EXPERIMENTAL IDENTIFICATION OF BI-STABLE PARAMETER ZONES IN MILLING PROCESSES

Gabor Stepan[*a)] & Zoltan Dombovari[*]

[*]*Department of Applied Mechanics, Budapest University of Technology and Economics, Budapest, H-1521, Hungary*

Summary Nonlinear effects in cutting processes result in an unsafe zone for cutting parameters where chatter may occur. A simple measurement method is worked out for the identification of the width of this bi-stable zone as function of chip thickness using wavelet transformation technique. It is shown that the constant width of the unsafe zone corresponds to the classical power law, while the existence of inflexion or asymptote in the cutting force characteristics leads to a global maximum of the width of this zone as a function of the chip thickness.

Cutting force characteristics have important role in designing cutting parameters and selecting the ones that are optimal in accordance with certain goal functions identified by the manufacturer. The identification of these cutting force characteristics is usually based on extensive (and sometimes expensive) experiments carried out for controlled fixed parameters in case of stable and stationary cutting often subject to orthogonal cutting conditions. Still, these experimentally identified stationary cutting force characteristics involve strong stochastic components that make it uncertain to select and/or identify any kind of approximate functions that describe the cutting force dependence on the cutting parameters like chip thickness, chip width and cutting speed.

Continuum mechanics also attempts to identify these cutting force characteristics based on the combination of plasticity and thermodynamics to model the stationary process of chip formation. However, the theoretical results are often hard to be validated by experimental observations and even the global shapes of the cutting force characteristics or the mathematical forms of these functions are not identified uniquely, which would be essential to the manufacturer especially for the chip width and partially for the cutting speed dependence. In this study, the nonlinear effects of the cutting force variation against the chip thickness are considered.

The appearance of regenerative chatter [1, 2] is related to the loss of the linear stability of the stationary cutting process; this primarily depends on the derivative of the specific cutting force $f = F / w$ with respect to the chip thickness h [3, 4] that is also called cutting coefficient $K = \partial f / \partial h$. Since the cutting force F depends linearly on the chip width w in accordance with most of the theories and measurements, the stability limits are usually checked in the experiments at constant cutting speeds with respect to the chip width. The corresponding linear stability limits in the parameter plane of the chip width and the cutting speed, also called 'lobes' in Figure 1*b*), show some kind of stochastic character during the experiments just like in the case of the stationary cutting force measurements against the chip thickness.

However, there is a relevant nonlinear effect that results in the existence of a so-called unsafe zone [5] (or bi-stability) in the cutting parameter region where regenerative chatter may occur depending on the level of dynamic perturbation during cutting. We show that the width of this bi-stable zone with respect to the chip width strongly depends on the chip thickness. The simple measurement method worked out for the identification of the width of the unsafe zone as a function of the chip thickness using wavelet transformation technique may also provide a reliable way to estimate the cutting force characteristics via nonlinear dynamic experiments.

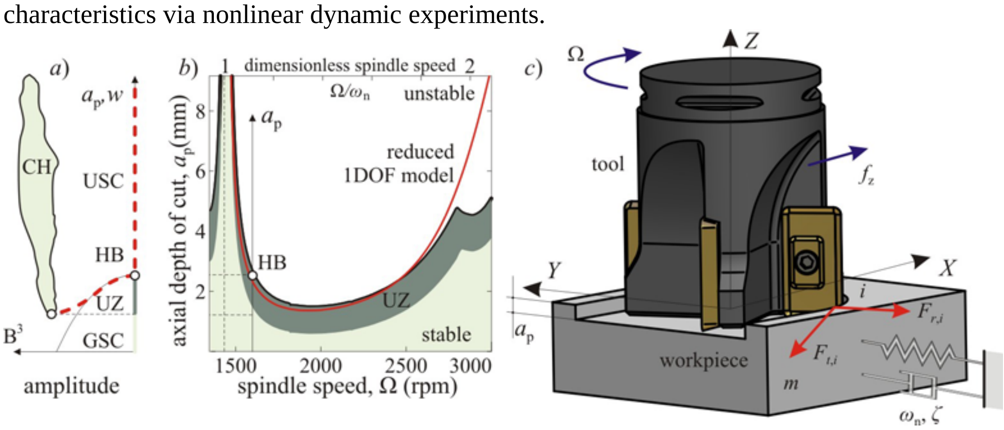

Figure 1. a) bifurcation diagram; b) stability chart combined with the bi-stable zone; c) mechanical model of milling

By means of the wavelet transformation of the measured acceleration signals of chatter induced by milling on work-pieces with carefully designed ramps and different feed rates, a simple method is introduced to measure the relative size of the hysteresis loops corresponding to the unsafe cutting parameter zones of regenerative chatter. From this cheap and fast measurement, formulae can be derived to reconstruct the cutting force characteristics against chip thickness. The method provides the classical power law when the unsafe zone is constant at about 3-5%; for 3.9%, it gives exactly the well-known ¾ rule. This is not valid, however, for large values of feed rates, for example, in case of high performance milling. In these cases a cubic polynomial approximation of the cutting force seems to be useful.

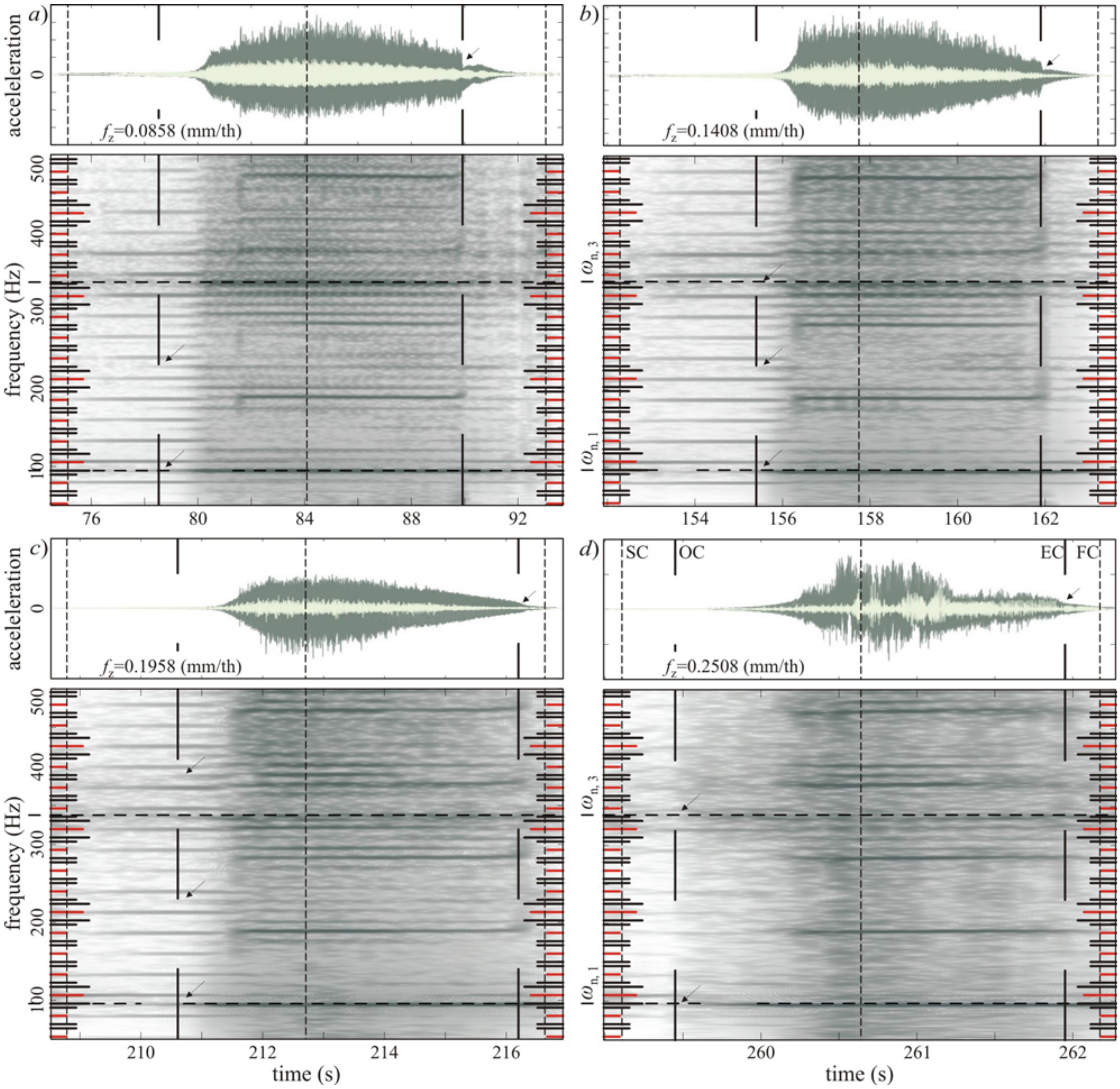

Figure 2. The series of figures show the measured acceleration in X (dark) and Y (bright) directions (see Figure 1 *c*) and the wavelet transform of signal Y in case of different feeds per tooth f_z. The three vertical dashed lines present the start of cutting (SC), the finish of cutting (FC) and the middle section of the 'ramp-like' workpiece. At the onset of chatter (OC) new frequency components and their harmonics (black ticks) occur apart from the harmonics of the spindle speed (red ticks). The chatter dies out at the end of chatter (EC) at a smaller depth of cut values than it started at OC.

One main result has already been confirmed by the experimental results presented in Figure 2: the hysteresis loop of regenerative chatter has a maximum point for increasing feed rates. That can be seen in the wavelet transform when the time of the onset of chatter (OC) takes place at higher depth of cut values than the end of the chatter (EC).

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References

[1] Tobias, S.: Machine-tool Vibration. Blackie. London, Glasgow, 1965.
[2] Tlusty, J., Spacek, L.: Self-excited vibrations on machine tools. Prague, Czech Republic, Nakl CSAV [In Czech.], 1954.
[3] Altintas, Y.: Manufacturing automation. Cambridge, UK, Cambridge University Press, 2000.
[4] Stepan, G.: Retarded Dynamical Systems. Longman, London, 1989.
[5] Domboovari, Z., Wilson, R., Stepan, G.: Estimates of the bistable region in metal cutting. *Proc. Roy. Soc. A*, 464:3255–3271, 2008.