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Chatter reliability prediction of turning process system with uncertainties

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ABSTRACT

In this paper, reliability analysis of dynamic structural system is introduced into chatter vibration prediction of a turning process system. Chatter reliability is defined to represent the probability of stability (no chatter occurs) for a turning process system. Probability model (reliability model) of chatter vibration is established to predict turning chatter vibration, in which structural parameters m, c, k and spindle speed Ω are considered as random variables. Choosing chatter frequency ω_c as an intermediate variable, reliability model is developed from a model impossible to solve to a new model related to chatter frequency, and the new model can be solved. The first-order second-moment, fourth moment method are adopted to solve the turning process system reliability model and obtain the reliability probability of the system. An example is used to demonstrate the feasibility of the proposed method. The reliability probability of turning chatter system was calculated using the FOSM method, fourth moment and compared with that calculated by Monte Carlo simulation method. The results using the three methods were consistent. Reliability lobe diagram (RLD) is proposed to identify the chatter and no chatter regions for chatter prediction instead of stability lobe diagram (SLD). Comparing with the traditional SLD method, chatter reliability and RLD can be used to judge the probability of stability of turning process system. The RLD and the index of chatter reliability have better prospects in workshop application.

1. Introduction

Regenerative chatter is a type of self-excited vibration with a time delayed displacement feedback in the turning process system. An important characteristic property is that external periodic forces do not induce chatter vibration. However, the forces, which bring it into being and maintain it, are generated during the vibratory process (dynamic cutting process). The disastrous nature of chatter vibration creates numerous problems such as poor surface finish, excessive noise, breakage of machine tool components, along with reduced tool lifetime and productivity. Extensive research have been carried out to avoid regenerative chatter using prediction methods, real time detection, or simply controlling chatter vibrations with active or passive strategies. However, chatter is still among the most complicated problems for a machinist.

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Tobias [1] proposed the idea that chatter vibrations stem from the instability of the machining system. They used an orthogonal cutting model to analyze turning stability. One technique used for pre-process chatter prediction and avoidance is the well-known stability lobe diagram (SLD). The stability lobe diagram identifies stable and unstable cutting zones based on parameters such as cutting width in turning and spindle speed. Altintas and co-workers [2] developed an analytical method to predict stability, where the stability lobes were directly determined in the frequency domain. This method is known as zero-order approximation. To improve prediction accuracy, Budak and Altintas suggested a higher-order model to predict the stability of the cutting process. However, Stépán et al. [3–5] employed a semi-discretization scheme determine stability parameters in discrete time domain. Ding et al. [6–8], proposed a full-discretization method to obtain the stability lobes diagram in time domain.

Various groups have reported in literature regarding the various aspects of analytical models based on the degrees of freedom (DOF) [9] and flexibility of tool–workpiece system [10]. In this paper, the orthogonal cutting model and the SLD theory proposed by Altintas have been adopted to obtain the SLD because of the factors of the analytical formulations.

When we evaluate the stability of the turning process system using any of the above methods, the structural parameters and the spindle speed are known. However, as suggested by Schmitz et al. [11], the measurement result is an approximation or estimation of the value of a specific measurand Thus, the result can be considered complete only when it is accompanied with a quantitative value expressing the measurement uncertainty. Based on this, we can conclude that the influence of the uncertainty on the structural parameters of turning process system to determine the SLD should be studied.

Duncan et al. [12] studied the influence of random parameters on the stability lobes diagram in the milling process. For the first time, they used the mean value along with the lower and upper limit values based on the standard deviation to determine three curves representing the lobes. However, a quantitative index to represent the influence of uncertainty was not provided. Graham et al. [13] developed the robust chatter stability model taking into consideration the uncertainty in the natural frequency and the cutting coefficient. Sims et al. [14] applied the fuzzy arithmetic techniques to the chatter stability problem. It is shown that the fuzzy arithmetic can be used to solve process design problems with robustness to the uncertain parameters. For the uncertain factors in a practical milling process, Zhang [15] developed a speed optimization formulation, in which the upper bound of surface location error and lower bound of lobe diagram are adopted as the optimization object and the constraint condition, respectively.

Random structural system reliability analysis is a method, which incorporates probability analysis along with probability design into structural analysis based on random factors. In reliability analysis, parameters such as reliability index and reliability probability are used to provide a quantitative index to represent the influence of uncertainty. A fundamental problem in structural reliability theory is the computation of the multi-fold probability integral, and difficulty in computing this probability has led to the development of various approximation methods. First-order second-moment method is considered to be one of the most reliable computational methods [16]. In the last decades, researchers have examined the shortcomings of FOSM, primarily accuracy and the difficulties involved in searching for the design point. In order to improve upon FOSM, fourth moment method was proposed and proved to be simple and no shortcomings with respect to design points [17,18]. Until now, reliability analysis studies including static and dynamic structural systems have made significant progress. The issue related to the reliability of dynamic structural systems mainly includes two aspects. The first is the structural response (displacement, stress, etc.) overrun, which is caused by forced vibration [19–22]. The second is fatigue caused by a resonant and non-resonant structure [23]. However, to the best of our knowledge reliability analysis of a dynamic structural system on the instability of self-excited vibration, e.g., regenerative chatter of a turning process system, has not be reported in literature.

The goal of this paper is to introduce the ideas of reliability analysis of a dynamic structural system into structural analysis of a turning process system. A turning process system consists of a holder and a support, cutter, workpiece. The interaction between cutter and workpiece is a dynamic system referring to the machining condition. The variation of cutting forces between the cutter and causes the chatter vibration and is an internal system force.

In this paper the dynamical model and SLD is reviewed. A chatter probability model is established to predict turning chatter vibration, in which structural parameters m, c, k, and spindle speed Ω are random variables. Chatter reliability is defined to represent the probability of stability (no chatter occurs) of turning process system. Choosing chatter frequency ω_c as an intermediate variable, reliability model is transformed from a model impossible to solve to a new model related to chatter frequency, and the new model can be solved. First-order second-moment method is adopted to solve the turning process system reliability model and obtain the reliability of the system. The reliability lobe diagram is proposed to predict the chatter vibration. Finally, an example is used to demonstrate the effectiveness of the chatter reliability analysis and the RLD method.

2. Dynamic modeling of turning chatter

2.1. Turning machining dynamic model

Fig. 1 shows the mechanical model for a regenerative chatter vibration cutting system of facing operation in turning. The following assumptions were made for the dynamic model: (1) the workpiece system is rigid and the tool holder system is the weakest link in the cutting system; (2) vibration system is linear and elastic resilience of the vibration system is proportional to vibration displacement; (3) direction of the dynamic cutting force and steady cutting force are the same, and