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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:

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

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

where:

$$\kappa = \frac{\Lambda_I}{\Lambda_R} \tag{3}$$

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

$$\begin{aligned} a_0 &= \Phi_{xx}\Phi_{yy}(\alpha_{xx}\alpha_{yy} - \alpha_{xy}\alpha_{xy}) \\ a_1 &= \alpha_{xx}\Phi_{xx} + \alpha_{yy}\Phi_{yy}) \end{aligned} \tag{5}$$

$$\begin{aligned} \alpha_{xx} &= \tfrac{1}{2}[\cos 2\phi - 2K_r\phi + K_r \sin 2\phi]_{\phi_{st}}^{\phi_{ex}} \\ \alpha_{xy} &= \tfrac{1}{2}[-\sin 2\phi - 2\phi + K_r \cos 2\phi]_{\phi_{st}}^{\phi_{ex}} \\ \alpha_{yx} &= \tfrac{1}{2}[-\sin 2\phi + 2\phi + K_r \cos 2\phi]_{\phi_{st}}^{\phi_{ex}} \\ \alpha_{yy} &= \tfrac{1}{2}[-\cos 2\phi - 2K_r\phi - K_r \sin 2\phi]_{\phi_{st}}^{\phi_{ex}} \end{aligned} \tag{6}$$

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 $\boldsymbol{\Phi}_{xx}$ and $\boldsymbol{\Phi}_{yy}$ 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.

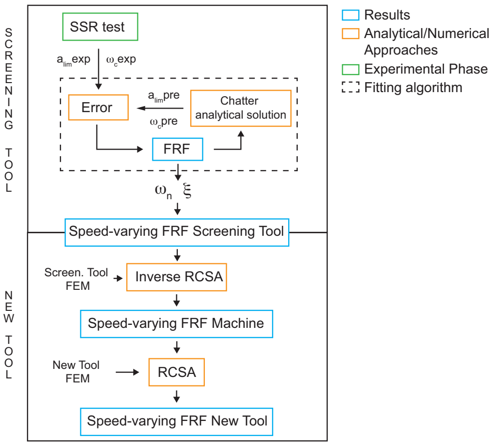

Fig. 1. Proposed method scheme.

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 chatter frequencies obtained by SSR are clustered in groups on the basis of lobes distribution, for each lobe a tool-tip FRFs is computed minimizing the following objective function *fo*:

$$f_1(j) = \frac{(a_{limEXP}(j) - a_{limPRE}(j))^2}{a_{limEXP}(j)^2}$$
$$f_2(j) = \frac{(\omega_{cEXP}(j) - \omega_{cPRE}(j))^2}{\omega_{cEXP}(j)^2} \qquad fo = \|f_1\| + \|f_2\| \tag{7}$$

where f_1 and f_2 are error vectors on depth of cut limit and chatter frequency respectively, j is the j_{th} chatter limiting condition considered, *PRE* stands for analytical predicted value, *EXP* for experimental obtained value. A population of 600 individuals and 10 generations were set for the algorithm. Using these parameters, a solution characterized by objective function value less than 1% is always found. The best solution is generally identified in the first few generations. However, since computation of analytical chatter solution is very fast, optimization procedure lasts less than a minute, therefore a high number of individuals and generations are kept to ensure high reliability of the solution. In summary, screening tool FRFs identification procedure steps are:

- Stationary tool-tip FRFs are computed via impact testing, and modes that affect chatter are identified. ω_n and ξ of defined modes are considered as unknowns.
- ω_{cEXP} and a_{limEXP} are calculated with few SSR tests in the spindle speed range of interest.
- *fo* (Eq. 3) is minimized by optimization algorithm (GA) for the limiting conditions, to compute modal parameters for each lobe.
- Speed-varying tool-tip FRFs and SLD are reconstructed.

2.2. Receptance coupling approach – new tool

Once speed-varying tool-tip FRFs are computed for the screening tool, a dedicated method based on RCSA technique proposed by authors [13] is implemented. The main advantage of this RCSA approach is that only FRFs measurements of the screening tool coupled to the machine are required. In particular, the method uses translation FRFs of two sections: tool-tip and the joint. These FRFs are calculated via modal parameters extracted by the first module of the method, using mode shapes calculated in the stationary condition.

Starting from tool-tip and joint FRFs varying with spindle speed, an inverse RCSA technique computes speed-varying FRFs of the machine without tool (both translational and rotational) at the joint interface. For this step FE model of the screening tool is required. Then, speed-varying FRFs of the new tool is calculated by direct RCSA approach, attaching the new tool FE model to the machine. The method is presented in detail in [13], a general overview is presented in Fig. 2.

3. Experimental validation

Experimental tests were performed to show the proposed method implementation and assess its accuracy. Aluminum 6082-T4 test-pieces were machined on a NMV 1500 DCG Mori Seiki 5 axis milling machine, equipped with a microphone (Bruel & Kjaer type 4165) installed inside the cutting chamber close to the cutting zone (Fig. 3c).

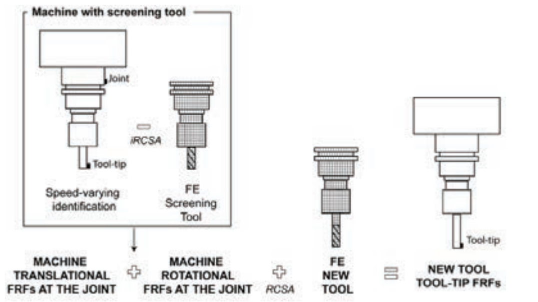

Fig. 2 Receptance coupling technique layout.

Microphone signal is acquired by LMS Scadas III and elaborated in LMS Test.Lab software to detect chatter (both in SSR test and chatter test with constant parameters).

Two tools are studied, coupled on a HSK32 holder and collet ER16. The screening tool is a two fluted end mill Garant 201770 with 8 mm diameter and 19.5 mm overhang (Fig. 3a), the new tool is a two fluted end mill Garant 201270 with 8 mm diameter and overhang equal to 30 mm (Fig. 3b). Slot milling (i.e., full-immersion) was performed for both tools, resulting in 8 mm radial depth of cut for all the tests.

3.1. Screening tool results

Six slotting SSR tests were performed at different depths of cut (1.0, 1.5, 2.0, 2.5, 3.0, 3.5 mm) from 13,000 to 30,000 rpm and 0.03 mm/tooth feed. Microphone signals were acquired and analyzed by means of Order Analysis [12]. By performing SSR tests, 34 chatter limiting conditions were extracted and presented in Fig. 4, as grey dots. These conditions were clustered in seven lobes and used to identify tool-tip FRFs at different spindle speed via proposed technique. Method implementation requires modal parameters and mode shapes of tool-tip stationary FRFs. These were experimentally identified via impact testing (Brüel & Kjaer Type 8202 impulse hammer and a PCB 352C22 accelerometer). For the machine setup, tool-tip FRFs are practically symmetric. Henceforth, tool-tip FRFs in x and y directions will be considered equal.

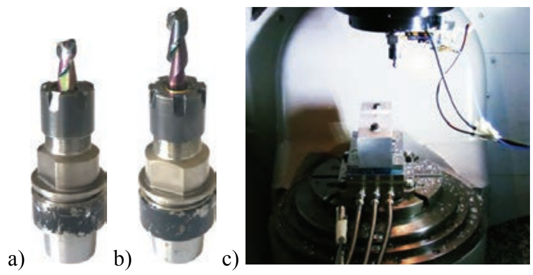

Fig. 3. Screening tool (a) new tool (b) machine set-up (c).

Table 1. Stationary modal parameters screening tool, dominant mode in bold.

Modes	1st	2nd	3rd	4th	5th	**6th**	7th
ω_n [Hz]	1052	2109	2400	3110	3624	**5366**	7383
ζ [%]	4.84	6.23	5.25	1.27	4.52	**1.39**	2.08

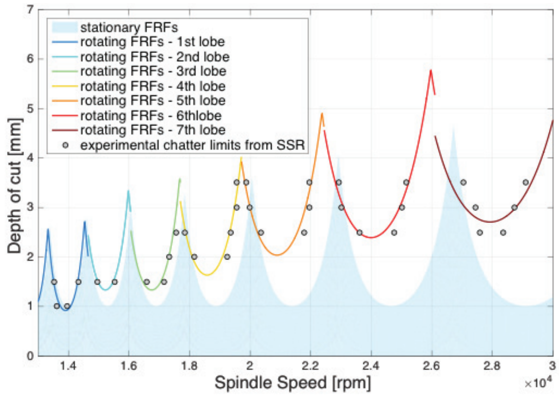

Fig. 4 Speed-varying SLD for the screening tool.

Modal parameters were extracted by Polymax [14] for the screening tool (Table 1). By using stationary FRFs, experimentally obtained, and cutting force coefficients for the material, identified by authors in [15,16], stationary SLD is computed by analytical solution [4] (Fig. 4). As clear from the figure, experimental results (grey dots) are far from stationary SLD, especially at high speed. Starting from stationary configuration, for each lobe proposed fitting procedure was applied to identify speed-varying tool-tip FRFs. In this process, ω_n and ξ of the dominant mode (5366 Hz), responsible of chatter, are considered as unknowns. Since information on the other modes cannot be identified by chatter tests, the same relative shift in natural frequency and damping ratio was assigned to all the other modes. Resulting speed-varying SLD (Fig. 4) is in accordance with experimental conditions extracted by SSR test, as imposed by the fitting strategy. Computed speed-varying FRFs is presented in Fig. 5. Increasing spindle speed, natural frequency decreases and damping ratio increases. This behavior is in agreement with the one experimentally identified in other works [6,10], and with the physical behavior of spindle model taking into account bearing stiffness changing with spindle speed [7].

3.2. New tool results

Speed-varying FRFs of the new tool is obtained by the second module of the proposed approach.

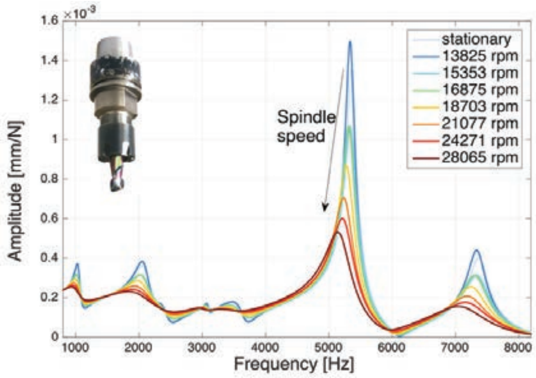

Fig. 5. Speed-varying FRFs of the screening tool.

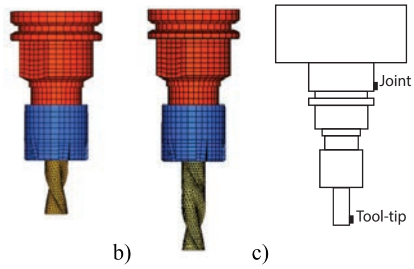

Fig. 6. Screening tool FE model (a) New tool FE model (b) Joint location (c).

RCSA technique previously presented is applied. Joint location was selected on the standard portion of the holder, as presented in Fig. 6c and already adopted in [17,18]. Related FE models of the remaining part for the tools are created (Fig. 6a and Fig. 6b). 3D FE modeling technique was preferred. Indeed, in collet holder as the one used in this work, tool is clamped tightening an elastic sleeve around the tool shank. The elastic deformation of the collet provides the friction force required to transmit the spindle torque. Therefore, a correct estimation of collet stiffness, is crucial to achieve an accurate modelling of tools dynamics. For this reason the modelling technique described in [19] was used: the two tools were modelled via 3D finite elements including the collet. This technique allows to take into account the actual connection stiffness without requiring any elastic connection elements, therefore no experimental fitting procedure must be carried out to identify the connection stiffness. Model implementation and FRFs computation were carried out using MSC Nastran. Before computing the speed-varying FRFs, RCSA approach was validated in the stationary condition. Tool-tip FRFs of the new tool are experimentally identified and compared with the one obtained by RCSA approach in stationary condition. Results of this analysis are reported in Fig. 7. Figure shows the accuracy of adopted RCSA method, as proven in [13]. Modal parameters for the new tool are presented in Table 2.

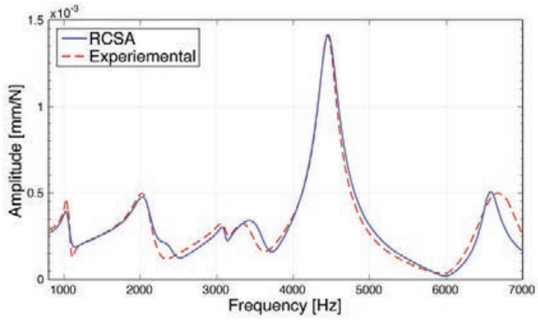

Fig. 7. RCSA results on stationary tool-tip FRF (new tool).

Table 2. Stationary modal parameters new tool, dominant mode in bold.

Modes	1st	2nd	3rd	4th	**5th**	6th
ω_n [Hz]	1054	2073	3111	3429	**4452**	6681
ζ [%]	4.50	6.05	2.25	5.86	**2.83**	4.77

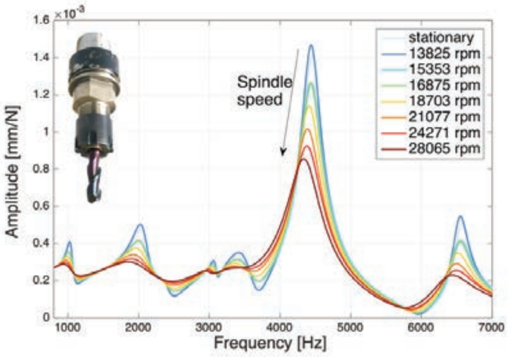

Fig. 8. Speed-varying FRFs for the new tool.

RCSA technique was, then, applied to speed-varying inputs, FRFs for the new tool is presented in Fig. 8. A trend similar to screening tool results is found for the new tool, increasing spindle speed dominant mode natural frequency decreases and damping ratio increases, however in this case this relative shifts are reduced.

Using the obtained FRFs, analytical SLD is computed, in Fig. 9 speed-varying SLD for the new tool is presented. The SLD was computed for the same material and same cutting conditions (i.e., slotting). A significant difference compared to stationary SLD (computed by tool-tip FRFs experimentally obtained by impact testing), is shown, especially for what concern lobe positioning, i.e., the spindle speeds allowing higher depths of cut.

3.3. Chatter prediction

In order to verify the accuracy of the speed-varying FRFs predicted by proposed method, an indirect validation was carried out, checking the accuracy of computed SLDs by experimental tests. Chatter detection tests were carried out with constant parameters (single points in the SLD). Different spindle speeds were tested for both SLDs, changing axial depth of cut, in full-immersion milling: chatter occurrence was evaluated based on frequency signals of sensors and checking distinctive marks on the surface. In particular, for the screening tool 59 tests on single configurations were performed: for each spindle speed, depth of cut was scanned every 0.5 mm (starting from 1 mm), till identifying chatter with at least two tests (red triangle in Fig. 10).

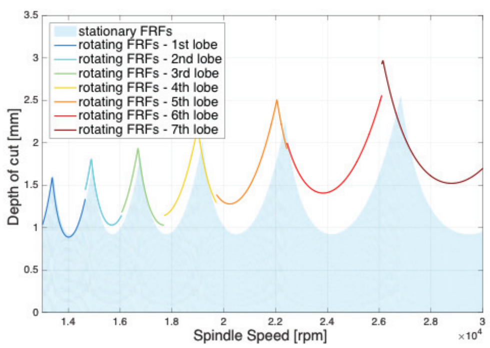

Fig. 9. Speed-varying SLD for the new tool.

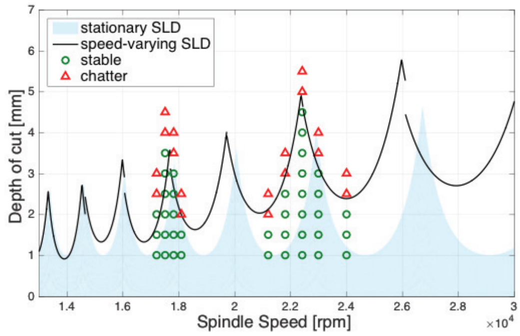

Fig. 10. Speed-varying SLD validation for the screening tool.

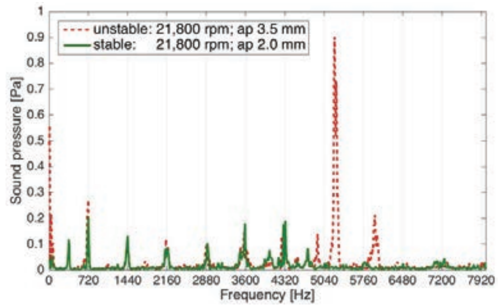

Fig. 11 Microphone spectra for the cutting tests with the screening tool.

In Fig. 10 speed-varying and stationary SLD for screening tool and chatter tests results are shown, while in Fig. 11 microphone spectra for two exemplary conditions are reported. Validation show a very good agreement between reconstructed SLD and chatter test outcomes. This is expected, considering that speed-varying SLD for the screening tool was obtained fitting chatter limiting conditions extracted by an experimental phase.

Same validation procedure was repeated for the new tool results. In this case, a deeper analysis was carried out focusing on lobe positioning. 93 tests at constant parameters were performed with a depth of cut increase of 0.2 mm, starting at 1 mm. Results are shown in Fig. 12, while in Fig. 13 microphone spectra for stable and unstable conditions are presented. SLD obtained by speed-varying FRFs identified via RCSA matches chatter experimental tests, with small differences at higher speed.

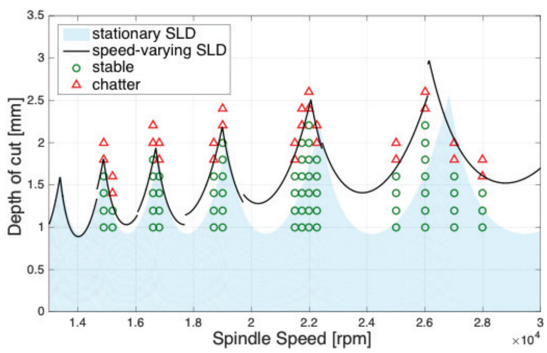

Fig. 12. Speed-varying SLD validation for the new tool.

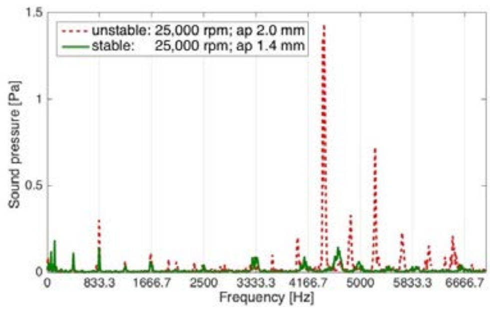

Fig. 13 Microphone spectra for the cutting tests with the new tool.

These differences could be due to the approximations of the method, e.g., assuming the same shift for all the modes, not considering gyroscopic effect in the FE models of the tools and neglecting mode shapes variation with spindle speed.

The significant discrepancies between experimental results and stationary SLDs for both tools confirms the importance of studying speed-varying FRFs to improve reliability of chatter prediction at high speed.

4. Conclusions

Chatter prediction at high speed suffers reduced accuracy due to tool-tip FRFs changing with spindle speed, but generally identified in stationary condition. This paper presents a comprehensive method to predict speed-varying FRFs, aiming at improving chatter prediction reliability. An experimental-analytical approach allows to compute speed-varying FRFs for a specific tool. Identification is performed efficiently thanks to an advanced experimental test and robustly through a dedicated optimization strategy. Then, FRFs identified by proposed approach are used for predicting speed-varying FRFs of any other tool, applying a tailored RCSA approach. Results show good accuracy of the predicted speed-varying SLDs both for the screening tool and the new tool. In this work, the two tools were selected with similar dynamics and close dominant modes. To assess method performances, further investigations should be carried out by using different tooling systems with various dynamics: e.g., low frequency dominant modes, different x and y direction behavior. Moreover, in this work speed-varying FRFs were experimentally identified using a shift of the stationary modes, considering bearings stiffness variation as dominant effect. However, dynamics of the spindle could be deeply studied (e.g., by using numerical models) to develop a specific strategy for non-dominant modes shift and gyroscopic effects implementation (e.g., considering potential resulting backward and forward modes).

Acknowledgments

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