A Mechanistic Ploughing Model for Chatter Magnitude Limitation in Thin-Walled Parts Turning

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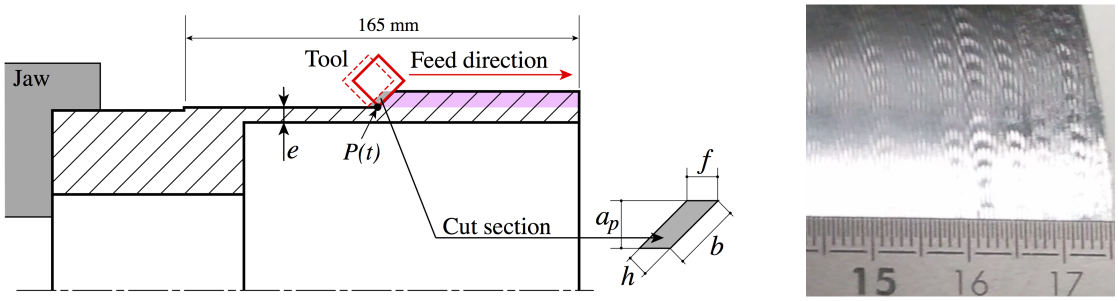
Summary. A reduced nonlinear model of the dynamics of tubular part turning process featuring chatter is investigated in time domain. The surface regeneration effect is accounted for in a delay differential equation. A simplified representation of flank face interaction for high-magnitude vibrations is proposed. Simulated results feature encouraging phenomenological similarity with the experimental observations in time and frequency domain.

Introduction. Investigated turning operation and observed phenomena

Thin-walled parts under turning are subject to the risk of regenerative chatter [1, 2, 3]. The modification of system's dynamical characteristics along the tool path, due to dynamic stiffness variation and to material removal, can drive the system through one or several stability boundaries.
A recent experiment on a thin-walled tubular part turning, demonstrated a case where several chatter-affected zones appear [4, 5]. On Fig. 1, the overall schematic of the workpiece and the turning operation is presented alongside the resulting surface bearing chatter marks.



a) Overall view b) Surface after chatter

Figure 1: Turning operation description

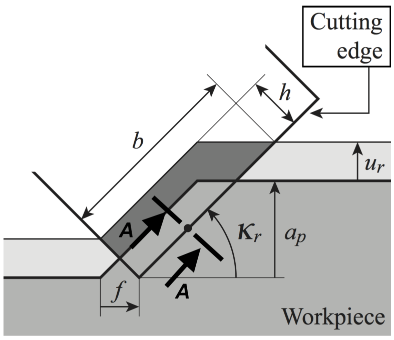
A preliminary analysis carried out in [5] suggests that when chatter vibrations arise, radial relative motion velocity magnitudes should induce an interaction on the flank face of the tool.
The subject of this work is to propose a mechanistic model of the chatter magnitude limitation, based on the flank face interaction force.

Modeling approach for workpiece and tool-workpiece interaction

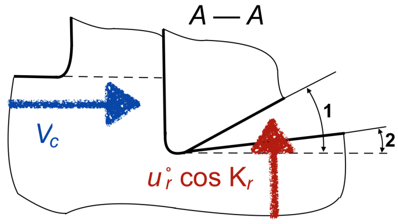
The workpiece dynamics is represented by a 1 DOF system, reduced to the specific eigenmode (first three-lobe shell bending mode), that is mainly subject to the regenerative chatter, as described in [4]:

$$\ddot{q} + 2\omega\,\zeta\,\dot{q} + \omega^2\,q = \phi F, \qquad F = \Pi \cdot (F_c + \Pi_p F_p). \tag{1}$$

with q modal degree of freedom, ϕ modal magnitude under tool (mass-normalized), ω eigenfrequency, ζ damping, F generalised force due to tool–workpiece interaction. The properties of this modal oscillator (ω and ϕ) undergo a slow variation during the operation, which is accounted for *via* an interpolation of the eigenfrequency and modal shape based on a finite element analysis performed at 5 reference points along the operation. The subsequent radial displacement field would write as $u_r(x, \theta, t) = q(t)\phi(x)\cos(3\theta)$. The tool-workpiece interaction is represented by a point force (radial component, applied at point $P(t)$, shown on Fig 1 (a)), composed of cutting and ploughing terms F_c and F_p. Π is a boolean function expressing the cut presence condition (Heaviside function of the tool-to surface distance, with a specific variable for the generated surface location), F_c is the cutting force (affine law based on the chip thickness experimental coefficient values), Π_p is a boolean function representing the ploughing condition and F_p is the ploughing force.
Terms like Π and F_c are typically present in DDE-based time domain works like [6] or [7]. As for the ploughing-related term proposed here, Π_p is a Heaviside function of the negative apparent clearance angledue to the radial motion (as shown on Fig. 2), while the force is defined in a manner analogous to that proposed in [8], representing the flank face contact as the work of a fictitious secondary cutting edge, which leads to a viscosity-like term, proportional to velocity.
In this investigation, for the sake of simplicity, the parameters of this model are set via a simple *a priori* estimation.
The simulation is carried out in the time domain in a formulation analogous to that of [7], over the final quarter of the pass where the chatter was observed.



← a) Cutting tool insert and uncut chip section schematic



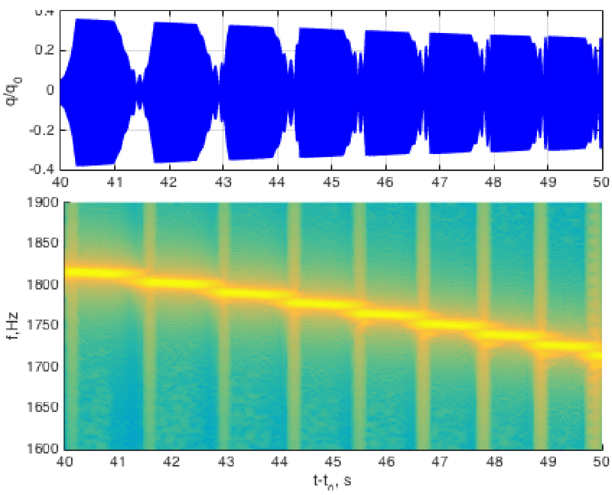
b) Flank face vs machined surface relative motion; (1: nominal clearance angle γ, 2: clearance angle perturbation $\Delta\gamma$ due to vibration)

Figure 2: Cut geometry and kinematics

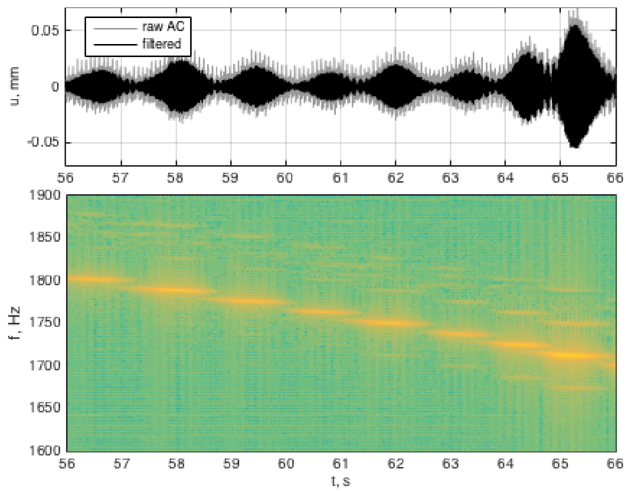
Results and discussion

Time series resulting from the simulation are shown on Fig. 3, alongside the corresponding experimental data. One can see that the signal is composed of a sequence of chatter bursts, for which the frequency follows a staircase-like pattern around the slowly varying eigenfrequency. This is consistent with the multiplicity of instability zones that are encountered by the considered mode in the end of the operation.

The shape of these bursts contains observable discrepancies between simulated and measured signals, that could suggest a need for further investigation concerning the ploughing model parameters. Nevertheless, the presence of ploughing would enable a limitation of vibration magnitudes that would keep the system from excessive vibrations when in unstable domains, so that once the system would exit these regions, the chatter burst would decay and the next instability will get to onset. It should be noted that although the marks on the surface left by the tool tip are discontinuous, the cut of the primary edge is not interrupted : the chip thickness remains above the half of the nominal value during all the simulation. Thus, from the phenomenological standpoint, the proposed ploughing model provides a potentially functional explanation of the work at limited magnitude without approaching the tool disengagement all the long.



a) solution of (1)



b) displacement measurement en the free end

Figure 3: Computation vs experiment results (top: time signal, bottom: spectrogram)

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