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Chatter stability prediction in milling using speed-varying cutting force coefficients

N.Grossi*[a], L.Sallese[a], A.Scippa[a], G.Campatelli[a]

[a]Department of Industrial Engineering, University of Florence, Via di Santa Marta 3, 50139, Firenze, Italy

* Corresponding author. Tel.: +39-055-4796291; fax: +39-055-4796400. *E-mail address:* niccolo.grossi@unifi.it

Abstract

Chatter prediction accuracy is significantly affected by reliability of data entry, i.e., cutting force coefficients and frequency response, both influenced by spindle speed. The evaluation of specific cutting force coefficients in High-Speed Milling (HSM) is challenging due to the frequency bandwidth of commercial force sensors. In this paper specific cutting coefficients have been identified at different spindle speeds: dynamometer signals have been compensated thanks to an improved technique based on Kalman filter estimator. The obtained speed-varying force coefficients have been used to improve the reliability of stability lobe diagrams for HSM, as proven by experimental tests.

Keywords: Cutting Force Coefficients; HSM; Chatter; Dynamic compensation.

1. Introduction

Milling is the most common and versatile technology for machining process characterized by a wide range of metal cutting capability, that places it in a central role in manufacturing industry. Chatter vibration is one of the main limitation of milling process performance [1]. The occurrence of this unstable regenerative phenomenon produces poor surface finish, tool wear and breakage. In the last decades chatter has been widely investigated and different predictive models have been developed [2-4]. These models lead to a chart known as Stability Lobe Diagram (SLD), used to select stable machining parameters. Even if literature counts several complex and accurate predictive models generally based on time domain simulations (e.g., [3]), the most widely used method still refers to zero-order analytical approach [4] because its simplicity and efficient SLD evaluation.

Stability lobes diagrams accuracy is strongly affected by reliability of data entries, i.e., machine dynamics at the tool-tip and coefficients for cutting forces prediction. Both these parameters are influenced by spindle speed [5-10]: this is an issue for High-Speed Milling (HSM), where the cutting speed could change significantly. Moreover accurate SLD are useful especially in HSM: increasing spindle speed, typical diagram lobes are more spaced creating stable zones at high depth of cut that can be exploited for increasing productivity. Therefore investigation of tool-tip dynamics and cutting force coefficients dependence on cutting speed becomes crucial to improve milling performance.

Machine tool dynamics generally is identified as frequency response function (FRF) at the tool-tip by means of impact test on non-rotating tool. At high speed, tool-tip dynamics could change because of influence of gyroscopic effects and centrifugal forces. This aspect has been studied in literature [5-7] leading to conflicting results. These studies are focused mainly on FE modeling of spindle under operation condition. Increasing spindle speed Cao's [5] model predicts a shift in natural frequency and an increasing of damping in FRF reflecting in a slight change of the SLD; in the same way Gagnol et al. [6] confirm, in their model based stability, that lobe diagram generated from the non-rotating transfer function underestimates the allowable depth of cut, but in

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their study the difference between stationary and rotating is more significant. Furthermore Mañé [7] presents an integrated method to identify chatter stability considering workpiece dynamics and spindle dependent tool-tip FRF, in his work frequency shift between stationary and rotating FRF results quite considerable.

On the other hand Rantalo [8] built a contactless dynamic spindle testing (CDST) instrument in order to experimentally identify tool-tip FRF at high spindle speed: the results of his research show a slight increase on depth of cut limit in stability lobe diagram, suggesting an increase of damping on the FRF without notable differences on natural frequencies.

For what concerns coefficients, cutting process and chip formation mechanics change as cutting speed varies, thus reflecting in a change of cutting coefficients. This trend has been presented in [9,10], and it's relevant especially for tangential forces: according to these studies coefficients are high at low speed, showing a decrease and then increasing again in HSM area. There are mainly two ways to identify cutting force coefficients: coefficients obtained using the mechanics of cutting or specific coefficients from experimental results. For the first approach one of the most used method is the one developed by Budak et al. [11] and named orthogonal to oblique transformation: a general approach that could identify cutting force coefficients for different cutting tool and operation from data extracted from orthogonal cutting tests. The coefficients obtained using the mechanics of cutting are more general, they can be applied to any different tool geometry thanks to the orthogonal to oblique transformation; nevertheless this transformation implies some approximation errors. On the other hand there are different options related to the second approach to obtain the specific cutting coefficients from the experimental results, among them, the most advanced are based on average forces measurements per revolution in slot milling tests [1,12] but there are some methods based on simulation [13] and instantaneous coefficients. Specific coefficients are consistent only for the particular material and tool used in the experimental tests but this approach results more accurate. The evaluation of such coefficients with high speed milling tests is challenging due to the limited frequency bandwidth of commercial force sensors that results inadequate for high rotational speeds (dynamometer's natural frequency limits measurements to low speed).

The aim of the presented study is to improve the reliability of chatter prediction implementing a speed-dependent stability lobe diagram starting from analytical prediction theory [4]. This work is focused on cutting force coefficients influence and its variation with cutting velocity. Variation of FRF in the spindle range is negligible in this study. Milling tests at different speed have been carried out to identify cutting force coefficients without cutting mechanics approximation. In order to overcome dynamometer dynamics issues an improved compensation technique, based on Kalman filter estimator [14] was employed, as already used by authors in [15].

Based on cutting speed dependent force coefficients, a method to create analytical SLD has been developed, taking into account different cutting coefficients changing continuously with spindle speed. The reliability of obtained stability lobe diagram for HSM has been proved by experimental tests.

2. Cutting coefficients

Cutting force model proposed by Altintas [16] has been used for the evaluation of cutting forces. This model computes the force components by means of 6 coefficients as expressed in equation (1) where db and dl are the chip width and length for an infinitesimal section of the chip respectively.

$$\begin{aligned} dF_t &= K_{tc}t_n db + K_{te}dl \\ dF_r &= K_{rc}t_n db + K_{re}dl \\ dF_a &= K_{ac}t_n db + K_{ae}dl \end{aligned} \qquad (1)$$

Identification of these coefficients has been carried out by average cutting force method [1] performing full-immersion (i.e., slotting) milling experiments to simplify identification. The average cutting forces can be expressed as a linear function of the feed rate, therefore average forces at different feed rates are measured and coefficients are estimated by data linear regression.

3. Speed-varying stability lobe diagram

Analytical chatter stability considering zero-order approximation [4] has been applied including speed-varying coefficients. Chatter critical depth of cut is:

$$a_{\lim} = -\frac{2\pi\Lambda_R}{NK_{tc}}\left(1+\frac{\Lambda_R}{\Lambda_I}\right) \qquad (2)$$

where N is number of flutes, K_{tc} is tangential cutting force coefficient, Λ_R Λ_I are real and imaginary parts of the eigenvalues calculated from the stability Nyquist criterion:

$$\det\left[[I]-\frac{1}{2}K_{tc}a(1-e^{-i\omega_c T})[A_0(K_r)][\Phi(i\omega_c)]\right]=0 \qquad (3)$$

where ω_c is chatter frequency, Φ is the directional FRF matrix and A_0 is the directional cutting coefficient matrix.

A_0 matrix is dependent on K_r, relative coefficient calculated as:

$$K_r = \frac{K_{rc}}{K_{tc}} \qquad (4)$$

Consequently the depth of cut limit (2), needed to create SLD, is dependent on K_{tc} and K_{rc}. Chatter stability changes as these parameters vary.

In the case of spindle-speed-varying coefficients different approaches can be applied to build an accurate SLD. Cao [5] proposed a method based on the same stability theory but for FRF varying with spindle speed, his basic idea is to check stability (3) for discrete spindle speeds while increasing depth of cut in order to identify the actual limit. This approach implies depth of cut discretization and consequently an approximation compared to the original theory.

In this paper a different method is proposed, the speed-dependent stability lobe diagram is calculated by the following procedure , displayed in Fig. 1:

1. According to the number of calculated coefficients, global spindle speed range is partitioned in different zones
2. Analytical stability diagram is calculated changing coefficients for every single zone, creating a step diagram
3. Starting from the diagram at point 2, a new continuous line diagram is calculated interpolating depth of cut limit between zones (e.g., linear).

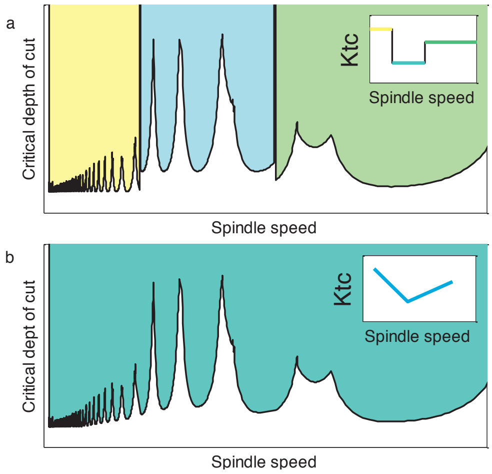

Fig. 1. Speed-varying coefficients stability lobe diagram (a) Step diagram (phase 2); (b) Continuous diagram (phase 3).

4. Experimental identification of cutting coefficients

Experimental characterization of workpiece material has been carried out using a CNC vertical machine with high speed spindle, a Mori Seiki NMV1500DCG. The material used for the machining tests is an Aluminum 6082-T4 alloy. According to [1], milling tests should be performed following these instructions:

1. Rigid workpiece, clamped rigidly to the dynamometer
2. Dynamometer clamped rigidly to the table
3. Collecting cutting forces for a full number of revolutions in order to eliminate influence of run-out
4. Measuring the cutting forces at a stable depth of cut

Workpiece used was a bar 60x60x150mm rigidly clamped to dynamometer with two screws (Fig. 2b). A three-component Kistler dynamometer type 9254 A has been mounted on machine tool and coordinates system has been set to level force sensor surfaces (Fig 2a). LMS Scadas III frontend and LMS Test.Lab 11A software have been used to acquire signals.

Tool has been chosen in order to ensure stable depth of cut in slotting operations. Different tools and overhangs have been tested, indentifying tool-tip FRF and calculating SLD with coefficients measured by the authors in [9] at low speed: a two flutes Garant 201770 with 8 mm diameter have been selected and mounted with a 20mm overhang on HSK32ER20 tool-holder (Fig 2c). In figure 3, stability diagram is presented, 2.5mm minimum critical depth of cut is identified, slot milling of 1.5mm are performed considering an adequate uncertainty margin.

In order to determine the average cutting force coefficients, cutting forces have been measured during slotting at different spindle speeds (Fig 2d). For each speed five different feed rates have been tested for better computing linear regression, cutting and tool parameters are summarized in table 1.

Table 1. Cutting and tool parameters

Tool parameters					
Diameter (mm)	8		Helix angle	45°	
Flutes number	2		Material	Carbide	
Cutting parameter for milling tests					
Spindle speed (rpm)	995	3979	7958	11937	15916
	19894	23873	27852	31831	
Feed per teeth (mm)	0.02	0.025	0.03	0.035	0.04
Axial depth (mm)	1.5		Radial depth	Slotting	

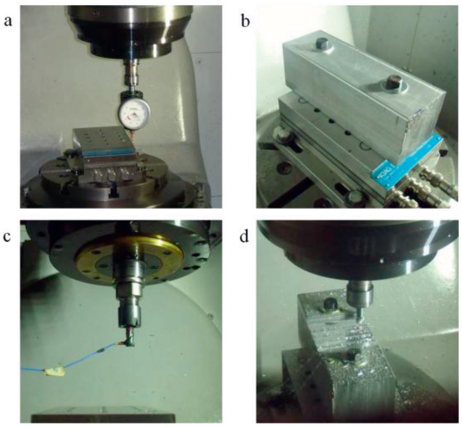

Fig. 2. Tests set-up (a) dynamometer (b) workpiece (c) tool (d) slotting tests

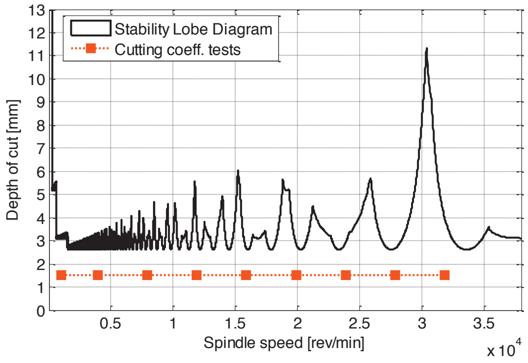

Fig. 3. SLD for coefficients identification tests

4.1. Dynamic compensation for cutting force signals

To ensure adequate accuracy of the cutting forces measured during the various cutting tests, a specific dynamic compensation technique has been applied; the purpose of this technique, based on Kalman filter estimation [14], is to cleanse the measured force signals from errors induced by the system's dynamic that could drastically affect the accuracy of measured force signals, especially when high spindle speeds (hence high tooth passing frequencies) are used.

To identify how the system's dynamic affects the cutting force measurements some impact modal tests were conducted along each of the three dynamometer's axis (X, Y and Z) using a Brüel & Kjaer Type 8202 impulse hammer, LMS Scadas III frontend and LMS Test.Lab 11A software. For each of the dynamometer's axis the transmissibility (i.e., measured force on applied force) frequency response functions have been identified, showing that without adequate compensation only low frequency force signals could accurately be measured. The measured FRFs are shown in Figure 4a.

The compensation filters have been computed in accordance with Altintas and Park work [14], nevertheless in our specific applications some adjustments revealed to be necessary to extend the application of the mentioned compensation technique over such a broad frequency range. In particular the curve-fitting technique accuracy have been improved using an iterative approach based on rational fraction polynomial method [17] that revealed to be more robust and accurate in fitting higher order transfer functions (TFs), such as the ones needed in our specific applications due to the relevant number of modes identified in the measured frequency ranges.

The effectiveness of the compensation technique used is mainly related to the transmissibility measurements accuracy and the curve fitting algorithm used; transmissibility FRF could vary sensibly along time with workpiece material removal, hence to ensure that adequate accuracy is maintained over the entire cutting tests session the FRFs were measured at three different times during the tests, at the beginning, in the middle and at the end of the test session. As an example in Figure 4b a comparison between the three measured FRFs in x-direction is shown.

The force signals acquired during cutting tests have been hence compensated with filter developed upon the specific measured FRFs. In Figure 5a a comparison of measured and compensated forces for four different cutting tests is shown: as clearly appears by analyzing the synthetic results shown in Figure 4c the effects of the compensation technique used revealed to be appreciable at higher spindle speeds (i.e., higher tooth passing frequencies) where errors in peak force magnitude without compensation could reach values as high as 60%. At lower spindle speeds, such as for the 995 rpm test (i.e., around 33 Hz tooth passing frequency), the effects of system's dynamic could actually be neglected instead, as should be expected by analyzing the measured FRFs.

Although the effects of the dynamically induced errors in cutting force measurements are quite significant in both magnitude and phase of the measured force signals, especially at higher spindle speeds, for what concerns the average cutting force no difference can actually be appreciated, as clearly exemplified by Figure 5a, where a comparison of both measured and compensated mean force signals is shown.

This effect could be understood by analyzing that cutting force signals are actually composed of a mean constant (i.e., 0 Hz) contribution and some frequency contributions related to the tooth passing frequency and its harmonics [1]. While the frequency contributions could be affected by errors induced by the dynamic of the system, as already shown in Figure 5b and c, the constant contribution should not be distorted by any dynamic effect, since the FRFs should have magnitude one and zero phase at 0 Hz, for physical reasons (i.e., rigid motion frequency).

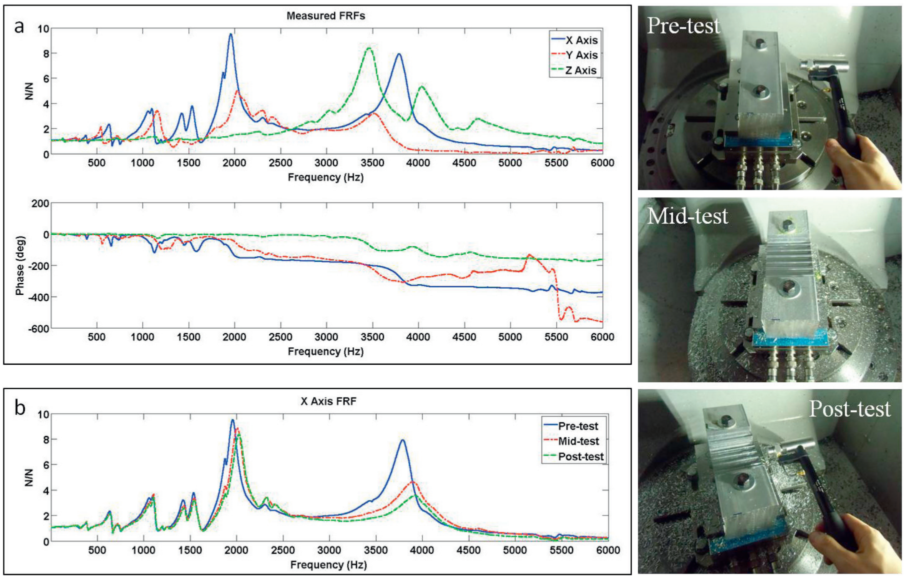

Fig. 4. (a) Measured transmissibility FRFs on the three axis (b) measured transmissibility FRFs on-X axis at different times

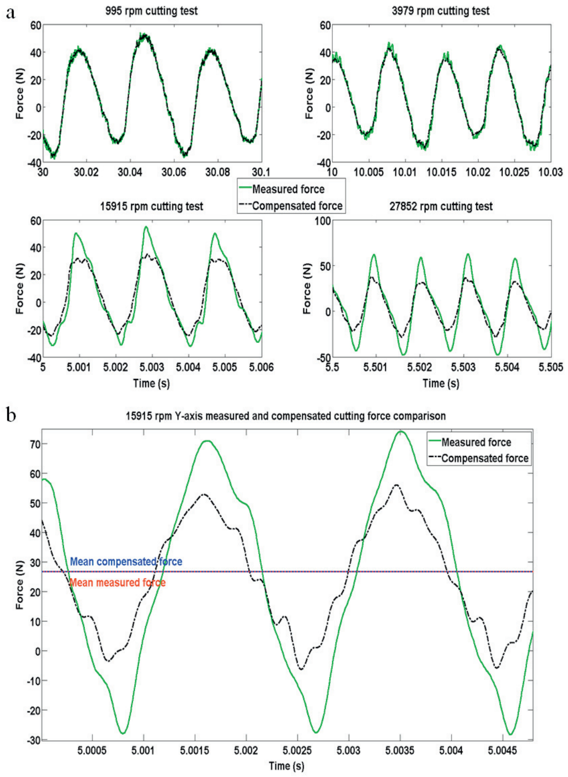

Fig. 5. (a) Compensated and measured force signals for four different spindle speeds (b) Mean compensated and mean measured forces comparison

The compensation results demonstrated that an effective, precise and robust compensation technique is actually an unavoidable requirement if realistic and accurate cutting force time series measurements are needed, especially as spindle speed increases, such as in high speed cutting tests.

As a matter of fact, instead, if interest is focused on average cutting force, just like in this specific application, the use of a dynamic compensation technique could also be avoided, since the average cutting force should not be distorted by effects related to system's dynamic. In conclusion if an average cutting force approach is followed, no compensation is needed; on the other hand if a more accurate technique is used, such as the ones based on instantaneous cutting forces signals, compensation is essential to reach accurate results.

4.2. Cutting force coefficients

Cutting coefficients extracted from milling tests are summarized in table 2. Results are obtained by average force on the three axis and then calculated from linear regression as a function of the feed rate as explained in section 2.

Figure 6 shows cutting coefficients of interest for stability varying with spindle speed. It's interesting to notice that at very low speed, where cutting tests generally are performed in order to avoid dynamometer dynamic effect, cutting coefficients are very high, resulting in a not reliable prediction of stability at higher speed.

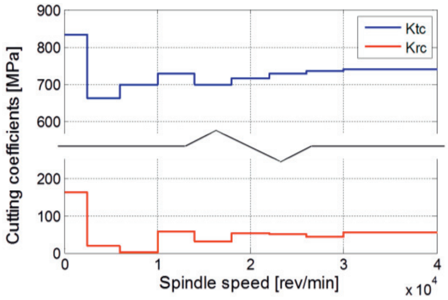

Fig. 6. Cutting coefficients for stability analysis

Table 2. Cutting coefficients at different spindle speeds.

Spindle speed *rpm*	V_c *m/min*	Ktc *MPa*	Kte *N/mm*	Krc *MPa*	Kre *N/mm*	Kac *MPa*	Kae *N/mm*
995	25	830.7	8.9	162.3	9.2	345.5	0.086
3979	100	661.5	8.1	17.7	7.0	309.8	0.486
7958	200	698.8	5.8	1.7	5.7	351.7	0.278
11937	300	729.3	4.6	57.4	3.8	336.4	0.083
15916	400	710.6	5.9	37.5	5.3	321.6	0.389
19894	500	716.1	5.7	52.3	4.8	333.4	0.131
23873	600	724.9	5.5	50.0	5.2	313.4	0.487
27852	700	732.6	5.7	43.0	5.6	332.5	0.339
31831	800	738.9	5.7	53.8	5.5	323.4	0.374

5. Experimental validation

Predicted cutting force coefficients have been applied to Stability Lobe Diagrams theory presented in section 3. Impact tests have been performed on the same tool with different overhang (36.5 mm), so different FRF have been used in SLD computation for the same operation (i.e., slotting) and material. Resulting SLD (blue line) is compared with the traditional theory (black line) built considering as coefficients the ones obtained by low speed test (i.e., 995 rpm), as shown in figure 7. Analyzing stability diagrams different cutting tests have been performed in order to experimentally validate proposed approach.

To check chatter onset, table dynamometer and microphone signals have been acquired by LMS Scadas III and elaborated in LMS Test.Lab software. Frequency spectra of the data have been calculated to check chatter frequency evolution. In figure 7 results are shown. Chatter mark (red square) is indicated when chatter frequency is dominant on the spectrum, in the limit points (violet triangle) chatter frequency is growing but it's not dominant, no chatter frequency is identified in the stable points (green square). As evident from the figure, speed-varying coefficients stability is more accurate than traditional approach, anyway some discrepancies are shown, experimental-suggested diagram is presented (dot line). The differences could be caused by variation of FRF with spindle speed, not considered in this work.

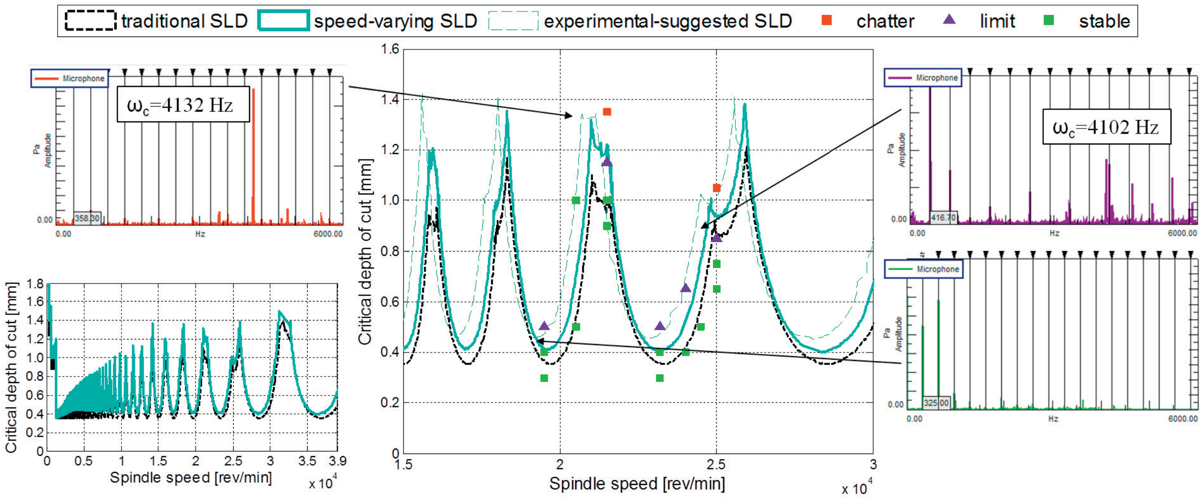

Fig. 7. Stability Lobe Diagrams for experimental validation

As presented in literature [5-8], increasing spindle speed an increase of damping should be expected, this should reflect in increased depth of cut. Moreover a frequency shift is experimentally determined by comparing experimental chatter frequencies and the ones coming from SLD theory, consequently a lobes shift can be hypothesized.

6. Conclusions

Chatter stability depends on cutting force coefficients and machine tool dynamics that can change at different cutting velocities.

In this work a method to include speed-dependent cutting force coefficients to traditional chatter stability theory is presented. Experimental validation demonstrated the accuracy of the proposed approach, nevertheless more accurate identification could be obtained introducing speed-varying FRFs, not considered in this work. Based on the results of this paper more reliable stability limits could be predicted after experimental characterization of materials at different spindle speeds. Cutting coefficients can be computed without compensating dynamometer dynamics in case of average cutting force method; on the other hand an effective compensation technique, as the one presented here, is needed for instantaneous force based methods.

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