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Estimation of safe chatter-free technological parameter regions for machining operations

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Abstract

Experimental cutting tests often show different dynamic behavior from the one predicted by means of theoretical mechanical models. One reason behind this observation is that stability lobe diagrams determined by standard linear stability analysis often under- or overestimate the region of chatter-free parameters. Therefore, reliable selection of technological parameters associated with optimal material removal rate is difficult in practice. In this paper, a simple formula is given to estimate the safe parameter region, where the machining operation is globally stable even for large disturbances. The analytical results are confirmed by numerical simulations.

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Keywords: machining; chatter; stability; nonlinear dynamics; unsafe zone

1. Introduction

The occurrence of harmful vibrations (chatter) adversely affects the achievable productivity and surface quality in high-speed metal cutting. Suppressing or avoiding chatter is therefore an important task for machining engineers. Thus, investigating the dynamics of machine tool chatter is an active field of research. One of the most commonly accepted explanations for chatter is the regenerative effect introduced by Tobias [1] and Tlusty [2]: the vibrations of the tool are recorded on the surface of the workpiece, which induces variations in the chip thickness and hence in the cutting-force one revolution later. Stability properties of machining processes are depicted by the so-called stability lobe diagrams, which plot the maximum stable depths of cut versus the spindle speed. There are many different numerical and semi-analytical methods to generate stability lobe diagrams using the dynamic parameters of the machine-tool-workpiece system (see, e.g., the methods listed in [3]). However, predicted stability diagrams do not always match experimental cutting tests [4].

There are several reasons behind the difference between experimental results and analytical stability predictions. First, the physics of chip formation is still not fully understood and developing new dynamical models for material removal is still an active field of research [5,6]. Uncertainties of the modal parameters of the machining system can also lead to significant differences in the stability diagrams [7,8,9]. Another reason for these differences is the nature of the mechanical models: most models in the literature use linear systems, which cannot predict the behavior of the process when large-amplitude vibrations arise. As it was shown in [10], machine tool chatter is a large-amplitude vibration evolved as a result of a subcritical Hopf bifurcation. From practical point of view, this means that below the linear stability boundaries, an unstable periodic orbit coexists together with the stable fixed point associated with stationary cutting. If the system gets out of the domain of attraction of the fixed point due to disturbances, then the amplitude of the vibrations grows and, at certain point, the tool leaves the workpiece. As a result, a large-amplitude vibration, which is known as chatter, is developed. The region where both stable machining and chatter may occur is called bistable or

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unsafe zone [11]. If the technological parameters are set within the unsafe zone, then machine tool chatter can suddenly evolve in spite of the fact that the system is linearly stable. Consequently, reliable estimation of the unsafe zone is of high importance.

The unsafe zone was observed experimentally already by Shi and Tobias in 1984 [12] (see Fig. 3 in [12]). They disturbed a stable machining process by hitting the cutter head by a hammer. For small hammer blow the vibrations settled after a transient, however, for large blow, chatter built up. A more sophisticated demonstration of the unsafe zone was presented in [13], where the axial depth of cut was first gradually increased and then gradually decreased during the cutting tests. The onset and the disappearance of chatter were detected for both cases. The depth of cut where chatter developed for the increasing depths of cut was found to be larger than that where chatter disappeared for the decreasing depths of cut. The difference between the two values gives the width of the unsafe zone.

As it was shown in [11], the size of the unsafe zone depends on the relation between the cutting force and the uncut chip thickness (see also [14] for more details). For instance, if the cutting-force characteristics is given by an exponential form (e.g., by the three-quarter rule), then the unsafe zone occupies only 4% of the linearly stable region. However, if the cutting-force characteristics is given by a cubic expression, then the unsafe zone can be significantly larger.

The analytical estimate for the size of the unsafe zone in [11] does not match the numerical results for large-amplitude vibrations. Therefore, an improved, higher-order estimation was recently derived in [15], which agrees well with numerical simulations. In this paper, the application of the improved estimation of [15] is demonstrated using series of time-domain simulations.

2. Mechanical model

In this paper, the single-degree-of-freedom mechanical model of orthogonal cutting is investigated. The model is shown in Fig. 1, where a turning operation of a solid shaft is presented. This model considers vibrations only in the feed direction, motion in other directions is neglected. The vibrations between the tool and the workpiece are described by

$$\ddot{x}(t)+2\zeta\omega_{\mathrm{n}}\dot{x}(t)+\omega_{\mathrm{n}}^2 x(t)=\frac{1}{m}F_x\big(h(t)\big), \tag{1}$$

where m is the modal mass, ζ is the damping ratio, and ω_{n} is the undamped natural angular frequency of the dominant vibration mode of the cutting process.

The x-directional component F_x of the cutting force acting on the tool can be given as a cubic polynomial of the chip thickness h according to the Tobias force expression [12]:

$$F_x(h)=\begin{cases} w\left(\rho_1 h+\rho_2 h^2+\rho_3 h^3\right) & \text{if } h\geq 0,\\ 0 & \text{if } h<0,\end{cases} \tag{2}$$

where w is the chip width, and the following constants were identified in the experiments of [12] for a milling tool of four teeth: $\rho_1=6.1096\times10^{9}$ N/m^2, $\rho_2=$ -5.41416 $\times10^{13}$ N/m^3, $\rho_3=2.03769\times10^{17}$ N/m^4. Note that when $h<0$, the tool is not touching the workpiece and the cutting force is zero. In the analysis presented below, this case is excluded, and it is assumed that the tool remains in contact with the workpiece during the entire cutting process. Also note that other cutting force expressions like the three-quarter rule are commonly used as well [13]. Such expressions can be expanded into Taylor series up to third order and can be written in the form (2).

The instantaneous uncut chip thickness $h(t)$ can be calculated according to the theory of regenerative machine tool chatter as

$$h(t)=h_0+x(t-\tau)-x(t), \tag{3}$$

where h_0 is the feed per revolution and τ is the regenerative delay, which is now equal to the rotational period of the spindle: $\tau=60/\Omega$, where Ω denotes the spindle speed in rpm.

Equations (1)-(3) form a delay-differential equation with cubic nonlinearity. Let us introduce the dimensionless time $\tilde{t}=\omega_{\mathrm{n}}t$, the dimensionless delay $\tilde{\tau}=\omega_{\mathrm{n}}\tau$, and the dimensionless tool position $\xi=(x-x_0)/h$, with $x_0=F_x(h_0)/(m\omega_{\mathrm{n}}^2)$. After dropping the tildes, the dimensionless equation of motion becomes

$$\begin{aligned}\xi''(t)+2\zeta\xi'(t)+\xi(t)=p\Big[&\big(\xi(t-\tau)-\xi(t)\big)\\ &+\eta_2\big(\xi(t-\tau)-\xi(t)\big)^2+\eta_3\big(\xi(t-\tau)-\xi(t)\big)^3\Big],\end{aligned} \tag{4}$$

where $p=w\left(\rho_1+2\rho_2h_0+3\rho_3h_0^2\right)/\left(m\omega_{\mathrm{n}}^2\right)$ is the dimensionless chip width and

$$\eta_2=\frac{\rho_2h_0+3\rho_3h_0^2}{\rho_1+2\rho_2h_0+3\rho_3h_0^2},\qquad \eta_3=\frac{\rho_3h_0^2}{\rho_1+2\rho_2h_0+3\rho_3h_0^2} \tag{5}$$

are dimensionless cutting force coefficients.

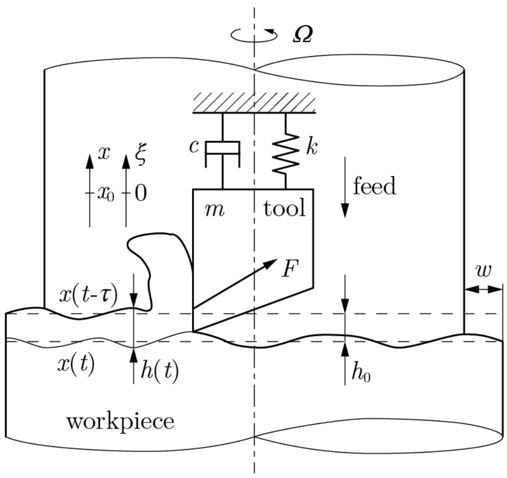

Fig. 1. Mechanical model of orthogonal cutting.

3. Unsafe zone in the stability lobe diagrams

The linear stability boundaries of Eq. (4) depicted on the plane of the dimensionless spindle speed $2\pi\Omega/60$ and the dimensionless chip width p are well known [1,2,3], and are referred to as stability lobe diagrams. An example is shown in Fig. 2 with $\zeta = 0.02$. Here, the linear stability boundaries are shown by solid lines.

Experimental results often show that the standard linear stability analysis under- or overestimates the region of chatter-free technological parameters. On the one hand, the difference between experimental results and theoretical predictions can be explained by the modeling uncertainties: the inaccuracy of the modal parameters of the machining system and the uncertainties in the cutting force characteristics (2). On the other hand, linear stability analysis can still fail to predict machine tool chatter even for a perfectly built mechanical model without uncertainties. The reason behind is the nonlinearity of the cutting force as a function of the chip thickness.

The effect of cutting force nonlinearity on the stability of machining operations has been studied since the 1980s. In [12], the phenomenon of *finite amplitude instability* was reported in cutting experiments. Accordingly, there exist certain technological parameter combinations such that stable stationary cutting may become unstable for large enough disturbances such as inhomogeneities in the workpiece material or discontinuities (e.g., holes or grooves) in the machined surface. These parameter regions are referred to as unsafe zone in the stability lobe diagrams. In the unsafe zone, the linear stability analysis predicts chatter-free cutting, but, due to nonlinear effects, machine tool vibrations initiate for external disturbances and large (but finite) amplitude vibrations arise.

In [11], the size of the unsafe zone was determined by analyzing Eq. (4). It was shown that the size of the unsafe zone relative to the size of the linearly stable region is approximately constant and can be estimated by

$$R_{\mathrm{bist}} = \frac{3\rho_3 h_0^2}{4\rho_1 + 8\rho_2 h_0 + 12\rho_3 h_0^2} \times 100\,[\%], \tag{6}$$

irrespective of the spindle speed and the and chip width. Therefore, R_{bist} percent of the stable region predicted by linear cutting force models is unsafe and should be avoided when selecting the technological parameters.

However, for large feed per revolutions when the unsafe zone itself is large, numerical stability analysis showed [11] that formula (6) tends to overestimate the size of the unsafe zone. Therefore, an improved version of this formula was derived in [15], which agrees well with the numerical stability analysis of Eq. (4) even for large feeds:

$$R_{\mathrm{bist}} = \frac{3\rho_3 h_0^2}{4\rho_1 + 8\rho_2 h_0 + 15\rho_3 h_0^2} \times 100\,[\%]. \tag{7}$$

The unsafe parameter region is indicated by dark grey shading in Fig. 2, and its boundary calculated according to Eq. (7) is shown by a dash-dot line. Here, the feed is $h_0 = 80\,[\mu\mathrm{m}]$ per revolution. The boundary of the unsafe zone obtained by Eq. (6) is also indicated by a dashed line. It can be seen that formula (6) overestimates the size of the unsafe zone in this example.

4. Numerical simulations

In order to verify the analytical estimation (7) for the size of the unsafe zone, numerical simulations were performed using the built-in Matlab solver *ddensd*. Although the analysis presented above excludes loss of contact between the tool and the workpiece during machine tool vibrations, it was taken into account during the numerical simulations shown in Fig. 2. Correspondingly, a nonsmooth system was simulated where switching occurs between the dynamics of a tool currently engaged in cutting and a tool which lost contact with the workpiece and is out of the cut due to large-amplitude chatter. The detection of contact loss $(h(t) = 0)$ was handled by the event location option of *ddensd*.

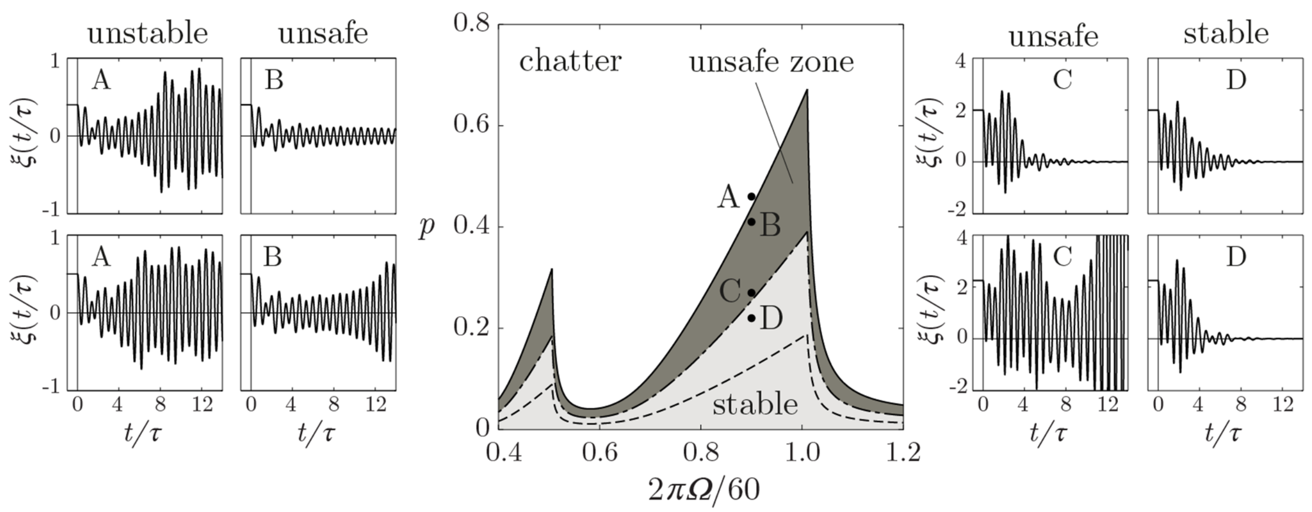

Fig. 2. Stability lobe diagram of the orthogonal cutting process and the results of numerical simulations corresponding to unstable (A), unsafe (B, C), and stable (D) technological parameter combinations.

The governing equations of this nonsmooth system are given by Eqs. (8)-(10) in [16], which correspond to Eqs. (1)-(2) of the present paper with chip thickness expression

$$h(t) = h_0 + \chi(t-\tau) - x(t). \tag{8}$$

Here, $\chi(t)$ denotes the position of the machined surface which is different from the position $x(t)$ of the tool when loss of contact occurs between tool and workpiece. When the tool is out of cut $(h(t) < 0)$, the machined surface does not change and $h_0 + \chi(t-\tau) = \chi(t)$ holds. When the tool is engaged in cutting $(h(t) > 0)$, the machined surface and the cutting edge are at the same position: $x(t) = \chi(t)$. The last two equations for $\chi(t)$ were differentiated with respect to time and were added to the set of governing differential equations to perform the simulations with *ddensd*.

The simulation results are shown for a set of four technological parameter combinations indicated by points A, B, C, and D in the stability lobe diagram in Fig. 2. At each point, the simulations are presented for two different initial conditions. The initial functions were constant along $-\tau \le t \le 0$ with value $\xi = 0.4$ and $\xi = 0.5$ for cases A and B, and $\xi = 2$ and $\xi = 2.25$ for cases C and D, respectively. According to the simulations, point A is unstable, point D is stable for both initial conditions. Whereas points B and C are stable for small initial values, but become unstable for large ones. Based on the simulations, points B and C are indeed unsafe and hence external disturbances may lead to machine tool chatter when these technological parameters are used.

5. Conclusions

In this paper the stability of orthogonal cutting processes was investigated with special attention to the cutting force nonlinearity. It is known that linear dynamical models may fail to predict machine tool chatter for certain technological parameters. Namely, there exists an unsafe zone in the stability lobe diagrams of machining, where the cutting process is linearly stable, but chatter may still initiate for large enough disturbances due to nonlinear effects. However, the results of linear stability analysis can easily be extended and used for nonlinear models: a simple estimating formula was given in Eq. (7) to calculate the size of the unsafe zone relative to the size of the linearly stable region. Therefore, in order to determine a safe chatter-free technological parameter region, one has to compute the chatter-free domain based on standard linear models, calculate the size of the unsafe zone using Eq. (7), and subtract the unsafe zone from the linearly stable region.

Apart from the nonlinear effects, there exist several other factors that cause differences between theoretical stability predictions and experimental results. On one hand, there are uncertainties in the mechanical model itself and in its modal parameters, as well as in the cutting force model. On the other hand, the complicated process of chip formation may include unknown phenomena affecting the stability of machining operations. Thus, our future research aims to investigate more detailed mechanical models of machine tool chatter that include effects like the distribution of the cutting force on the tool's rake face, process damping, and the intermittent contact between the workpiece an the tool's flank face.

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