Bifurcation scenarios in the hardware-in-the-loop experiments of highly interrupted milling processes

Rudolf R. Toth*, Daniel Bachrathy* and Gabor Stepan*

*Department of Applied Mechanics, Budapest University of Technology and Economics, Budapest, Hungary

Abstract. Hardware-in-the-loop (HIL) measurements of highly interrupted milling processes were conducted. A real spindle was used with a dummy tool on which the cutting forces were emulated with contactless sensors and actuators. During the experiments, Hopf- and period-doubling bifurcations were identified. The results of these measurements were compared with a 1 degree of freedom (DoF) delayed oscillator model. While the two show good agreement in the stability charts and the types of bifurcations observed, they also draw attention to the relevance of run-out compensation.

Introduction

The main limiting factor of efficiency and productivity in machining operations is the occurrence of regenerative vibrations (called chatter), which can increase wear on machine tools and produce intolerable machined surface quality. One approach to limit these harmful vibrations is the design of milling tools with irregular geometry [1]. The manufacturing of these tools themselves is a complex process making their design and prototyping expensive and time-consuming. The HIL environment allows for the emulation of cutting forces related to any tool geometry and material property without a need for prototyping. It has previously been shown that our HIL system is capable of reproducing the Hopf-bifurcation related vibrations in turning processes [2]. In the measurement presented here, a highly-interrupted down-milling process is investigated with a simple straight edge three-tooth ($Z = 3$) milling tool with 10% radial immersion. The oscillations of the dummy tool were measured at different axial depths of cut and spindle speeds. The emulated forces are updated at a frequency of 100 kHz using a low inductance coil. This high frequency is necessary to describe the sudden changes related to the virtual milling tool entering and leaving the material. The regenerative effects are emulated using a laser-based sensor, while the ferrite dummy tool is held by a real spindle (Fig. 1 panel a)) [2].

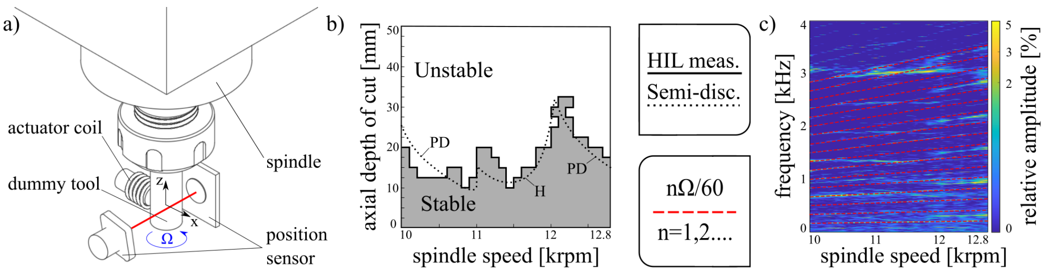

Figure 1: Panel a) Components of HIL system. Panel b) Stability charts. Panel c) Frequency content.

Results and discussion

The stability of the milling process was determined by the amplitude of the resulting vibrations at each parameter combination (Fig. 1 panel b)). This is compared to a stability map produced with the semi-discretization method applied to the corresponding 1 DoF mechanical model [3], which predicts the existence of three lobes in the actual spindle speed region. This calculation also describes the bifurcations related to the loss of stability, which is period-doubling for the lobes on the left and the right, and Hopf-bifurcation for the lobe in the middle. The stability regions show good agreement of the calculations and the measurements. For the identification of the bifurcations, the frequency content of the measured oscillations was used (Fig. 1 panel c)). In the region of the middle lobe, the dominant frequency is close to the natural frequency of the dummy tool with no linear dependence on the spindle speed Ω, which is in accordance with the Hopf-bifurcation. The right-side lobe shows the period-doubling frequencies, which are linearly dependent on the spindle speed and are harmonics of the half tooth-pass frequency. The results of this measurement show, that this HIL system is capable of emulating real milling processes by capturing the period-doubling bifurcations unique to milling processes besides the Hopf-bifurcations shown in previous turning experiments. The deviation between theory and experiment at the left-side lobe draw the attention to the relevance of run-out compensation in the HIL system.

References

[1] Stepan G., Hajdu D., Iglesias A., Takacs D., Dombovari Z. (2018) Ultimate capability of variable pitch milling cutters. *CIRP Ann.-Manuf.Technol.* **67**:373-376.

[2] Beri B., Miklos A., Takacs D., Stepan G. (2020) Nonlinearities of hardware-in-the-loop environment affecting turning process emulation. *Int. J. Mach. Tools Manuf.* **157**: Article 103611.

[3] Insperger T., Mann B.P., Stepan G., Bayly P.V. (2003) Stability of up-milling and down-milling, part 1: alternative analytical methods. *Int. J. Mach. Tools Manuf.* **43**:25-34.