

# DEVELOPMENT OF AN INTERNET-BASED PLATFORM FOR HIGH-SPEED MILLING PROCESS PARAMETER SELECTION

Tony L. Schmitz<sup>1</sup>, Michael Tummond<sup>1</sup>, G. Scott Duncan<sup>1</sup>, Christopher Zahner<sup>1</sup>, John P. Snyder<sup>2</sup>  
<sup>1</sup>University of Florida, Department of Mechanical and Aerospace Engineering, Gainesville, FL 32611  
<sup>2</sup>TechSolve, Cincinnati, OH 45216

## 1.0 Introduction

This paper describes the initial development of an Internet-based application, ‘Machinist Online’, that will allow process planners to select high-speed milling parameters for maximized material removal rates in a science-based pre-process manner, rather than relying on experience. The primary mechanism for realizing this capability is dynamics prediction for the tool/holder/spindle/machine assembly using Receptance Coupling Substructure Analysis, or RCSA [1-4]. This method analytically predicts the assembly response by combining models and/or measurements of the individual components through empirically-obtained connection parameters. Currently, a primary impediment to full implementation of the academic research in high-speed machining, particularly linear and nonlinear chatter (or unstable machining) models, at the production level is the necessity of measuring each tool/holder/spindle/machine frequency response, typically by impact testing where an instrumented hammer is used to excite the structure and the response is recorded using an appropriate transducer, such as an accelerometer.

The chatter models, which can be used to select cutting conditions for both dramatic increases in material removal rates and improved part accuracy, require knowledge of the system frequency response as reflected at the tool point. Due to a potential lack of engineering support and sometimes limited knowledge of dynamic testing procedures, the frequency response measurements are rarely carried out, especially at Tier I and II manufacturing facilities that fabricate a large fraction of the total number of US discrete parts due to outsourcing from major automotive and aerospace manufacturers. Therefore, the well-established stability improvement technology (i.e., stability lobe diagrams, which separate stable and unstable cutting zones graphically as a function of chip width and spindle speed [e.g., 5-10]) afforded by high-speed machining is very often not applied. The result is reduced process efficiency and part quality and increased cost.

The development of the Internet-based parameter selection platform described here will require no frequency response measurements or specialized knowledge from the user. Rather, the user will select tool geometry and material, holder type, spindle model and manufacturer, and workpiece material from drop-down menus that access a local database. This information is passed to a MATLAB program using the MATLAB Web Server, where the RCSA frequency response prediction and corresponding stability lobe diagram calculation are completed. Using the stability lobe diagram, suggested operating conditions will be selected. The surface speed of the cutting tool is then compared to entries in TechSolve’s web-based CUTDATA database [11], which contains entries for 3750 work materials and over 40 machining operations providing upwards of 90000 feed/speed recommendations. Due to temperature-driven chemical/diffusive wear, an upper bound on surface speed may be imposed on the stability lobe-based spindle speed. In this case, the selected spindle speed is revised to avoid excessive tool wear, while still maintaining a reasonable depth of cut. The final result is then passed back to the user. It is anticipated that the Internet tool will provide both the necessary predictive capability and a means of effective dissemination.

## 2.0 RCSA description

RCSA analytically predicts the tool point frequency response function (FRF) by coupling an experimental measurement of the holder/spindle substructure, or component, to an analytical or finite-element (FE) model of the tool through two empirical complex stiffness vectors, which include linear and rotational stiffness and viscous damping terms that characterize the non-rigid behavior of the connection between the holder and tool (e.g., thermal shrink fit, collet, or elastic deformation interference fit [12]). This technique is based on earlier receptance coupling work by Duncan [13], Bishop and Johnson [14], and, later, Ferreira and Ewins [15].

The model for the coupling between the holder/spindle and tool components is shown in Fig. 1. There are three translational and three rotational assembly coordinates identified, with spatial positions coincident with the coupling locations (coordinates  $X_2/\Theta_2$  on the tool and  $X_3/\Theta_3$  on the holder/spindle component) and the point of interest (coordinates  $X_1/\Theta_1$  at the free end of tool). The connection between  $X_2/\Theta_2$  and  $X_3/\Theta_3$  is composed of a linear spring,  $k_x$ , torsional spring,  $k_\theta$ , linear viscous damper,  $c_x$ , and rotational viscous damper,  $c_\theta$ . In order to determine the

assembly direct, or driving point, FRF at the tool point,  $G_{11}(\omega) = X_1(\omega)/F_1(\omega)$ , which is used as input to the selected process stability simulation, the following steps must be completed:

a) Use impact testing to measure the holder/spindle component (i.e., no tool inserted in holder) FRF,  $H_{33} = X_3/F_3$ , at the free end perpendicular to the spindle centerline. Typically, the measurement directions are selected to be coincident with the feed directions of the machine tool.

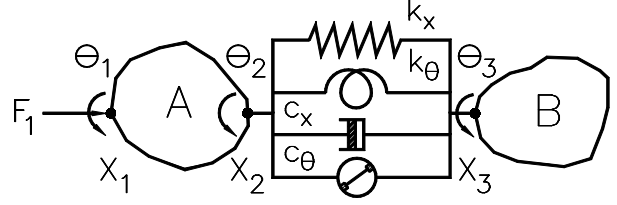


Figure 1: RCSA holder/spindle/tool model including connection parameters.

b) Develop an analytic model of the free-free tool using the closed form receptance terms, which capture both the rigid body and transverse vibration behavior of the tool, developed by Bishop and Johnson [14] (an FE model is also an option). Here, we have selected to treat the tool as an Euler-Bernoulli beam with a constant cross-section, which requires that an effective diameter,  $d_{eff}$ , be determined for calculation of the 2<sup>nd</sup> area moment of inertia,  $I = \pi d_{eff}^4/64$ . The effective diameter is based on the tool overhang length,  $L$ , total length,  $L_T$ , tool material density,  $\rho$ , shank diameter,  $d$ , and tool mass,  $M$ . See Eq. 1. Fundamentally, this equation calculates the diameter of a uniform cross-section beam with 1) a mass equal to the difference between the total tool mass and the mass of the tool shank inside the holder; and 2) a length equal to the overhang length of the tool, given the tool material density.

$$d_{eff} = \sqrt{\frac{4M - \pi\rho d^2(L_T - L)}{\pi\rho L}} \quad (1)$$

We have also added structural, or hysteretic, damping to the tool model by replacing Young's elastic modulus,  $E$ , for the tool material with the complex modulus,  $E' = (1 + i\eta)E$ , where  $\eta$  is the structural damping factor, a small dimensionless constant. This modifies the frequency-dependent term  $\lambda = \left(\frac{\omega^2 m}{EI}\right)^{\frac{1}{4}}$  from Bishop and Johnson [14] to

be  $\lambda' = \left(\frac{\omega^2 m}{(1 + i\eta)EI}\right)^{\frac{1}{4}} = \frac{\lambda}{(1 + i\eta)^{\frac{1}{4}}} \approx \lambda \left(1 - i\frac{\eta}{4}\right)$ . To simplify notation, we drop the primes from  $E'$  and  $\lambda'$  in the

expressions shown in Eq. 2, which define the required free-free tool component receptance terms. In these expressions, different designations have been applied to the four receptance types found in our model, specifically,

$$H_{ij} = \frac{x_i}{f_j}, \quad L_{ij} = \frac{x_i}{m_j}, \quad N_{ij} = \frac{\theta_i}{f_j}, \quad \text{and} \quad P_{ij} = \frac{\theta_i}{m_j}.$$

$$\begin{aligned} \frac{x_1}{f_1}(\omega) = H_{11} &= \frac{-(\cos L\lambda \cdot \sinh L\lambda - \sin L\lambda \cdot \cosh L\lambda)}{\lambda^3 EI(\cos L\lambda \cdot \cosh L\lambda - 1)} & \frac{x_2}{f_2}(\omega) = H_{22} = H_{11} \\ \frac{x_2}{m_2}(\omega) = L_{22} &= \frac{\sin L\lambda \cdot \sinh L\lambda}{\lambda^2 EI(\cos L\lambda \cdot \cosh L\lambda - 1)} & \frac{\theta_2}{f_2}(\omega) = N_{22} = L_{22} \\ \frac{\theta_2}{m_2}(\omega) = P_{22} &= \frac{\cos L\lambda \cdot \sinh L\lambda + \sin L\lambda \cdot \cosh L\lambda}{\lambda EI(\cos L\lambda \cdot \cosh L\lambda - 1)} \\ \frac{x_1}{f_2}(\omega) = H_{12} &= \frac{\sin L\lambda - \sinh L\lambda}{\lambda^3 EI(\cos L\lambda \cdot \cosh L\lambda - 1)} & \frac{x_2}{f_1}(\omega) = H_{21} = H_{12} \\ \frac{x_1}{m_2}(\omega) = L_{12} &= \frac{\cos L\lambda - \cosh L\lambda}{\lambda^2 EI(\cos L\lambda \cdot \cosh L\lambda - 1)} & \frac{\theta_2}{f_1}(\omega) = N_{21} = L_{12} \end{aligned} \quad (2)$$

c) Measure the tool point response for the assembly in one direction at a known overhang. This data allows the determination of the connection parameters,  $k_x$ ,  $k_\theta$ ,  $c_x$ , and  $c_\theta$ , by nonlinear least squares best fit. This allows the model shown in Fig. 1 to be developed and analytic prediction of FRFs to be completed.

The desired tool point assembly receptance  $G_{11}(\omega)$  is shown in Eq. 3, where we have substituted the complex, frequency dependent stiffness terms  $K_x = k_x + i\omega c_x$  and  $K_\theta = k_\theta + i\omega c_\theta$  to simplify notation; the full development of this equation is available in reference [4].

$$G_{11}(\omega) = \frac{X_1}{F_1} = H_{11} - \frac{H_{12}}{\det A} [K_x H_{21} (K_\theta (P_{33} + P_{22}) + 1) - K_\theta N_{21} K_x (L_{33} + L_{22})] \quad (3)$$

$$- \frac{L_{12}}{\det A} [K_\theta N_{21} (K_x (H_{33} + H_{22}) + 1) - K_x H_{21} K_\theta (N_{33} + N_{22})] \quad \text{where}$$

$$\det A = (K_x (H_{33} + H_{22}) + 1)(K_\theta (P_{33} + P_{22}) + 1) - K_x (L_{33} + L_{22}) K_\theta (N_{33} + N_{22})$$

### 3.0 Example experimental results

A tool/holder/spindle model was constructed using a two flute helical endmill, collet-type tool/holder connection, HSK-63A holder/spindle interface, and 20000 rpm spindle. The carbide endmill was 152.4 mm long with a 12.7 mm diameter shank and had a mass of 246.8 g. The flute length was 16 mm, the shank length was 65 mm, and the neck was relieved to a diameter of 11.1 mm. An allowable overhang range of 112.5 mm (8.9:1 length to diameter, or L:D, ratio) to 124.0 mm (9.8:1) was selected. The carbide density and modulus were taken to be  $14.5 \times 10^3 \text{ kg/m}^3$  and  $5.853 \times 10^{11} \text{ N/m}^2$ , respectively [16]. In all measurements, the collet torque was set to the manufacturer-recommended value of 61 N-m (45 ft-lb) using a torque wrench.

Following the algorithm described in Section 2.0, the holder was placed in the spindle and the direct FRF at the holder free end was recorded using impact testing in the vertical ( $y$ ) and horizontal ( $x$ ) directions for the horizontal spindle axis ( $z$ ) machine configuration. Next, the tool receptances were calculated for a mid-range overhang length of 118.5 mm using Eqs. 1 and 2. A structural damping factor of 0.001 was assumed for the complex modulus calculation due to the difficulty in completing free-free FRF measurements on endmills. Finally, an  $x$ -direction tool point FRF was recorded for the tool/holder/spindle assembly and fit using Eq. 3 to determine the connection parameters and complete the RCSA model. The nonlinear least squares fit connection parameters are provided in Table 1.

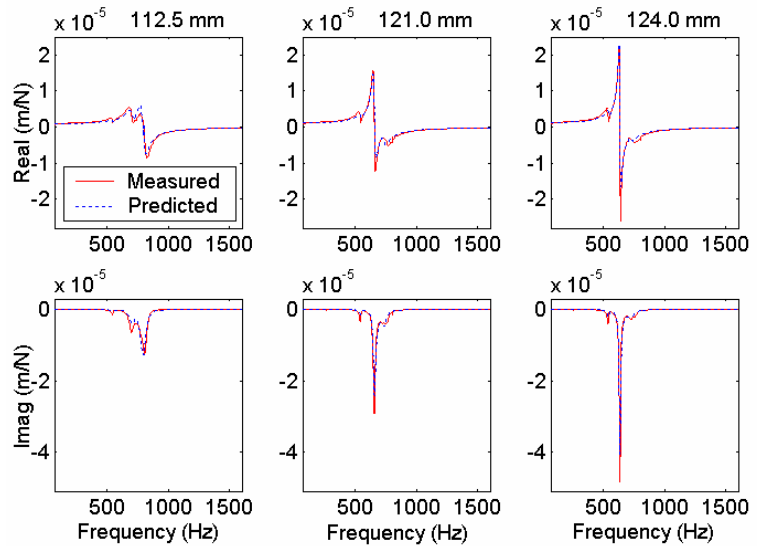


Figure 2. Assembly tool point FRF measurements and predictions for  $y$ -direction.

Table 1: Nonlinear least squares fit connection parameters.

$k_x$ (N/m)	$k_\theta$ (N-m/rad)	$c_x$ (N-s/m)	$c_\theta$ (N-m-s/rad)
$6.8 \times 10^7$	$2.7 \times 10^6$	3816	406

Predicted results for the  $y$ -direction using the fit parameters in Table 1 are shown in Fig. 2. The overhang lengths are the minimum and maximum values, 112.5 mm and 124.0 mm, respectively, and a near mid-range value of 121.0 mm. For the full range of measurements, good agreement was observed between the measured and predicted data in both the  $x$  and  $y$ -directions.

### 3.0 Web site description

As noted, the purpose of the ‘Machinist Online’ web site is to allow users without extensive knowledge of chatter theory or mechanical vibrations to take full advantage of the available improvements in process efficiency when using stability lobe diagrams. In the first generation of the web site, a measurement of the spindle/holder substructure, archived in a database, is coupled to the endmill via the experimentally-obtained connection

parameters, also contained in the local database, using RCSA. Once the tool point FRF is predicted, the corresponding stability lobes are generated using the analytic stability lobe algorithm developed by Tlustý [7] or Altintas and Budak [10]. These computations are carried out using MATLAB and the stability lobe diagram passed to the user using the MATLAB Web Server [17].

Inputs from the user are obtained either from nested drop-down menus or keyboard entry. These inputs include the machine/spindle/holder substructure (including the spindle specifications such as top speed and available power and torque), end mill material and geometry, workpiece material (specific cutting energy coefficients can be selected from the local database or input by the user), and radial immersion. Based on this information, recommendations for chip load and maximum surface speed are made using the web-based CUTDATA. The data passed back to the user includes the stability lobe diagram, corresponding spindle speed-dependent material removal rate (which may be power or torque limited in some instances), and recommended peripheral endmilling operating parameters, i.e., spindle speed and axial depth of cut.

The first release of 'Machinist Online' can be found at <http://highspeedmachining.mae.ufl.edu/>. The web site includes the predictive 'Parameter Selection' option, as well as a 'Parameter Simulation' module that will allow time-domain simulations of cutting force and deflections to be completed. It also includes a Frequently Asked Questions, or FAQ, section that provides introductory information on such topics as: 1) History of Chatter Research; 2) What is High-Speed Machining?; 3) What is Chatter?; 4) What is Impact Testing?; 5) What is a Stability Lobe Diagram?; 6) What is Tool Tuning?; and 7) What is RCSA? Descriptions of the University of Florida's Machine Tool Research Center and collaborating faculty and students are also provided.

The 'Machinist Online' will be continually updated to expand the machine, spindle, holder, connection parameters, and workpiece material databases. Additionally, future efforts will focus on a three-element assembly where the holder is considered separately from the spindle.

#### 4.0 Acknowledgements

The authors gratefully acknowledge partial financial support for this research from the National Science Foundation (DMII-0238019) and Office of Naval Research (2003 Young Investigator Program), as well as technical contributions from T. Burns, National Institute of Standards and Technology, Gaithersburg, MD, and M. Davies, UNCC, Charlotte, NC.

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