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Chatter mitigation using moving damper

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ABSTRACT

Chatter vibration will lead to poor surface quality of the resulting component and shorten the life of the machine tool unless it is avoided. Damping method is widely used in the engineering practice to mitigate the chatter. Using a moving damper, present paper concerns with the chatter suppression during milling the flexible components. It is realized by supporting the damper at the back surface of the workpiece. During milling process, the damper will move with the cutter at the same velocity. Considering the varying dynamics of the component, coupled with the moving damper, the chatter equation is constructed. The so-called stability lobe diagram (SLD) of the novel method, which describes the relationship between the critical stable depth of cut and corresponding rotational speed of the milling cutter, is also presented and it is compared with the SLD of flexible milling without damper. It is founded that the novel method can significantly improve the system stability. At the end of the paper, the method is experimentally validated.

1. Introduction

Self-excited vibration, also known as chatter, is a kind of undesirable vibration during metal cutting. It is often caused by the low-rigidity of the machine tool or the workpiece. It will lead to the poor surface quality of the final component and shorten the life of machine tool. It has become a major limitation to the high productivity of the machining process. Therefore, chatter suppression is necessary for the manufacturing industry.

Chatter vibration was thought to be mainly caused by the negative damping effect, mode coupling or regeneration. The last one mechanism is found to be the most common cause of chatter. During cutting process, the vibration of the cutting tool or the workpiece will result in the variable chip thickness, leaving the wave on the machined surface. This is regenerated in the subsequent cutting process. The process can be controlled by a set of differential equations with time delays. The SLD, which reflects the stability of the milling system, can therefore be plotted by solving the time-delay equation using zero-order approximate method [1] or semi-discretization method [2] or fully discretization method [3]. The chatter can be avoided and the stable cutting can be realized according to the SLD. However, to guarantee the high-productivity in engineering

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practice, the actual depth of cut may be much larger than the critical stable depth of cut. This will lead to chatter vibration. To suppress it and improve the system stability, many methods had been presented, such as proper fixture design [4–6], spindle speed variation [7,8], milling path planning [9], sacrificial structures method [10], robot arm [11], etc. Among all the methods, the damping method is widely used.

Damping is a concept to illustrate a group of different physical mechanisms that dissipate the mechanical energy. Damping techniques in the chatter suppression can be classified as active damping and passive damping. The active one is based on the measurement of one vibration parameter and introduction of a controlled force signal in response of the measured signal through an actuator [12]. Namely, an external energy is introduced and applied to the chatter object during active damping. Ganguli, Deraemaeker and Preumont demonstrated the effect of active damping on chatter stability for turning process through two different methods, i.e. traditional stability lobe diagram method and the method of plotting the root locus of the system poles [13]. The conclusions showed that the active damping can develop the system stability, especially for the low spindle region. Chen et al. used the magnetic actuator, which can deliver two radial force components and a torsional torque, to actively damp the boring bar [14,15]. Chen et al. proposed an adaptive active chatter control algorithm based on Fourier series analysis to process the milling force that leads to chatter [16]. Munoa et al. actively damped the structural chatter based on the machine drives and accelerometers [17]. The measured acceleration signal was fed back as an additional control loop. Long, Jiang and Meng designed an active table to adjust the relative vibration between the tool and part in milling [18]. Other active damping methods such as proof-mass damper can be founded in reference [19].

The passive damping, on the other hand, is a kind of method to dissipate the vibration energy without any external power supply. Moradi et al. [20] and Miguelez et al. [21] applied the passive absorbers to suppress the chatter and thus improve the stability in boring process. Saffur and Altus investigated the feasibility of dynamic absorbers for chatter resistance in turning process with non-uniform bar [22]. Moradi et al. also applied the tuned vibration absorbers in nonlinear milling process to mitigate chatter [23]. Sims introduced an analytical method to solve the problem of chatter mitigation with tuned vibration absorbers [24]. Nonlinear dampers such as friction damper and impact damper were also investigated. Wang proposed a nonlinear damper which was equipped with an extra series friction-spring element [25]. Compared to the optimized linear one, the new nonlinear damper realized the more than 30% development in the critical depth of cut. Gourc et al. quenched the chatter with a vibro-impact nonlinear energy sink [26] and improved the system stability of turning process. The damping effect can be provided by many techniques such as smart materials like magnetorheological (MR) fluids [27], eddy current effect [28]and piezoelectric effect and electromagnetic induction principle [29]. As the single degree of freedom (DOF) damper can only damp a single target mode, tuned mass damper (TMD) with multiple DOFs was developed [29,30]. It showed the TMD with multiple DOFs is more effective in chatter suppression. For some large structures, one damper is not enough to dissipate the system energy. Thus, multiple dampers are employed [31].

The damping methods mentioned above were realized on the objects of the machine tool such as turning bar, boring bar and milling cutter. During milling a thin-walled workpiece, it is more flexible compared with the cutting tool. Thus, the damper should be applied on the workpiece. Actively, Parus et al. employed the Linear Quadratic Gaussian (LQG) algorithm and the piezoelectric actuator to suppress the vibration during milling flexible workpieces [32]. Zhang and Sims discussed the feasibility of using piezoelectric actuator to mitigate chatter during machining of flexible workpieces [33]. The critical depth of cut was improved by a factor of seven using the forward position feedback controller. Passively, Bolsunovsky et al. eliminated the vibration of the flexible workpiece with TMD [34]. The mass damper was tuned by a new method which didn't require the frequency response determination of workpiece. The vibration reduction by 20 times was achieved while the device relative weight was just 2%. Considering the material removal of the cutting process, Yang, Xie and Liu proposed that using the tunable stiffness passive damper to suppress the chatter in thin-walled part milling [35]. It was concluded that the critical stable depth of cut is increased 1.8 folds under optimal tuning while the surface roughness of the machined surface is decreased by more than 80%. Hamed et al. suppressed regenerative chatter in milling process of cantilever plate with nonlinear milling force using the tunable vibration absorber (TVA) [36]. Optimal absorber position and its spring stiffness under the chatter conditions were presented. The use of damping during machining resulted in cutting forces reduced by a factor of 10 and surface R_a reduced by a factor of 25. Atsushi et al. presented a soft surface contact between the workpiece and the support with a pivot mechanism to suppress the milling vibration of thin walls [37]. For large flexible structures, especially for the monolithic structures in the aerospace industry, one damper may not work in the vibration dissipation. In this condition, more than one damper will be needed. The numbers, locations and parameters should be analyzed before attaching them to the workpiece. It will be very difficult to implement either active or passive damping. Thus, this paper presents that using moving damper to dissipate the mechanical energy during milling the flexible structures. It is realized by supporting just one damper at the back surface of the workpiece. During milling process, the damper will move with the cutter at the same velocity. This paper performs a theoretical and experimental study about the novel method. The rest of the paper is organized as follows: Section 2 reviews the chatter mechanism of milling the flexible structures. Section 3 models the developed method. Section 4 validates the feasibility of the new method experimentally and the conclusion is presented in Section 5.