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Investigating the Performance Dynamics and Stability Boundaries of Machine Tool Spindle and Cutting Tool Assembly

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Abstract: Optimizing cutting operations to minimize costs has become crucial in the competitive manufacturing industry. This study combines experimental and analytical modeling to understand the dynamic properties of machine tool spindle and cutting tool assembly. By characterizing the system and employing finite element analysis, the research aims to enhance cutting tool development, process planning, and productivity while minimizing dynamic testing. The focus is on achieving stability, reliability, and efficiency in cutting operations.

Key words:

Introduction

The stability limit in cutting operations refers to the threshold where vibrations cause instability. Previous studies (references [1], [2], [3], [4]) developed analytical models for turning and milling operations, considering directional force coefficients. However, these models assume linear dependencies between cutting forces, feed/depth of cut, which may not hold true in practice. Non-linear factors like tool jumping and cutting force-chip thickness relations can affect stability beyond the analytical solution's scope. To address this, time domain stability charts have been proposed, requiring system modeling and more time. These charts offer non-linear solutions but require additional effort [5, 6-9].

Models in structural dynamics

Dynamic structural analysis of linear discrete physical models is commonly performed using a second-order ordinary differential equation (ODE) formulation, as outlined by Craig and Kurdila. This formulation relates the nodal displacement vector {q} ∈ R m, where m represents the number of degrees-of-freedom (DOF) in the system, to the load vector {f} using symmetric mass matrix M, viscous damping matrix V, and stiffness matrix K, as shown in the following equation:

M{$\ddot{q}$(t)} + V {$\dot{q}$(t)} + K {q (t)} = {f (t)} (1)

As f is associated with the applied load at each DOF the load vector can preferably be rewritten using a matrix P_u to relate the applied stimuli vector, {u} ∈ R^p where p denotes the number of inputs, to a subset of DOFs

{f (t)} = P_u {u (t)} (2)

Similarly, it is also possible to selectively establish the displacement output, {y} ∈ R^r where r denotes the number of outputs, at a desired set of DOFs using

{y (t)} = P_d {q (t)} (3)

Provided that the mass matrix is non-singular, hence invertible, the second order formulation, Equation (1), lends itself to a reformulation into first order form known as state-space form

$$\begin{cases} \left\{\dot{x}(t) = A\left\{x(t) + B\{u(t)\}\right\}\right\} \\ \{y(t)\} = C\{x(t)\} + D\{u(t)\} \end{cases} \quad (4)$$

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here $\dot{x}(t)$ is the n-dimensional state vector where n = 2m. The constant coefficient matrices quadruple {A, B, C, D}, holds the state matrix A ∈ $R^{n\times n}$, the input matrix B ∈ $R^{n\times p}$, the output matrix C ∈ $R^{r\times n}$ and the feed-through matrix D ∈ $R^{r\times p}$.

This structure is often preferred in control theory but is also very suitable in system identification of experimentally obtained model descriptions. The second order equation is cast in a first order form by introduction of the state vector

$$\{x(t)\} = \begin{Bmatrix} \{q(t)\} \\ \{\dot{q}(t)\} \end{Bmatrix} \quad (5)$$

after some manipulation of Equation (1) with the extension of Equation (2) and introduction of the dummy equation $\{\dot{q}(t)\} = \{\dot{q}(t)\}$, the state coefficient matrices in Equation (4) are made to relate to the second order form as

$$A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}V \end{bmatrix},\ B = \begin{bmatrix} 0 \\ M^{-1}P_u \end{bmatrix},\ C = \begin{bmatrix} P_d & 0 \\ 0 & P_v \end{bmatrix} \quad (6)$$

where subscripts d and v relate to displacement and velocity respectively. The output equation, for selected displacements, y_d, and velocities, y_v, is

$$\{y(t)\} = \begin{Bmatrix} \{y_d(t)\} \\ \{y_v(t)\} \end{Bmatrix} = \begin{bmatrix} P_d & 0 \\ 0 & P_v \end{bmatrix} \{x(t)\} \ (7)$$

$$\{y_a(t)\} = [0 \quad P_v] A \{x(t)\} + [0 \quad P_v] B \{u(t)\} \ (8)$$

Verification of the force models

To validate the force model, a cutting force experiment was conducted using two indexable tools. Tool 1 had 4 negative round ceramic inserts, while Tool 2 had 5 positive round ceramic inserts, both with a diameter of 63 mm and 12.7 mm inserts. Tool 1 had a -7° axial rake angle and a -13° radial rake angle, while Tool 2 had a -3° radial rake angle and 0° axial rake angle. The experiment took place on a NF-630 machine, using Cr12N18 as the workpiece material for slot milling with an axial depth of 0.5 mm. Various spindle speeds (800, 850, and 900 rpm) and feed rates (0.0465, 0.0775, 0.0969, and 0.1162 mm/tooth) were tested. Cutting forces were measured using a Kistler 9255B dynamometer.

Figures in the study compare cutting forces for each tool type. Fig. 10(a) displays cutting forces for Tool 1 without run-out effect, while Fig. 10(b) shows Tool 2 with evident run-out effect, resulting in uneven force contributions among the teeth. The static force model was adjusted to accommodate the run-out effect in Tool 2, improving alignment with measured forces.

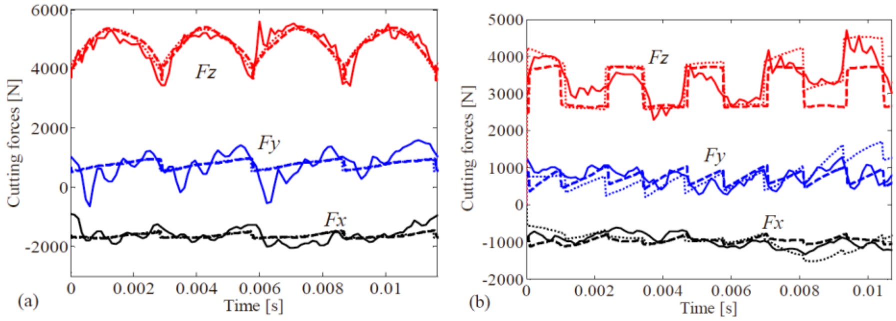

Fig. 1. Comparison of measured cutting forces (solid line), simulated static cutting forces (dotted line) and simulated dynamic cutting forces (dashed line), 100% radial immersion, *sp* =519 rpm, *ft* = 0.116 mm/tooth. a) First tool. b) Second tool.

Table 1. Stability limits

Spindle speed (rpm)	Axial cutting stability limit (mm)	
	Tool 1	Tool 2
800	6.3	4.7
1000	3.4	2.1
1200	1.7	3.7

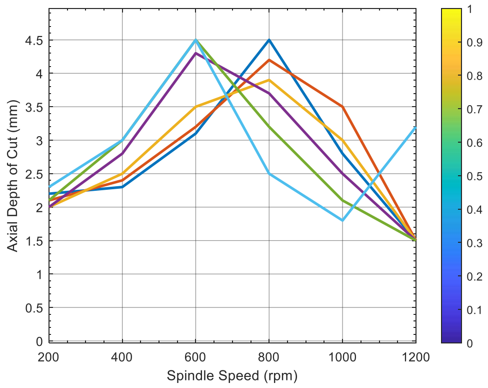

Fig. 2. Stability limits

Conclusion

The article presents cutting force models for indexable tools with round inserts. The models were experimentally verified, and the results showed reasonable accuracy. Stability limits were predicted for both tools, and future work will verify these predictions with additional cutting tests. The developed models can be used to optimize cutting parameters for different tool configurations, reducing time and costs of cutting trials.

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