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Analytical modeling of chatter vibration in orthogonal cutting using a predictive force model

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A B S T R A C T

This work is motivated by the fact that the conventional chatter models cannot capture the thermo-mechanical properties of realistic cutting processes intuitively and the involved cutting force coefficients are generally constant identified through experimental methods less accurately. In this paper, a new analytical chatter model is presented for the simulation and analysis of chatter vibration in orthogonal cutting processes. This model is developed using a predicted force model, which can determine the dynamic cutting forces theoretically with the equivalent cutting parameters from the material properties, tool geometry and cutting conditions. Moreover, the dynamic cutting force coefficients are derived significantly from the geometric approximations over a given wide range of cutting parameters. Then, a single degree-of-freedom (SDOF) dynamic model of the machine tool system for chatter vibration in orthogonal cutting is considered and formulated as a time delay-differential equation. The stability analysis of the proposed model is investigated and the stability lobe diagram (SLD) is obtained further by the time domain semi-discrete method. Finally, Comparisons among the proposed model, the semi-analytical model, the existing chatter model and experimental results available in the literatures are provided. It is shown that the results agree well with the analytically established SLD and thus validate the effectiveness of the proposed model.

1. Introduction

Chatter vibration, which results from the cutting forces variation and the flexibility of the machine tool system in the generation of chip thickness during cutting process, belongs to a kind of self-excited vibrations [1,2]. When uncontrolled, it has adverse influence on machining quality and efficiency, material removal rates (MRR), surface finish and dimensional accuracy of the workpiece, even the tool and machine life and so on. Even worse, among all other vibrations, regenerative vibration which is caused by the regeneration of wavy surface on the workpiece is the most destructive. Therefore, efficient models of chatter vibration should be critical for understanding the chatter phenomenon completely and predicting or avoiding its occurrence during cutting processes as well.

So far, many models of chatter vibration have been developed using the analytical, numerical and experimental methods [1–23] and studies on the effects of cutting parameters on process instability have been carried out [13–15], [19–23]. The initial works about chatter vibration were conducted by Tobias and Fichwic [3], Tlusty and Polacek [4], Meritt [5], who presented the linear model of chatter vibration in orthogonal cutting and identified dynamic cutting forces as the source of regenerative vibrations. Moreover, they predicted the stability limits in order to eliminate these vibrations. Later, Altintas et al. [6] stated the basis of such models that presented the dynamics of the chatter in the form of a time delay-differential equation, which was solved to obtain the SLDs for various cutting processes. Turkes et al. [8] predicted chatter vibrations in orthogonal cutting by modeling the process according to the oriented transfer function and the decomposition forms of revolution period. Mahnama et al. [11] investigated the FEM simulation of chip formation to chatter vibration in orthogonal cutting process and the effects of various cutting conditions on the onset of chatter stability using the software MSC/MARC. But FEM simulation was very time consuming and the accuracy of results always needed to be improved. A SDOF orthogonal cutting model incorporating variables like round inserts, tool lead angle, cutting speed and depth of cut was presented by Urbikain et al. [12] using Chebyshev collocation method for predicting chatter vibration, and the compliant model was useful for low order lobes and provided accuracy in stability prediction for up to 87.5%. Furthermore, Liu et al. [13] and Wu et al. [14], [15] have shown experimentally that the stability of an orthogonal turning process may be significantly enhanced by

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controlling the rake angle and clearance angle during cutting. They found that a larger rake angle increased the stability range of the cutting process. However, most of these models are based on the assumption that the cutting force is simply proportional to the cutting area, i.e. the cutting force coefficients are generally constant and identified through experimental methods. It is obvious that obtaining reliable experimental data for a given wide range of cutting parameters is extremely time-consuming. Moreover, the cutting force coefficients are hardly constant in realistic cutting processes and assuming it as an empirical constant will yield less accurate results. Besides, these models are at the cost of a lack of physical insight into the effect of cutting parameters such as the material properties and tool geometry on chatter stability without restoring to the empirical or experimental approach.

Therefore, a predictive force mode is necessary to determine the dynamic cutting forces from a knowledge of the material properties, tool geometry and cutting conditions for the simulation and analysis of chatter vibration. In Trang et al. [22], the dynamic cutting process was supposed to be equivalent to a series of steady-state cutting process with the time-varying undeformed chip thickness, rake angle and clearance angle. In addition, the dynamic cutting forces were obtained from the predictive force model proposed by Oxley [25]. Moufki et al. [23] developed the semi-analytical model of orthogonal cutting including the thermo-mechanical effects [24], velocity-dependent friction and plough force based on the knowledge of the workpiece material flow stress and verified their model by experimental results. Unfortunately, the semi-analytical model, even with inclusion of plough effect, did not match with the results of the experiment at lower velocities. Wu et al. [14] developed a dynamic cutting force model based on the single shear plane model of chip formation for orthogonal cutting, which model was known for its shortcomings [25], [27]. Therefore, it is reasonable to suggest that a new shear zone model of chip formation that is in better agreements with experimental results should be used. Li et al. [28] proposed a non-equidistant shear zone model of chip formation which appears to be more accurate than other models [25–27]. And it would appear to be logical to incorporate it into the analysis of the dynamic cutting forces model.

The objective of this work is to develop a new analytical modeling of chatter vibration using a predictive force model for the simulation and analysis of chatter vibration in orthogonal cutting processes. First, a predictive force model for determining the quasi-static cutting forces is introduced. With the assumption that the dynamic cutting process is equivalent to a series of quasi-static cutting processes [22], the dynamic cutting forces are determined theoretically from the predictive force model with the time-varying undeformed chip thickness, rake angle and clearance angle. Moreover, the dynamic cutting force coefficients are derived significantly from the geometric approximations over a given wide range of cutting parameters. The dynamic model of machine tool system for chatter vibration in orthogonal cutting is still considered as a SDOF system in feed direction and formulated as a time delay-differential equation as in many previous literatures [1], [6], [22], [23]. By solving this time delay-differential equation for each case, the SLD given the boundary between the stable and the unstable cuts is plotted using the time domain semi-discrete method [33], and the corresponding time domain solutions are also obtained using the Matlab function *dde23* [34]. The effect of some cutting conditions on chatter stability, such as the rake angle, is investigated as well. Finally, we compare the proposed analytical model with the semi-analytical model [23], the existing chatter models and experimental results obtained in the literatures [1,17,36].

The rest of this paper is organized as follows. Section 2 describes a predictive force model for determining the quasi-static cutting forces in orthogonal cutting. With these equivalence cutting parameters from static cutting forces, the dynamic cutting forces model is obtained and the expression of dynamic cutting force coefficients are also derived theoretically, furthermore, an analytical model of chatter vibration is developed and the corresponding stability analysis is investigated in Section 3. Comparisons between the proposed model, the semi-analytical model, the existing chatter model and experimental results available in the literatures are discussed in Section 4. Finally, conclusions of this study are drawn in Section 5.

2. The predictive force model

In this section, a predictive force model for determining the quasi-static cutting forces in orthogonal cutting is introduced [28]. In this model, the material properties such as flow stress, strain, strain rate and temperature in this non-equidistant shear zone are derived theoretically from the governing equations, i.e. material constitutive equations and thermo-mechanical equations.

2.1. Non-equidistant shear zone model

The non-equidistant shear zone model, which was presented and proved by Astakhov.et al. [29], is considered as a thin shear band of constant thickness $h = 0.025mm$, as shown in Fig. 1. In this model, the entry boundary (CD) and the exit boundary (EF) are parallel but non-equidistant to the main shear plane (AB). The shear band consists of two non-equidistant thickness κh and $(1-\kappa)h$, characterized by the portion $\kappa \in [0, 1]$. In addition, the shear angle is ϕ, the rake angle of the tool is γ_0, the cutting depth is h_0, and the chip thickness is h_c. In the hodograph, V, V_c, V_n and V_s are denoted as the cutting velocity, the chip velocity, the normal velocity and the shear velocity, respectively.

The chip formation flowing through this shear band is analyzed under the following assumptions:

- The tool tip is perfectly sharp.
- The cutting process is assumed to be quasi-static without vibration and cutting fluid.
- The chip formation is supposed to occur by plastic deformation within the shear zone and be continuous.

To conduct this process, two Cartesian frames, $\Re = \{o, x, y, z\}$ and $\Re^s = \{o, x_s, y_s, z_s\}$, are defined in Fig. 1. o is the tool tip, x, y are aligned to the directions of the trust and of the cutting speed respectively, x_s, y_s are the tangential and normal to the main shear plane (AB) respectively. For this parallel and non-equidistant shear zone, the corresponding physical values can be obtained

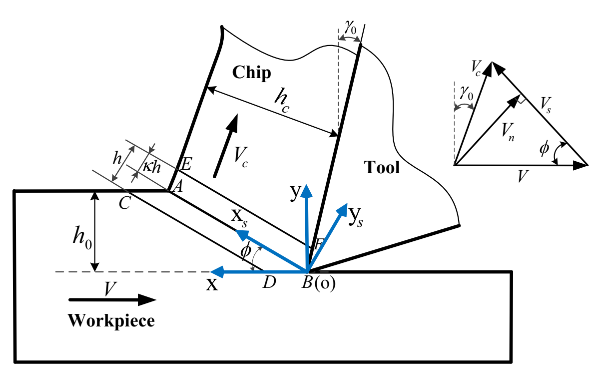

Fig. 1. The diagram of non-equidistant shear zone model