**CLOSING REPORT**

Development of engineering measurement methodologies for identification of nonlinear mechanical effects

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## 1 BACKGROUND

Machine tools have complex mechanical structures with large connecting parts all subjected to the nonlinear and intermittent periodic cutting forces in case of milling operations. In the recent OTKA PD (108779) project, modelling and experimental problems with the machine tool structure and the nonlinear/nonsmooth behaviour of the milling force were investigated. Structural nonlinearities are especially important to be dealt with properly during the characterization of the machine tool. The minimal requirement is that to at least showing whether the usual linear techniques are in their working range at all. On the other hand, it would be important to determine a measure for a given nonlinearity of the machine tool structure. Also, it is well known the operational dynamics very much differs from the dynamics measured in steady case, which problem is usually faced in modelling. The cutting force characteristics also introduces a difficult-to-handle factor, because it is often nonlinear introducing bistable nonlinear effect disturbing the pure prediction of linear stability analysis.

## 2 ACHIEVED GOALS

The project achieved goals in both research topics, namely in 'Method of experimental nonlinear modal analysis' and in 'Unsafe zone investigation of milling processes', although in a different scale. It was clear in the beginning building the measurement equipment for the nonlinear structural investigation will delay that part. Also, the main measurements related to the second part were performed in IK4-Ideko (in the research partner by the PI, Figure 1*f*), which delayed the 'practical-side' publication about the nonlinear hysteresis effect of the milling machine. In this manner, the project carried many important results explained below, but the whole picture (Figure 1) needs more time to mature. Overall the project had achieved goals to accelerate industrial measurement techniques.

Before any nonlinear investigation it is important to make sure that the linear theories are matching with the reality. This was presented in [1, 11], where the experimental stability boundaries were checked for different cylindrical milling tools. In these calculations it was clear achieving high frequency ratios the so-called semi-discretization needs to be improved in its efficiency. Introducing implicit subspace iteration the high frequency ratio ranges were also achieved in the developed numerics [2]. From numerical point of view the project has developed a fast algorithm, with which the so-called period doubling stability limits can be calculated extremely fast [7].

The project presented a completely new method achieving the modal modelling of a mechanical structure in a rather new way (Figure 1*a*). This can be considered as one of the strong point of the project's achievements [9], which is unavoidable even for nonlinear structural characterizations. This method can be used also to compile data in operational modal analysis. In this case the question was, is this “steady” dynamics really changing during the cutting operation? In order to see the effect, the excitation was made by the periodic cutting force itself [8].

Stability predictions can be performed in two ways based on frequency domain and time domain solutions. Frequency domain solutions usually more inaccurate and does not need expert interaction for fitting, while time domain predictions are more time consuming, accurate and fitting are necessary for predicting dynamic parameters. A unique method was developed that combines both together actually based on the impulse response space introduced in [9]. This method [3] is able to perform time domain predictions without the need of any fitting on the so-called frequency response functions and by any extraction of the so-called modal parameters (Figure 1*c*).

In order to investigate the effect of the nonlinear and nonsmooth cutting force in milling operation a strict modelling of the operation was carried out. The very first nonsmooth milling model (Figure 1*b*) was presented in the oldest and widely respected scientific journal [4]. In this paper a numerical method is presented to calculate the unstable, nonlinear torus solution that emerged from the linear stability limits. The paper shows calculations for one and more practical two degrees of freedom milling operations with one and two parameter continuations. Since this numerical calculation is time consuming an analytical method was developed to extend semi-discretization for nonlinear systems and perform central manifold reduction for time-periodic systems presented in [15]. Further development of [4] allows predictions on attraction zone that is an important measure for the quality of linear stability predictions [12] (Figure 1*d*).

Closely related to the knowhow in the project, the dynamic behaviour of a newly designed variable stiffness semi-active vibration absorber is shown in [5]. This designed variable passive damper is realized in a fixturing system on which tests proved its effectivity [6]. Also based on the now optimized semi-discretization code a general numerical method is developed for variable pitch optimization [13], which is able to take into account the nonlinearities involved in the dynamic characterization of the machine tool. The dynamic modelling of mechanical structures were tested in metal foams, where material properties were determined by the modal analysis knowledge involved in the project [14, 10].

## 3 ONGOING RESEARCH

The project envisioned a nonlinear structural and dynamic measurements, which were both carried out. However, in the case of the nonlinear structural measurement some theoretical obstacles arisen, which are all slowly under releasing. These obstacles are related to the nonlinear version of the completely new description (‘impulse dynamic subspace’) introduced in [9]. The main goal was to develop an ‘easy’ nonlinear measurement technique, which was partially done (Figure *e*). On the self-made measurement rig now it is possible to test measurement methods and results are expected for publications.

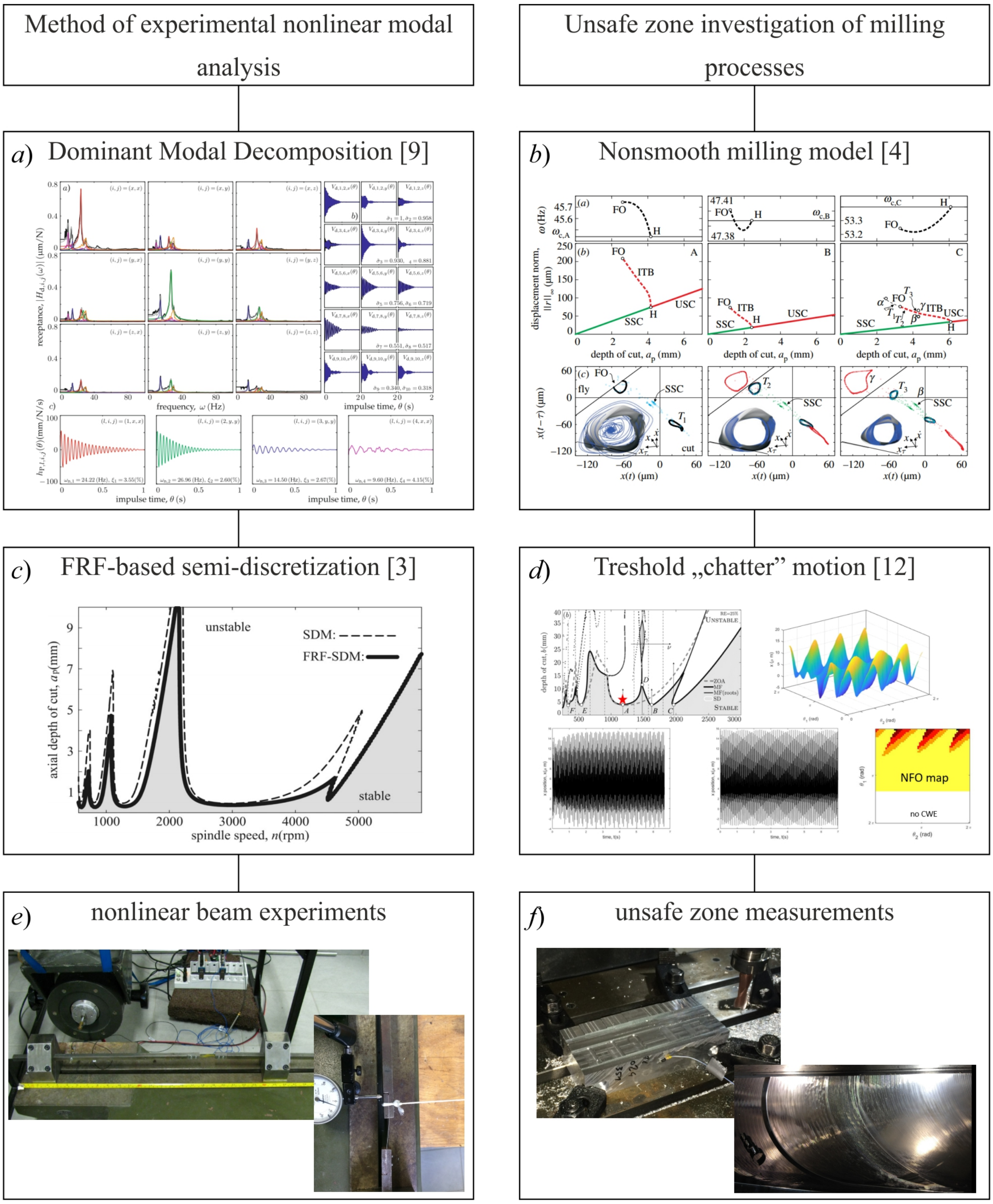


Figure 1. Summary of the main research path of OTKA PD 108779

Also in terms of the nonlinear and nonsmooth effects during milling operations the measurements were performed in our research partner (IK4-Ideko) although the publication is still under construction (Figure 1*f*).

## 4 EXPLOITATIVE RESULTS

In the framework of the project there are several achievements, which are clearly shows the strength of the project carried out. The semi-discretization was made efficient by applying subspace iteration for large frequency ratios [2]. The first nonsmooth milling model was developed [4]. A novel modal analysis technique was developed [9]. Dynamic testing was developed that can be used on an operating machine tool using the cutting force as excitation [8]. And lastly, it is possible to use the semi-discretisation method for nonlinear systems [15].

In summary the project was able to make impact on the industry related to dynamic characterizations of machines and on improving milling mechanical models. The project also presents numerical and applied mathematical improvements, that are all can be used for future efforts of the PI.

## 5 DISSEMINATION

During the OTKA PD project seven journal papers were published, among which six were done in Q1 journals. Approximately the overall impact factor contribution is 19,8. During the project the published papers are received 19 independent Web of Science (WOS) citations, based on which the project can be considered as a well-received international contribution. It is important to emphasize the project was able to publish in the oldest and well respected journal in the Phil.Trans.[1] [4]. Two papers were published in the most respected journal of production technology (CIRP Annals) [1, 6]. Two other papers were published in one of the most respected vibration engineering journal (Journal of Sound and Vibration) [9, 7]. One of this was completely a solo work of the PI [9]. During the project the PI sent 7 proceedings or extended abstract to international conferences. It is important to highlight the CIRP organized conferences [3, 5, 8].

## 6 COLLABORATION AND IMPACT ON PI'S RESEARCH

The project facilitated the PI's collaborative work. The PI was in constant connection with his production technology partner IK4-Ideko. Collaborations were established around the material models of metal foams, too. For the request of Dr. Imre Orbulov (Department of Materials Science and Engineering, BME) homogenised material properties were determined using modal analysis techniques, which results were published in [14, 10]. As an important collaboration Rachel Kuske (GT, Atlanta, USA) can be mentioned, with whom large amplitude threshold (chattering) motions are modelled and presented in [12]. Also the PI had collaboration with the Sándor Beregi [16], who is the member of vehicle dynamics team in the Department of Applied Mechanics in BME lead by Dr. Dénes Takács. In his study the nonlinear dynamics of towed elastic wheels is investigated considering the effect of contact-delay in the tyre-ground interaction and the non-smoothness caused by dry friction simultaneously. This enabled us to identify subcritical Hopf bifurcation of the equilibrium corresponding to the straight-line motion creating a bistable parameter range beside the linearly stable domain where a stable equilibrium and periodic orbit coexist.

The project initiated several seed projects for the PI. It is important to predict the nonsmooth threshold (chatteing) motion in order to predict the attraction zone of the linearly stable domains. Furthermore, with these threshold orbits presented in [12], even the chattering milling operations can be

[1] Philosophical Transactions of the Royal Society A, Mathematical, Physical and Engineering Sciences

characterised. It is well known in the industry not all chattering motions are arisen as a sever significant vibrations. Especially, high frequency modes introduce moderate energy contribution compared to the already present forced vibration. Also, the collaborative work with Rachel Kuske had initiated another seed project related to the slowly changing dynamics of the milling operation. This envisions such stability calculations where the effect of the slowly changing parameters are taking into account. These models will be well received in the industry and in the applied mathematical society, too. Also based on the effective way of calculating stability of stationary cutting solution it is possible to optimize milling tool geometry [13], which is a future direction to have better more effective milling operations.

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