Frequency response prediction of spindle-workpiece assemblies for ultra-precision diamond turning based on substructure analysis

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Abstract

For the prediction of the dynamic behaviour during ultra-precision turning, the dynamical model of spindle-workpiece assemblies is one prerequisite component of the machine-process interaction governing the machining processes. In this paper, a modelling method for frequency response function (FRF) prediction of spindle-workpiece assemblies in ultra-precision diamond turning is proposed. The spindle dynamics are obtained via modal testing experiments, while the workpiece dynamics are predicted by employing analytical solutions of beams. On the basis of the receptance coupling substructure analysis (RCSA) approach, the spindle-workpiece interface is modelled as a lumped parameter dynamics model and the corresponding parameters are identified through the optimization procedure. Combining the analytical-experimental FRFs of the spindle, interfaces and workpiece, the FRFs of spindle-workpiece assemblies can be predicted by using receptance coupling. One experimental case is utilized to demonstrate the effectiveness of the presented method.

1 Introduction

As one of the most important nanometric machining approaches, ultra-precision diamond turning is widely utilized in manufacturing of mechanical parts or optical parts with form tolerance in sub-micrometer range and with surface roughness of a few nanometers. To reveal the process-machine interaction mechanism and the corresponding effect on the machined surface quality, a comprehensive machine-process-workpiece dynamic model which characterizes the process-machine interaction mechanism is required. Spindle-workpiece dynamics is a crucial subtask for machine-process-workpiece dynamic systems.

Much effort has been dedicated to dual plane balancing [1] and cutting force modelling [2] in ultraprecision diamond machining. However, the influence of the interface dynamics between the spindle and workpiece has not yet been investigated for ultraprecision diamond turning machines and machining processes. This paper proposes a modelling method for identification of the interface dynamics and prediction of spindle-workpiece frequency response functions (FRFs) in ultra-precision diamond turning based on the theory of receptance coupling substructure analysis (RCSA), which was proposed by Schimitz et al. [3] and has been widely utilized for prediction of milling tool point frequency response [4-5].

2 Modelling and Calculation

The test stand for ultra-precision diamond machining with an automatic dual-plane balancing system is shown in Figure 1. As spindle and workpiece are connected by screws and based on the lumped parameter model for this kind of interface, the spindle-joint-workpiece system can be characterized by the dynamic model as shown in Figure 2.

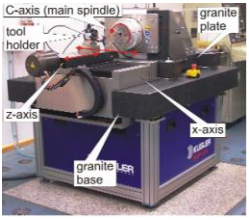

Figure 1: Test stand with dual-plane-balancing capability

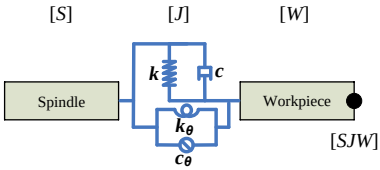

Figure 2: Dynamic model of the spindle-joint-workpiece system

As shown in Figure 2, denoting the end-point receptance matrices of spindle, joint and workpiece by [*S*], [*J*] and [*W*], respectively, the end-point receptance matrix of the system [*SJW*], can be expressed as Eq. (1) according to the RCSA method [3-5]:

$$SJW = W_{11} - W_{12}\left[W_{22} + J^{-1} + S\right]^{-1} W_{21} \tag{1}$$

where [*S*] is a 2×2 frequency-dependent matrix, obtained by modal tests and finite difference approaches. [*W*] is a 4×4 frequency-dependent matrix, obtained by employing analytical beam theory. [W_{11}], [W_{12}], [W_{21}] and [W_{22}] in Eq. (1) are submatrices of [*W*], such that $W = \begin{bmatrix} W_{11} & W_{12} \\ W_{21} & W_{22} \end{bmatrix}$. [*J*] can be written as

$$J = \begin{bmatrix} k + i\omega c & 0 \\ 0 & k_\theta + i\omega c_\theta \end{bmatrix} \tag{2}$$

where k, c, k_θ and c_θ are the translational stiffness, translational damping, rotational stiffness and rotational damping of the spindle-workpiece interface, respectively, ω is the frequency. To identify these parameters, an optimization model is constructed by comparing the analytical FRF of [*SJW*] and the experimentally obtained FRF of the end-point of the spindle-joint-workpiece system $[SJW]_E$, i.e.

$$\min_{k,c,k_\theta,c_\theta} \log\left\{\sum_{n=1}^{N}\left| SJW_{11}(\omega_n)_E - SJW_{11}(\omega_n,k,c,k_\theta,c_\theta)\right|\right\} \tag{3}$$

where $\omega_n (n=1,...,N)$ denote the discrete sampled frequencies, the subscript 11 denotes the first element of the corresponding receptance matrix. In this paper, the pattern search method (Matlab routine *patternsearch*) is utilized to solve the optimization problem with different initial values.

3 Experimental Verification

The modal testing setup for the system is demonstrated in Figure 3. The acceleration sensor (type: B&K Accelerometer 4915-003) and the impact hammer (type: Endevco Modal hammer 2302-100) are used to obtain the FRFs of the spindle and the workpieces with different sizes. To eliminate setup error, the torques for the screws connecting the workpieces and spindle are all chosen as 2 Nm, and to eliminate the measurement error of the modal testing, five impacts are conducted for each test point.

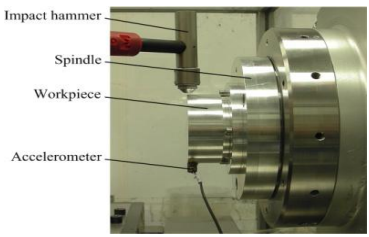

Figure 3: Modal testing for the spindle-joint-workpiece system

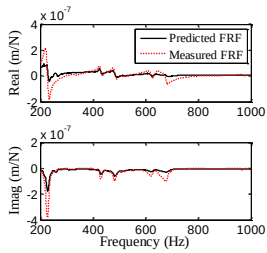

Figure 4: Comparison of the predicted and measured FRFs for the longer workpiece

To identify the interface parameters, the FRFs of the spindle are firstly obtained via modal testing. Then, a workpiece with an overhang length of 24 mm is mounted on the spindle. After obtaining the FRF of the end-point of the workpiece, the joint parameters are calculated by using Eq. (3) and shown in Table 1 (along the vertical direction). After that, a longer workpiece with an overhang length of 48 mm is mounted on the spindle to check the validation of the method. The comparison of the predicted and measured FRFs for the longer workpiece is shown in Figure 4.

From Figure 4, we can observe that the prediction is acceptable for the frequency range from 400 to 600 Hz. The unperfect prediction for other range might be due to the complexity of the diamond turning machine itself. The characteristics of air bearings in the spindle system might induce inherent numerical errors when using the difference approach to construct the end-point receptance matrix of the spindle. In addition, the solid damping factor of the workpiece might also be an important effect factor for the prediction.

Table1: Identified interface parameters

k (N/m)	c (N-s/m)	k_θ (N-m/rad)	c_θ (N-m-s/rad)
2.99×10^8	10	1.08×10^5	40

4 Conclusion

This paper presents a RCSA-based method to model the interface of the spindle and the workpiece and predict the FRF of the spindle-joint-workpiece system in ultra-precision diamond turning machine. Due to the complexity of the air-bearing equipped system, the experimental result verifies the effectiveness of the presented method only for a certain range of frequency. In the next step, more precise interface model and receptance coupling method should be employed to update the proposed method. Furthermore, the relationship between the FRFs of the system and the surface accuracy [6] will be investigated.

References:

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