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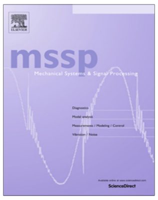

Destabilizing effect of low frequency modes on process damped stability of multi-mode milling systems

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ABSTRACT

Process damping is a nonlinear phenomenon significantly affecting dynamics and stability of machining operations at low cutting speeds. In the literature, almost all of the studies rely on the single dominant mode assumption in modelling of process damping. However, as process damping nonlinearly decreases with decreasing vibration frequency, multi-mode consideration may lead to new conclusions towards understanding of process damped stability especially in the presence of low frequency modes. Although there are well developed models to simulate dynamics and stability of multi-mode milling, the effect of multi-mode interaction at process damped stability regions is yet to be well investigated. In this study, this gap is addressed through investigation and modelling of process damping coefficients specific to individual modes. Stability diagrams are predicted in frequency domain using the updated frequency response functions (FRF) with the corresponding modal process damping coefficients, which are nonlinearly increasing with vibration frequency. It is analytically and experimentally shown that, although the low frequency mode may not be excited at lower cutting depths within the process damped region where higher frequency mode is stabilized, at the higher cutting depths the lower frequency mode starts to govern stability, resulting in completely different stability behavior, which has not been previously addressed in the process damping literature. In other words, due to insufficient modal process damping, the lower frequency mode is not suppressed, leading to a destabilizing effect for the whole milling system. The results show that for accurate prediction of chatter stability limits at low cutting speeds, all dynamic modes need to be considered even if some of them are much more rigid compared to the others.

1. Introduction

In machining operations, productivity is usually related with the material removal rate. Although the ultimate objective is to maximize the material removal rate, the process planner should make sure not to violate constraints such as surface quality, form errors and tool life. Machining chatter once occurs, causes poor surface quality, increased scrap rate of manufactured parts and tools, leading to high economic lost as emphasized by Tlusty and Ismail [1]. Thus, accurate prediction

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of chatter stability limits is essential for increased productivity with acceptable part quality as emphasized by Budak [2]. This is even more critical for machining of difficult-to-cut materials such as nickel and titanium alloys, where the cutting speed is inherently bounded due to low machinability resulting in high tool wear rate and the cutting depth should be increased as much as possible to the limits of stability to compensate the reduction of material removal rate (MRR) as summarized in a recent CIRP Keynote paper by Munoa et al. [3].

Although the primary source of damping is the loss factor due to the cutting tool material itself, damping may also be generated due to the cutting process, which may be much more significant than the structural damping, at low speeds. In an early study, Sisson and Kegg [4] put their efforts to explain the chatter behavior at low speeds, which was consistent with published experimental observations. They studied the forces acting on the flank face of tool and concluded that such forces, which are functions of tool edge roundness and clearance angles, can increase the stability. Later, Tlusty and Ismail [1] showed for the first time that the stability limit increases by decreasing the cutting speed because of process damping which is caused by periodic contact between the wavy surface and the flank of the tool. Later, Wu [5] reported that the indentation of the workpiece material by the tool's flank face is a huge source of process damping and developed a model in which process damping effect is described by the indentation forces acting in the tool-workpiece interference. Assuming small amplitude of vibration, Wu's indentation model was simplified by Chiou and Liang [6] to a piecewise linear viscous damper. Clancy and Shin [7] proposed a stability model including the effect of tool wear, where the stability limit increases with the increased damping due to the tool wear land. They showed that, the flattened flank face of the tool increases the indentation area. In one of the relatively recent studies, Altintas et al. [8] modeled process damping by oscillating the tool at a known vibration amplitude using a piezo actuator. In this way, they calculated the indentation volume for that vibration amplitude and then related this information to the amount of process damping through dynamic cutting force coefficients. In another early work, Ranganath et al. [9] introduced the process damping effect into milling stability by calculating the indentation volume through time domain simulations. Then, Huang and Wang [10] investigated mechanisms of cutting and process damping separately on stability of peripheral milling. They developed a cutting force model including the process damping forces. Moreover, Ahmadi and Ismail [11] studied the nonlinear effect of process damping in the stability diagram analytically. They developed upper and lower bound stability lobes in which between these two boundaries the process is in a limit cycle oscillation (LCO) state.

Budak and Tunc [12] proposed an inverse stability method to identify the average process damping coefficient from experimentally identified stability limits at low speeds. The total damping acting on the system is identified, and the structural damping obtained from the impact hammer tests is subtracted to obtain the process damping coefficients. They used an energy dissipation model to relate the process damping coefficients to the flank-wave contact volume through an indentation coefficient. This enabled estimation of the amount of damping force for different cutting conditions and tool geometry. Besides analytical and experimental approaches, Chandiramani and Pothala [13] proposed a numerical stability model with nonlinear process damping for better understanding of dynamics of two degrees of freedom regenerative chatter in turning processes. Furthermore, Jin and Altintas [14] identified the process damping coefficients utilizing the finite element (FE) models of micro-milling processes based on material constitutive property. In a later study on modelling of process damping in micro milling processes, Wang et al. [15] derived the expressions to determine the stable cutting depth and the critical spindle speed after which the stability limit with process damping reaches asymptotic infinity in with the effect of process damping. The proposed approach relied on the use of two sets of experiments for in-process identification of the critical speed without requiring modal parameters.

Eynian and Altintas [16] studied the stability prediction at process damping speeds for milling of flexible parts, where the tool has asymmetrical dynamics, where the rotating coordinate frames are considered. Although their model is capable of handling multi-mode dynamics, the process damping was modeled as a linear function of vibration velocity due to a single dominant vibration mode. In a recent study on modelling of process damping for milling processes, Molnár et al. [17] proposed a model for the low-radial immersion milling case. They pointed out that accounting the process damping effect as a velocity-dependent term in the dynamic cutting force equation captures the cases such as turning or large radial immersion. One of the important outcomes was that for low radial immersion cases, the process damping may lead to a negative damping effect. In their study, they considered process damping for the single dominant mode cases. In one of the other latest studies, Wan et al. [18] proposed a novel approach to identify process damping coefficients from stable cutting tests. They used the inverse Fourier transformation to extract the process damping ratios leading to tangential and radial ploughing force coefficients based on energy balance principle. Although, the proposed model and approach is suitable for extension towards multiple-mode dynamics, in the experimental and simulation study, they considered the effect of process damping on single dominant dynamic mode cases.

Prediction of stability limits for multi-mode systems is more complicated than the conventional systems, where only one dominant mode is considered. Berglind and Ziegert [19] developed an analytical time-domain model for a turning system with multiple modes. Using their model, total tool-tip vibrations can be obtained as a combination of sequential responses of the governing delay differential equations with existence of multiple modes. Tang et al. [20] proposed a model to predict stability limits in high-speed finish milling considering the multi-modes. They proposed an analytical stability prediction approach with multi-degree-of-freedom (MDOF) system modal analysis. The proposed method allowed including the effects of multi-mode dynamics, leading to higher excitation frequency and wider stability pockets on stability limits in high-speed milling. Wan et al. [21] studied the mechanism for construction of stability lobes in milling process with multiple modes and showed that the stability border for a multi-mode system can be effectively predicted by the lowest envelop of the stability