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Rapid dynamics prediction of tool point for bi-rotary head five-axis machine tool

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ABSTRACT

Receptance Coupling Substructure Analysis (RCSA), an effective approach to rapidly predict the tool point frequency response function (FRF), generally requires the response of spindle-machine assembly by experiments. This method is feasible for three-axis machine tool because the spindle and its posture are normally unchangeable. But in terms of five-axis milling, the spindle-machine assembly changes continuously. The purpose of this study is to propose new techniques to solve the constantly-changing assembly response in order that RCSA can be used for bi-rotary head five-axis machine tools. Based on receptance matrix determination in coupling direction and single degree of freedom coupling simplification, the swivel model for holder tip receptances is established for swivel motion. According to the concept of oriented frequency response function, the rotational model is derived to calculate the holder tip receptances with rotary motion. By combining the swivel model and the rotational model, the holder tip receptance of arbitrary posture can be calculated by three orthogonal postures. A five-axis machine tool with bi-rotary head is used to conduct FRF tests on different postures. Experimental results show that the models proposed can accurately predict tool point frequency response of any posture and large difference in FRFs among those postures of bi-rotary head is detected.

1. Introduction

Five-axis milling plays an important role in sculptured surfaces machining in industries such as aerospace, automobile and turbine. The five-axis machine is usually equipped with "3+2" axes, namely three linear perpendicular axes (X, Y, Z) and two of three rotational axes (A, B, C) which rotate around (X, Y, Z) axes respectively. There are three combinations of two rotational axes, bi-rotary head, rotary head and table and bi-rotary table [1]. The machine with bi-rotary head is widely used for manufacturing large sculptured surface components, for example, aircraft structural parts [2]. Bi-rotary head offers further possibilities of cutting movements which require less positions and shorter overhang length of milling tools in deep pocket machining, leading to improved machining quality in less process time [3–5].

In five-axis machining, the tool orientations should be carefully adjusted so as to achieve the maximum machining strip width [6]. The swivel axis is generally perpendicular to the tangential direction of the part surface, thus causing a tilting angle between spindle axis and Z axis. The rotary axis brings extra difficulties due to the effect of tilting angle. As for the rotation of bi-rotary head, the spindle system stiffness may vary frequently with the changed posture, which may lead to the change of tool point dynamic characteristic. Therefore, using constant cutting parameters (cutting depth, rotational speed, etc.) may cause chatter during the whole cutting process. Hung et al. [7] investigated the influence of the spindle orientation on tool point dynamics and machining stability for a milling machine with swiveling head. Law et al. [8] proposed a dynamic substructuring procedure to model the orientation-dependent dynamic behavior of machine tools with gimbal heads. Du et al. [9,10] developed a multi-rigid-body dynamic model of bi-rotary milling head at different postures considering the flexible joint to facilitate rapid evaluation and optimization of the dynamic behavior of the bi-rotary milling head. Both researches above [7–10] indicate a strong dependence of machining stability on spindle orientation. Ozturk and Budak [11] analyzed the stability of the five-axis ball-end milling using analytical (frequency domain), numerical (time-domain) and experimental methods, and concluded the effects of the lead and tilt angels of five-axis machine tool with bi-rotary tables on the stability diagrams.

An effective way to avoid chatter in engineering is to select appropriate cutting parameters based on stability lobe diagrams [12–15] where tool point FRFs are required. Schmitz et al. [16–18] proposed receptance coupling substructure analysis (RCSA) to

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rapidly predict tool point dynamics. The RCSA method separated machine tool into two substructures: machine-spindle and holder-tool. The machine-spindle response was acquired by impact testing, while the holder-tool was modeled as Euler-Bernoulli or Timoshenko beam. The two components were then coupled to obtain tool point dynamics. RCSA saves the time of testing for different tool and holder combinations, thus enables rapid generation of stability lobe diagrams. Later Schmitz made some improvements about RCSA and came up with the second generation RCSA [19] and the third generation RCSA [20], which improved the prediction accuracy greatly. Besides, Park et al. [21], Kivanc and Budak [22], Budak et al. [23], Namazi et al. [24], Filiz et al. [25] also made contribution to improve the method itself and its accuracy.

However, current RCSA method is only feasible for three-axis machine tools, but fall short for five-axis machine tools due to the existence of swivel angle and rotational angle. This study aims to analyze the coupling relationship of tool point receptances and then propose its rapid prediction method for bi-rotary head five-axis machine tool at any arbitrary orientation. Firstly, the swivel model is derived to calculate the FRFs at any swivel angle from measured FRFs at 0 and 90°. Secondly, the rotational model is also developed to predict the FRFs at any rotational angle from measured FRFs at 0°. Thirdly, the tool point receptances in rotational-swivel angle are obtained by using the two models. Finally experiments are conducted to verify the model.

2. Substructure and coordinate definition of bi-rotary head

2.1. Substructure definition

Three-axis machine tool is generally divided into three parts by RCSA method including machine-spindle-holder base, extended holder and tool. For five-axis machine with bi-rotary head, the bi-rotary head base and spindle do not change any more once assembled in the machine tool. During machining, constantly changing parts or parameters are holder, tool, length of extended tool, tool orientation including swivel angle and rotational angle. Therefore, the whole bi-rotary head system can be separated into three substructures: bi-rotary head base-spindle-holder base, extended holder and tool, as shown in Fig. 1.

2.2. Coordinate definition

The spindle moves with the change of A and C axis, which causes the variation of tool orientation and position. The two directions X and Y in global coordinate system are usually used for three-axis machine tool to indicate the directions of tool point FRFs, but it is not suitable for five-axis machine tools. A local coordinate, therefore, is established in the plane perpendicular to the tool axis. In this plane, the direction parallel to A axis (swivel axis) is α direction and the direction perpendicular to α is β direction, as shown in Fig. 1. If the FRFs of holder tip (one end of holder near to tool) in both α and β directions are available, the tool point FRFs in the two directions can be obtained by RCSA. Here the holder tip FRFs matrix is described as Eq. (1).

$$\begin{cases} R_{\alpha\alpha(\theta,\varphi)} = \begin{bmatrix} H_{\alpha\alpha(\theta,\varphi)} & L_{\alpha\alpha(\theta,\varphi)} \\ N_{\alpha\alpha(\theta,\varphi)} & P_{\alpha\alpha(\theta,\varphi)} \end{bmatrix} \\ R_{\beta\beta(\theta,\varphi)} = \begin{bmatrix} H_{\beta\beta(\theta,\varphi)} & L_{\beta\beta(\theta,\varphi)} \\ N_{\beta\beta(\theta,\varphi)} & P_{\beta\beta(\theta,\varphi)} \end{bmatrix} \end{cases} \quad (1)$$

where H, L, N and P are displacement-to-force, displacement-to-couple, rotation-to-force and rotation-to-couple receptances, respectively. θ is the swivel angle around the A axis and φ is the rotational angle around the C axis. The subscripts $\alpha\alpha$ and $\beta\beta$ indicate the direction of FRF.

3. Receptance prediction model of swivel axis

Consider a model (see Fig. 1) with two components (here, the spindle, the holder and the tool was treated as a whole) coupled by a revolute joint. In order to describe the receptances of the tool point in two mutually orthogonal directions with the change of swivel angle and rotational angle, the translational (displacement/force), rotational (rotation/moment, also called bending) and torsional (rotation/torque) [26] receptances should be considered in the α direction; translational, rotational and axial (axial displacement/force) receptances should be considered in the β direction (details are described in Appendix A), meanwhile translational and rotational receptances are coupled. However, the coupling formula cannot be used to calculate holder tip receptance while the dynamic characteristics of machine base and bi-rotary head are both unknown. As the bi-rotary head is relatively small in size and less stiff compared to Z axis and the whole machine, it can be treated that a small component rotates around a large base. Here, the two DOFs (translation and rotation) which is more influential was taken into consideration as axial stiffness is much greater than the other two, and the receptance matrix of machine base in coupling direction from that in original direction was derived. Holder tip receptance was then obtained based on two components coupling equation. Finally, according to the stiffness relationship between machine base and bi-rotary head, an assumption related to the stiffness ratio was proposed, receptance prediction model was obtained by analyzing the relationship of holder tip receptances between two orthogonal postures and others.

3.1. Receptance matrix in coupling direction

To calculate bi-rotary head base receptance matrix in a certain direction, receptances of the β and α directions are desired. Only translational and rotational receptances were taken into consideration, see Appendix A. The basic idea of derivation comes from the concept of oriented frequency response function [27].

3.1.1. β direction

Suppose the receptance matrix of the assembly of bi-rotary head-tool holder-tool in the Y direction is noted as Eq. (2). To get its receptances at an arbitrary swivel angle θ, force $F_{\beta,\theta}$ and bending couple $M_{\beta,\theta}$ are applied when the swivel angle is θ, the associated displacement and rotation are defined as $Y_{\beta,\theta}$ and $\Theta_{\beta,\theta}$, as shown in Fig. 2(a).

$$R_{\beta\beta} = \begin{bmatrix} H_{\beta\beta} & L_{\beta\beta} \\ N_{\beta\beta} & P_{\beta\beta} \end{bmatrix} = \begin{bmatrix} \dfrac{Y_\beta}{F_\beta} & \dfrac{Y_\beta}{M_\beta} \\ \dfrac{\Theta_\beta}{F_\beta} & \dfrac{\Theta_\beta}{M_\beta} \end{bmatrix} \quad (2)$$

In Fig. 2(b), $F_{\beta,0}$ is the projection of $F_{\beta,\theta}$ in the Y direction when the swivel angle is θ, thus $F_{\beta,0} = F_{\beta,\theta}\cos\theta$. The corresponding displacement in the Y direction produced by $F_{\beta,0}$ is $Y_{\beta,0}{}^{f} = F_{\beta,0}H_{\beta\beta} = H_{\beta\beta}F_{\beta,\theta}\cos\theta$. The displacement component of $Y_{\beta,0}{}^{f}$ in β direction is $Y_{\beta,\theta}{}^{f} = Y_{\beta,0}{}^{f}\cos\theta = H_{\beta\beta}F_{\beta,\theta}\cos^2\theta$. The corresponding rotation in the Y direction produced by $F_{\beta,0}$ is $\Theta_{\beta,0}{}^{f} = F_{\beta,0}N_{\beta\beta} = N_{\beta\beta}F_{\beta,\theta}\cos\theta$. The rotation component of $\Theta_{\beta,0}{}^{f}$ in the β direction is $\Theta_{\beta,\theta}{}^{f} = \Theta_{\beta,0}{}^{f}$. Thus, displacement-to-force FRF in the β direction is given by:

$$H_{\beta\beta,\theta} = \frac{Y_{\beta,\theta}{}^{f}}{F_{\beta,\theta}} = H_{\beta\beta}\cos^2\theta \quad (3)$$