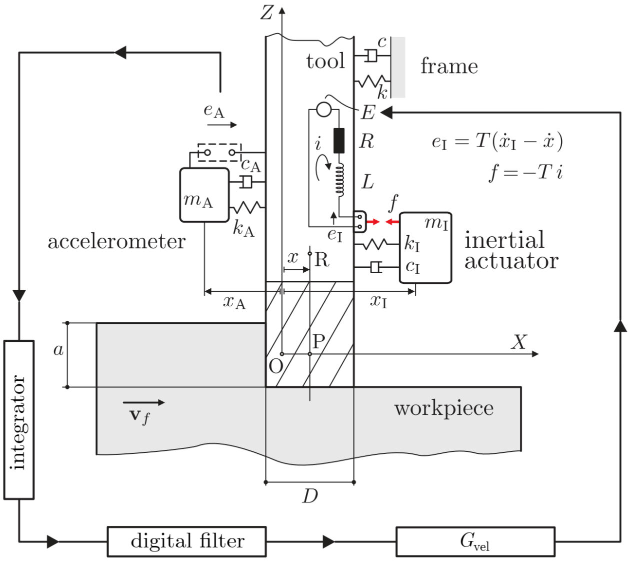
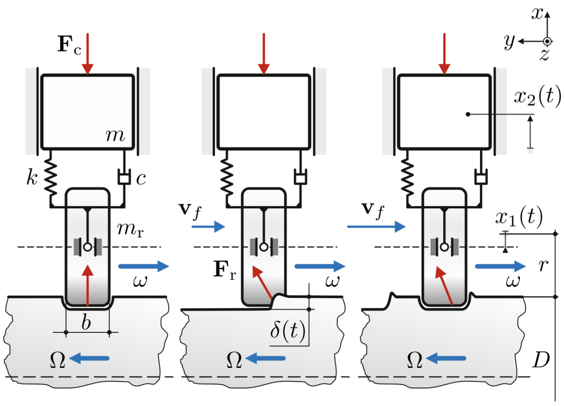
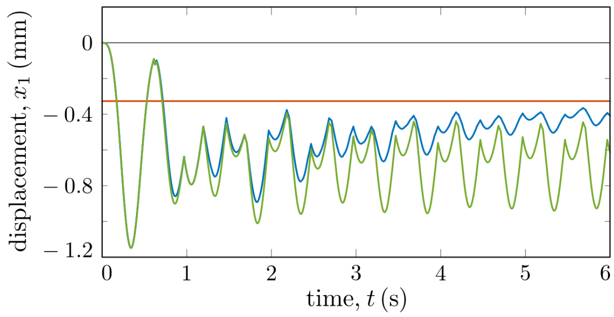


Fig. 4. Montage of the results achieved in NKFI PD 124361 project.

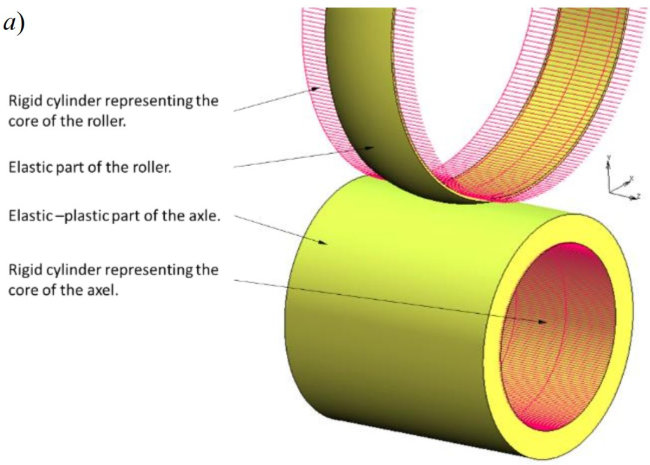
a) axles rolling nonsmooth model [19]



b) axles rolling model shows stable and unstable rolling [19]



c) axles rolling complete time simulation MARC-based FEM model [20]



d) quasi-static Ansys-based FEM mode

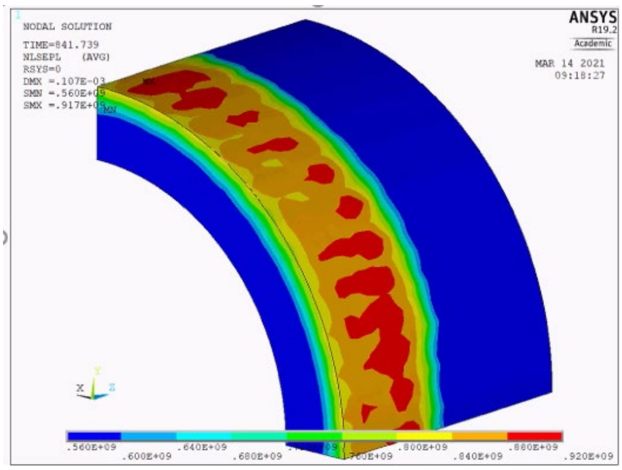
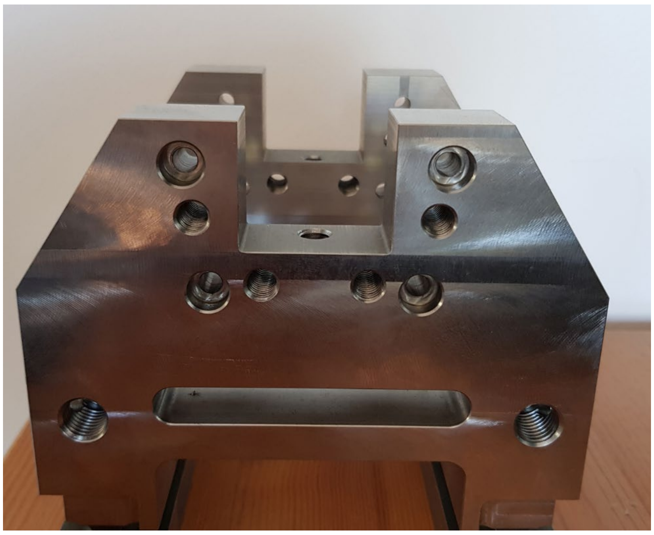
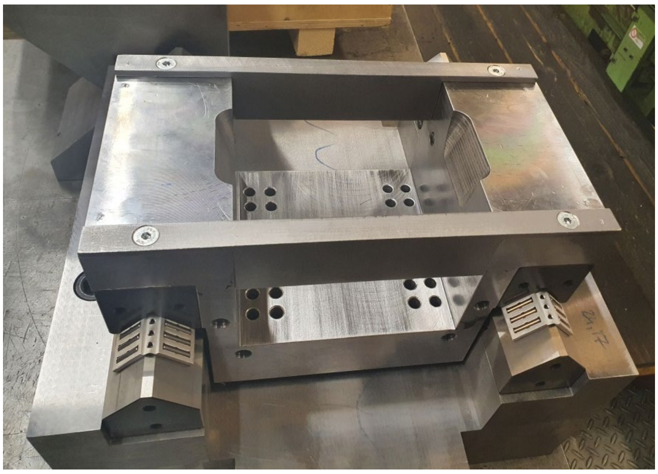


Fig. 5. Montage of the results achieved in NKFI PD 124361 project related to axles rolling process.

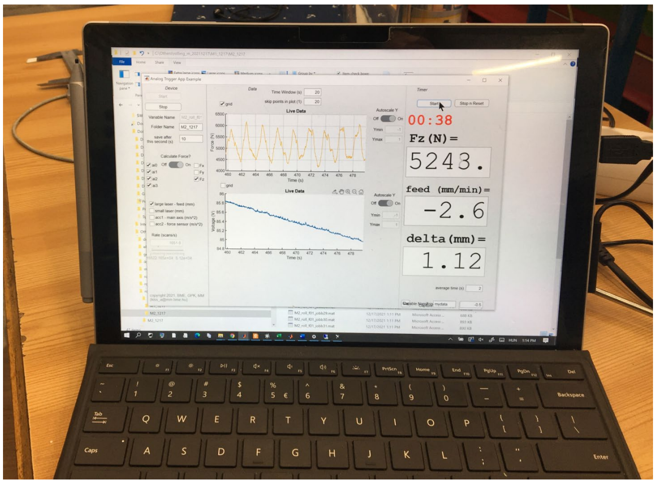
a) body work of the high load rolling force sensor



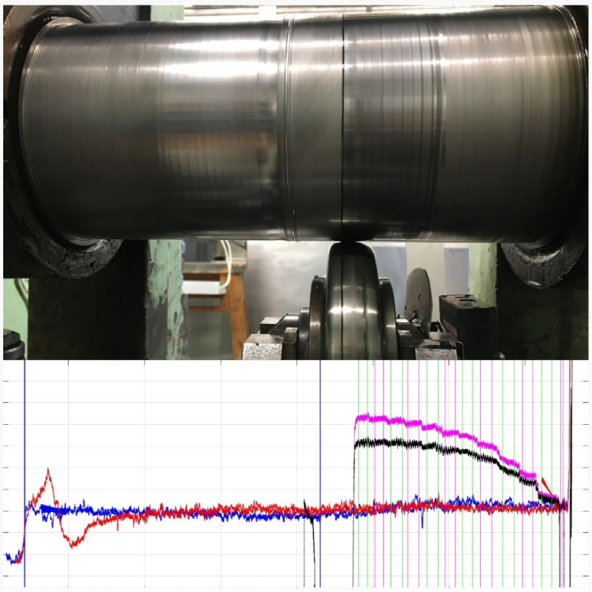
b) retrofitted rolling machine roller guide system



c) online rolling process force monitoring system

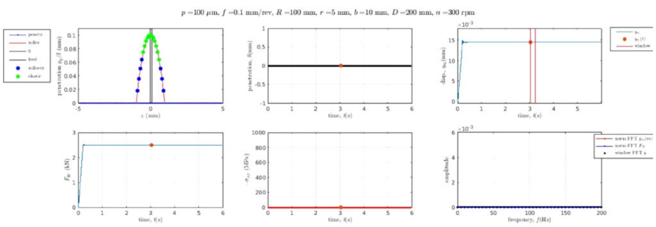


d) sample for “ditch” measurement

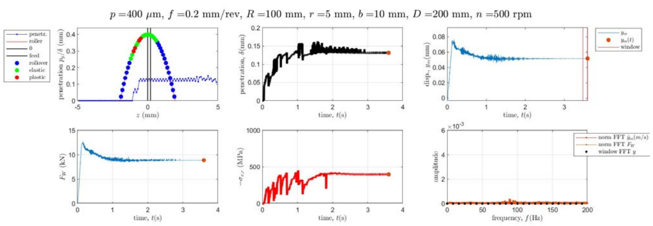


e) rolling process simulation

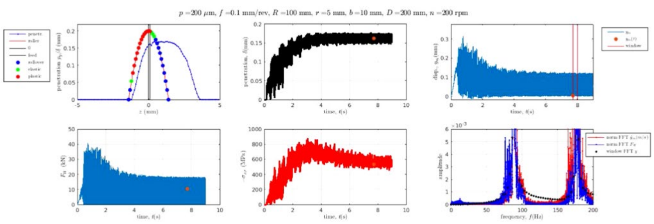
i) inefficient rollingforce, no deformation



ii) stable axles rolling process



iii) unstable axles rolling process



iv) stable deep low feed axles rolling

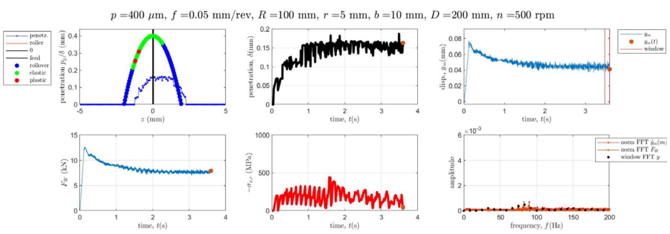
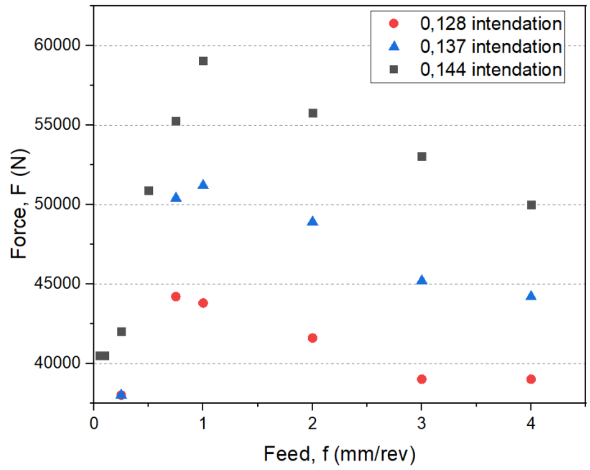
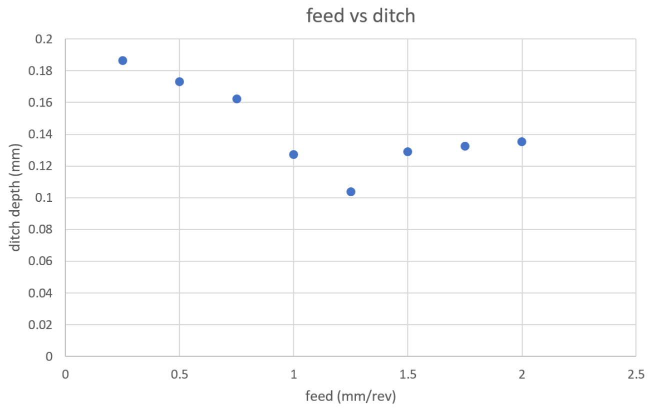


Fig. 6. Montage of the results achieved in NKFI PD 124361 project related to axles rolling process.

a) FEM feed characteristics (indentation driven)



b) experimental feed characteristics (force driven)



c) completely retrofitted rolling machine with new feed drive, horizontal guide, force sensor and roller device.

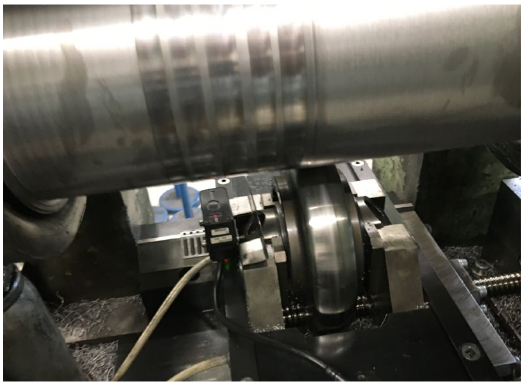


Fig. 7. Montage of the results achieved in NKFI PD 124361 project related to axles rolling process.

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