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Tool point analysis for bending, torsional and axial receptances of tool-holder-spindle assembly

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Abstract

A generalized method for the analysis of the tool point receptances related to all axes (X, Y and Z) is presented in this paper. In order to facilitate modeling, the tool-holder-spindle assembly is divided into four substructures, i.e., spindle-holder subassembly, shank of tool, fluted part of tool and tool-holder joint interface. The fluted part of tool is modeled using three-dimensional Timoshenko theory. The tool-holder joint interface is regarded as a zero-thickness distributed layer. A set of independent spring-damper elements is employed to simulate the dynamic properties of the joint interface. The dynamic responses of all substructures is assembled to calculate the tool point receptances. Finally the proposed method is experimentally verified.

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Keywords: tool point dynamics; Timoshenko beam; distributed tool-holder joint interface; stability lobe diagram (SLD)

1. Introduction

Regenerative chatter [1], one kind of self-excited vibrations caused by regeneration of waviness in machining, often results in unstable cutting process, poor surface finish, reduced productivity and damage on machine tools and cutters. In order to avoid these defectiveness, much effort was made by predicting stability lobe diagrams (SLDs) to select the chatter-free cutting process parameters in the past several decades. To predict reliable SLDs, accurate frequency response function (FRF) of tool point is always required. Usually, FRF of tool point is experimentally obtained by standard impact testing. However, this kind of means may limit its wide applications in machining industries, because repeated and time-consuming FRF measurements should be conducted once the sizes or materials of holder and tool change. Thus development of generalized computing methods becomes a vital alternative to predict the tool point receptance of the tool-holder-spindle assembly.

The key issues to compute FRFs lie in damping estimation at the interfaces, contact stiffness determination of bearings, full geometric knowledge of the commercial components, such as spindles and holders. To solve these problems, Schmitz et al. [2] proposed a receptance coupling substructure analysis (RCSA) procedure by which the lateral dynamic response of the tool is coupled with the experimentally determined receptance of the spindle-holder subassembly to predict the tool point receptances. Regarding this technique, much effort has been made to improve prediction accuracy by including the effect of rotational dynamic responses related to bending vibration, shear deformation of tool and holder, and stiffness and damping properties of joint interfaces of tool-holder-spindle assembly. While Park et al. [3] derived theoretical equations to analytically calculate tool point FRFs by considering spindle-holder substructure's lateral and rotational dynamic responses, Albertelli et al. [4] used finite difference method to take into account both effects. Erturk et al. [5] proved that prediction accuracy can be improved by including the shear deformation of tool and holder. Ozsahin and Altintas [6] studied the influence of tools' asymmetry on the tool point receptances by using Timoshenko beam theory with varying cross-sections. Many attentions were paid on modelling stiffness and damping properties of joint interfaces of tool-holder-spindle assembly. Schmitz et al. [7] developed

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multiple connection models for the tool-holder interface, and employed finite element method to determine the stiffness and equivalent viscous damping values for thermal shrink fit holders. Ahmadi and Ahmadian [8] combined the measured FRFs of spindle-holder and analytical models of the tool via a distributed damped-elastic tool-holder interface.

It should be highlighted that the above work is mostly focused on the prediction of the tool point bending receptances that are generally sufficient for peripheral milling. However, both the bending and axial receptances of tool-holder-spindle assemblies become important in ball end milling, bull-nose end milling and plunge milling applications. What's more, the combined torsional-axial dynamics, as well as bending responses, are essential for drilling analysis. Within this framework, Schmitz [9] took into account these types of modes in his extended work of RCSA method, in which the fluted part of the tool is modeled as a uniform beam with an equivalent diameter. By employing spectral-Tchebyshev (ST) technique, Filiz and Ozdoganlar [10] considered the effect of actual fluted geometry on three-dimensional dynamic behavior of drilling and milling tools.

In this paper, the tool point bending, torsional and axial receptances of tool-holder-spindle assembly are modeled for chatter stability prediction of machining operations. The substructure synthesis technique is adopted to analyze tool-holder-spindle assembly. The spindle-holder subassembly are experimentally determined, while the tool is modeled as Timoshenko beam considering the actual fluted geometry. The tool-holder joint interface is considered as distributed damped-elastic layer and discretized as a set of spring-damper elements based on FEM. The proposed method is verified by experiments for bending, torsional and axial receptances.

Nomenclature

Matrix and vector

$\mathbf{M}_c$	the mass matrix associated with the N_c nodes of the component c, where c = S or F
$\mathbf{C}_c$	the damping matrices associated with the N_c nodes of the component c, where c = S, F or TH
$\mathbf{K}_c$	the stiffness matrices associated with the N_c nodes of the component c, where c = S, F or TH
$\mathbf{Q}_c$	the displacements vector of the component c related to N_c nodes with c = H, S, F or TH
$\mathbf{F}_{c-\tilde{c}}$	the loads vector corresponding to the N_c nodes at the component c, and they are applied by the component $\tilde{c}$ (c = H, S or F; $\tilde{c}$ = H, S, F or TH and $\tilde{c} \neq c$)

Subscript

H	the spindle-holder subassembly
S	the shank of tool component
F	the fluted part of tool component
TH	the tool-holder joint interface component

2. Methodology

In substructure synthesis technique, a complex structure is divided into individual substructures (also known as components). After analytically or numerically modeling each relatively simple substructure and experimentally determining dynamic response of the relatively complex substructures, these substructures are synthesized. In this paper, the tool-holder-spindle assembly in Fig. 1 is separated into four components, i.e., the spindle-holder subassembly, the shank of tool component, the fluted part of tool component and the tool-holder joint interface component. The tool rests on the holder via the tool-holder joint interface. In the following subsections, the dynamic equation of each component will be introduced firstly. They are then assembled based on substructure synthesis technique. Finally, the tool point bending, torsional and axial receptances are extracted from the frequency response matrix of the assembly.

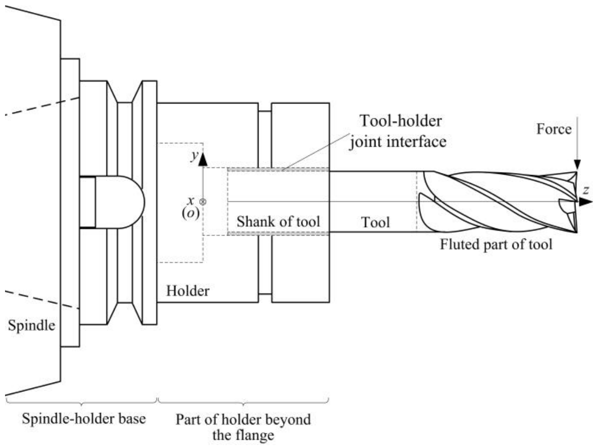

Fig. 1. Tool-holder-spindle assembly.

2.1. Dynamics of the holder-spindle subassembly

As shown in Fig. 1, the spindle-holder subassembly is divided into ($N_{\mathrm{H}}-1$) number of elements and in contact with tool-holder joint interface component through N_{H} number of nodes. Dynamics of the spindle-holder subassembly yields the following equation:

$$\mathbf{Q}_{\mathrm{H}}(\omega) = \mathbf{H}_{\mathrm{H}}(\omega)\mathbf{F}_{\text{H-TH}}(\omega) \tag{1}$$

where $\mathbf{H}_{\mathrm{H}}(\omega)$ denotes the frequency response function (FRF) matrix of the holder-spindle subassembly and can be obtained by experiments [11].

2.2. Dynamics of tool considering the actual fluted geometry

Shank of tool is divided into ($N_{\mathrm{S}}-1$) elements and has N_{S} nodes, while fluted part of tool is divided into ($N_{\mathrm{F}}-1$) elements and has N_{F} nodes, as shown in Fig. 1. Shank of tool connects with fluted part of tool through the node at right end of shank of tool and the node at left end of fluted part of tool. Dynamics of the shank of tool component and the fluted part of tool component yield the following equations:

$$\begin{aligned} &\mathbf{M}_{\mathrm{S}}\ddot{\mathbf{Q}}_{\mathrm{S}}(t) + \mathbf{C}_{\mathrm{S}}\dot{\mathbf{Q}}_{\mathrm{S}}(t) + \mathbf{K}_{\mathrm{S}}\mathbf{Q}_{\mathrm{S}}(t) = \mathbf{F}_{\text{S-TC}}(t) + \mathbf{F}_{\text{S-F}}(t) \\ &\mathbf{M}_{\mathrm{F}}\ddot{\mathbf{Q}}_{\mathrm{F}}(t) + \mathbf{C}_{\mathrm{F}}\dot{\mathbf{Q}}_{\mathrm{F}}(t) + \mathbf{K}_{\mathrm{F}}\mathbf{Q}_{\mathrm{F}}(t) = \mathbf{F}_{\text{F-S}}(t) + \mathbf{F}_{\text{FE}}(t) \end{aligned} \tag{2}$$