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Budapest University of Technology and Economics
Department of Applied Mechanics

Booklet of PhD Theses

**Local and Global Dynamics of Cutting
Processes**

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Introduction

“... In addition, chatter is so inconsistent in character that the tendency of a machine to exhibit chatter effects is often not observed during the development stage.”
Tobias, S.A.¹

Many different types of machine tools are available in the market to satisfy the requirements that appear in production. It is important to note that nowadays, machine tool builders offer entire manufacturing procedures besides the individual machines. This fact forces the machine tool builders to not only design the machines but plan reliable operations for them, which fulfil the productivity requirements of the customers. In order to be successful in this competition, they increasingly start using simulation/optimization techniques to predict the limits of the offered machining procedure. Among other problems, the following tasks need preliminary planning: optimization of the production line, isolation of the machine and/or its environment, the static stiffness of the structure to reach good quality, the overall dynamical behaviour that is correctly tuned to the required operations, and the tool path optimization. While the production line optimization is more like a timing issue, and while the tooth path generation and the static stiffness are geometrical issues, the design of the machine responses for external excitations or self-excitations requires the application of the tools and methods of Newtonian mechanics together with the recent achievements of nonlinear differential equations.

In order to reach the required accuracy of the machine tools, first, the controls are to guide precisely their high inertia superstructures. Also, the static stiffness of the machine needs to resist the stationary cutting forces of the chip separation process to ensure small relative displacement between the tool and the workpiece in the cutting zone. In addition, in milling, the time-periodic roaming of the tool causes an additional deviation, the so-called surface location error. The surface location error is actually the result of the appearing time-periodic forced vibration. However, all the above mentioned efforts for keeping the accuracy of certain machines can be ineffective if self-excited vibrations arise during the chip removing operation.

Beside the possible occurrence of stick-slip type self-excited vibrations, the regenerative effect is the major cause of stability loss in metal cutting. The regenerative vibration leads to poor surface quality and may even damage the machine tool and/or the workpiece. The regenerative effect appears during the chip separation process, because the corresponding edge segments (present motion) remove surface segments of the workpiece that basically contain the past motion-patterns of the tool left by related edge segments some specific time before.

¹Tobias, S.A., 1965. Machine-tool Vibration, Blackie, London, Glasgow

Aim of the work

The focus of this dissertation is on the complex dynamics of turning and milling processes. More specifically, we constructed low degrees of freedom models (Figure 1) which are considered as reduced-order models compared to finite element calculations, but easy-to-manage from dynamical point of view. The intricate local coupled physical environment of the chip separation zone is considered with empirical static cutting force characteristics, although some parts of the work deals with the chip separation itself directly.

The topics such as nonlinear/nonsmooth dynamic analysis and the short delay effect are investigated by means of the one degree of freedom orthogonal cutting model (Figure 1a) in order to have a model that is simple enough to capture the basic dynamics of interest. Milling operation is analysed in multi degrees of freedom environment (Figure 1b) while the asymptotic behaviour of the stationary solution is investigated.

Most of the developed theories are confirmed by experiments carried out partly in Manufacturing Automation Laboratory² of the University of British Columbia and Ideko³ research centre at DanobatGroup. Oscillation measurements were carried out to investigate dynamic chip separation processes, the general milling model was confirmed by means of special serrated cutters, the predicted dominant frequencies were identified in milling tests and finally, the conclusions of our nonlinear studies were verified qualitatively by milling operations.

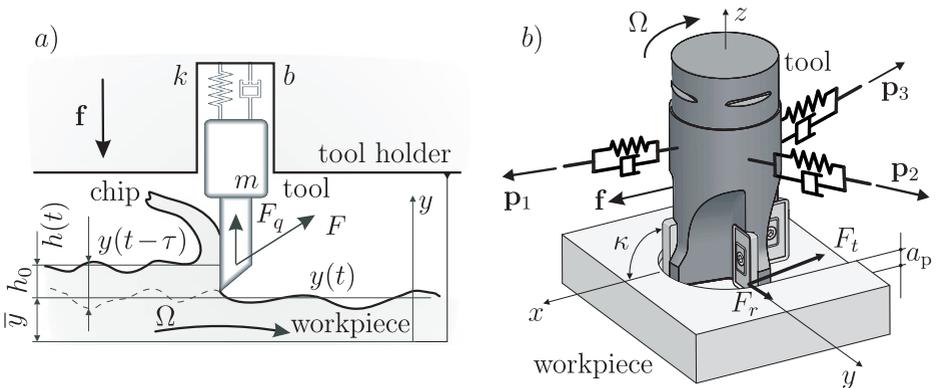


Figure 1: shows the single degree of freedom orthogonal cutting model a) for turning, and the multi degrees of freedom milling model b).

²MAL: <http://www.mal.mech.ubc.ca/>

³Ideko: <http://www.ideko.es/>

Theses

Thesis 1

In the one degree-of-freedom mechanical model of orthogonal cutting with nonlinear cutting force of cubic characteristics w.r.t. chip thickness h :

$$F(h) = w(\rho_1 h + \rho_2 h^2 + \rho_3 h^3), \quad \rho_{1,3} > 0 \quad \text{and} \quad \rho_2 < 0, \quad (1)$$

it was proven that the Hopf bifurcations related to the linear stability boundaries w.r.t. chip width w are subcritical for

$$3\rho_1\rho_3 - \rho_2^2 > 0. \quad (2)$$

This statement coincides with the realistic condition of having positive tangent to the nonlinear cutting force characteristics at the inflexion, while the existence of an inflexion is common for high performance cutting.

An improved analytical estimate was given for the size of the bi-stable zone below the linear stability limit. The estimate was based on the calculation of the critical cutting parameters where the amplitude of the unstable periodic motion originated in the subcritical Hopf bifurcation reaches the theoretical chip thickness h_0 divided by $\sqrt{2}$. This result is relevant when the safe globally stable cutting parameters are needed.

It was shown that the size of the bi-stable (unsafe) chip width zone has a maximum as a function of the chip thickness at the analytically estimated value

$$h_{\text{worst}} = -\frac{\rho_1}{\rho_2}, \quad (3)$$

where the unsafe zone is the largest. With the help of the numerical bifurcation continuation software DDE-BIFTOOL, the accurate shape of the feed-characteristics of the bi-stable zone was given and the estimation of h_{worst} was confirmed with satisfactory engineering accuracy.

These results are detailed in Chapter 2 of the dissertation.

Related publications: [2, 3, 11, 20, 21, 22].

Thesis 2

A piecewise smooth nonlinear model was constructed that provides a unified description of the tool-tip motion when it stays in, when it leaves, and when it flies above the surface of the workpiece. The relevance of the model lies in making it possible to smooth the equations combined with a singular perturbation. This opened the way to the application of the bifurcation continuation software DDE-BIFTOOL.

With this model and method, it was shown that there exists an organising parameter centre for the cutting dynamics, where the unstable period-one orbit originated in the subcritical Hopf bifurcation touches the switching surface that separates the fly-over and cutting motion of the tool-tip in the infinite dimensional phase space. At this grazing bifurcation point period-one, -two, -four, -three and -six orbits were found to emerge. The fact that all numerically continued branches were shown to be unstable in the neighbourhood of this parameter point refers to a structural explosion in the dynamics, which explains the terminology of Big Bang Bifurcation (B^3).

The existence of this B^3 together with the stable period-three and period-two orbits identified off the B^3 neighbourhood indicate that strange attractors are likely to exist at the unsafe (bi-stable) cutting parameters. Time-domain simulations presenting chaotic windows in the corresponding cutting parameter domains confirmed the results of the applied numerical continuation method.

These results are detailed in Chapter 3 of the dissertation.

Related publications: [5, 23].

Thesis 3

One of the existing theoretical models was improved and validated experimentally, which describes the so-called process damping by means of an additional short delay effect in the one degree-of-freedom orthogonal cutting model. An experimental set-up was compiled for a horizontal lathe that made it possible to provide a prescribed vibration of the cutting tool-tip during cutting and to measure the cutting force and the tool-tip displacement, synchronously, with high precision.

The experiments clearly presented the hysteresis loop predicted by the short-delay model in the plane of the chip thickness and cutting force variations, which served as a qualitative confirmation of the theory. It was also detected, however, that the principal axes of the experimentally identified ellipses deviate from the theoretically predicted directions as the phase shift is varied between the wavy just-cut surface and the wavy surface-to-cut. This deviation was explained by a tiny decrease of the large delay related to the

classical regenerative effect. This tiny decrement of the delay was identified by means of a series of experiments which were extrapolated to the case of prescribed zero phase shift.

By means of the analysis of the measurement results of a series of experiments, the length of the short delay relative to the large delay was identified and the shape of the weight function of the distributed delay was also estimated. The stability chart constructed with these parameters clearly presented the process damping effect.

These results are detailed in Chapter 4 of the dissertation.

Related publication: [14].

Thesis 4

A general geometrical model of milling tools was constructed, which was adapted in the dynamical model of the corresponding milling process that involves intricate regeneration effects due to the serrated edges of the tool. In the cases when the chip thickness is much smaller than the amplitude of the serration waves, it was derived from the theoretical model that the number of delays increases and the serrations attenuate the regeneration, consequently, the stability limits increase. It was also shown that when the feedrate increases, the material contact along the serrated flutes increases, the stability limits are reduced and the machining process approaches the performance of regular, smooth end mills.

An easy-to-use but counter-intuitive engineering rule was formed, namely, that the serrated cutters can be used for stable cutting with the number-of-flutes-times higher axial depth of cuts than the regular end-mills provided that the feed rate is less than the peak-to-peak amplitude of serration waves. In other words, serrated cutters behave as one-fluted regular end mills at low feed ranges.

With the help of detailed experimental stability charts for milling with serrated cutters, the theoretical predictions were confirmed.

These results are detailed in Chapter 5 of the dissertation.

Related publications: [1, 4, 8, 12, 15, 17].

Thesis 5

The idea of ‘dominant vibration frequencies’ was introduced by means of the relevant part of the kinetic energy of the vibration that occurs at the dynamic loss of stability of linear time-periodic parametrically excited delayed systems like milling. It was shown that the magnitudes of the vibrations corresponding to these dominant frequencies are large compared to the infinitely many harmonics of the vibration frequencies emerging from the Floquet multipliers of the monodromy operator. A method was developed that can select the dominant frequencies among the infinitely many harmonics of the non-harmonic quasi-periodic self-excited vibration. The method is based on the decomposition of this vibration signal and on the calculation of that periodic part which has the time-period of the parametric excitation. The dominant frequencies are selected by means of the Fourier components of this time-periodic part of the corresponding critical vibration signal.

Based on the above theoretical result, the semi-discretization method was extended by a time-efficient numerical algorithm that determines the dominant vibration frequencies numerically for linear parametrically excited delayed systems at the limit of stability. The approximate multipliers are determined as the eigenvalues of the transition matrix constructed by means of semi-discretization as the finite dimensional counterpart of the monodromy operator. The strengths of the harmonics can be determined by means of the Fourier components, and the efficiency of the method is guaranteed by the application of a low resolution FFT applied for one period of the calculated critical periodic part.

Milling experiments confirmed the predicted dominant frequencies. These frequencies are usually grouped around the natural frequencies of the machine tool structure, but the experiments captured intricate cases when strong frequency components appeared far from the natural frequencies exactly where they were predicted by the theory and calculated by the numerical algorithm.

These results are detailed in Chapter 6 of the dissertation.

Related publications: [6, 13]

Thesis 6

A dynamic measurement method was developed to identify the cutting force characteristics against chip thickness based on the result of Thesis 1. During the experiments, full immersion milling is performed on a ‘ramp-like’ workpiece that is mounted on a fixture, which has only one well separated vibration mode to ease the precise modelling of the dynamics.

The existence of the bi-stable zone excludes the linear sense of the cutting force characteristics. Furthermore, the well distinguishable trend on the feed characteristics of the bi-stable zone precludes also the power-law characteristics, which would imply a bi-stable zone independent of feed.

The feed characteristics of the bi-stable zone width was measured using the above special workpiece and fixture. The experiments confirmed indirectly that the cutting force has neither the linear nor the power-law characteristics with respect to the chip thickness. The experiments also confirmed the existence of a maximum of the bi-stable zone on feed, which was predicted by normal form transformation in Thesis 1. These results show that the third degree polynomial cutting force characteristics introduced by Tobias, S.A.⁴ is the appropriate approximation from nonlinear dynamics view-point among the available formulae used in practice.

These results are detailed in Chapter 7 of the dissertation.

Related publication: [7]

Thesis 7

The time-periodic parametrically excited distributed delay constructed at Thesis 4 was used to describe the dynamics of milling tools with non-uniform continuous variation on their helix angle. In order to carry out the stability analysis of the corresponding milling process, an axial discretization of the milling tool geometry was used in the calculations and the semi-discretization method was applied to the resulting time delayed mathematical model. It was proven for a machine with one dominant mode only that both the non-uniform and the harmonically varied helix angle on milling tools improves the linear stability compared to their conventional counterpart. For cylindrical symmetric machine tool dynamics with two nearby modes, however, the improvement in stability can be identified for symmetric highly interrupted cutting operations only.

These results are detailed in Chapter 8 of the dissertation.

Related publications: [9, 16].

⁴Shi, H., and Tobias, S., 1984, Theory of finite-amplitude instability. *International Journal of Machine Tools and Manufacture*, 24(1), pp. 45-69

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