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Speed-varying machine tool dynamics identification through chatter detection and receptance coupling

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Abstract

Tool-tip Frequency Response Function (FRF) represents one of the essential inputs to predict chatter vibration and compute the Stability Lobe Diagram (SLD). Tool-tip FRFs are generally obtained for the stationary (non-rotating) condition. However, high speeds influence spindle dynamics, leading to a reduced accuracy of the SLD prediction. This paper presents a comprehensive method to identify speed-varying tool-tip FRFs and improve chatter prediction. First, FRFs for a screening tool is identified by a novel technique based on a dedicated experimental test and analytical stability solution. Then, a tailored receptance coupling technique is used to predict speed-varying tool-tip FRFs of any other tool. Proposed method was experimentally validated: chatter prediction accuracy was demonstrated through chatter tests.

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Keywords: Milling; Dynamics; Chatter; Spindle; Receptance coupling substructure analysis; In-process dynamics identification.

1. Introduction

High Speed Milling (HSM) is increasingly adopted in manufacturing companies for its high productivity and flexibility; however, its performances could be drastically limited by the occurrence of unstable vibration, known as chatter [1].

Besides active suppression techniques [2,3], the main approach in preventing such a detrimental vibration is based on the identification of stable and unstable cutting parameters, usually presented as a Stability Lobe Diagram (SLD). Tool-tip Frequency Response Functions (FRFs) represent one of the essential inputs to simulate cutting process dynamics and compute the SLD [4]. Tool-tip FRFs are generally obtained experimentally or analytically [5] for the stationary (non-rotating) condition. It is hence assumed that dynamics of the system is independent of spindle speed. However, during high speed milling gyroscopic moments, centrifugal forces and high temperature influence spindle dynamics, leading to a reduced accuracy of the SLD prediction at high speeds [6].

In the last decades, several works were focused on investigating speed-varying machine tool dynamics both via numerical models [6,7] and experimental techniques [8,9]. The latter are limited to research laboratories, due to expensive equipment or restrictions in bandwidth and tooling system. On the other hand, numerical spindle models need many efforts in the pre-processing and validation phases, since they are significantly affected by input data (e.g., bearing preload, stiffness), difficult to be accurately identified. Recently, Özşahin et al. [10] presented a technique to compute FRFs under operational condition by combining chatter stability solution and experimental values of depth of cut and chatter frequency. In their method experimental phase is time-consuming, especially if a wide range of spindle speeds has to be investigated. Moreover, a new identification has to be repeated for every new tool. To overcome this last issue, the same authors [11] proposed to compute spindle bearings dynamics changing with spindle speed, using FRFs previously identified and Receptance Coupling Substructure

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Analysis (RCSA), however the approach requires an accurate model of the spindle unit, limiting its industrial application.

This paper presents a comprehensive method for the identification of the speed-varying tool-tip FRFs and SLD. An efficient and quick experimental phase is performed for a screening tool by means of an advanced test [12] able to identify several chatter limits conditions (i.e., depth of cut and chatter frequency). By matching the experimental results and the analytical predicted SLD through a dedicated optimization strategy, speed-varying tool-tip FRFs is determined for the screening tool. A tailored RCSA technique [13] is then adopted to compute speed-varying FRFs for any other tool, requiring only tools FE models.

2. Proposed method

Proposed method consists in two modules. The first aims at identifying the speed-varying FRFs for the tested tool (i.e., the screening tool) by an experimental-analytical approach. The second computes the FRFs for any new tool by receptance coupling technique and FE models of the tools. The general layout of the proposed method is presented in Fig. 1.

2.1. FRFs identification method – screening tool

Tool-tip FRFs varying with spindle speed are identified by matching experimental chatter results (depth of cut a_{lim} and chatter frequency ω_c) with computed ones by analytical stability approach [4]. According to the predictive method [4]. these two parameters can be computed as:

$$a_{lim} = -\frac{2\pi\Lambda_R}{NK_t}(1+\kappa^2) \quad (1)$$

$$\omega_c = \frac{\pi - 2tan^{-1}\kappa + 2k\pi}{\frac{60}{nN}} \quad (2)$$

where:

$$\kappa = \frac{\Lambda_I}{\Lambda_R} \quad (3)$$

$$\Lambda = \Lambda_R + i\Lambda_I = -\frac{1}{2a_0}\left(a_1 \pm \sqrt{{a_1}^2 - 4a_0}\right) \quad (4)$$

$$a_0 = \Phi_{xx}\Phi_{yy}(a_{xx}a_{yy} - a_{xy}a_{xy}) \\ a_1 = a_{xx}\Phi_{xx} + a_{yy}\Phi_{yy}) \quad (5)$$

$$a_{xx} = \frac{1}{2}[cos2\phi - 2K_r\phi + K_r sin2\phi]_{\phi_{st}}^{\phi_{ex}} \\ a_{xy} = \frac{1}{2}[-sin2\phi - 2\phi + K_r cos2\phi]_{\phi_{st}}^{\phi_{ex}} \\ a_{yx} = \frac{1}{2}[-sin2\phi + 2\phi + K_r cos2\phi]_{\phi_{st}}^{\phi_{ex}} \\ a_{yy} = \frac{1}{2}[-cos2\phi - 2K_r\phi - K_r sin2\phi]_{\phi_{st}}^{\phi_{ex}} \quad (6)$$

where N is the number of flutes, K_t is the tangential cutting force coefficient, K_r is the ratio of radial and tangential cutting force coefficients, ϕ_{st} and ϕ_{ex} are the start and exit angle of the cutting (using coordinate system as in [4]), n is the spindle speed, k is the integer number of full vibration waves (i.e., lobes), and Φ_{xx} and Φ_{yy} are tool-tip FRFs that can be written as function of modal parameters (natural frequency ω_n, damping ratio ξ). Further details are reported in [4]. In the adopted fitting approach, modal parameters are the unknowns to be computed by matching analytically predicted results with experimental values.

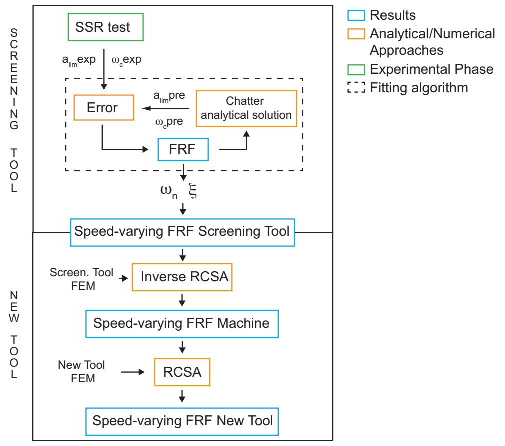

Fig. 1. Proposed method scheme.

Two assumptions are defined for the method implementation:

1. A specific chatter condition is considered caused by a single dominant mode, therefore proposed method is applied to identify dominant modes causing chatter and then extended to the other modes. As first attempt, in the paper the same relative variation computed for the dominant mode is applied to all the other modes. Investigating the modes and the speed effects could allow the development of more complex and accurate strategies for extending results to the non dominant modes.
2. Participation factors and mode shapes do not vary with spindle speed, this would allow to consider only natural frequency and damping ratio as unknowns and calculate speed-varying FRFs of the tool in different sections.

Although the first module of proposed method follows similar idea already presented in [10], it differs for both experimental phase and fitting strategy, in order to obtain a more efficient and robust approach. Instead of time-consuming single chatter tests, Spindle Speed Ramp-up (SSR) test presented by authors in [12] is used, allowing to identify a large number of limiting chatter conditions with very few tests. The main idea of the SSR test is to investigate SLD horizontally (i.e., fixed depth of cut, varying spindle speed), changing spindle speed in the entire range of interest during a single test. Sensor signal is acquired and analysed in the frequency domain in order to investigate the presence of the characteristic frequency of the phenomenon (i.e., chatter frequency). This allows to distinguish between stable and unstable spindle speeds at the specific depth of cut. SSR is very fast and few tests allow to extract multiple chatter conditions to be used in the FRFs computation. For what concern fitting strategy, Özşahin et al. method [10] relies on single chatter conditions to extract exact solution for modal parameters. As consequence, the method is sensitive to inaccuracies and noise on chatter detection procedure, that can significantly affect the results. In this paper a robust identification is achieved by means of multiple conditions. An optimization strategy based on Genetic Algorithm is used to identify tool-tip FRF on different groups of chatter conditions. The large number of limiting axial depths of cut and related