Mechanical Systems and Signal Processing 100 (2018) 814–826

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Model-based chatter stability prediction and detection for the turning of a flexible workpiece

Kaibo Lu [a,*], Zisheng Lian [a], Fengshou Gu [a,b], Hunju Liu [a]

[a] College of Mechanical Engineering, Taiyuan University of Technology, Shanxi 030024, PR China
[b] School of Computing and Engineering, University of Huddersfield, Huddersfield HD1 3DH, UK

ARTICLE INFO

Article history:
Received 14 November 2016
Received in revised form 15 July 2017
Accepted 9 August 2017

Keywords:
Chatter stability
Turning
Flexible workpieces
Feed direction
Chatter detection

ABSTRACT

Machining long slender workpieces still presents a technical challenge on the shop floor due to their low stiffness and damping. Regenerative chatter is a major hindrance in machining processes, reducing the geometric accuracies and dynamic stability of the cutting system. This study has been motivated by the fact that chatter occurrence is generally in relation to the cutting position in straight turning of slender workpieces, which has seldom been investigated comprehensively in literature. In the present paper, a predictive chatter model of turning a tailstock supported slender workpiece considering the cutting position change during machining is explored. Based on linear stability analysis and stiffness distribution at different cutting positions along the workpiece, the effect of the cutting tool movement along the length of the workpiece on chatter stability is studied. As a result, an entire stability chart for a single cutting pass is constructed. Through this stability chart the critical cutting condition and the chatter onset location along the workpiece in a turning operation can be estimated. The difference between the predicted tool locations and the experimental results was within 9% at high speed cutting. Also, on the basis of the predictive model the dynamic behavior during chatter that when chatter arises at some cutting location it will continue for a period of time until another specified location is arrived at, can be inferred. The experimental observation is in good agreement with the theoretical inference. In chatter detection respect, besides the delay strategy and overlap processing technique, a relative threshold algorithm is proposed to detect chatter by comparing the spectrum and variance of the acquired acceleration signals with the reference saved during stable cutting. The chatter monitoring method has shown reliability for various machining conditions.

1. Introduction

Chatter, the violent dynamic motion occurring between the machine tool and the workpiece in a machining process, is often encountered in turning of a long slender workpiece. It not only reduces the machining accuracy but also causes damages to machine tools. Therefore, many investigations have been carried out to predict and thereby take adequate measures to avoid it during a machining process. Largely, the investigations can be viewed into two main categories: chatter stability analysis [1,2] and chatter monitoring and control [3,4].

Chatter vibrations result from the interaction between the metal cutting process and the workpiece or machine tool structure. According to the relative flexibility of the workpiece and the cutting tool, different chatter models were

* Corresponding author.
E-mail address: lvkaibo@tyut.edu.cn (K. Lu).

http://dx.doi.org/10.1016/j.ymssp.2017.08.022

Nomenclature

A	cross sectional area of the workpiece (mm^2)
d	depth of cut (*doc*) for a single cutting pass (mm)
$d_{\lim}$	critical *doc* (mm)
C	damping coefficient
D	diameter of workpiece (mm)
E	Young's modulus (MPa)
f	feedrate of the tool (mm/rev)
f_C	critical chatter frequency (Hz)
f_{SR}	spindle rotation frequency (Hz)
F	cutting force (N)
I	moment of inertia of the work cross section (mm^4)
k_e	equivalent stiffness (N/m)
K_f	cutting force coefficient (N/mm^2)
k^*	non-dimensional z-coordinate
L	length of workpiece (mm)
$\min(d_{\lim})$	minimum critical *doc* (mm)
M_1, M_2, M_3, M_4	configurable parameters for chatter detection
s^*	length-to-diameter ratio
T	time delay (s)
$T_j(t)$	generalized coordinate in the jth mode
$(v_1)_{cr}$	first critical feedrate (mm/s)
$W_j(z)$	the jth normal mode
X, Y, Z	coordinate axes
z^+, z^-	Z coordinates for feeding in +Z and −Z directions
α_j, B_j, R_j	constants related to the jth normal mode
$\delta(z, t)$	impulse function
ζ	equivalent damping ratio
μ	overlap factor
μ^*	non-dimensional feedrate of the cutting tool
ρ	density of the workpiece
τ^*	non-dimensional time
ω	chatter frequency (rad/s)
ω_d	frequency of damped vibration (rad/s)
ω_n	natural frequency of the vibration system (rad/s)
Ω	rotational speed of spindle (rpm)

Subscript

j	corresponding to the jth normal mode of a workpiece

formultated. In the earlier chatter studies, the turning tool was often modeled as a single lumped vibration system for representing the motion of the orthogonal facing or grooving processes [5,6]. Apparently, it is a time-invariant single degree of freedom (SDOF) chatter model if the tool wear factor [7] is not included. By calculating the corresponding mathematical expressions using analytical or numerical methods, the chatter stability lobes of the cutting system that plot the boundary between the stable and unstable zones with respect to the spindle speed and the width or depth of cut (*doc*), can be obtained. On the contrary, if the flexibility of the workpiece is predominant, the cutting tool can be assumed to be rigid. In this case the flexible workpiece was generally modeled as an SDOF model [8], a continuous system [9], or a finite element model [10,11] to analyze chatter onset using Nyquist criterion.

In the past years, many researchers took into account the compliance between the cutting tool and the workpiece in chatter stability prediction. Chen and Tsao [12,13] formulated a 2DOF dynamic chatter model for modeling an orthogonal cutting process with and without the tailstock supported flexible workpieces. The workpiece is regarded as a continuous Euler-Bernoulli beam, in which only the first mode shape is accounted in the compliant chatter model. The simulation results have demonstrated that the critical chip width of the deformed work case is constantly larger than the rigid body case. Vela-Martinez et al. [14] introduced a multiple degrees of freedom chatter model based on the compliance between the tool and the workpiece. The experimental validation was absent in the study. Sekar et al. [15] conducted machining experiments in the case that the tool cut the workpiece at a fixed position to verify a compliant 2DOF chatter model. The influence of various cutting positions on the frequency response function and chatter stability was investigated in [16]. Recently, Otto et al. [17] extended the number of the mode shapes of Chen and Tsao's compliant model and analyzed the influence of cutting positions on chatter stability theoretically.