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Amplitude Ratio: A New Metric for Milling Stability Identification

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Abstract

This paper describes a metric referred to as the "amplitude ratio" for evaluating the stability of milling operations via time domain simulation. The amplitude ratio is used to generate contour diagrams that identify stability behavior over a range of spindle speeds and axial depths of cut. The suitability of the amplitude ratio stability metric is evaluated through comparison to independently published results obtained using semi-analytical techniques.

Keywords: *Milling, stability, chatter, simulation*

1. Introduction

The study of machining vibrations can be traced back to the early 1900s. In work published by Taylor [1] the challenges presented by chatter are noted as the "most obscure and delicate of all problems facing the machinist." However, it wasn't until the 1950s and 1960s that the primary mechanism of chatter was revealed by Tobias, Tlusty, and Merritt [2-4]. Their research revealed regeneration of surface waviness (or the regenerative effect) as a primary chatter mechanism. This discovery led to the development of analytical models for predicting the occurrence of chatter using stability lobe diagrams, which separate the domain of spindle speed and axial depth of cut into stable and unstable regions. Since that time numerous researchers have used analytical, semi-analytical, and numerical models to predict stability behavior in milling. In many cases, chatter is the critical factor influencing milling productivity and the technical challenge of chatter prediction motivates continuing research efforts.

Time domain simulation is a powerful tool for studying machining stability. Each iteration of the simulation results in "local" information (i.e., specific to an individual set of machining process parameters) such as

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accelerations, velocities, and displacements of the cutting tool and workpiece. Researchers have used this “local” information to develop stability metrics for evaluating “global” stability behavior over a range of spindle speeds and axial depths of cut similar to the traditional stability lobe diagram. In [5] Smith and Tlusty use peak-to-peak cutting forces to generate contour maps. These contour maps, referred to as peak-to-peak force diagrams, indicate stability by the rate of change of cutting forces over the spindle speed-axial depth of cut domain. Campomanes and Altintas use the actual trochoidal tooth path to improve the simulation of low radial immersion milling. Chatter detection is facilitated by calculating a “nondimensional chatter coefficient” which is the ratio of the maximum uncut chip thickness during a time domain simulation with flexible dynamics and the maximum uncut chip thickness during a time domain simulation with rigid dynamics [6]. In [7] Honeycutt and Schmitz develop a stability metric based on the once-per-tooth sampled displacement of the cutting tool. The absolute value of the difference in the successive sampled points is summed. If the cut is stable (forced vibrations), the sampled points repeat and the stability metric value is nominally zero. Otherwise the sampled points do not repeat and the stability metric is greater than zero.

In this paper, a new stability metric, which will be referred to as the “amplitude ratio,” is presented. The time domain simulation model is described which includes a mechanistic force model and Eulerian integration approach for solving the dynamic equations of motion. The suitability of the amplitude ratio is evaluated through comparison with independently published results. The conclusions summarize the usefulness of the new metric.

Nomenclature

$h(t)$	instantaneous, uncut chip thickness
f_t	feed per tooth
τ	tooth passing period
$n(t)$	relative vibration between the tool and workpiece in the instantaneous surface normal direction for the current cutting tooth
$n(t-\tau)$	relative vibration between the tool and workpiece in the instantaneous surface normal direction for the previous cutting tooth
r	cutting tooth specific runout
x_t	tool vibration in the *x* direction
y_t	tool vibration in the *y* direction
x_w	workpiece vibration in the *x* direction
y_w	workpiece vibration in the *y* direction
φ	cutter rotation angle
F_t	instantaneous tangential cutting force
F_r	instantaneous radial cutting force
F_a	instantaneous axial cutting force
K_{tc}	specific cutting force coefficient in the tangential direction
K_{rc}	specific cutting force coefficient in the radial direction
K_{ac}	specific cutting force coefficient in the axial direction
K_{te}	edge force coefficient in the tangential direction
K_{re}	edge force coefficient in the radial direction
K_{ae}	edge force coefficient in the axial direction
C_t	process damping coefficient in the tangential direction
C_r	process damping coefficient in the radial direction
b	chip width (axial depth of cut)
$\dot{r}$	velocity in the radial direction
V	cutting speed
m_q	modal mass
c_q	modal damping
k_q	modal stiffness
Δt	time step
$\ddot{q}$	modal acceleration