Cutting dynamics and surface quality

Booklet of PhD Theses

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Outline of Thesis Work

The dissertation summarizes our results on the exploration of the correlation between machined surface quality and the dynamics of cutting processes. The main goal is to predict the machined surface properties in hard turning and in general milling processes, where machine tool vibrations are likely to appear at cutting parameters, which were optimized for high material removal rates (HMRR).

The dissertation is divided into Chapters based on three main research topics.

Surface Quality Prediction for Interrupted Turning Processes

The machined workpiece surface is modelled in case of hard turning processes, optimization criteria are defined and optimal cutting parameters are selected.

Our goals are partly to determine the optimal technological parameters of hard turning considering the dynamical properties of the machine tool, and partly to predict the machined surface quality in these cases. The cutting force is modelled by a discontinuous (rectangular step) time-function and a simple easy-to-use formula for the optimal cutting velocities is derived where the surface error is minimal.

The surface pattern is also calculated for a workpiece of arbitrary geometry.

Then, instead of the rectangular step function, an improved time-continuous cutting force model is introduced with the help of appropriately chosen smoothing parameters. The effects of the dimensionless smoothing parameters on the surface waviness and on the optimal cutting velocities are analysed. Cutting tests are presented for the validation of the theoretical results by means of measurements of tool-tip acceleration.

Surface Quality Prediction for Milling Processes

The milling processes are analised in several aspects. First, optimal machining parameters are determined based on the simulated workpice quality for two different mechanical models. Second, the stability properties of the milling process are analysed considering large amplitude resonant vibrations and the so-called process damping phenomenon.

In milling processes, vibrations are always generated by the rotating milling tool providing periodic material removal. This forced vibration is occasionally combined with the so-called chatter vibration which has its origin in the possible instability of the periodic milling process.

The level of the stable periodic forced vibrations is usually small and create negligible surface errors due to the high dynamic rigidity of the machine tool structure. However, large periodic forced vibrations are likely to occur just for the most efficient near-resonant spindle speeds, which are related to low-damped modes (for instance, in case of thin walled workpieces). In these cases, the surface integrity is usually still acceptable, but the surface location error, the surface roughness and waviness may be large and intolerable. These forced near-resonant vibrations also create an additional undesired load on the machine tool. These problems result further limitation to the increase of the material removal rates, and the use of the cutting parameters in the efficient stable parameter pockets requires additional careful analysis.

The effects of these large amplitude forced vibrations are analysed with special attention to surface quality. First of all, three specific parameters are introduced for engineering use to characterize the spatial machined surfaces created by helical fluted milling tools. After that, it is analytically proven and verified by measurements for helical milling tools that the resonant vibrations caused by the periodic cutting force can be minimized with the help of appropriately chosen axial immersions.

The description of the rigid-body motion of the milling tool is not satisfactory for long finger-like milling tools. In this case, the deformation of the tool shlould also be modelled in order to describe the surface topography accurately.

Stability Prediction for Milling Processes

The self-excited vibrations in milling represent an essential limit for the increase of the material removal rate; this is called chatter caused by the surface regeneration effect. The corresponding periodic, quasi-periodic or chaotic vibrations appear when stationary milling loses its stability, in other words, when the stationary periodic forced vibration becomes unstable. These types of vibrations destroy the surface integrity and can create heavy load on the machine tool. The so-called stability chart presents and predicts the chatter-free parameter domains of the milling process traditionally in the plane of the spindle speed and the axial immersion.

Most of the mathematical models neglect some essential non-linear effects due to the fact that they use constant time delay only that is inversely proportional to the fixed cutting speed. Since the forced vibrations may become very large in the near-resonant parameter domains, the path of the individual cutting edges will strongly deviate from the approximate circular paths.

The governing equation of milling processes is generalized with the help of accurate chip thickness derivation resulting in a state dependent delay model. The periodic motions of this non-linear system and its stability are calculated. It is observed that the influence of the state dependent delay on linear stability can be significant in the near-resonant parameter domains. The existence of an unusual fold bifurcation is shown where a kind of hysteresis phenomenon may appear between two different stable periodic motions.

In the literature, good correlation is found between the measured and the computed stability boundaries during the experimental verification of theoretically predicted stability charts for high spindle speeds. However, the theoretical predictions are too conservative in the low-speed domain, that is, the experiments present stable cutting for larger axial immersions compared to the critical ones calculated from the model. The process damping effect is often used to improve these models. Additional damping proportional to the time delay is added to the structural damping to characterize the contact force at the tiny region between the flank face and the workpiece.

The above mentioned classical process damping is used to improve the milling model, which leads to a system with a non-smooth (unilateral) damping. The improved model predicts the expected higher stability limits at low spindle speeds, but it describes a new intricate pattern of the lobe-structure. It is also shown, that the mathematically correct description of the widely used classical process damping model is the same as the one based on the so-called short regenerative effect that contains distributed delay terms. It is proven, that the short regenerative model linearised with respect to the time delay leads to the classical process damping model, and some other higher-order approximations can also be derived as its special cases.

Multi-Dimensional Bisection Method

In many engineering problems, the roots of a system of non-linear equations $\mathbf{f}(\mathbf{x}) = \mathbf{0}$ must be computed. In case of the stability calculation with the semi-discretization method, one equation is given in a two parameter space (spindle speed and axial immersion). If we apply the Extended Multi-Frequency Solution then two equations are given in a three dimensional parameter space.

The computational time of these methods can radically be decreased if we evaluate the functions only around the stability boundary lines. In practice, it is important to have a robust and automatic method which finds all the roots including those sets which are formed by closed curves.

Theses

Thesis 1

Interrupted turning processes are considered on a lathe having a well separated dominant vibration mode with angular natural frequency ω_n. When a discontinuous (rectangular step) cutting force function is assumed, the simple formula

$$v_{opt} = \frac{e}{jT_n} \qquad j = 1, 2, 3, \ldots$$

is derived for the optimal cutting speeds v_opt, where the surface waviness created by the transient vibration after the interruption is minimized. These optimal cutting speeds depend on the the width e of the groove, and on the time period $T_n = 2\pi/\omega_\mathrm{n}$.

In case of facing, the machined surface pattern of a workpiece with general interrupted geometry is accurately modelled by the transformation of the numerical simulation results from the time domain to the tool path relative to the workpiece.

A more accurate model is also constructed to determine the optimal cutting speeds by means of improved (empirical) continuous cutting force functions. It is shown that the influence of the continuous decrease and increase of the cutting force at the entrance and exit of the interruption can be described by the time constants $\varepsilon_\mathrm{exit}$ and $\varepsilon_\mathrm{enter}$, which significantly improve the model accuracy. In the meantime, the effect of a possible impact-like increase of the cutting force at the entrance has no relevance regarding the optimal cutting speed, which has the improved formula

$$v_\mathrm{opt} = \frac{e}{T_\mathrm{n}} \frac{2\pi}{j2\pi - \arctan\left(\frac{\varepsilon_\mathrm{enter}}{1+2\xi\varepsilon_\mathrm{enter}}\right) - \arctan\left(\frac{\varepsilon_\mathrm{enter}}{1+2\xi\varepsilon_\mathrm{enter}}\right)} \qquad j = 1, 2, 3, \ldots$$

with damping ratio ξ.

All these results are confirmed in an industrial case study and by test measurements for hard turning processes.

Related publications:
[1, 2, 3, 4, 5, 6, 7]

Thesis 2

Peripheral milling tools are considered which can vibrate with two modes normal to the tool axial direction. It is shown that the helical fluted tools produce complex spatial machined surface even along the axial direction. Three specific parameters are introduced to characterize these spatial machined surfaces created by helical fluted milling tools, which are sufficient to optimally describe the surface and easy-to-use in engineering practice. The first parameter is the maximal surface location error, which is a generalization of the classical surface location error defined for straight fluted tools. The second parameter is the total height of the profile in feed direction that can also be considered as surface roughness. This parameter is shown to be only slightly affected by the helix angle of the tool. The third introduced parameter is the total height of the profile in axial direction that can also be considered as a kind of surface waviness. This is the most relevant parameter in case of milling with helical fluted tools, which has no classical counterpart.

Related publications:
[8, 9, 10, 11]

Thesis 3

Classical stability charts of milling processes predict that the highest material removal rates can be achieved when one of the harmonics of the periodic cutting force is close to one of the natural frequencies ω_n of the machine tool structure. The corresponding near-resonant spindle speeds are between the subsequent instability lobes of the stability charts. Cutting with one of these resonant vibrations does not result self-excited vibration (chatter) but it still causes large surface waviness in case of helical tools, which cannot be compensated.

It is proven analytically and verified by measurements for helical milling tools that the resonant vibrations caused by the periodic cutting force can be minimized for certain cutting parameters that can be arranged into two classes. The first class is formed by the trivial appropriate axial immersions $a_\mathrm{p} = jp/N$ that are equal to the helix pitch p over the number of teeth N and its integer multipliers j. In this case, the cutting force is constant, no forced vibration occurs, which is a direct consequence of the application of helical tools. It is shown that non-trivial appropriate axial immersions exist, defined by

$$a_{\mathrm{p}} = \frac{p\Omega}{\omega_n} j \qquad j = 1, 2, 3, \ldots,$$

which depend linearly on the spindle speed Ω. At these parameter values, the cutting force varies periodically but the harmonic component close to resonance is still eliminated.

The above simple formula of the non-trivial appropriate axial immersions can also be used in case of multi DoF systems if the resonant spindle speeds are isolated.

Related publications: [8, 9, 10, 11, 12, 13, 14, 15]

Thesis 4

A combined dynamical model of the milling machine is constructed that consists of a finite element beam model of the finger-like milling tool, a model of the machine tool structure based on its frequency response measurement, and an experimentally verified dynamic coupling model between them, while the workpiece-side is considered to be rigid. This dynamical model is subject to the cutting force which is measured online during the milling process, and the machined surface profile is generated with high accuracy numerical simulations of the cutting edge path and by means of Boolean operations. The advantage of this method is that the surface quality of the workpiece can be predicted online during the cutting process by means of cutting force measurements.

The method is verified experimentally for the case of forced vibrations of milling processes for both stationary and transient vibrations: the accuracy of the predicted surface quality shows good quantitative agreement with the offline direct measurement of the machined surface. In case of self-excited vibrations, the experiments showed only qualitative agreement with the predicted structure of the machined surface, which might still be useful in chatter identification.

Related publication: [16]

Thesis 5

In case of milling with near-resonant spindle speeds, the amplitudes of the forced vibrations can be very large relative to the tool diameter. It is shown, that the stable parameter regions predicted by linear time delayed mechanical models do not provide conservative estimates for the selection of the milling parameters due to the existence of an unusual bistable parameter domain within the near-resonant zone. The corresponding fold-type bifurcation is identified by two improved non-linear mechanical models.

The first model uses the chip thickness variation projected to the velocity vector of the tooltip in contrast to the conventional approximation of the chip thickness variation by means of the approximated circular path of the tooltip. The second model is the most accurate by describing the exact path of the tooltip leading to a state-dependent delay model with an implicit algebraic expression of the delay.

A numerical method was developed for state-dependent delay differential equations to determine the periodic forced vibration and to follow it by continuation as one bifurcation parameter varies. Both models predict the first fold bifurcation of stationary milling in the near-resonant zone.

Related publications:
[17, 18, 19, 20, 21]

Thesis 6

An improved model of the process damping effect is developed for milling which was originally introduced to explain the improved stability properties of cutting at low cutting speeds. This model takes into account the ratio of the feed velocity and the cutting speed, which is traditionally neglected. This leads to a non-linear phenomenon due to the fact that the process damping effect at the flank face is switched off when the stationary forced vibration results in large vibration velocities of the tool-tip while moving outwards of the workpiece material. This way, an accurate stationary forced vibration can be calculated and its linear stability is different from the traditional stability boundary of stationary milling. The intricate structure of the stability chart for milling models with the improved process damping description is explored.

It is shown, that the mathematically correct description of the widely used process damping model is equivalent to the description of the so-called short regenerative effect that contains distributed delay terms. It is proven, that the short regenerative model linearised with respect to the time delay leads to the traditional process damping model, and some other higher-order approximations can also be derived as its special cases.

Related publications:
[22]

Thesis 7

In industrial applications of chatter predictions for cutting, the fast, possibly online reconstruction of the stability charts is essential even in cases of complex real-world machine tool dynamics. To achieve this goal, the bisection method is generalized to higher dimensions for stability chart reconstruction. A fast numerical algorithm of this 'Multi-Dimensional Bisection Method' is built in Matlab, which is able to find the submanifolds formed by the sets of the roots of a system of nonlinear equations, where the number of equations, that is the codimension D_C of the submanifolds, is smaller or equal than the number of the independent variables, which gives the dimension D_S of the parameter space. The developed method can be used for the automatic determination of disjunct solution sets in selected regions for optional dimensions and codimensions.

An efficiency number is introduced to characterize the performance of the corresponding numerical methods. It is based on the box-counting dimension D_P of the evaluated points in the space of the parameters, and it is defined as

$$E = \frac{1}{D_P - D_F},$$

where D_F is the fractal dimension of the submanifolds. It is shown that the efficiency number of the so-called brute force method, that checks a uniform net of the selected region of the space ($D_P = D_S$), is the small value $E = 1/(D_S - D_F)$, which is $E = 1/D_C$ in case of non-fractal type submanifolds. An ideal perfect method, which computes the dense pointcloud on the submanifold only, would have $D_P = D_F$ and $E \to \infty$.

Based on numerical tests, the efficiency number of the proposed 'Multi-Dimensional Bisection Method' is approximated by $E \approx 3/D_C$. This means that the developed numerical method is efficient enough to present stability charts online for milling processes in the $D_S = 3$ dimensional parameter space of spindle speed, axial depth of cut and chatter frequency and for the $D_F = 1$ dimensional instability lobes, even when the lobes have fractal-like structure and/or they form closed stability or instability islands.

Related publications:
[23, 24, 25]

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