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A Study of Milling Surface Quality during Period-2 Bifurcations

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Abstract

This paper provides time domain simulation and experimental results for surface location error and surface roughness when machining under both stable (forced vibration) and unstable (period-2 bifurcation) conditions. It is shown that the surface location error follows similar trends observed for forced vibration, so zero or low error conditions may be selected even for period-2 bifurcation behavior. The surface roughness for the period-2 instability, on the other hand, is always larger than for stable conditions because the surface is defined by every other tooth passage and the apparent feed per tooth is subsequently increased. Good agreement is observed between simulation and experiment for stability, surface location error, and surface roughness results.

Keywords: *Milling, dynamics, chatter, bifurcation, surface location error, surface roughness*

1. Introduction

Research in machining dynamics and instability covered more than seven decades. In 1946 Arnold analyzed tool vibration during steel machining [1]. Follow-on work used time-delay differential equations to describe the self-excited vibrations (chatter) that can occur when machining [2], identified regeneration of surface waviness from one revolution (turning) or tooth (milling) to the next as the feedback mechanism that also defines the time delay [3-6], and provided analytical algorithms to predict stable and unstable cutting conditions [4-12]. In 1998, approximately 50 years after Arnold's paper, Davies et al. measured period-n milling bifurcations, which complemented the traditional secondary (subcritical) Hopf bifurcation that had been previously studied [13]. This research led to

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multiple publications that modeled and predicted both the secondary Hopf and period-n behavior with a focus on the period-2 and period-3 cases [14-18]. Recently, Honeycutt and Schmitz presented the extended milling bifurcation diagram that revealed higher order period-n bifurcations at depths of cut well above the traditional stability limit [19]. They also predicted and experimentally validated period-2, -3, -6, -7, and -15 bifurcations for milling [20]. The sensitivity of period-n bifurcation behavior to the structural dynamics (natural frequency and damping) was studied both numerically and experimentally.

When stable machining conditions are selected, two additional considerations for high quality part manufacture are: 1) surface location error, or part geometric errors that occur due to forced vibrations; and 2) surface roughness. Surface location error, or SLE, has been modeled and predicted for stable milling conditions by several authors [21-28]. In these publications, the difference between the machined surface location and the commanded location is measured and/or predicted to determine the influence of (stable) machining conditions on the error. Similarly, surface roughness has been considered as an important quality metric for machined parts since it influences fatigue, sealing performance, wear, and aesthetics, for example. However, prior studies of period-n bifurcations (instabilities) have evaluated neither SLE nor surface roughness. The purpose of this paper is to predict and measure both quantities for stable and period-2 bifurcation behaviors. In the following sections the time domain simulation algorithm is described, a numerical example is provided, the experimental setup is detailed, and numerical and experimental results are presented for SLE and surface roughness when milling under both stable and period-2 bifurcation conditions.

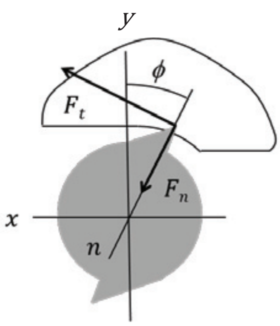

Fig. 1. Cutting force geometry. The normal and tangential direction cutting forces, F_n and F_t, are displayed. The fixed x (feed) and y directions, as well as the rotating normal direction, n, are also shown. The angle ϕ defines the tooth angle. The tool feed is to the right for the clockwise tool rotation and the axial depth is in the z direction.

Nomenclature

F_n	force in the normal direction
F_t	force in the thrust direction
r	endmill radius
ϕ	tooth angle
x	feed direction
y	perpendicular to feed direction in plane of the cut
z	tool axis direction
f_t	feed per tooth
N_t	number of teeth on the endmill
SR	steps per revolution in the time domain simulation
Ω	spindle speed (rpm)
b	axial depth of cut
SLE	surface location error