Analysis and Improvement of Dynamic Stability of a Thin-Walled Cylinder during Turning

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Abstract

The retarded dynamics of the turning process of a thin-walled cylinder in manufacturing is modeled using flexible multibody system theory. The obtained model is the basis for a subsequent analysis of the stability of the process using the semi-discretization method. The use of an adaptronic turning chisel comprising actuators and sensors to improve the dynamic stability is then investigated and a comparison of different control concepts is performed.

Keywords: dynamics, industrial problems, multibody dynamics, stability, vibrations

1. Introduction

In machining technology, the striving for even higher machining speeds at good surface finish is limited by the occurance of vibrations of workpiece and tool. These vibrations, called chatter, are inherently self-excited and do not only lead to a poor surface quality, but also cause tool wear and can even damage tool, workpiece and machine. In [1], four chatter mechanisms have been identified. Of those, regenerative chatter, which is caused by consecutive cuts on the same surface, is the most important by occurance and intensity. In general, it is modeled as an interaction between the dynamics of the machine structure and the time-delay of the system. The resulting dynamics is described by a set of delay-differential equations (DDE). Because of the detrimental effects on the machining operation, the dynamic stability of the process needs to be analyzed and unstable machining must be avoided. Stability depends not only on the dynamical properties of the system, but also on the process parameters like rotational velocity and depth or width of cut. It is usually characterized in terms of those parameters and displayed in so called stability charts.

In this contribution, stability of the turning of a thin-walled cylinder is investigated and then improved using modern control theory. First, a model of the process is derived using flexible multibody system theory, [2], which can account for the large, nonlinear rotations of the cylinder as well as the small elastic deformations of cylinder and tool. Then, a stability analysis of the resulting system is performed using an approximation as a discrete system via the semi-discretization method, [3].

To improve the dynamic behaviour, a feedback control based on the adaptronic turning chisel shown in Figure 1 is conceived. Several control laws, ranging from simple collocated concepts to advanced model based methods, are implemented and compared. The different methods are rated by time-domain simulations and their influence on the stability domain.

2. System model

Figure 2 shows a schematic of the considered system. Workpiece and tool are elastic bodies coupled by the cutting force $\boldsymbol{F}$. The workpiece performs large nonlinear rotations, the tool is fixed to the machine structure and moves with the feed velocity

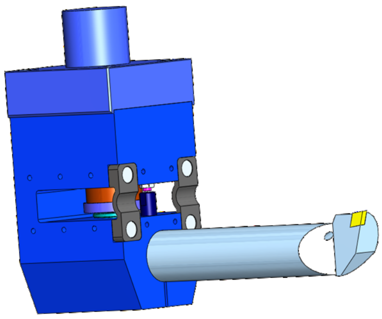

Figure 1: Active tool comprising actuators and sensors

v_f toward the jaw. The cutting force itself is a function of the chip thickness h. For small variations δh, it can be modeled by the linear force law $\boldsymbol{F} = \boldsymbol{k}\delta h(t) + \boldsymbol{F}_0$, the cutting force coefficients in $\boldsymbol{k}$ are hereby taken from literature, e.g. from [4]. The chip thickness variation depends not only on the present but also on past values of workpiece and tool displacement, modeled by the discrete delay $\tau = 2\pi/\omega$, resulting in

$$\delta h(t) = y_t(t) + y_{wp}(t) - \mu\delta h(t-\tau)\,. \tag{1}$$

The scalar values y_t and y_{wp} are the workpiece and tool displacements in chip thickness direction, the factor μ comprised between 0 and 1 is used to describe the overlapping of consecutive cuts.

Using flexible multibody system theory and the floating frame of reference approach, the equations of tool and workpiece can both be written in the form

$$\begin{bmatrix} \boldsymbol{M}_{r,i} & \boldsymbol{M}_{er,i}^T \\ \boldsymbol{M}_{er,i} & \boldsymbol{M}_{e,i} \end{bmatrix} \cdot \begin{bmatrix} \ddot{\boldsymbol{x}}_{r,i} \\ \ddot{\boldsymbol{x}}_{e,i} \end{bmatrix} = \begin{bmatrix} \boldsymbol{h}_{r,i} \\ \boldsymbol{h}_{e,i} \end{bmatrix} + \begin{bmatrix} \boldsymbol{0} \\ -\boldsymbol{K}_i \cdot \boldsymbol{x}_{e,i} - \boldsymbol{D}_i \cdot \dot{\boldsymbol{x}}_{e,i} \end{bmatrix} + \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{B}_i \cdot \boldsymbol{F} \end{bmatrix}, \tag{2}$$

where the submatrix $\boldsymbol{M}_{r,i} \in \mathbb{R}^{6\times 6}$ corresponds to the mass matrix known from rigid multibody dynamics, $\boldsymbol{M}_{e,i} \in \mathbb{R}^{N\times N}$, $\boldsymbol{D}_{e,i} \in \mathbb{R}^{N\times N}$ and $\boldsymbol{K}_{e,i} \in \mathbb{R}^{N\times N}$ are the flexible mass, damping and stiffness matrices obtained from finite element analysis.

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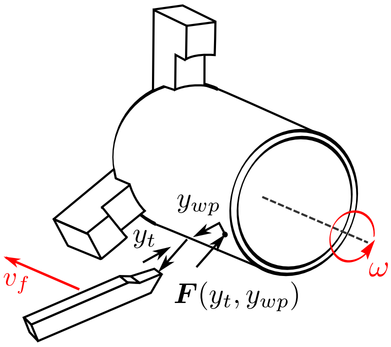

Figure 2: Workpiece and tool coupled by cutting force law

The matrix $\boldsymbol{M}_{er,i}$ couples the elastic deformations and the rigid body movement. The vector $\ddot{\boldsymbol{x}}_{r,i}$ contains the accelerations of the floating frame of reference, $\boldsymbol{x}_{e,t}$ the deformations of the elastic dofs, the vectors $\boldsymbol{h}_r$ and $\boldsymbol{h}_e$ collect generalized inertia forces. The input matrix $\boldsymbol{B}_i$ distributes the cutting force on the elastic dofs of the corresponding body i, while i is either workpiece wp or tool t. While $\boldsymbol{B}_t$ is a constant matrix, $\boldsymbol{B}_{wp}$ is not. Due to rotation, feed and the elastic deformations, it is a function of both the rigid and flexible dofs,

$$\boldsymbol{B}_{wp} = \boldsymbol{N}_{wp}(\boldsymbol{x}_{e,wp}, \boldsymbol{x}_{r,wp}, \boldsymbol{x}_{r,t}, \boldsymbol{x}_{e,t}) \ . \tag{3}$$

Figure 3 shows the general case where the force application point is not coincident with a node of the underlying finite element mesh of the cylinder surface. The force $\boldsymbol{F}$ has to be expressed via forces acting on the dofs of the adjacent nodes h,i,j and k. This is done by means of bilinear shape functions using local distances ξ and η. The matrix $\boldsymbol{N}_{wp}$ contains thus nonzero entries only on positions corresponding to the dofs of nodes h,i,j and k.

The displacements of workpiece and tool in chip thickness direction, y_t and y_{wp} are expressed using the input matrices $\boldsymbol{C}_t$ and $\boldsymbol{C}_{wp}$ of tool and workpiece, $y_t = \boldsymbol{C}_t \cdot \boldsymbol{x}_{e,t}$ and $y_{wp} = \boldsymbol{C}_{wp} \cdot \boldsymbol{x}_{e,wp}$. As y_{wp} is the displacement on the force application point in chip thickness direction, it becomes clear that $\boldsymbol{C}_{wp}$ also depends on the rigid and elastic dofs. With the same reasoning as before we can write

$$\boldsymbol{C}_{wp} = \boldsymbol{C}_h \cdot \boldsymbol{N}_{wp}^T(\boldsymbol{x}_{e,wp}, \boldsymbol{x}_{r,wp}, \boldsymbol{x}_{r,t}, \boldsymbol{x}_{e,t}) \ . \tag{4}$$

The same shape functions as before are used, with $\boldsymbol{C}_h$ being the constant matrix representing the projection in chip thickness direction. The derived nonlinear model is subsequently used to analyze the dynamic stability of the turning process. Actuators and sensors are then added to the tool and different control concepts investigated.

3. Stability analysis

The equations of motion of tool and workpiece (2) form together with the cutting force law (1) a system of nonlinear delay differential equations (DDE). Analysis of its stability is a difficult task that could for example be performed using time domain simulations. Neglecting the small elastic deformations in the determination of $\boldsymbol{N}$ and assuming constant rotational velocity and feed, Equations (4) and (3) and thus the system become linear time-dependent. This linear time-dependent system can be approximated by a discrete one using the semi-discretization method presented in [3]. The stability is then analyzed by means of the eigenvalues λ_i of the fundamental matrix of the so obtained discrete system.

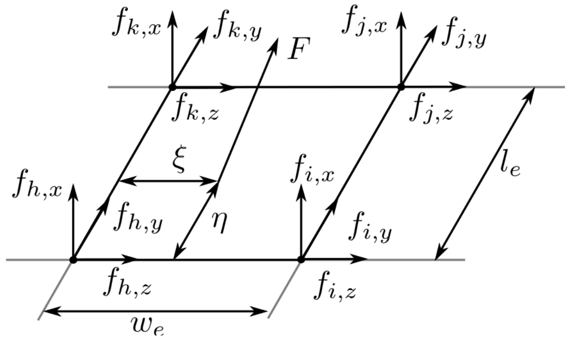

Figure 3: Cutting force acting on a surface element

For a stable system, they have to be located inside the unit circle of the complex plane. The boundary of stability is determined and stability charts are drawn.

4. Feedback control to improve dynamic stability

In order to improve the dynamic behaviour of the system, different control concepts are implemented in simulation using a modified turning chisel comprising sensors and actuators. The implemented control concepts range from active vibration damping concepts, e.g. simple collocated control and frequency shaped LQG, [5], to modern robust control techniques like H_∞ control, [6]. Those modern controller synthesis methods allow to define the desired closed loop behaviour more precisely by "shaping" the closed loop transfer functions. The control concepts are compared by their influence on the stability charts obtained through the presented stability analysis procedure.

5. Conclusions

The use of an active tool can improve the stability of the system and allows thus to increase machining speed without loss of quality. Collocated concepts damp vibrations locally and are therefore not able to improve stability for the considered case. Model-based concepts, in contrast, act globally on the system dynamics. When the dynamic behaviour is dominated by the tool, i.e for moderate wall thicknesses, they allow to increase the domain of stable turning significantly. When the dynamic behaviour is dominated by the cylinder, i.e. with decreasing wall thickness, they can still obtain good results but are sensitive to modeling errors, e.g. the difficult to obtain cutting force parameters coupling tool and cylinder.

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