CLOSING REPORT

Modelling of non-smooth behaviour in manufacturing related self-excited vibration problems

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1 BACKGROUND

The main aim of the project was to develop new mathematical and numerical tools to deal 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. 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 postdoctoral PD 124362 project is the twin-project of the young researcher FK 124361, which is still running for a year. Also, both PD and FK 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 during the project has achieved all major milestones however some results has not reached the expected maturity level due to some modelling issues. These expected to be corrected during the end of the twin 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 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 these models to deal with nonsmooth problems, however in the axles rolling case the underlying mechanics in the process still causes modelling issues.

In turning we had introduced a general actuator close to the tip of the so-called boring tool [13], with which significant improvement can be achieved on the stability properties shown in Fig. 1 *gh*). We have showed, in velocity feedback control the turning process can be unstable in quite unexpected regions [6] presented in 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, in which higher rotation speed can be achieved resulting in better environment for validation. During the project the effect of slowly varying parameters (typically natural frequencies) were dealt with in [2], where we showed that the expected stability limit can shift in the parameter domain and this shift has mathematical reason. In Fig. 1 *c*) the dashed line shows the original "static-parameter" stability limit, while the process escapes seemingly around the predicted continuous black line. We showed that by using pitch angle optimization higher material removal rate can be achieved in [8]. By solving this nonsmooth optimisation problem new stabilization technique is possible for milling cutters Fig. 1 *e*). We also presented a new mathematical formalism for determining grinding tool path for manufacturing harmonically varying milling tool in [16] (Fig. 1 *kl*). We have extended the milling model to the nonlinear domain in [4] (Fig. 1 *j*), 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 to deal with delayed states and additional conditions. We have presented a tunable clamping device in which we achieved higher stability for flexible workpieces [15] (Fig. 1 *mn*). We also presented an automatic iterative tuning mechanism for the tunable table in [18] (Fig. 1 *op*). The PI made a proof of concept investigation about the direct derivation of stability limits using impulse response functions in [17] (Fig. 1 *q*), while the same concept was used for setting Kalman filter for a force sensor in [14] (Fig. 1 *rs*). We also implemented a general control scheme for milling process resulting in piecewise smooth sampled hybrid system shown in [5, 19] (Fig. 1 *t*). Describing the rolling process we have presented the general nonsmooth model of this process in [1] (Fig. 1 *b*), with which we were able to show this nonsmooth regenerative effect alone can cause instability in the process shown in (Fig. 1 *d*). Moreover, it is important to mention in [1] 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 [3] (Fig. 1 *u*) we simulate the process with complete time integration, while in the ANSYS model we perform quasi-static cases (Fig. 1 *v*).

3 ONGOING RESEARCH

As it was mentioned the piecewise smooth elastic/plastic relay model of axles rolling process is not completely finished, due to the lack of mature force model for the process. We try to compile a hybrid FEM-based model, in which a FEM simulation-based function will play the main role. This simulation-based function is compiled by performing fitting on so-called latin cube calculation. Also, during the project a measurement test bench is also built for testing axles rolling process. It is expected to have the comparison result in the end of 2021 resulting in the extension of the main project NKFI FK 124361.

4 EXPLOITATIVE RESULTS

The design of the tunable table was submitted to the Hungarian Patent Office and we still waiting for decision [20]. 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.

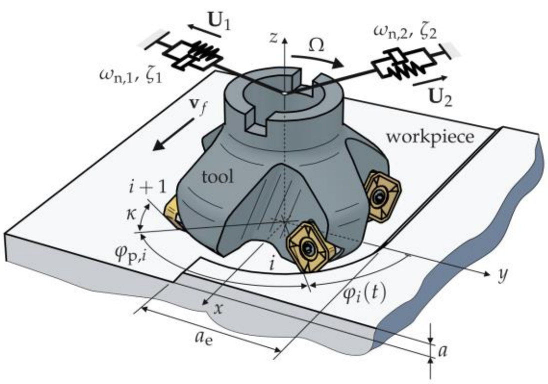
5 DISSEMINATION

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 [4], while the tunable table design was presented in the CIRP Annals Manufacturing Technology [15]. This result has a submitted patented also in [20]. We also submitted a journal paper [19] in the ASME Journal of Computational and Nonlinear Dynamics, for which we expect to have decision soon. In conference-wise the project participated in prestigious conferences like ASME [5, 7, 9], IFACTDS [1], CIRP HPC [2] and HSM [13]. The project and the PI are represented themselves in the most important Turkish manufacturing conference in the UTIS [3] and in the Hungarian Mechanical Conference [11, 12]. 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 rolling modelling. The results of the project can be openly followed in the webpage (https://www.mm.bme.hu/sci/nkfifk124361/news.html)

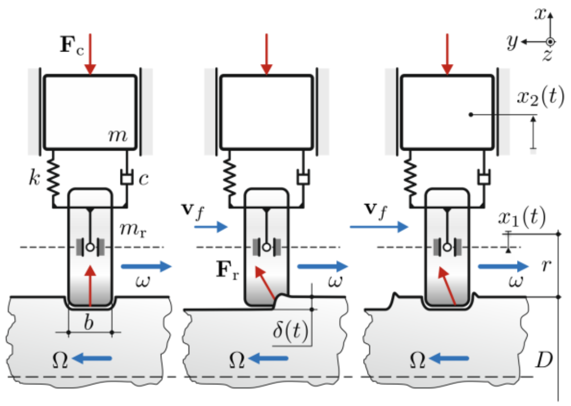
6 COLLABORATION AND IMPACT ON PI’S RESEARCH

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 engineer 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 Danobat. As it can be seen in the publications, further collaboration is going on related to varying dynamic modelling with Rachel Kuske from GeorgiaTech (USA).

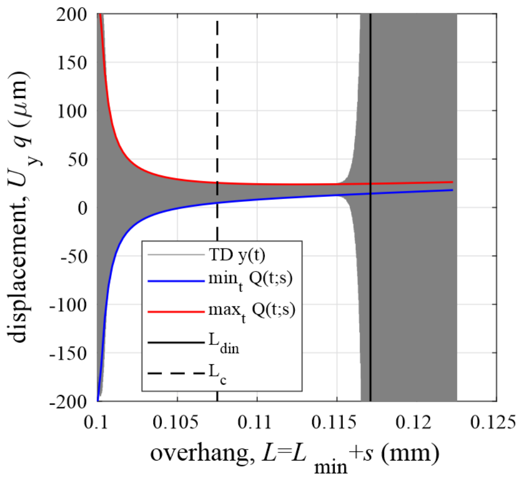
a) general milling model for slowly varing parameter and pitch angle optimization [2, 8]



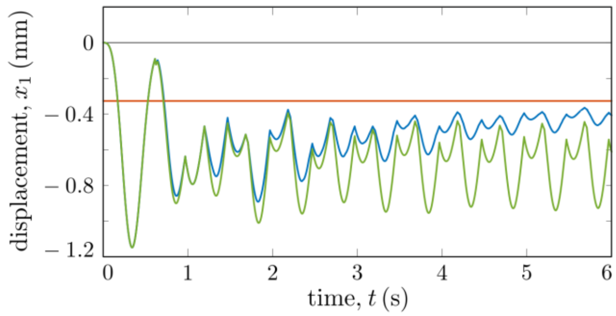
b) axles rolling nonsmooth model [1]



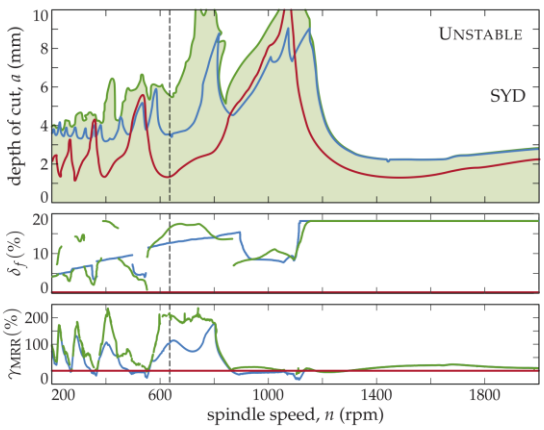
c) results of slowly varying parameter simulation [2]



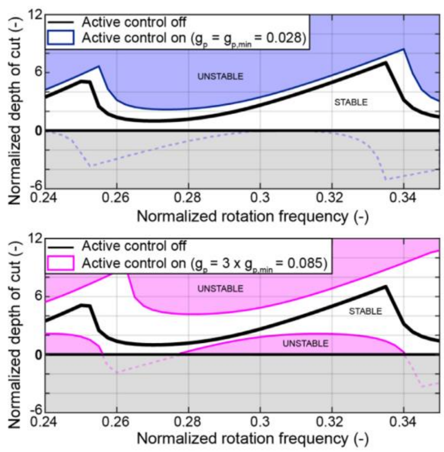
d) axles rolling model shows stable and unstable rolling [1]



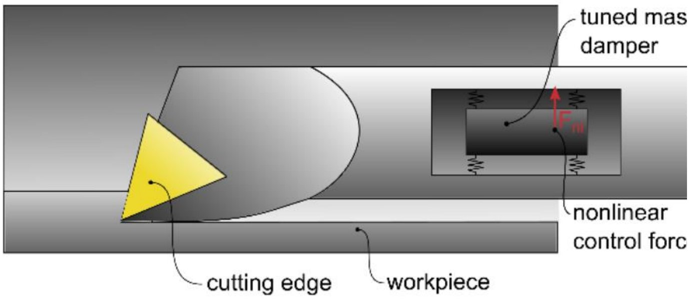
e) advanced material removal rate γ_{MRR} [8]



f) unstable control at 0 depth of cut [6]



g) damped boring bar control development [13]



h) advanced stability of boring bars [13]

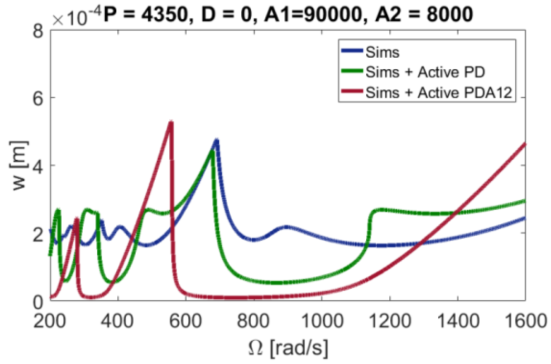
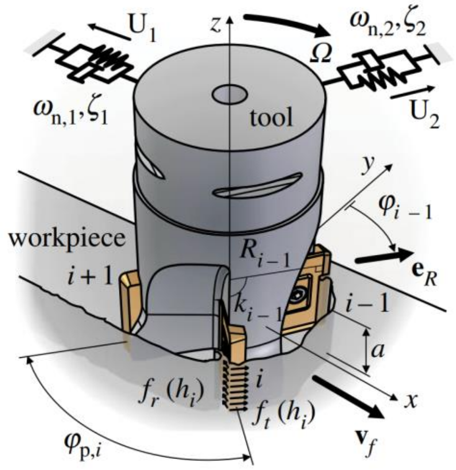
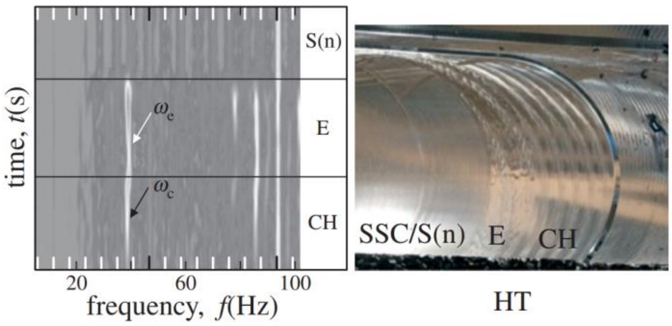


Fig. 8: The effect of PD and PDA12 control on the boring [sic] process.

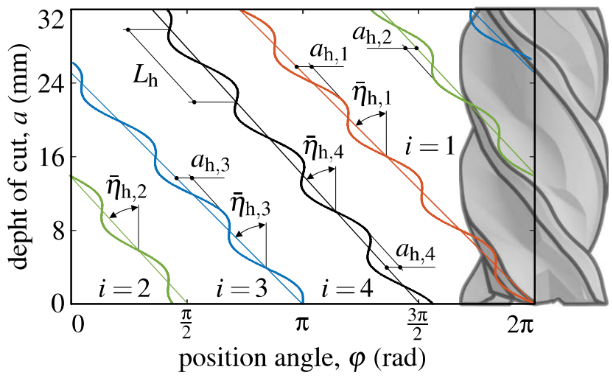
i) nonlinear milling model [4]



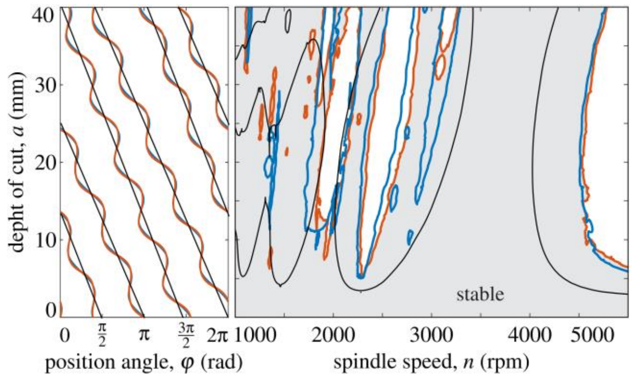
j) unsafe zone measurement results [4]



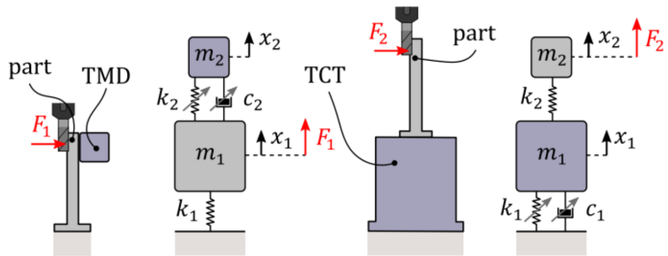
k) new harmonically varying milling tool model [16]



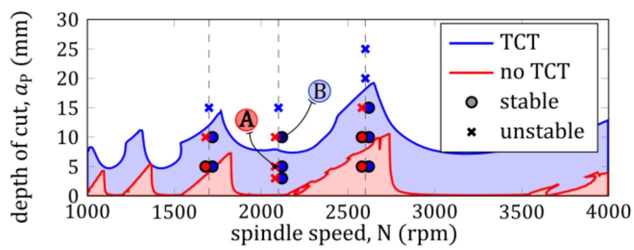
l) robust and sensity regions with helix variation [16]



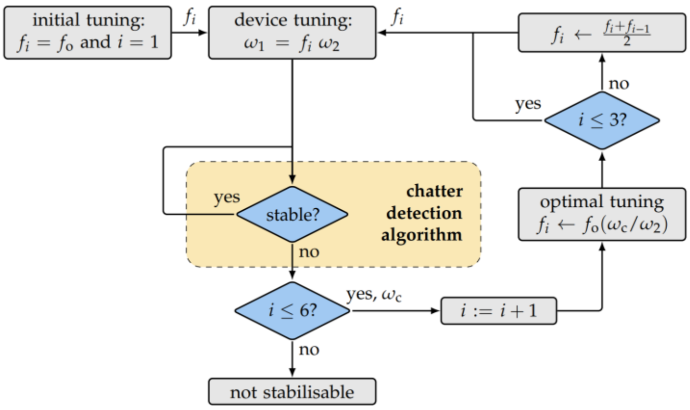
m) tuneable table tamper concept [15]



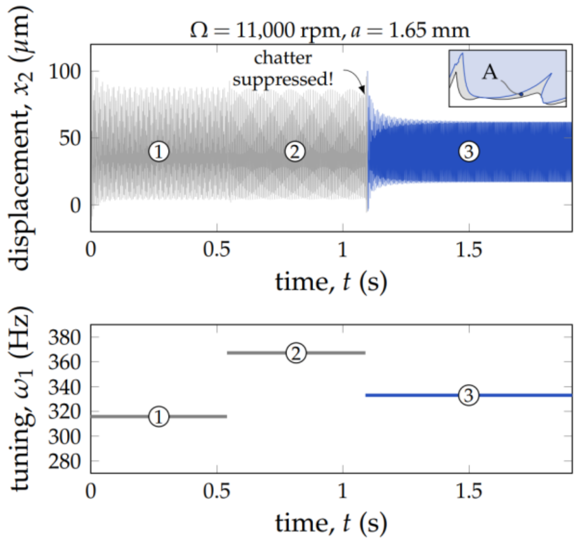
n) effectivity of the tuneable table [15]



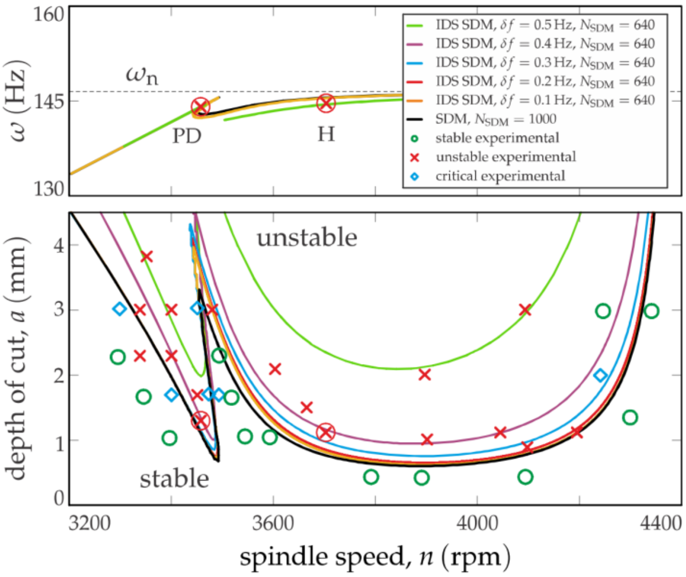
o) flowchart of control developed for the tuneable table [18]



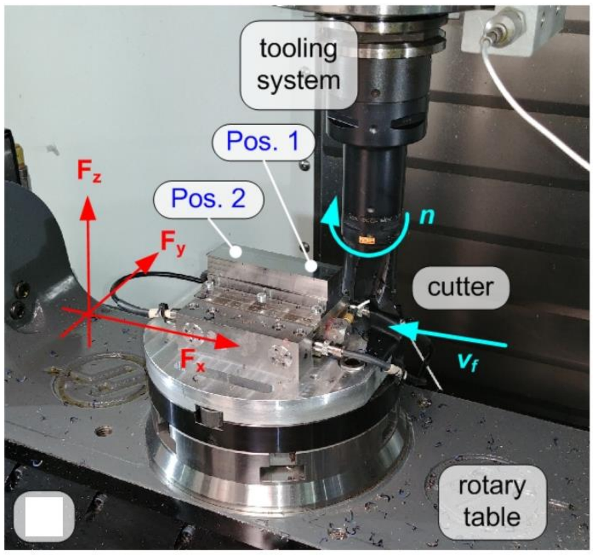
p) a stabilization performed by the table [18]



q) stability boundaries constructed using IDS [17]

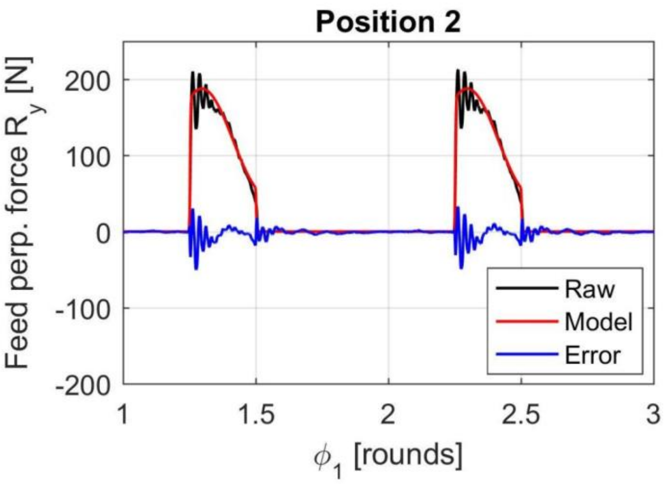


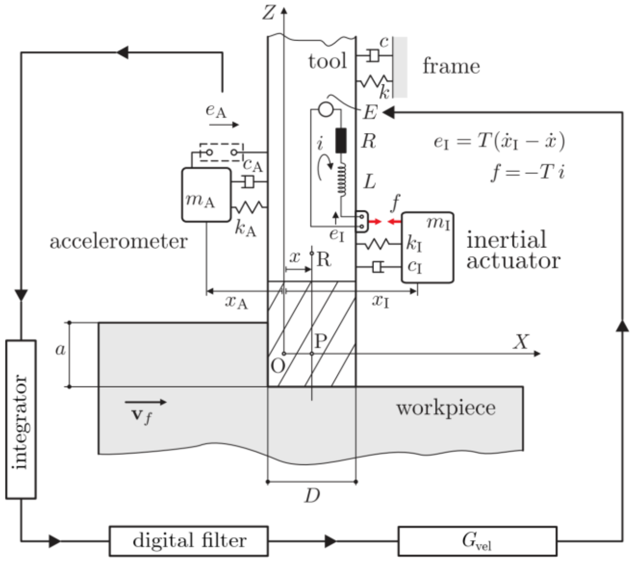
r) special load cell measurement [14]



s) compensate load cell measurement by Kalman filter using IDS [14]

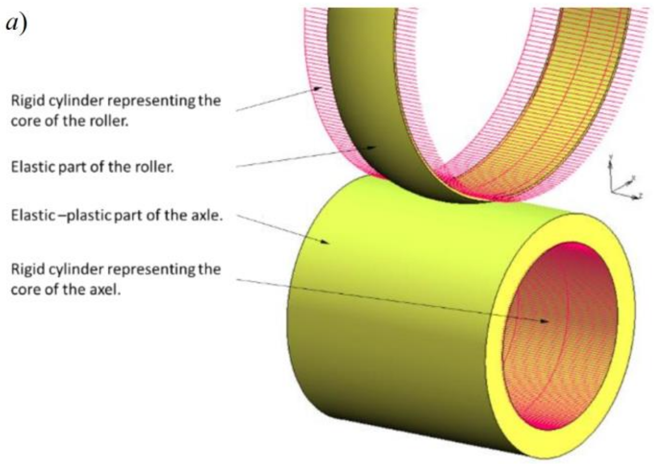
t) model of general active milling process [5, 19]





u) axles rolling complete time simulation MARC-based FEM model [3]

v) quasi-static Ansys-based FEM mode



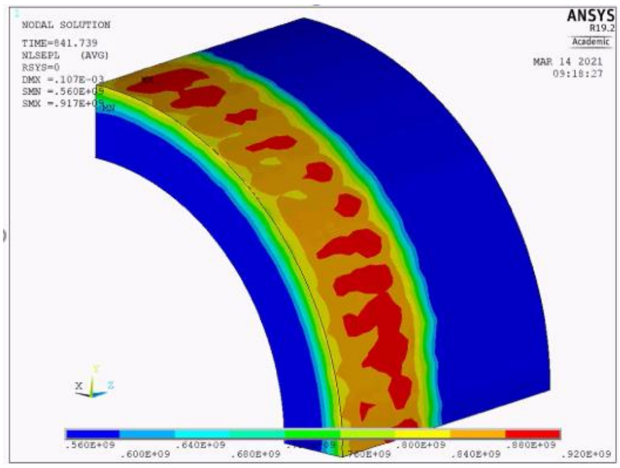


Fig. 1. Montage of the results achieved in NKFI PD 124362 project.

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