THE EFFECT OF RUNOUT ON THE STABILITY OF MILLING WITH VARIABLE HELIX TOOLS

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Summary The stability of chatter vibrations in milling processes with variable helix tools is studied. Variable helix tools are characterized by different helix angles at different teeth of the cutter. With the tool rotation a distributed time delay, specifying the time between two subsequent cuts, arises in the model equations for the description of the machine-tool vibrations. The stability analysis of the distributed delay differential equation is done in the frequency domain and the effect of cutter runout on the stability is studied.

INTRODUCTION

Large vibrations in milling processes often called chatter vibrations cause noise, increased tool wear and poor surface finish. The chatter stability analysis for milling processes can help to understand the reason for the occurrence of chatter, to find stable cutting conditions without undesired vibrations and strategies to suppress chatter vibrations. The main reason for chatter is an unstable self-excited mechanism. Vibrations at the contact zone between the tool and the workpiece result in a wavy workpiece surface, which affect the chip thickness and the value of the cutting force at the next cut. These dynamical variations of the cutting force induce new vibrations of the structure at the current cut. As a result, the underlying model equation for chatter vibrations is a non-autonomous delay differential equation (DDE).
The stability analysis can be done by numerical simulations of the DDE and the analysis of the time series of the vibrations. Alternatively, the semidiscretization method [1] can be used to construct a discrete version of the solution operator of the DDE in form of a monodromy matrix. The eigenvalues of this monodromy matrix are the Floquet multipliers and determine the stability of the chatter vibrations. In [2] a frequency domain stability analysis is proposed for the calculation of the stability lobes for milling processes. The stability lobes separate stable cutting conditions from unstable conditions with large chatter vibrations.
For milling processes with variable helix tools the time delay in the model equation is a distributed one, because of the special geometrical nature of the milling cutter. For this case, the frequency domain stability analysis of regenerative chatter is presented in [3]. In the present contribution the method of [3] is used to calculate the stability lobes for a prototype milling process with a variable helix tool and the effect of cutter runout on chatter vibrations is shown.

MILLING MECHANICS

The process force in milling depends on the geometry of the milling cutter, the cutting conditions and the cutting force law. The geometry of the variable helix tool is specified by the number of teeth N, the radius R_i, the initial pitch $\Delta\varphi_i(0)$ at the tool tip and the helix angles η_i for each tooth i (see Figure 1). For a regular tool with uniform pitch and uniform helix angles the values of $\Delta\varphi_i(0)$ and η_i are independent of the tooth number i. The effect of runout is considered by slightly different R_i for different teeth. The cutting force law describes the local behavior $dF_t(h)$ and $dF_r(h)$ of the cutting force in tangential and radial direction at differential cutting edge segments dz of the milling tool axis z. The form and the parameters of the cutting force law are often identified empirically. In this paper a power law dependence of the cutting force on the chip thickness h is considered:

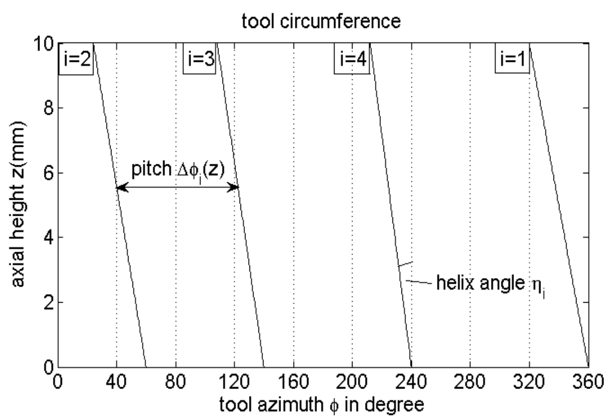

Figure 1: Circumference of the variable helix tool.

Structural model			
mode number	k=1	k=2	k=3
m_k in kg	3	0.62	0.12
ζ_k	0.02	0.025	0.034
ω_k in Hz	410	1353	2234
mode orientation $(x, y, z)^T$	-2 1 2	5 -3 1	1 4 -2
Parameters of cutting force law			
K_t=950$N/mm^{1.7}$	γ_t=0.7	K_r=170$N/mm^{1.5}$	γ_r=0.5
Variable helix tool with runout N=4			

$\Delta\varphi_i(0)$ in °	120	60	80	100
η_i in °	35	32	29	26
R_i in mm	10.010	9.995	10.005	9.990

Table 1: Parameters of milling example.

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$$dF_t(h) = K_t h^{\gamma_t} dz, \quad dF_r(h) = K_r h^{\gamma_r} dz. \tag{1}$$

K_t and K_r are the tangential and radial cutting force coefficients. If the tangential and radial exponents, γ_t and γ_r, are equal to one, eq. (1) reduces to a simple linear cutting force model, which is often studied in the literature.
For milling processes with variable helix tools the chip thickness $h=h(t, \boldsymbol{r}(t), \boldsymbol{r}(t-\tau(i,z)), i, z)$ depends explicitly on time t due to the tool rotation and on the tooth number i and the axial height z due to the non-uniform geometry of the cutting tool. Furthermore, current and time-delayed vibrations, $\boldsymbol{r}(t)$ and $\boldsymbol{r}(t-\tau(i,z))$, at the inner and outer surface of the chip influence the chip thickness h. The time delay $\tau(i,z)$ is the time between two subsequent cuts and depends on the spindle speed Ω and the pitch $\Delta\varphi_i(z)$ at the axial height z between the present tooth i and the previous tooth (cf. Figure 1). With the transformation matrix $\boldsymbol{T}=\boldsymbol{T}(t, i, z)$ the cutting forces can be transformed from local radial and tangential coordinates at the cutting edge segment dz into x, y and z coordinates of a fixed machine tool coordinate system. The complete process force is the sum of the local forces over all teeth and the integral from $z=0$ to the axial depth of cut $z=a_p$.

$$\boldsymbol{F}\left(t,\boldsymbol{r}(t), \int_{\min\tau}^{\max\tau}\boldsymbol{W}(t,\vartheta)\boldsymbol{r}(t-\vartheta)d\vartheta\right) = \sum_{i=1}^{N}\int_{0}^{a_p}\boldsymbol{T}(t,i,z)\begin{pmatrix} K_t h(t,\boldsymbol{r}(t),\boldsymbol{r}(t-\tau(i,z)),i,z))^{\gamma_t} \\ K_r h(t,\boldsymbol{r}(t),\boldsymbol{r}(t-\tau(i,z)),i,z))^{\gamma_r}\end{pmatrix} dz. \tag{2}$$

The cutting force $\boldsymbol{F}$ depends on the current time t, the current dynamical displacements $\boldsymbol{r}(t)$ and all $\boldsymbol{W}(t, \vartheta)$-weighted time-delayed displacements $\boldsymbol{r}(t-\vartheta)$ bounded by a minimum and a maximum value of the delay $\tau(i,z)$. The time dependence is periodically with the period Ω of the spindle rotation.

RESULTS OF LINEAR STABILITY ANALYSIS

Regenerative chatter occurs due to dynamical process-machine interactions. The dynamical model of the machine tool is a system of uncoupled harmonic oscillators, with the dominant modal masses m_k, damping ratios ζ_k and eigenfrequencies ω_k. The connection of the process force of eq. (2) with the structural dynamical model and a following linearization with respect to the dynamical displacements $\boldsymbol{r}$ leads to a DDE with time-varying distributed delay:

$$\dot{\boldsymbol{r}}(t) = \boldsymbol{A}(t)\boldsymbol{r}(t) + \int_{\min\tau}^{\max\tau}\boldsymbol{B}(t,\vartheta)\boldsymbol{r}(t-\vartheta)d\vartheta. \tag{3}$$

The coefficient matrices $\boldsymbol{A}(t)$ and $\boldsymbol{B}(t, \vartheta)$ are Ω-periodic. If the system is at the stability border, a periodic solution can be assumed for the displacements $\boldsymbol{r}(t)$. Then, the coefficient matrices $\boldsymbol{A}$, $\boldsymbol{B}$ and the state variable $\boldsymbol{r}$ can be developed into Fourier series and transformed into the frequency domain. If a finite truncation of the Fourier series is considered, it is possible to determine the critical cutting conditions at the stability border from the so-called Hill determinant, which can be interpreted as the characteristic equation of the problem. Details of the frequency domain stability analysis for the case of milling processes with variable helix tools can be found in [3].
The structural dynamical, the force and the tool geometry parameters of a milling example with a variable helix tool with cutter runout are shown in Table 1. The cutting conditions are half immersion down milling with a feed per round f_R=0.4*mm* in x-direction. The chatter stability borders, indicating the limiting depth of cut a_p dependent on Ω, are shown for four milling cutters in Figure 2. The 'Variable helix tool' is characterized by the parameters of Table 1 with the tool circumference, illustrated in Figure 1. 'Regular tool' refers to a comparable tool with uniform pitch $\Delta\varphi_i(z)= \Delta\varphi$=90° and uniform helix angle $\eta_i=\eta$=30.5°. The exact radius of the teeth for the tools without runout is uniformly $R_i=R$=10.000*mm*.

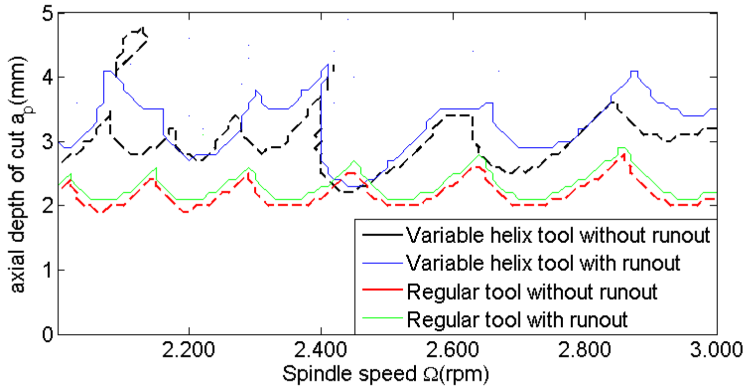

Figure 2: Stability lobes for milling processes with variable helix

CONCLUSIONS

In general, variable helix angles and cutter runout can stabilize milling processes and suppress chatter. It can be expected, that the stable island for the variable helix tool without runout (black, dashed) can not be detected in experiments, since for its calculation only three structural modes were considered. Though, only radial deviations due to runout in the size of a few micrometers are assumed, the limiting depth of cut is up to 30% larger than for the comparable tool without runout. The effects of runout on the stability are much larger for variable helix tools in contrast to uniform pitch and uniform helix tools.

References

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