Journal of Sound and Vibration 434 (2018) 358–378

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Nonlinear dynamic analysis of flexible workpiece and tool in turning operation with delay and internal resonance

Arnab Chanda *, Santosha K. Dwivedy

Department of Mechanical Engineering, Indian Institute of Technology Guwahati, Guwahati, 781039, India

ARTICLE INFO

Article history:
Received 27 March 2017
Revised 23 May 2018
Accepted 28 May 2018
Available online XXX
Handling Editor: H. Ouyang

Keywords:
Thin cylinder
Turning
Chatter
Delay
Internal resonance

ABSTRACT

In this work, the nonlinear dynamics of the tool and the thin cylindrical workpiece are studied simultaneously for turning operation. To capture the flexibility of thin workpiece, structural nonlinearity is taken into consideration. Regenerative chatter effect in turning operation is considered in terms of effective chip thickness which is driven by relative motion of the tool and the workpiece during the present cut and the earlier cut. Higher order method of multiple scales (MMS) is used to study the nonlinear responses and stability of tool and workpiece for both internal resonance and primary resonance conditions. The critical values of the cutting parameters like spindle speed, chip width (or depth of cut), cutting force coefficient, workpiece to tool stiffness ratio, and workpiece diameter to thickness ratio etc. are estimated using both time and frequency response curves to have stable chatter free turning operation. The effects of stiffness nonlinearities on the workpiece and the tool responses are also investigated.

1. Introduction

In manufacturing science, the sources of self excited vibration or chatter still is a research of interest to have precise and stable turning operation as its presence leads to the poor surface finish, loss of energy, workpiece dimensional inaccuracy and reduction of tool life due to large amplitude of vibration. Apart from regenerative effect, mode coupling effect [1], frictional [2], thermo-mechanical effect came out as main contributory factors for the onset of chatter. Starting from the work of Taylor [3] and Tobias [4] till today, several linear and nonlinear models are studied on the chatter in turning process which are briefly described below.

Hanna and Tobias [5,6], Grabec [7] generated a nonlinear theory of regenerative chatter taking into account a single degree of freedom (SDOF) structure with nonlinear stiffness and cutting force. The analyses of these models reveal the chaotic behavior for the intensive cutting. Lin and Weng [8] presented a nonlinear orthogonal cutting force model considering the effective geometry of cutting tool due to wavy surface on the workpiece. Going one step ahead, in Ref. [9], the stiffness nonlinearities and nonlinear time delay terms are included in the model of [8] which yields chaotic oscillations for some cutting parameters. In paper of Moradi et al. [10], a SDOF model of turning process considering quadratic and cubic structural nonlinearities and contact force due to the presence of tool flank wear between the workpiece and the tool, is investigated for primary, subharmonic and superharmonic resonance conditions. A nonlinear dynamic model of orthogonal cutting is presented in Nosyreva et al. [11] where effects of the cutting velocity on the mean friction coefficient are accounted for. Both strong and weak nonlinear dynamic models of cutting processes are investigated in Hwang et al. [12] using numerical method and the method of multiple scales. The

* Corresponding author.
E-mail addresses: a.chanda@iitg.ac.in (A. Chanda), dwivedy@iitg.ac.in (S.K. Dwivedy).

https://doi.org/10.1016/j.jsv.2018.05.043
0022-460X/

Nomenclature

c_r	damping coefficient where suffix $r = 1$ for the workpiece and $r = 2$ for the tool
D	workpiece diameter
F	external harmonic force amplitude
f	nondimensionalized external harmonic force amplitude on the workpiece
h	workpiece thickness
h_0	desired chip thickness
$h_c(t)$	instantaneous effective chip thickness
$\Delta h(t)$	chip thickness variation
k_{r1}	linear structural stiffness for the workpiece ($r = 1$) and the tool ($r = 2$)
k_{r2}	quadratic structural stiffness for the workpiece ($r = 1$) and the tool ($r = 2$)
k_{r3}	cubic structural stiffness for the workpiece ($r = 1$) and the tool ($r = 2$)
k_c	cutting force coefficient
m_r	mass for the workpiece ($r = 1$) and the tool ($r = 2$)
$x_r(t)$	displacement for the workpiece ($r = 1$) and the tool ($r = 2$) at present state
$x_r(t - \tau)$	displacement for the workpiece ($r = 1$) and the tool ($r = 2$) at past state
w_c	chip width or depth of cut
α_{r2}	nondimensionalized scaled down quadratic stiffness for the workpiece ($r = 1$) and the tool ($r = 2$)
α_{r3}	nondimensionalized scaled down cubic stiffness for the workpiece ($r = 1$) and the tool ($r = 2$)
β_r	nondimensionalized cutting force coefficient per unit chip thickness for the workpiece ($r = 1$) and the tool ($r = 2$)
ζ_r	nondimensionalized damping parameter for the workpiece ($r = 1$) and the tool ($r = 2$)
ω_{r1}	nondimensionalized fundamental frequency for the workpiece ($r = 1$) and the tool ($r = 2$)
Ω	frequency of harmonic forcing term

literature review in Wiercigroch et al. [13] shows that, cutting operation like turning itself is a complex and highly nonlinear phenomenon which includes nonlinearity because of complex interrelation in between its dynamics and thermo-dynamics apart from structural nonlinearity, force nonlinearity [14], multiple delays etc. It is observed that the perturbation methods like method of multiple scales are very much efficient to investigate nonlinear cutting process which may include weak structural or force nonlinearity. In Refs. [15–18], higher order MMS are used in the presence of large delay to study the stability, bifurcation diagram and time response.

Most of the previously studied research works concentrate on either the tool or the workpiece vibration to study the stability of turning operation. It is assumed that either the tool or the workpiece is sufficiently stiffer compared to the other one which means that either the tool or the workpiece will have more motion than the other one. Urbikain et al. [19,20] and Ozturk et al. [21] proposed a model to avoid the chatter considering only the tool dynamics. Quyang and Wang [22] suggested to consider the three directional moving cutting force and deflection dependent axial feed force's induced bending moment on the study of dynamic behavior of rotating beam like workpiece for turning operation. Chanda et al. [23] plotted the stability diagram only for thin cylindrical workpiece turning operation considering three directional cutting force using semi-discretization method. The bifurcation study is performed in Kim et al. [24] considering only the tool motion in feed and cutting force direction. In case of parallel turning, the dynamics of tool is tuned in feed direction only to increase the stability in the study of [21] where it is assumed that each tool has SDOF motion. But, in actual case, there may be comparable stiffness difference; thus tool and workpiece both have a prominent individual motion. So the effective chip thickness variation becomes a combined effect of tool and workpiece motion. Keeping such a consideration, the stability of the turning process is studied in Chen and Tsao [25]. Experimental investigation of regenerative chatter, induced by phase lag of the undulation due to deflection of workpiece is made in Kato and Marui [26]. Srinivas and Kotaiah [27] studied the stability in turning using a nonlinear force feed dynamic model by considering three-dimensional cutting tool geometry and relative motion of the workpiece and the tool where each has two-degree of freedom.

In overall, it is observed that till now, most of the studies are performed considering either the workpiece or the tool vibration. But, in many occasions, the tool and the workpiece both may have a prominent individual motion which will contribute to the cutting force in terms of effective chip thickness because of relative motion and hence a 2-DOF model becomes more realistic and important. Though in Refs. [25,27,28], stability study of turning operation are found considering tool and workpiece interaction, no study is performed for internal resonance condition due to the tool and the workpiece interaction. In some cases, it may happen that internal resonance condition appears during turning operation when any of the natural frequencies of the workpiece may come closer to any of the natural frequencies of the tool.

Hence, in the present work, a unique case is studied when internal resonance and primary resonance may occur due to cross-coupling of two degree of freedom system in terms of effective chip thickness and harmonic force on workpiece. Thus, present study will be very interesting to see the tool and workpiece dynamics with the consideration of regenerative effect for the internal and primary resonance conditions. Apart from that, stiffness nonlinearity is considered in equation of motion. The instability regions are investigated for different system parameters like chip width (depth of cut), speed, delay, cutting force coefficient, workpiece to tool stiffness ratio, workpiece diameter to wall thickness ratio. The stability of the systems are studied