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To cite this version :

Mikhail GUSKOV - Flank face interaction in high magnitude chatter investigation in time domain. -
In: 9th CIRP Conference on High Performance Cutting, Royaume-Uni, 2021 - 9th CIRP
Conference on High Performance Cutting (HPC 2020) - 2021

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9th CIRP Conference on High Performance Cutting (HPC 2020)

Flank face interaction in high magnitude chatter investigation in time domain.

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Abstract

A case of high magnitude chatter vibrations of a flexible tubular part is considered via dynamical modelling in time domain, in a delayed differential equation (DDE) framework. A ploughing term is introduced into the tool-workpiece interaction law. This term is based on a penalty-type law depending on the instant effective clearance angle. This ploughing interaction produces a vibration limiting mechanism featuring realistic maximum magnitudes, as compared to experimental measurements. It is also shown that in spite of interrupted surface pattern, the cut remains continuous under chatter. Furthermore, this model restitutes re-stabilisation at the exit of a stability lobe, with several instabilities occurring during the operation.

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Peer-review under responsibility of the scientific committee of the 9th CIRP Conference on High Performance Cutting.

Keywords: Chatter; Flexible part turning; Delay Differential Equation; Flank face interaction; Ploughing

1. introduction

Investigations of machining-induced vibrations depend on models of tool-workpiece interactions, linking relative motion of cutting edges and of workpiece, efforts and matter removal. One of components of such interaction takes place on the flank face of the cutter and induces velocity-dependent terms. Numerous works have addressed such interactions, starting with Albrecht [1], especially in the domain of small vibrations, i.e. related to so-called process damping, in particular Wu [2] proposed an approach for including flank face interaction into cutting process transfer function. Altintas et al. [3] have analysed chatter stability limits in turning, in relationship with process damping, especially in view of assessing the influence of the tool wear. When it comes to high magnitude vibrations, additional interactions may occur on the flank face of the cutter, in particular Seguy et al. [4] investigated vibrations in milling and modelled ploughing occurring on the flank face by a drastic increase in damping (500 fold) when the clearance angle is exceeded.

Another case of high magnitude vibration-induced ploughing has been observed in chatter vibrations arising in thin-walled tubular parts turning by Gerasimenko et al. [5, 6, 7]. Nevertheless, a priori estimations of ploughing model parameters induce quite different waveforms in comparison with experiment.

The goal of the present work is to analyse the influence of a ploughing model for high magnitude vibrations and to propose realistic parameter values for such model, based on a comparison with experimental measurements. The rest of the paper is composed as follows. Section 2 exposes the operation under study, experimental setup and results. Section 3 presents used modelling and simulation approach. In section 4 simulation results are shown and sensitivity to ploughing model parameters is investigated and compared to the experiment.

2. Experimental observation of high-magnitude chatter in turning

The present investigation focuses on a case of turning of a tubular part that has also been analyzed in [5, 6]. Fig. 1 (a) presents a description of the workpiece and of the operation, as well as nominal cut section schematic and cylindrical coordinates.

Turning operation conditions. The parameters of the pass under consideration are the following : feed per turn $f = 0,25$ mm, cut depth $a_p = 1$ mm, edge angle $\kappa_r = 45^\circ$, revolution

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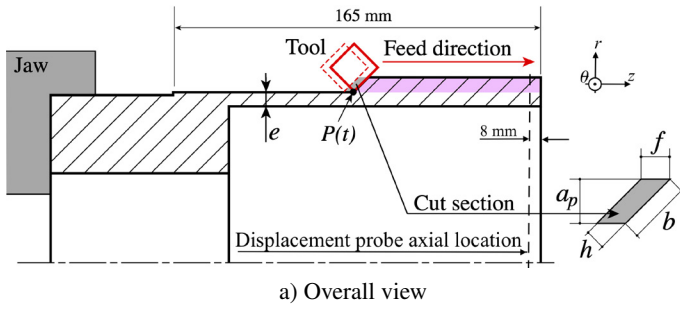


Fig. 1. Turning of a thin-walled tubular part operation description.

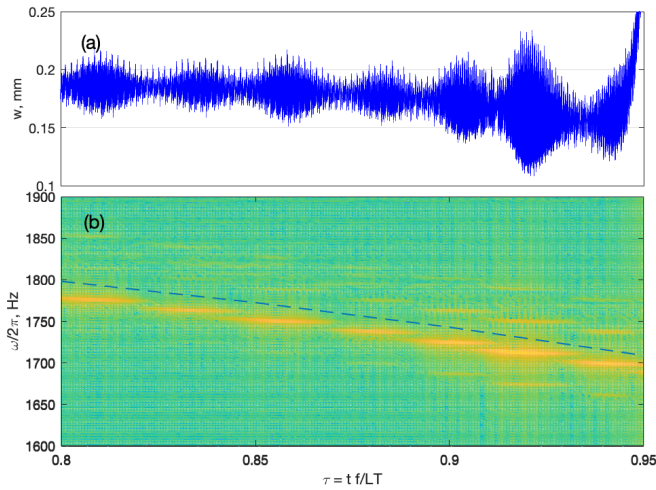


Fig. 2. General view of workpiece vibrations: (a) Experimental measurement of displacement; (b) Spectrogram of experimental measurements (dashed line — $P^{(3)}$, i.e. interpolated FE eigenfrequency data, colour surface — spectrogram of the signal (a): Sampling frequency 25 kHz, FFT analysis segment over 23736 points (12 turns), applied every 39.57 s); (c) Simulated displacement signal at measurement station w_d and ploughing force F_p history; (d) Spectrogram of simulated signal (dashed line — $P^{(3)}$, i.e. interpolated FE eigenfrequency data, colour surface — spectrogram of the signal w_d (c): Sampling frequency 63.2 kHz (5 ksamples/turn), FFT segment 20000 (4 turns), analysed on 60000 points (with zero-padding), executed every 39.57 ms)

period $T = 79.14$ ms, outer diameter before pass $D_0 = 160.3$ mm, machined length $L = 165$ mm. Workpiece material is C38 steel, cutting insert Sandvik 432-PR (clearance angle $\alpha = 7^\circ$). Cutting conditions correspond to nominal radial cutting force magnitude $F_{c0} = 290$ N and apparent stiffness $k_c = 569$ kN/m, as determined by a specific experiment.

Experimental observations. The experiment revealed a chatter vibrations occurrence during operation, as illustrated on Fig. 2. These vibrations followed a specific eigenfrequency, corresponding to a tubular shell bending eigenmode (circumferential three-lobe, axial first bending mode shape). This eigenfrequency evolves in clear correlation with matter removal, as confirmed by finite-element analyses.

Chatter occurs in several bursts, for which the vibration frequencies follow, in a discrete way (so-called "staircase" pattern), the evolution of the above-mentioned eigenfrequency. These bursts, as stability analyses suggest, would correspond to the system gradually leaving and entering several stability lobes of decreasing order. Each burst features increasing then decreasing vibration magnitude that can also be traced on the surface of the part, where along the axis several bands of increasingly intense marks remain after the operation.

Although these marks appear as interrupted, displacement measurements show too limited magnitudes for the tool to entirely leave the cutting state. Thus, ploughing is supposed to provide magnitude-limiting action, which we intend to reproduce via simulation, on the basis of a model introduced in the next section.

3. Variable parameter SDOF modelling in time domain

Similar to the approach developed in [5], the system's dynamics is represented by a single degree of freedom system

$$\ddot{q} + 2\omega\zeta\dot{q} + \omega^2q = \phi F. \quad (1)$$

Here q is the magnitude for the dominant eigenmode, F is radial component of the tool-workpiece interaction force, while ω , ζ and ϕ are properties of this mode: ζ damping ratio, ω eigenfrequency, ϕ mass normalised eigenshape magnitude under tool. Two latter parameters, due to tool displacement and to matter removal, vary during the turning operation. Their evolution is taken into account based on a FE model, polynomially interpolated with respect to the operation progress represented by the axial tool location z , the latter evolving at constant feed rate

along the tool path:

$$\omega = P_{\omega}^{(3)}(z), \quad \phi = P_{\phi}^{(3)}(z), \quad z = f \frac{t}{T} \quad (2)$$

Here $P_Q^{(3)}$ stands for a 3rd degree polynomial in Q quantity ($Q \in \{\omega, \phi\}$), as illustrated on Fig. 1 (b). Damping ratio $\zeta = 0.0007$ is kept constant.

The tool-workpiece interaction force term is composed of two main components, namely cutting force F_c (rake face) and ploughing force F_p (flank face):

$$F = F_c + F_p, \quad (3)$$

In the present work, we use experimental data for cutting force modelling and investigate a ploughing model,

Cutting interaction model. The cutting force model used in the present work is a power law [8]:

$$F_c(\Delta w) = F_{c0} \left(\frac{h}{h_0} \right)^n = F_{c0} \left(1 + \frac{\Delta w}{w_{out}} \right)^n, \quad (4)$$

with F_{c0} and k_{c0} nominal cutting force value and apparent cutting stiffness (experimental data), h chip thickness, $h_0 = f \sin \kappa_r$ its nominal value, $w_{out} = f \tan \kappa_r$ nominal cut interruption radial displacement under tool, $n = \frac{k_{c0} w_{out}}{F_{c0}}$. Finally, Δw is vibratory cut section thickness perturbation, calculated as follows:

$$\Delta w = w - w_T = \phi \cdot (q - q_T), \quad (5)$$

involving radial displacement under tool $w = \phi q$ as well as its T -delayed value defining actual location of the transitional surface issued from previous tool passage.

The geometry of the cut section is provided on Fig. 3 (a), where MN represents the cutting edge, in its actual position, as well as its nominal location (superscript 'o') at current and previous turn (subscript 'T'), as related to the vibratory radial displacement w . Although the nose radius (0.8 mm) is neglected here, it is implicitly accounted for via experiment-based values of F_{c0} and k_{c0} .

Based on this kinematics description, this model depends on the assumption that the tool wouldn't leave the cutting process, i.e. $\Delta w > -w_{out}$.

Ploughing interaction model. Following the observations of [6] and [7], flank face interaction is modelled via a linear penalty-like law for vibratory motion:

$$F_p(\dot{w}) = c_p (\dot{w} - V_{r0}) \mathcal{H} \left(\frac{\dot{w}}{V_{r0}} - 1 \right) \quad (6)$$

with limit radial relative velocity limit V_{r0} to which an effective clearance angle α' can be associated, as shown on Fig. 3 (b), \mathcal{H} step function (Heaviside). Thus, to the difference from the process damping, this high magnitude ploughing is unilateral.

Resulting DDE system. For numerical simulation, the equation (1) can be reformulated under the form

$$\dot{\mathbf{y}} = \boldsymbol{\varphi}(\mathbf{y}, \mathbf{y}_T, t) \quad (7)$$

that would be suitable for available DDE solvers, such as `dde23` [9], with

$$\mathbf{y} = \begin{bmatrix} q \\ \dot{q} \end{bmatrix}, \quad \boldsymbol{\varphi} = \begin{bmatrix} y_2 \\ -(2\zeta\omega\dot{y}_2 + \omega^2 y_1) + \phi F \end{bmatrix}, \quad (8)$$

$$F = F_c(\phi(y_1 - y_{1T})) + F_p(\phi y_2) \quad (9)$$

The initial set is taken null for all simulations: $\mathbf{y}(t) \forall t \in [-T, 0]$.

4. Simulation results and discussion

In this work we focus on the final part of the operation, where high magnitude vibrations are well present ($\frac{z}{L} > 0.8$). The comparison with the experiment is only possible before the tool machines the surface below the displacement probe (artefact visible on Fig. 2 (a), $\tau \approx 0.94$).

After manual research of suitable ploughing parameters, the following values have been retained as reference: $c_{p0} = 50$ N·s/m and $V_{r0} = 0.05V_{r*}$ with $V_{r*} = V_c \tan \alpha / \cos \kappa_r = 0.174V_c = 1.09$ m/s, although in the end of the operation ($\tau > 0.9$), $V_{r0} = 0.10V_{r*}$ appears to provide better agreement in magnitude, as discussed below.

The results for the reference case are shown on Fig. 2 (c,d). The values of displacement at displacement sensor location are calculated to the dynamical DOF q as

$$w_d = P_{\phi}^{(3)}(z_d) q, \quad z_d = 157 \text{ mm}. \quad (10)$$

Qualitatively, these results reproduce principal features observed experimentally, namely: vibrations occurring in finite magnitude bursts of decreasing frequency.

Thus, the presence of the ploughing force term F_p , visualised on Fig. 2 (c) allows for chatter vibration magnitude limitation at levels commensurate with those observed in experiments, preventing the tool from leaving the cutting process.

To further investigate the influence of the ploughing model parameters, a set of simulations for various values of c_p and V_{r0} is shown on Fig. 4. For the sake of readability, only upper envelopes are plotted (vibratory maxima). The main trend is that response magnitudes would increase with V_{r0} and decrease with c_p . At the extremes, very high values of c_p would clip vibration magnitudes at velocities V_{r0} , very small c_p or very high V_{r0} would make F_p negligible, and $V_{r0} \rightarrow 0$ can completely prevent chatter, providing directly process damping in the vicinity of the quasi-static nominal cutting regime. An example of excessive vibration levels is the upper line on Fig. 4 (b), for which at its top point cut interruption is detected.

The comparison with experimental measurements, shown on Fig. 4 (c), features qualitative correspondence of the proposed model to the observed phenomena. It is noticeable that the effective values of V_{r0} are at least 10 times below a mere geometrical estimation V_{r*} based on the clearance angle of the tool. A possible explanation for this discrepancy is that the interaction at the flank face takes place in a smoother way than

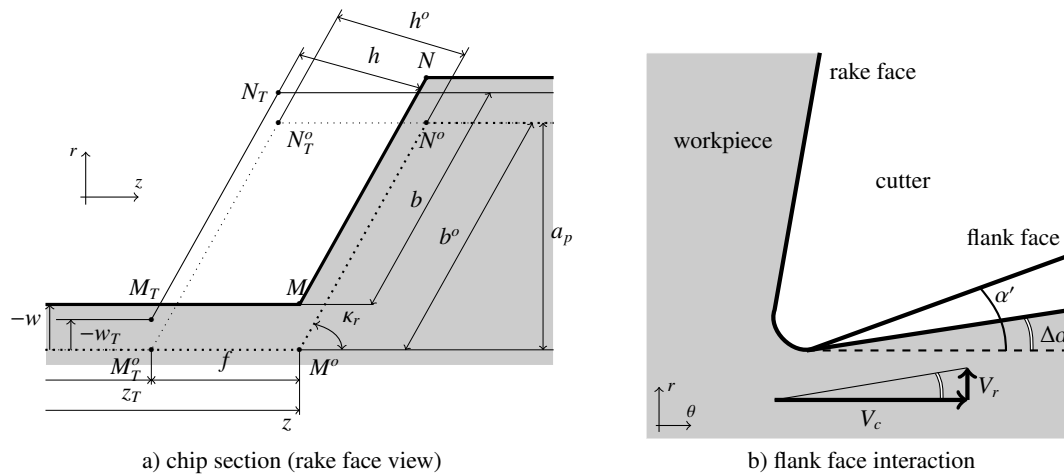
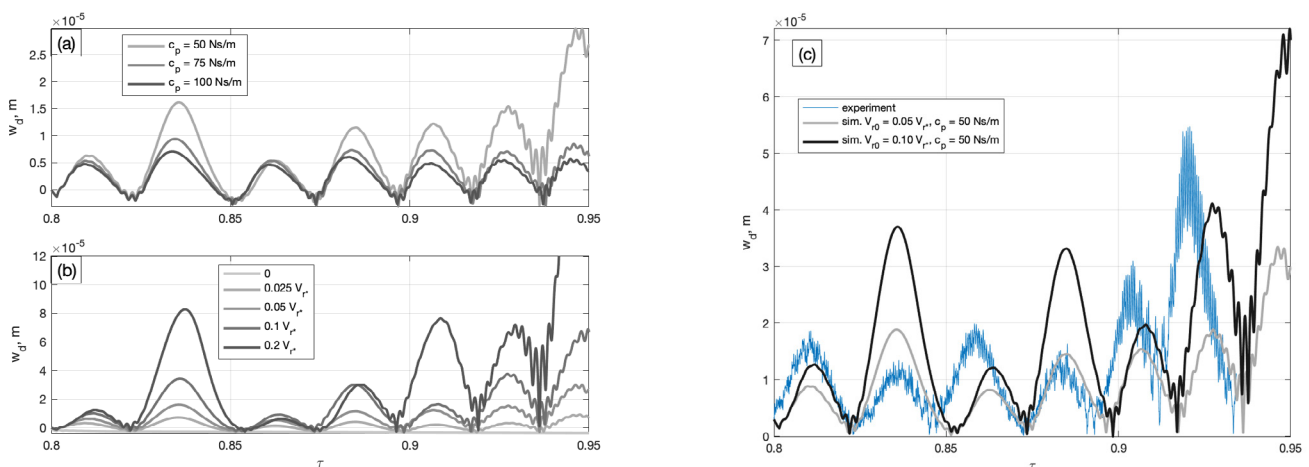


Fig. 3. Tool-workpiece interaction kinematics.

Fig. 4. Influence of ploughing parameters and comparison with experimental data. (a) $V_{r0} = 0.05V_{r*}$, various c_p ; (b) $c_p = 50$ N/m, various V_{r0} ; (c) comparison: simulation vs experiment

the proposed piecewise linear approximation, due to the cutting edge finite radius. Also, one can notice discrepancies in peaks occurrence timing and ratio of magnitudes of different bursts, and that different combinations of model parameters are provide better representations of the experiment at different stages ($V_{r0} = 0.05V_{r*}$ at $\tau < 0.9$ and $V_{r0} = 0.10V_{r*}$ at $0.9 < \tau < 0.93$). Such variations are consistent with modelling approximations of a SDOF dynamical system (approximate eigenfrequency and mode shape, possibility of excitation of the paired three-lobed eigenmode), power law for F_c and piecewise linear formulation of F_p .

5. Conclusion

Proposed modelling approach for high magnitude ploughing enables reproducing physically relevant behaviour of an unstable turning operation of a tubular part, especially in terms of magnitude limitation and occurrence of several chatter vibration bursts, corresponding to switching several stability lobes.

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