Journal of Sound and Vibration 333 (2014) 3996–4006

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

# Regenerative vibration avoidance due to tool tangential dynamics in interrupted turning operations

G. Urbikain*, L.N. López de Lacalle, A. Fernández

*University of the Basque Country, UPV/EHU, School of Engineering, ETSI, Department of Mechanical Engineering, Alameda de Urquijo s/n, 48013 Bilbao, Bizkaia, Spain*

ARTICLE INFO

*Article history:*
Received 28 October 2013
Received in revised form
21 March 2014
Accepted 21 March 2014
Handling Editor: H. Ouyang
Available online 30 April 2014

ABSTRACT

Linear stability models are often used to predict regenerative vibrations in turning representing continuous operations, simple cutting geometries with constant coefficients and/or dominant modes acting in the feed direction. However, turning of components with interrupted features, such as turbine cases, may lead to large tool overhangs with vibration motions in the cutting speed direction and tool cut-off periods that result in the latter approaches being insufficient. This paper proposes a stability model for chatter in interrupted turning when the dominant vibration is orthogonal to the chip section plane. The method requires the calculation of a dynamic displacement factor that depends on the tool vibration frequency. The simulations of the model are supported by experimental tests for different contact fractions.



## 1. Introduction

Chatter is one of the main problems in machining leading to poor surface quality and low productivity. The regeneration mechanism, responsible for chatter vibrations, can be avoided applying stability diagrams which are built using stability models. The traditional theory of regenerative chatter is appropriate for cutting conditions where the ratio of time spent cutting to the spindle period (denoted $\rho$) is high or near unity. For such scenarios, numerous works detail the theory underlying linearised models of turning and milling [1–5], laying the groundwork for increasingly complex models that consider cutters with variable geometry or systems with variable/multiple dynamic parameters [6–8]. However, in modern cutting operations, such as turning of asymmetric workpiece cases, high-speed machining of difficult-to-machine materials, contoured surfaces or finishing operations on thin walls, the tool may spend only a fraction of the spindle period cutting the material. It has been proven in such cases that the system benefits from higher admissible depths of cut, which leads to significant deviations from the linear theory predictions. Fig. 1 shows the stability plots generated by numerical simulations for decreasing contact fractions $\rho$ for turning. In the case of milling, the structure of the Hopf lobes is altered because of the period doubling bifurcation (flip lobes) typical at low radial immersion levels. In the case of turning (Fig. 1), the high order of the lobes (due to low cutting speeds) avoids the emergence of flip lobes, but the system still benefits from higher stability margins.

The period doubling effect is one of the most significant findings concerning chatter in recent years and is a hot topic in high-speed milling. It was first demonstrated and analytically described by Davies et al. [9] and then studied by numerous

* Corresponding author.
*E-mail address:* gorka.urbikain@ehu.es (G. Urbikain).

http://dx.doi.org/10.1016/j.jsv.2014.03.028
0022-460X/

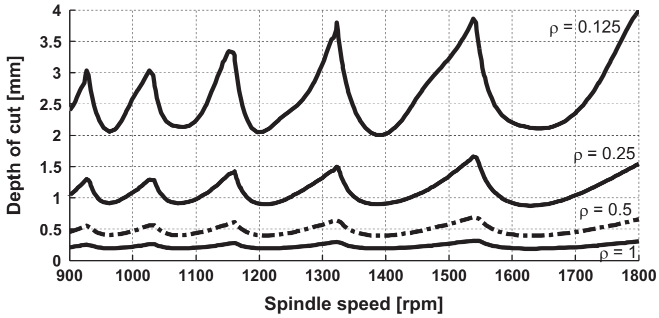


**Fig. 1.** Stability lobes from continuous to orthogonal interrupted turning ($f_n$=150 Hz, $k$=1.2e6 N/m, $\xi$=0.0438, $K_z$=6e8 N/m$^2$, $\kappa_r$=90°).

authors [10–21] who mathematically represented the phenomenon using numerical approaches such as semi-discretisation methods [10–13], temporal finite element methods [18], multi-frequency analytical methods [19] or Chebyshev polynomial-based methods [20]. However, this phenomenon has been solved almost exclusively for milling cases involving the benefit from cutting at low-order lobes, whereas studies concerning interrupted turning have focused more on tool wear, including tool material [22–25] and coatings [26] performance, than on stability aspects.

During the turning of cylindrical components, slots, interrupted flanges, lugs or flat surfaces cause intermittent cutting. In addition, depending on tool setup, the toolholder flexibility in the cutting speed direction may lead to less common chatter cases. Section 2 describes the tangential mode dynamic cutting force model, the special features of interrupted turning and the collocation method as a method to solve the stability equation. Section 3 examines the dynamic characterisation of the system, including modal parameters and the dynamic displacement factor, exploring the effects of the main variables affecting this parameter. Section 4 presents the stability charts for different contact fractions and provides some practical guidelines regarding the stability aspects. Section 5 presents the main conclusions of the work.

## 2. Interrupted turning model

### 2.1. Tangential mode dynamic force model

It has already been mentioned that there are a high number of previous studies focusing on the stability of turning processes. Normally, these works consider the dominant mode acting in the feed direction. This statement is not valid in some turning or grinding cases where the tool vibration amplitude has a major component in the direction of the cutting speed. In this type of instability, the chip thickness will vary only if the cutting edge is separated from the cutting speed plane because of the dynamic deformation of the toolholder (Fig. 2). This downward deflection ($\delta_y$) of the toolholder is accompanied by a horizontal displacement in the radial direction ($\delta_x$). The ratio between these two magnitudes is the dynamic displacement factor $\nu$ [27–28].

The dynamic displacement factor is a complex dimensionless coefficient built from different cutting parameters. It can be positive or negative depending on the vibration-to-natural frequency ratio:

$$\nu = \frac{k}{K_{cy} a_p}\left[\left(\frac{f_c}{f_n}\right)^2 - 1\right], \tag{1}$$

where k is the modal stiffness, $K_{cy}$ the cutting coefficient in y direction, $a_p$ the depth of cut and $f_c/f_n$ the vibration-to-natural frequency ratio. A negative sign of v moves the system toward chatter vibrations ($f_c$ decreases). Some aspects regarding this parameter will be developed in Section 3.2. As explained in [29] and assuming a couple rigid workpiece-slender tool in the y axis, the dynamic equation is expressed as follows:

$$m\ddot{y}(t) + c\dot{y}(t) + ky(t) = \tilde{F}_y(y(t), y(t-T)), \tag{2}$$

where $m$, $c$ and $k$ are the modal parameters of the system and $\tilde{F}_y$ is the dynamic force in the $y$ axis, which depends on the relative tool displacement from one period to the following:

$$\tilde{F}_y = K_{cy} l h(t) = K_{cy} a_p \nu[-(y(t) - y(t-T))]. \tag{3}$$

Combining Eqs. (1) and (3), the dynamic force can be rewritten as follows:

$$\tilde{F}_y = \nu^*[-(y(t) - y(t-T))], \tag{4}$$

where $\nu^* = k[(f_c/f_n)^2 - 1]$.