Available online at www.sciencedirect.com
ScienceDirect
Chinese Journal of Aeronautics 21(2008) 169-178
Chinese Journal of Aeronautics
www.elsevier.com/locate/cja

Solution and Analysis of Chatter Stability for End Milling in the Time-domain

Li Zhongqun[a,b,*], Liu Qiang[a]

[a]*School of Mechanical Engineering and Automation, Beijing University of Aeronautics and Astronautics, Beijing 100083, China*

[b]*School of Metallurgy, Hunan University of Technology, Zhuzhou 412000, China*

Received 1 September 2007; accepted 15 February 2008

Abstract

In this paper, the instantaneous undeformed chip thickness is modeled to include the dynamic modulation caused by the tool vibration while the dynamic regenerative effects are taken into account. The numerical method is used to solve the differential equations governing the dynamics of the milling system. Several chatter detection criteria are applied synthetically to the simulated signals and the stability diagram is obtained in time-domain. The simulation results in time-domain show a good agreement with the analytical prediction, which is validated by the cutting experiments. By simulating the chatter stability lobes in the time-domain and analyzing the influences of different spindle speeds on the vibration amplitudes of the tool under a fixed chip-load condition, conclusions could be drawn as follows: In rough milling, higher machining efficiency can be achieved by selecting a spindle speed corresponding to the axial depth of cut in accordance with the simulated chatter stability lobes, and in finish milling, lower surface roughness can be achieved by selecting a spindle speed well beyond the resonant frequency of machining system.

Keywords: high-speed milling; chatter stability lobe; dynamic cutting force; time-domain simulation; cutting parameter optimization

1 Introduction

High speed milling has been widely used in a variety of industries, such as aerospace craft, automobiles, moulds and dies and others. Process optimization affects the efficiency of the milling process directly. However, chatter is a major factor that hampers the milling process optimization. Chatter means the dynamic instability material removal rate, causes poor surface finish and probably damages the tools and the workpieces. Inspired by the current requirements of highly automated manufacturing, the establishment of accurate cutting force and chatter models is especially urgent for realizing high-efficient, high-quality and low-cost milling.

Taylor firstly discovered and described chatter in 1907, but only as late as in the 1950's, Tobias[1] and Tlusty[2] began the study of machine chatter with establishment of the basis of the regenerative chatter theory. They identified the structural dynamics of the machine tool and the feedback of the subsequent cutting on the same cut surface as the utmost important source of the self-excited regenerative vibration. Sridhar et al[3] firstly introduced the time-varying directional cutting force coefficients in modeling the chatter stability of milling. Minis and Yanushevsky[4] used Floquet's theorem and the Fourier series to formulate the milling stability, and numerically solved it using the Nyquist

*Corresponding author. Tel.: +86-10-82316699.
E-mail address: zhqunli@163.com
Foundation items: National Key Technologies R&D Program (2006BA103A16); Fundamental Research Project of COSTIND (K1203020507, B2120061326)

criterion. Altintas and Budak[5] developed a stability approach enabling to make an analytical determination of stability limits. This approach was verified by experimental and numerical results.

Used to predict chatter stability lobe in milling process, the analytical approach is also termed the frequency approach, by which the chatter-free cutting conditions including spindle speed, axial and radial depth of cut could be found. Also, it is helpful in fast generating stability lobe diagrams. Nevertheless, the prediction precision of this approach is relatively low because some simplifications and assumptions have been introduced in modeling. As an alternative, modeling in the time-domain is relatively precise because it allows for the nonlinearity of machining system.

The time-domain model is used to predict the cutting forces, the torques, the power, the dimensional surface finish and the amplitudes and frequencies of vibration in a milling operation. With this method, Ismail and Tlusty[6] described the dynamic behaviors of milling and investigated the boundary zone between the stable and the unstable conditions. Lee et al[7] studied the effects of the dynamics of workpieces on the milling process. Altintas and Spence[8] presented a much more detailed cutting mechanics model to predict the cutting forces in end milling. Ko and Altintas[9] developed a time-domain model for plunge milling operation. In this model, two lateral x, y vibrations, an axial z and a torsional θ vibration are considered and the fourth-order Runge-Kutta method is used to solve the differential equations thus predicting the vibration under the cutting forces and torques applied to the plunge mill. Lazoglu et al[10] presented a mathematical model and a computational algorithm for the time-domain solution of boring process dynamics. In this model, also the fourth-order Runge-Kutta method is used in numerically integrating the state space equation.

It is noted that although the time-domain model is quite helpful, the time-domain simulation of the dynamic milling process still lacks a clear chatter stability criterion.

Smith and Tlusty[11] outlined the use of peak-to-peak (PTP) diagrams to evaluate the results of the multiple runs of a time domain simulation of a milling process. Campomanes and Altintas[12] proposed a non-dimensional chatter coefficient based upon the predicted chip thickness. In this method, the maximum chip thickness that occurs during a simulation with the flexible machine system is compared to that with the rigid system. Li et al[13] suggested a similar approach, in which the coefficient is calculated with the resultant forces rather than the chip thickness. Bayly et al[14] used another approach that applied signal processing techniques to the simulated tool displacement data. Schmitz[15] sampled the data once per tooth revolution and calculated the statistical variance of the signal, making the large variance the good indicator of chatter. Sims[16] proposed a new chatter criterion for the time-domain milling simulation in order to overcome this drawback by considering the transient response of the modeled behavior in stead of the steady-state response. It is proved that in many cases the new criterion enables the numerical prediction to be made over five times faster than the old one. However, this method is only applicable to the tools with regular pitch teeth.

This paper presents a predictive time-domain chatter model for the simulation and analysis of the dynamic milling process and makes synthetic use of several chatter stability criteria to overcome the limitation imposed by the single chatter stability criterion. In order to take into account the dynamic regenerative effects, the instantaneous undeformed chip thickness is modeled to include the dynamic modulations caused by the tool vibrations. The cutting forces are calculated based on the instantaneous undeformed chip thickness, the cutting conditions, the properties of the workpiece material and the tool geometry as well as the dynamics of milling system. Further more, directives are given on the determination of the cutting conditions in rough and finish milling.