CIRP Journal of Manufacturing Science and Technology 13 (2016) 37–45

Contents lists available at ScienceDirect

CIRP Journal of Manufacturing Science and Technology

journal homepage: www.elsevier.com/locate/cirpj

Receptance coupling based algorithm for the identification of contact parameters at holder–tool interface

W. Matthias [a], O. Özşahin [a,*], Y. Altintas [a], B. Denkena [b]

[a] *Manufacturing Automation Laboratory, Department of Mechanical Engineering, The University of British Columbia, Vancouver, BC, Canada V6T 1Z4* [1]
[b] *Institute of Production Engineering and Machine Tools (IFW), Leibniz Universität Hannover, An der Universität 2, Garbsen 30823, Germany*

ARTICLE INFO

Article history:
Available online 19 March 2016

Keywords:
Chatter stability
Machine tool dynamics
Contact dynamics
Parameter identification

ABSTRACT

To identify stable cutting conditions with a high depth of cut, stability lobe diagrams are used. In order to predict these diagrams, frequency response functions (FRF) at the tool tip are required for every tool, holder and machine combination. To reduce the number of experimental tests, receptance coupling substructure analysis (RSCA) is proposed in the literature. In order to take full advantage of this method, contact parameters between holder and tool must be known. To identify these parameters this paper presents a new method based on free-free measurements. The obtained contact parameters led to good results for various tool lengths. Based on this, an extensive investigation is performed for the ER32 holder interface. Afterwards, the RCSA method is tested. Therefore, different spindle–holder–tool assemblies are modeled for two machine tools. Prediction and measurement of obtained tool-tip FRF shows a good match, especially for the frequency position.

Introduction

The instability of the cutting process as the cause of chattering is detected at the same time from Tlusty and Polacek [1] and Tobias and Fishwick [2]. Even today chatter is one of the main influences which set a limit to machining processes like turning, drilling, boring and milling. It has several effects, which have a negative influence on the cutting process. For example a poor surface quality, unacceptable inaccuracy and increased stress for the tool and machine [3]. For this reason the topic of chatter vibrations is still current. A variety of papers are giving a good summary about the research advancements in this field [3–5]. However, to get an efficiently operation process it is necessary to use process parameters, which were detected close to the border of chatter conditions. Altintas and Budak [6] proposed a control system approach to make an analytical determination of stability limits. This stability lobe diagram (SLD) presents the stable and unstable cutting conditions for a specific cutting process. In order to obtain stability diagrams frequency response functions (FRF) at tool tip are required. Tool point FRF is usually determined experimentally. But it is usual to use a lot of different tools and holders on a machine. Thus, tool point FRF measurement is required for each combination of tool and holder. But this approach is very time-consuming and increases the downtime of the machine and therefore the production costs. For this reason [7–9], proposed the receptance coupling substructure analysis method (RSCA) to eliminate the experimental dependency. One of the main obstacles for using the RCSA method is the joint interfaces between spindle, holder and tool. While spindle–holder contact dynamics will be approximated, in many cases, during identification of spindle receptance [10,11], the holder–tool interface causes more problems. Rezaei et al. [12] adopt Namazi et al. [10] approach and used inverse Receptance Coupling, first provided in [13], to approximate contact conditions between holder and tool. Instead of separating only the spindle they isolated the holder and inner tool path. Therefore, they approximate both joint dynamics in one receptance matrix. But this approach limits the possibilities, which will be offered by RCSA. To avoid this problem the dynamical behavior of the joint has to be modeled and the interface parameters between holder and tool must been known. Therefore, many researches are available which are dealing with various modeling approaches [14–18].

Schmitz and Donaldson [7] used for the first investigations a lump stiffness model. They coupled the outer tool part through linear and rotational springs and dampers to the spindle–holder assembly. The connection parameters are identified using a single tool-tip measurement and fit this FRF by the experimental data.

* Corresponding author. Tel.: +1 90 312 586 8315; fax: +1 90 312 586 8091.
E-mail address: orkun.ozsahin@atilim.edu.tr (O. Özşahin).
[1] www.mal.mech.ubc.ca.

http://dx.doi.org/10.1016/j.cirpj.2016.02.005
1755-5817/© 2016 CIRP.

But the measurement of rotational response at joints is complicated. For this reason, Movahhedy and Germai [14] proposed a contact model with two parallel linear springs. To obtain the contact parameters they used a genetic algorithm. Later Schmitz and Powell [15] extended the three component model for a shrink fit holder and included multiple connections between tool and holder along the interface contact. The stiffness values are determined directly from the slope of the load-displacement curves for different positions inside the holder. They assumed that energy dissipation in the shrink fit connection occurred due to relative micro-slip between tool and holder. Thus, they calculated the damping by using the Coulomb damping approach. To extract the interface parameters of the joint interface between modular tools Park and Chae [16] used the inverse RCSA method. Like Schmitz and Donaldson [7] they used a lump stiffness model to describe the joint dynamics. The cross-coupled properties of the joint between translational and rotational degrees of freedom are assumed to be negligible because they have not a significant effect on the response of the assembled system. They obtain the contact parameters of the fastener joint by minimizing the deviation between the FRFs of the rigid system and the measured system. Ahmadi et al. [17,18] replaced the lump-stiffness model with a new approach. They modeled the joint interface between tool and holder using an elastic interface layer. Thereby, the interface stiffness can be defined as a variable function along the tool inserted shank length. Introduction of this layer enables to consider the varying contact pressure along this interface. The interface parameters are identified again by minimizing the deviation between the predicted FRF at the free end of the holder from the corresponding measured one. An approach, which is not based on a minimization between the deviation of the predicted and measured FRF, is presented by Ozsahin et al. [19]. They used an inverse RCSA method to calculate the complex stiffness matrix. For this purpose they need the receptance matrix of spindle, holder and tool and furthermore it is necessary to perform a tool-tip measurement. This stiffness matrix describes contact parameters for each frequency. The idea is to pick values close to the frequency of the first eigenvalue because there they expected the biggest impact of contact parameters. But, this approach is time consuming, due to the large area which has to be checked to identify the joint parameters. Moreover, this practice is very sensitive to noise and errors because during the method matrices with very small elements and low ranks are inverted. Thus, this approach is better suited for initial assessment. However, this method is used in many researches to obtain the contact parameters for further investigations [20–22].

Regardless of which model is used to couple parts it is indispensable to know stiffness and damping parameters between single interfaces. In literature, there does not exist an analytical model for the determination of interface parameters. Therefore, contact parameters at holder–tool and spindle–holder interfaces are identified using experimental methods. These determined contact parameters will be valid only for the investigated setup. Thus, the advantage of the idea of receptance coupling does not longer exist.

This paper presents an identification method for the contact parameters at holder–tool interface. In identification method proposed, holder–tool assembly dynamics is measured at free–free end conditions and contact parameters are identified using a fitting algorithm. The contact parameters obtained by this method are applicable for similar clamping setups. To verify the accuracy of the results different setups with blank tools of various lengths are modeled using identified contact parameters and measured by experimental modal analysis (EMA). Further, a differentiation between the previous experimental methods and the method developed in this study is made. Based on the new method, the influence of different clamping conditions on joint parameters of collet holders and thereby on dynamical behavior is presented. Afterwards, the generality of the identified parameters is demonstrated. Therefore, two machine tools are modeled and in each case a collet holder is clamped into the machine tool. For different blank tools the predicted dynamical transfer functions at the tool tip are compared with tool-tip measurements.

Mathematical modeling

Theory of receptance coupling

In this section, a brief review of the RCSA method is presented based on the previous literature [23,24]. The basic receptance coupling equation for the rigid coupling of two structures in a free–free condition is presented in Eq. (1):

$$\begin{Bmatrix} X_1 \\ X_2 \end{Bmatrix} = \begin{bmatrix} (H_{A,11} - H_{A,12}(H_2)^{-1}H_{A,21}) & (H_{A,21} - H_{A,12}(H_2)^{-1}H_{A,22}) \\ (H_{A,21} - H_{A,22}(H_2)^{-1}H_{A,21}) & (H_{A,22} - H_{A,22}(H_2)^{-1}H_{A,22}) \end{bmatrix} \begin{Bmatrix} F_1 \\ F_2 \end{Bmatrix} \tag{1}$$

The displacement vector X is for translational and angular displacement components. Force vector F includes the force and moment applied at position 1 and 2. $H_{A,ij}$ are the generalized receptance matrices between the positions i and j. However not every connection can be assumed as inflexible like depicted in Fig. 1.

To consider the stiffness and damping between such connections H_2 can be modified with the complex stiffness matrix K:

$$H_2 = H_{A,22} + H_{B,22} + K^{-1} \tag{2}$$

Complex stiffness matrix contains interface parameters between two substructures and can be expressed by the translational stiffness k_{yf} and damping c_{yf} and the rotational stiffness $k_{\theta M}$ and $c_{\theta M}$ damping [16].

$$K = \begin{bmatrix} k_{yf} + i\omega c_{yf} & 0 \\ 0 & k_{\theta M} + i\omega c_{\theta M} \end{bmatrix} \tag{3}$$

$$\begin{aligned} [H_{11}] &= \begin{bmatrix} h_{11,ff} & h_{11,fM} \\ h_{11,Mf} & h_{11,MM} \end{bmatrix} = \begin{bmatrix} h_{A11,ff} & h_{A11,fM} \\ h_{A11,Mf} & h_{A11,MM} \end{bmatrix} - \begin{bmatrix} h_{A12,ff} & h_{A12,fM} \\ h_{A12,Mf} & h_{A12,MM} \end{bmatrix} [H_2]^{-1} \begin{bmatrix} h_{A21,ff} & h_{A21,fM} \\ h_{A21,Mf} & h_{A21,MM} \end{bmatrix} \\ [H_{21}] &= \begin{bmatrix} h_{21,ff} & h_{21,fM} \\ h_{21,Mf} & h_{21,MM} \end{bmatrix} = \begin{bmatrix} h_{A21,ff} & h_{A21,fM} \\ h_{A21,Mf} & h_{A21,MM} \end{bmatrix} - \begin{bmatrix} h_{A12,ff} & h_{A12,fM} \\ h_{A12,Mf} & h_{A12,MM} \end{bmatrix} [H_2]^{-1} \begin{bmatrix} h_{A21,ff} & h_{A21,fM} \\ h_{A21,Mf} & h_{A21,MM} \end{bmatrix} \\ [H_{22}] &= \begin{bmatrix} h_{22,ff} & h_{22,fM} \\ h_{22,Mf} & h_{22,MM} \end{bmatrix} = \begin{bmatrix} h_{A22,ff} & h_{A22,fM} \\ h_{A22,Mf} & h_{A22,MM} \end{bmatrix} - \begin{bmatrix} h_{A22,ff} & h_{A22,fM} \\ h_{A22,Mf} & h_{A22,MM} \end{bmatrix} [H_2]^{-1} \begin{bmatrix} h_{A22,ff} & h_{A22,fM} \\ h_{A22,Mf} & h_{A22,MM} \end{bmatrix} \end{aligned} \tag{4}$$

Including contact dynamics, elastic coupling of two substructures can be expressed as follows: