Dynamics, stability and material removal rate of turning processes

Booklet of PhD Thesis

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Preliminaries and Outline of the Thesis

Based on industrial requirements, research and development in the field of machining technologies focuses on the simultaneous increase of cutting performance and accuracy. Productivity is closely related to the material removal rate (MRR), thus the maximisation of the MRR is a goal of highest priority. Still, in order to satisfy accuracy and quality demands, stable (vibration-free) machining is an inevitable criterion, which has to be assured by all means. Our research results on the field of single- and multi-cutter turning stability are summarized in this dissertation.

In Chapter 1 of the thesis, the mechanical model of the orthogonal turning operation is introduced, which is taken as a basis for stability predictions. Some selected methods to increase productivity of turning operations are discussed in Chapter 2. One of the main optimisation criteria for cutting processes is the maximisation of chatter-free MRR. In machining situations, where productivity has to be pushed to the limit, one may be forced to exploit parameter regions in the vicinity of the intersection points of two adjacent lobes in the so-called stability pockets of the spindle speed and the chip width parameters. It is shown, that for the practically relevant range of the damping ratios, the intersection points of two adjacent lobes are local maxima for the MRR.

A safer machining strategy is to choose machining parameter pairs, which are robustly stable. This means for example, that the turning lathe is operated with width of cut values which result in stable machining for all spindle speeds. This machining strategy is only affordable, if productivity requirements are not violated and the so-called robust stability limit of the corresponding turning process is sufficiently high. If this is not assured, the robust stability limit has to be extended. Some methods to increase the robust stability limit are proposed, discussed and tested.

One possible technique to increase the robust stability limit of turning processes is to include more tools with detuned dynamics in the cutting operation. In Chapter 3, the dynamically decoupled mechanical model of an n-cutter turning system and the corresponding stability calculations are introduced. The effect of detuning the dynamical tool parameters on the robustly stable chip width value is presented for different tool numbers. Theoretical stability predictions and robust stability limits are validated with experimental results of industrial cutting tests on a parallel turning machine.

Further experimental investigations are presented in Chapter 4 on a test fixture with two turning tools. Different modal parameter estimation techniques are used in the design process of the 2-cutter test fixture. Cutting tests are performed to compare measurement results with theoretically predicted stability charts. Experiments drew the attention to the fact, that non-proportional damping in the clamper part of the test fixture plays an important role in the increased damping effect, which was experienced in the measurement results. Enhanced modelling of the 2-cutter turning system taking into account the non-proportional damping effect leads to a more realistic way of modelling of dynamic and stability properties of the system, which are essential tools for the improved design of cutting technologies.

Theses

Thesis 1

Analytical calculations were carried out to determine the stability lobes of regenerative machine tool chatter in the plane of spindle speed Ω and chip width w parameters in case of orthogonal turning processes, where the machine tool structure has a relevant, well separated first vibration mode characterized by the modal stiffness k, natural angular frequency ω_n and damping ratio ζ. The stability lobes were used as upper bounds during the optimisation of material removal rates. This results a nonlinear and concave permissible range of technological parameters, which makes the optimisation strategies non-standard. The following statements provide guidance for optimisation of the practical parameter domains of machine tools by means of identifying characteristic parameter points of maximal and minimal material removal rates:

i) The intersection points of adjacent stability lobes of index r and $r+1$ are given by

$$\tilde{\Omega}_\mathrm{INT} = \frac{\sqrt{1+\frac{4\zeta^2}{\tilde{\omega}_\mathrm{c}^2-1}}}{(r+1)-\frac{1}{\pi}\arctan\left(\frac{2\zeta}{\sqrt{(\tilde{\omega}_\mathrm{c}^2-1)(\tilde{\omega}_\mathrm{c}^2+4\zeta^2-1)}}\right)}$$

and

$$\tilde{w}_\mathrm{INT} = \frac{1}{2}\left(\tilde{\omega}_\mathrm{c}^2\left(1+\frac{4\zeta^2}{\tilde{\omega}_\mathrm{c}^2-1}\right)-1\right),$$

where the dimensionless chip width $\tilde{w}_\mathrm{INT} = k_\mathrm{c}/k$ is the cutting coefficient divided by the stiffness, the dimensionless spindle speed is $\tilde{\Omega}_\mathrm{INT} = \Omega/\omega_\mathrm{n}$ and the dimensionless chatter frequency $\tilde{\omega}_\mathrm{c} = \omega_\mathrm{c}/\omega_\mathrm{n}$ belongs to the stability lobe curve with lobe number r.

These parameter points are local optima of the material removal rate for lobe numbers less than 40 and damping ratios less than 0.1.

ii) For orthogonal turning processes, in the presence of process damping characterized by the process damping coefficient c_p and its dimensionless form $\tilde{c} = c_\mathrm{p}/k$, there exists a parameter point:

$$\tilde{\Omega}_\mathrm{T} = \frac{\tilde{c}\pi}{\sqrt{\zeta(1+\zeta)}}$$

and

$$\tilde{w}_\mathrm{T} = 2\sqrt{\zeta(1+\zeta)}\left(1 + 2\zeta + 2\sqrt{\zeta(1+\zeta)}\right) ,$$

where the material removal rate has local minimum along the robust stability limit that is the lower envelope of the stability lobes.

Related publications:
[1, 2]

Thesis 2

The mechanical model of a dynamically uncoupled n-cutter turning system with optional circumferential arrangement, where the tools are coupled via the workpiece through the regenerative effect only, is equivalent to the mechanical model of a 1-cutter turning system with n degrees of freedom and with time delay that is equal to the time period of the revolution of the workpiece.

Related publication:
[3]

Thesis 3

The robust stability limit of a dynamically uncoupled n-cutter turning system with cutters of identical mechanical properties is the same as it is for the corresponding 1-cutter system, which is

$$\tilde{w} = 2\zeta(1+\zeta)\,,$$

where $\tilde{w} = k_{\mathrm{c}}/k$ is the dimensionless chip width and ζ is the uniform damping ratio. The stability pockets between the lobes become smaller with the increase of the number of cutters, which deteriorates the stability properties.

Related publications:
[4, 5, 6]

Thesis 4

The n-cutter turning systems with decoupled and proportionally damped tools were analysed, where the natural frequencies of the tools are detuned by means of the variation of their stiffness values. Theoretical stability computations proved and experimental results confirmed that:

There exist optimal stiffness ratios for the decoupled n-cutter turning system where the robust stability limit is maximal and significantly higher than that of the corresponding decoupled n-cutter turning system with identical tools.

The calculations were carried out for a 2-cutter system used in the laboratory experiments. The results showed that the optimal detuning can be achieved in practice by means of making one of the tools more flexible. Cutting tests performed on a parallel turning center showed correlation to the theoretically predicted robustly stable chip width values for different natural frequency ratios of the two tools.

Related publications:
[3, 7, 5, 8]

Thesis 5

A tool holder for 2-cutter turning was designed and built for validation purposes. With the help of experimental modal analysis one order of magnitude higher damping ratios were identified for the detuned system compared to the symmetric one. Different mechanical models were constructed in order to describe the dynamic behaviour of the test rig.

The assumption of an ideally stiff base of the tool fixture leads to quantitatively realistic robust stability limits, but does not provide qualitative explanation for the experimentally detected increase of damping ratios when one tool is detuned against the other.

The mechanical model taking into account the physical coupling of the two tools by including the dynamics of the fixture with non-proportional damping accurately describes the increased damping behaviour of the detuned tool holder structure in a wide range of stiffness ratios and it also confirms the predicted robust stability limits.

Cutting tests were carried out to validate the theoretically predicted robust stability limits for the 2-cutter turning process. With the mechanical model assuming non-proportional damping for the base of the tool fixture, it was possible to predict both the dynamic behaviour of the test structure and the stability properties of the turning process in a wide range of stiffness ratios.

Related publications:
[9, 4, 10, 6, 7, 11]

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