Fast and accurate estimation of the unconditional stability threshold in milling by including the effects of tooling system bending

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Summary. Self-excited anomalous vibrations called chatter may frequently arise during the cutting process. This awkward phenomenon causes a bad surface quality of the machined part and it may severely damage the machine tool components. For this reason, it has to be absolutely avoided by a proper selection of cutting parameters. When depth of cut is smaller than a critical threshold, the cutting process is unconditionally stable independently from the selected spindle speed. A simple but accurate formula for the preliminary estimation of this threshold - which should only depend on basic parameters characterizing the milling operation - would be very useful for many practical reasons. The classical formula derived from the classical model may be very inaccurate when considering large milling cutters with inclined cutting edges. In this work an improved version of the classical formula will be provided. The new formula has been obtained by applying an upgraded dynamic milling model including some important effects due to tooling system bending. The effect of tooling system geometry and cutting edge inclination on process stability can now be easily evaluated. The correction provided by the new model in comparison to the classical approach can exceed $+200\%$ for many cases of practical interest.

Introduction and aim

Chatter vibrations are responsible for unacceptable surface finish and poor dimensional accuracy of the machined parts [1]. Besides, they may cause sudden tool breakage or damage the machining system. For these reasons, chatter must be avoided. In the last 50 years, several techniques and practical solutions were proposed for eliminating or reducing chatter vibrations, such as for instance passive approaches [2] or semi-active strategies [3]. However, an effective understanding of this problem started only a couple of decades ago, thanks to sophisticate physical models of milling dynamics which may even allow the selection of sub-optimal cutting parameters [4].
In the medium-high spindle speed range chatter is mainly caused by the regenerative effect. The regenerative effect is the influence of the undulation left on the workpiece by the previous tooth passage on the actual uncut chip thickness acting on the tooth passing through the same angular position [1]. According to all current models, the instantaneous chip thickness evaluation on a given cutting tooth is performed by only considering tool tip transversal vibrations in the working plane orthogonal to spindle axis. Moreover, only the transverse forces are taken into account for modeling tooling system deflection, while the bending momenta associated to the axial forces are always neglected.
Nevertheless, when considering tooling systems with a relatively large cutter diameter to tooling system overhang ratio D/L, which are also characterized by inclined cutting edges (with an average working cutting edge angle $\bar{\chi} < 90°$), this simplification is too rough and it may lead to a significant underestimate of the stability boundaries. For this reason a new model of milling dynamics and regenerative chatter vibrations was recently introduced and validated in [5][6].

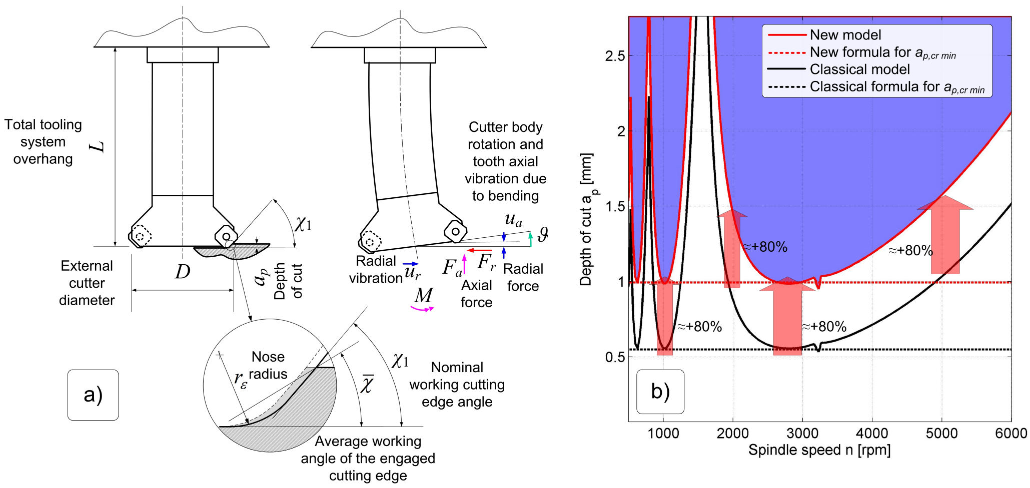

Figure 1: a) Schematic diagram of the tooling system showing the key ideas behind the new dynamic milling model. b) Example of application of the new model and new formula for preliminary estimation of the minimum criticl depth of cut by assuming $D = 100$ mm. $L = 280$ mm, $\xi = 0.0487$, $G = 1.14 \cdot 10^{-7}$ N/m, $k_{cs} = 8 \cdot 10^8$ N/m^2 (aluminum), $z_t = 10$ teeth, $a_L/D = 50\%$, $\chi_1 = 45°$, $r_\varepsilon = 1.5$ mm, $\bar{\chi}(a_{p,crmin}) \approx 31°$.

When adopting the classical model, stability lobes minima can be roughly estimated by the very simple and fast formula [7]

$$a_{p,cr\,min\,classic} \approx 4.5 \frac{\xi}{G k_{cs} z_t \left(a_L/D\right)^{1.2}} 1000 \quad [\text{mm}] \tag{1}$$

where ξ is an equivalent damping coefficient used for approximating the dominant vibration mode, G [N/m] is the tool tip static compliance in the transverse direction, k_{cs} [N/m^2] is the main shearing cutting pressure, z_t is the teeth number, a_L [m] is the lateral width of cut used to represent the tool-workpiece radial immersion a_L/D [%].
In this work, a new formula for a fast and more accurate estimation of stability lobes minima based on the upgraded model of milling dynamics will be conceived. In addition to be potentially very useful for engineers and technicians, the new formula gives a deep insight on the correction provided by the new model with respect to the classical model.

Main result

According to [6], the regenerative chip section area δA and the regenerative radial vibration δu_r are proportional to the same factor, i.e.

$$\delta A \propto \left(\sin\bar{\chi} - \frac{3}{4}\frac{D}{L}\cos\bar{\chi}\right); \quad \delta u_r\,(j\omega) \propto \delta A\,(j\omega)\left(\sin\bar{\chi} - \frac{3}{4}\frac{D}{L}\cos\bar{\chi}\right) \tag{2}$$

This is the key idea behind the new model, which was also incorporated in the new formula for estimating the unconditional stability threshold $a_{p,cr\,min}$. In order to model the effect of tooling system geometry and average cutting edge inclination $\bar{\chi}$, the following term was introduced

$$\chi_{rel} = (\bar{\chi} - \chi_0)/(90^\circ - \chi_0); \quad \chi_0 = \arctan\left(\frac{3}{4}\frac{D}{L}\right) \tag{3}$$

where χ_0 can be defined as the optimal working edge angle minimizing the term of Equation 2. Accordingly, the new estimate of the unconditional stability threshold can be expressed as follows

$$a_{p,cr\,min\,new} \approx 1.033\frac{\xi^{0.97}}{G^{1.08}k_{cs}z_t\left(a_L/D\right)^{1.19}\chi_{rel}^{0.42}}1000 \quad [\text{mm}] \tag{4}$$

provided that $\chi_{rel} > 0$. The formula was determined by performing multiple linear regression on the critical thresholds corresponding to 384 different milling configurations. Specifically, the following factors were varied according to a full factorial design of experiments: cutter diameter D and total tooling system overhang L (affecting the static compliance G), damping ξ, main shearing cutting pressure k_{cs}, teeth number z_t, tool-workpiece lateral immersion a_L/D and the nominal cutting edge angle χ_1, by assuming a straight cutting edge without nose radius.
This formula was also successfully applied to some realistic case studies with curved cutting edges (due to the presence of nose radius). Specifically, face shoulder cutters, general face milling cutters with $\chi_1 = 45^\circ$ and round insert cutters were tested. An example of the predicted stability lobes and thresholds is reported in Figure 1 b).

Conclusions

The corrections provided by the new dynamic milling model and by the new formula for estimating the threshold for unconditional stability become very important when $D/L \geq 1/4$ and $\bar{\chi} \leq 45^\circ$, i.e. when the new parameter χ_{rel} is relatively small.
The critical depth of cut is almost proportional to equivalent damping ξ and inversely proportional to tool tip static compliance G, main shearing cutting pressure k_{cs}, teeth number z_t as well as to tool-workpiece lateral immersion a_L/D. When one of latter parameters is increased the critical depth of cut may become very small, triggering the effect of nose radius which tends to increase process stability thanks to the reduction $\bar{\chi}$. This effect can be very strong when considering face milling cutters with round cutting inserts having $r_\varepsilon \geq 4$ mm. In such circumstances the correction of the new approach in comparison to the classical prediction may even exceed $+200\%$, as can now be easily verified by applying the new formula.

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