

Manuscript Number: PROCIR-D-15-00892R2

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Article Type: SI: 7th HPC 2016

Section/Category: SI: 7th HPC 2016

Keywords: Stability; dynamics; FRF; lobes; chatter.

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7th HPC 2016 – CIRP Conference on High Performance Cutting

FRF Estimation through Sweep Milling Force Excitation (SMFE)

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Abstract

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Peer-review under responsibility of the International Scientific Committee of 7th HPC 2016 in the person of the Conference Chair Prof. Matthias Putz.

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1. Introduction

Self-excited (chatter) vibrations are one of the most critical problems in machining processes, since they affect machined workpiece quality and tool life, and jeopardize machine integrity. Stability models are the main tool to predict unstable machining and select suitable process parameters. However, currently this technique lacks of reliability to apply it intensively in the manufacturing industry [1, 2].

In heavy-duty milling with roughing conditions, critical modes are usually complex shaped, with many different machine components and assembly joints that contribute to define the dynamic characteristics of the mechanical system. Therefore, stability lobes cannot be used as effectively as in aluminum milling due to the resulting inaccuracies [1, 2]. The source of inaccuracies is usually attributed to nonlinearities of the process or dynamic parameter identification errors [2, 3].

Nowadays, impact hammer or shaker testing are the usual methods for dynamic parameter identification in industrial environments. These traditional techniques to measure the FRF are doubtful since the nonlinear response cannot be

captured through impulse response with hardly repeatable force levels in a steady non-operating machine [4].

Alternative experimental methods could improve significantly model input data quality and therefore enhance chatter prediction model reliability [5].

The real cutting forces generated by the cutting process have been used as input excitation for FRF estimation. Two main approaches have been followed. Firstly, discrete frequency FRF points have been obtained at different cutting speeds, measuring the response at the corresponding speed [6]. Secondly, in order to avoid the harmonic content problem of the cutting forces, specially designed workpieces with randomly distributed slots [7, 8] or variable thickness thin walls [9] have been machined to perform this kind of testing. This way a random excitation of the system was achieved. Both approaches showed significant changes in system dynamic parameters in comparison with the standard hammer test.

In this work the actual milling force is used as the input excitation to estimate the FRF. The difference with previous works is that, in this case, the cutting speed is steadily decreased or increased in order to perform a frequency sweep

excitation. Thus, the frequency range of interest is excited in a continuous way. Moreover, a rotary dynamometric tool holder is used to measure cutting forces. The advantage of the rotary dynamometric tool holder is that the cutting span is not limited by a dynamometric plate. This speeds up the process and makes the procedure feasible for dynamic parameter estimation in an industrial workshop.

2. FRF estimation procedure: SMFE method

Previous researches using the real cutting force as input excitation for FRF estimation tried to avoid the typical harmonic content of the milling force. However, in this work this harmonic content will be the input excitation used to obtain the FRF through the sweep milling force excitation (SMFE) method, analyzing the frequency response function in an analogue way as a chirp excitation case.

2.1. Selection of the excitation parameters

First of all, the frequency range of interest is defined. The main modes involved in the process stability must be within this range, in order to perform a complete dynamic characterization. The milling rotating speed is varied continuously over a defined range, in such way that the tooth passing frequency and/or its first harmonics are swept over the desired frequency range. These harmonics should have high energy content in order to apply a strong excitation. An interrupted cutting process, with a small width of cut, is therefore used for this purpose. Fig. 1 shows the spectrogram of two different tools when performing the SMFE method. The main tooth passing harmonic Ω is swept from the beginning to the end of the frequency range of interest (12–42 Hz in this case). This explains the different spindle speed range selected for each tool. Depending on the number of inserts of each tool, there are other harmonics exciting the frequency range of interest partially.

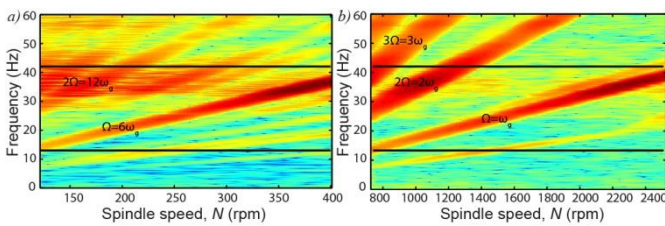


Fig. 1. Spectrogram of the vibration acceleration signal in the SMFE method for 2 different tools: (a) $D=125\text{mm}$, $Z=6$; (b) $D=32$, $Z=1$. Ω : tooth passing frequency; ω_s : rotation frequency.

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The frequency response function $\Phi(f)$ relates the input excitation and the output response and can be calculated by different methods. In this case the Φ_1 estimate will be used:

$$\Phi_1 = \frac{G_{rF}}{G_{FF}}, \quad (1)$$

where G_{rF} is the cross spectrum between the output r and the input F and G_{FF} is the power spectrum of the input F .

According to previous works [10], single-block DFT computation along the entire sweep data collection leads to a good FRF estimation. The cross and power spectra are computed as:

$$\begin{aligned} G_{rF}(f) &= \frac{1}{N_a} \sum_{i=1}^{N_a} r_i(f) F_i^*(f), \\ G_{rr}(f) &= \frac{1}{N_a} \sum_{i=1}^{N_a} r_i(f) r_i^*(f), \\ G_{FF}(f) &= \frac{1}{N_a} \sum_{i=1}^{N_a} F_i(f) F_i^*(f) \end{aligned} \quad (2)$$

where N_a is the number of averages.

The cutting force is divided into three spatial components. The system is regarded as a MIMO system, where multiple inputs and multiple outputs are produced with each cutting speed sweep.

$$\begin{aligned} G_{xFx} &= \Phi_{xx} G_{FxFx} + \Phi_{xy} G_{FyFx} + \Phi_{xz} G_{FzFx}, \\ G_{yFx} &= \Phi_{yx} G_{FxFx} + \Phi_{yy} G_{FyFx} + \Phi_{yz} G_{FzFx}, \\ G_{zFx} &= \Phi_{zx} G_{FxFx} + \Phi_{zy} G_{FyFx} + \Phi_{zz} G_{FzFx}, \end{aligned} \quad (3)$$

As there are nine unknowns to solve, at least three different cutting tests must be performed in order to solve the system. If a 90° lead angle tool is used, the axial force F_z can be neglected and a 2-input 2-output system is obtained. In this case, at least two cutting tests are needed to obtain as many equations as unknown terms [11].

It has to be considered that the different cutting tests must be independent from each other, modifying the ratio of amplitudes or phases between the different force terms F_x , F_y and F_z . When two dimensions are considered, an easy way to accomplish this condition is changing the cutting strategy from down-milling to up-milling direction, whereas for three directions, at least three cutting tests are needed. A good option for this case is performing cutting tests in down-milling, up-milling and central-milling, as defined in Fig. 2:

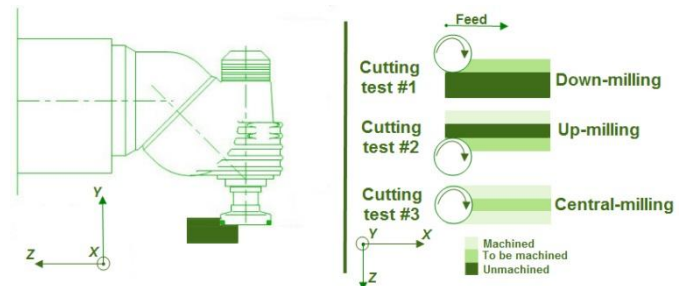


Fig. 2. Cutting tests outline. Three different cutting tests are performed in order to obtain the 9 terms of $[\Phi]$ matrix: down-milling cut, up-milling cut and central-milling cut.

The frequency response functions will be calculated from the cutting tests. Therefore, the force must be measured by

means of a dynamometric plate or a dynamometric tool holder, whereas the response could be measured by means of accelerometers. Initial value time domain simulations are useful in order to define the parameters of cutting tests to perform.

2.3. Test performance and post-processing

The cutting test plan for 3-axis system defined in section 2.2 is performed and the measured data post-processed, solving the system of 9 equations and 9 unknowns of the 3x3 $[\Phi]$ matrix:

$$[\Phi] = \begin{bmatrix} \Phi_{xx} & \Phi_{xy} & \Phi_{xz} \\ \Phi_{yx} & \Phi_{yy} & \Phi_{yz} \\ \Phi_{zx} & \Phi_{zy} & \Phi_{zz} \end{bmatrix}, \quad (4)$$

A higher number of tests could be carried out in order to have a redundant system and increase the accuracy of the solution.

2.4. Measurement quality check

It is important to check the following indicators, in order to make sure that the $[\Phi]$ matrix obtained is reliable.

- **Condition number.**

When the set of equations to solve the system is built, it is important to check the conditioning of the coefficient matrix in order to make sure that the system is completely independent. A low condition number will be proof of a well-conditioned matrix.

- **Coherence function.**

The coherence function, which gives an estimate of the quality of the measurement by analyzing the repeatability of the performed averages, is defined as:

$$\gamma_{rF}^2 = \frac{G_{rF} G_{rF}^*}{G_{rr} G_{FF}}, \quad (5)$$

3. Experimental tests

Real SMFE experiments have been carried out on the 3+2 axes SV milling machine. The forces in the three axes x , y and z have been measured with a dynamometric tool holder (Kistler 9124B1111) and a dynamometric plate (Kistler 9257BA) attached to the machined workpiece, whereas the response in the spindle head has been measured by means of three accelerometers. Every cutting test has an approximate duration of 30s and three different cutting tests are performed in order to completely define the matrix in equation (4).

Finally, every test is repeated four times and frequency averaging is carried out in order to minimize noise.

Two different tools have been used for SMFE implementation. The purpose was to test different ratios between the applied cutting forces in the Cartesian axes, due to their different insert geometry (Table 1).

The cutting conditions used for each type of tool vary, due to their different diameter to number of teeth D/Z ratio, in order to excite the same frequency region (Table 2).

Table 1. Tools used for SMFE experimental tests.



Tool	Picture	Diameter (D)	Number of inserts	Lead angle (κ)	Tool reference
1		125	2	45°	Sandvik R245-080Q27-12M
2		125	6	0-11°	Hitachi GFH476 ASF5125RM

Table 2. Cutting conditions for SMFE.

Tool	N range (rpm)	a_p (mm)	f_z (mm/z)	Width of cut (%D)	Cutting direction
1	1260-360	1	0.2	12.5	x- Down-milling
					x- Up-milling
					x- Central-milling
2	400-120	0.2	0.2	12.5	x- Down-milling
					x- Up-milling
					x- Central-milling

The FRFs obtained through the SMFE method considering simultaneously the signals from both tools at the same time have been compared to standard hammer and shaker tests (see Fig. 3). In x direction, the hammer FRF presents lower dynamic stiffness and a single peak, in opposition to the two peaks shown in the other two FRFs. In y direction, the FRF through the SMFE method differs slightly from the FRFs obtained through traditional methods.

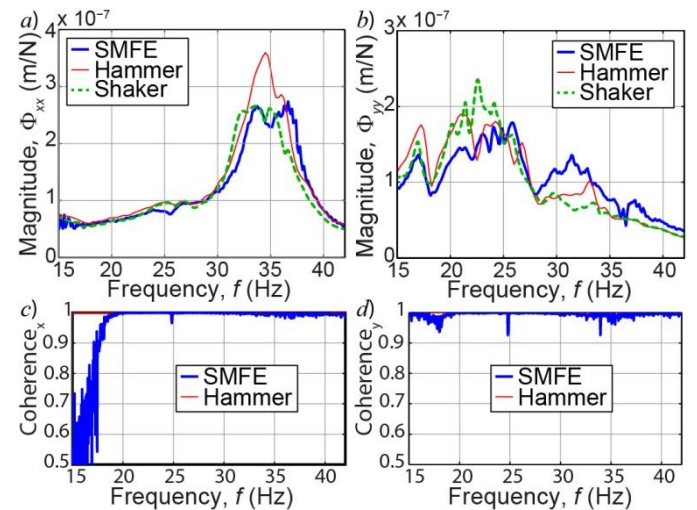



Fig. 3: Comparison of the SMFE FRFs with traditionally obtained FRFs: SMFE FRF with tool 1&2, hammer FRF and shaker FRF. a) Φ_{xx} ; b) Φ_{yy} ; c) Coherence_x; d) Coherence_y.

The coherence of the FRF is slightly poorer than typical hammer or shaker coherences but it is still acceptable in the frequency range of interest, as it can be appreciated in Fig. 3c and Fig. 3d.

The theoretical stability lobes can be calculated according to the zeroth order approximation (ZOA) model [12]. The conditions of the cutting process that has been simulated are

shown in Table 3. With these conditions the first lobe related to the low frequency modes limits the stability and therefore, it is suitable to compare the new FRF estimation method developed versus the traditional methods to obtain the FRF.

Table 3. Cutting parameters for stability lobe calculation.

Tool						
Diameter (D)	Number of flutes (Z)	Picture	Lead angle (κ)	Tool reference		
125mm	12		45	Sandvik R245-125Q40-12M		
Cutting conditions & cutting force coefficients						
Width of cut (mm)	f_z (mm/z)	Feed direction	N (rpm)	K_t (N/mm ²)	K_r (1)	K_a (1)
118mm (Down-milling)	0.2	x-	180-200-250-300-360	1889.1	0.411	0.193

Real cutting tests were carried out under the same cutting conditions. The comparison of the theoretical and experimental results is shown in Fig. 4. The lobes calculated by means of the traditional FRF estimation procedures overestimate machine's cutting capability, whereas the lobes calculated by means of the SMFE FRF match reasonably well with the experimental tests. The average experimental vs. simulation error in depth of cut a with the lobes obtained from the SMFE FRFs is 34%, whereas in the lobes obtained from the standard FRFs the average error grows up to 51%. Regarding chatter frequency f_c error, the average error from the SMFE FRF prediction is 5.4%, whereas the average error from the hammer FRF prediction is 5.6%.

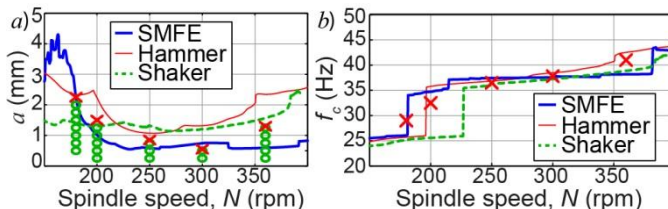


Fig. 4. Comparison of lobes obtained from SMFE FRFs with lobes obtained from standard FRFs: lobe from SMFE FRF with tool 1&2, lobe from hammer FRF and lobe from shaker FRF. a) chatter frequency f_c ; b) depth of cut a . Experimental stable tests (green circles) and unstable tests (red crosses).

In conclusion, these experiments validate the expected higher accuracy of the new dynamic characterization method developed in this work (SMFE method).

4. Conclusions

A new simple and fast methodology for FRF estimation using the milling force itself as input excitation (SMFE method) has been developed. This method provides a closer excitation to the real in-process conditions than traditional

FRF estimation methods like hammer or shaker tests. The methodology consists of exciting the structure through several independent interrupted milling cuts, with proportional ascending or descending cutting speed, in order to perform a frequency sweep over the frequency range of interest by means of the cutting harmonics.

The obtained FRFs through SMFE method do not differ dramatically from traditional FRF methods (hammer and shaker). However these slight differences may have a considerable effect on stability lobes. Thus stability lobes calculated through SMFE FRFs show a more restrictive cutting limit that matches the experimental tests more accurately, although a slight deviation with respect to the experimental tests still remains.

Acknowledgements

This research was partially supported by the EU H2020 MMTECH project (633776/H2020-MG-2014) and Hungarian Scientific Research Foundation OTKA (K108779).

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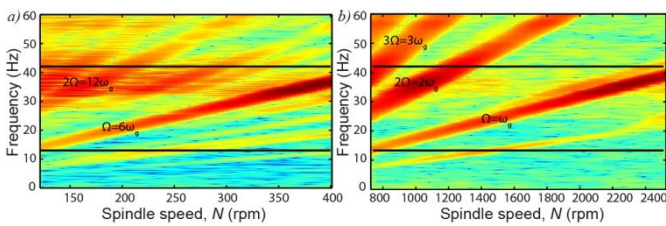


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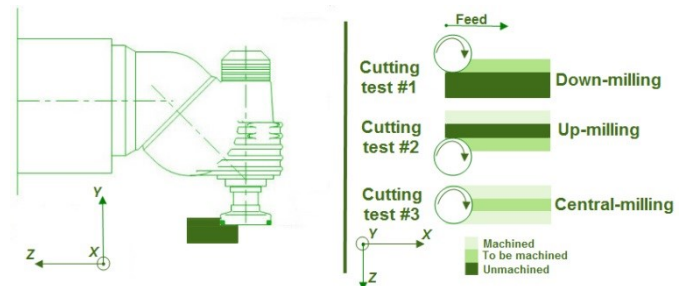


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A higher number of tests could be carried out in order to have a redundant system and increase the accuracy of the solution.

2.4. Measurement quality check

It is important to check the following indicators, in order to make sure that the $[\Phi]$ matrix obtained is reliable.

- **Condition number.**

When the set of equations to solve the system is built, it is important to check the conditioning of the coefficient matrix in order to make sure that the system is completely independent. A low condition number will be proof of a well-conditioned matrix.

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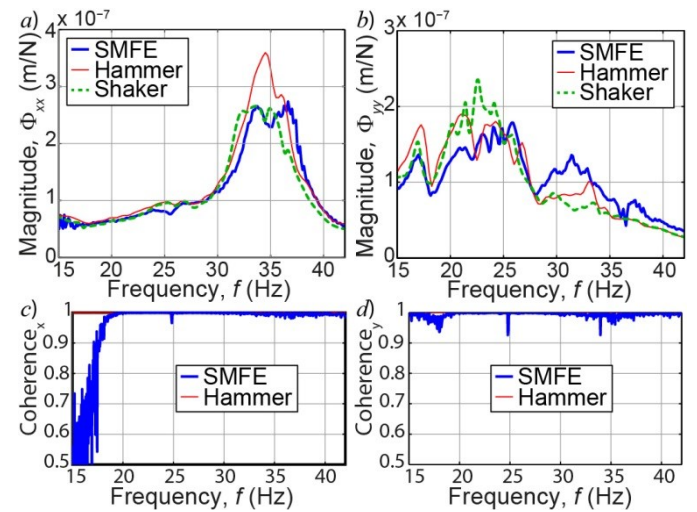



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The coherence of the FRF is slightly poorer than typical hammer or shaker coherences but it is still acceptable in the frequency range of interest, as it can be appreciated in Fig. 3c and Fig. 3d.

The theoretical stability lobes can be calculated according to the zeroth order approximation (ZOA) model [12]. The conditions of the cutting process that has been simulated are

shown in Table 3. With these conditions the first lobe related to the low frequency modes limits the stability and therefore, it is suitable to compare the new FRF estimation method developed versus the traditional methods to obtain the FRF.

Table 3. Cutting parameters for stability lobe calculation.

Tool						
Diameter (D)	Number of flutes (Z)	Picture	Lead angle (κ)	Tool reference		
125mm	12		45	Sandvik R245-125Q40-12M		
Cutting conditions & cutting force coefficients						
Width of cut (mm)	f_z (mm/z)	Feed direction	N (rpm)	K_t (N/mm ²)	K_r (1)	K_a (1)
118mm (Down-milling)	0.2	x-	180-200-250-300-360	1889.1	0.411	0.193

Real cutting tests were carried out under the same cutting conditions. The comparison of the theoretical and experimental results is shown in Fig. 4. The lobes calculated by means of the traditional FRF estimation procedures overestimate machine's cutting capability, whereas the lobes calculated by means of the SMFE FRF match reasonably well with the experimental tests. The average experimental vs. simulation error in depth of cut a with the lobes obtained from the SMFE FRFs is 34%, whereas in the lobes obtained from the standard FRFs the average error grows up to 51%. Regarding chatter frequency f_c error, the average error from the SMFE FRF prediction is 5.4%, whereas the average error from the hammer FRF prediction is 5.6%.

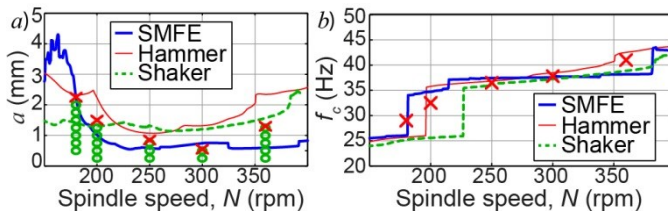


Fig. 4. Comparison of lobes obtained from SMFE FRFs with lobes obtained from standard FRFs: lobe from SMFE FRF with tool 1&2, lobe from hammer FRF and lobe from shaker FRF. a) chatter frequency f_c ; b) depth of cut a . Experimental stable tests (green circles) and unstable tests (red crosses).

In conclusion, these experiments validate the expected higher accuracy of the new dynamic characterization method developed in this work (SMFE method).

4. Conclusions

A new simple and fast methodology for FRF estimation using the milling force itself as input excitation (SMFE method) has been developed. This method provides a closer excitation to the real in-process conditions than traditional

FRF estimation methods like hammer or shaker tests. The methodology consists of exciting the structure through several independent interrupted milling cuts, with proportional ascending or descending cutting speed, in order to perform a frequency sweep over the frequency range of interest by means of the cutting harmonics.

The obtained FRFs through SMFE method do not differ dramatically from traditional FRF methods (hammer and shaker). However these slight differences may have a considerable effect on stability lobes. Thus stability lobes calculated through SMFE FRFs show a more restrictive cutting limit that matches the experimental tests more accurately, although a slight deviation with respect to the experimental tests still remains.

Acknowledgements

This research was partially supported by the EU H2020 MMTECH project (633776/H2020-MG-2014) and Hungarian Scientific Research Foundation OTKA (K108779).

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21 March 2016

Matthias Putz
Managing Guest Editor
Procedia CIRP

Ms. Ref. No.: PROCIR-D-15-00892R1

Dear Prof. Dr. Matthias Putz,

Thank you very much for your feedback on the manuscript "FRF estimation through Sweep Milling Force Excitation (SMFE)" (manuscript no. PROCIR-D-15-00892R1) submitted for HPC 2016 Conference. In response to the suggestions and comments of the reviewers, please find the new version of the paper together with this letter explaining the modifications done.

LIST OF RESPONSES

Reviewer #2:

The paper is clearly written, however, the explanation of the results in Figures 3 and 4 are very short without indication of critical values.

Figures 3 and 4 have been further explained, with a quantification of the approximation of the simulation in case of Fig. 4. The added test is detailed:

"In x direction, the hammer FRF presents lower dynamic stiffness and a single peak, in opposition to the two peaks shown in the other two FRFs. In y direction, the FRF through the SMFE method differs slightly from the FRFs obtained through traditional methods."

&

"The average experimental vs. simulation error in depth of cut a with the lobes obtained from the SMFE FRFs is 34%, whereas in the lobes obtained from the standard FRFs the average error grows up to 51%. Regarding chatter frequency f_c error, the average error from the SMFE FRF prediction is 5.4%, whereas the average error from the hammer FRF prediction is 5.6%."

It seems to be that the tool in table 3 is solid carbide cutter with Helix angle, 12 flutes - not inserts as tools 1 and 2. Please clarify conditions.

Tool in table 3 is also an insert cutter. Probably the column named "Helix angle" has mislead the reviewer. This column has been substituted by the reference of the tool.

It is believed that a in table 2 is ap and "immersion" relates to the width of cut. Is it 12.5% or given in [mm]?

In table 2, " a " has been substituted by " ap " and "immersion" by "width of cut". 12.5% is the width of cut expressed as a percentage of the diameter of the tool, not mm.

Is the lead angle in table 1 0 or 90 degrees?;

The lead angle is near 0 degrees, but it varies according to the depth of cut due to the shape of the insert. The variable range has been written in the table "0-11°". This tool uses high feed inserts which have very small lead angle. This lead angle grows slightly as depth of cut is increased.

Is a in table 2 the width of cut or depth of cut?, both are very small for milling operations with 125 mm diameter tools!

The values 1mm and 0.2mm stand for depth of cut. It is true that these values are rather small, but they were selected in order to keep a stability margin and avoid the onset of chatter while doing the dynamic characterisation tests. It is also remarkable that Tool 2 is a high feed tool and the maximum depth of cut of its inserts is only 2mm.

This methodology assumes that a single dynamic characterisation, with specific cutting force values, can be representative of any cutting condition, therefore the depth of cut value used for the FRF estimation value is not influential.

Are the coefficients K_1 , K_r , K_f in table 3 related to the other parameters mentioned in the paper or only force coefficients? please clarify.

They stand for the cutting force coefficients. The title "cutting force coefficients" has been added in Table 3.

In table 3 is the "Engagement" the width of cut? "down milling" for 118/125 is almost irrelevant.

Yes, "engagement" has been substituted by "width of cut". 118/125 is almost slotting, but the cutting direction (down milling) has been kept in order to allow an accurate reproducibility of the test.

Is the tool in table 3 used only for calculations while tools 1 and 2 only for real tests?

In fact, tools 1 and 2 in Table 2 are used to obtain the FRF of the system, whereas tool in Table 3, which is different from previous ones, is used for validation purposes. Cutting conditions in Table 3 are used both for simulating the theoretical stability limit according to the different FRFs estimated and also to perform the real cutting tests that will validate the theoretical simulation.

In Figure 4 - is the depth of cut a changed during the presented tests?

Yes. Each green circle and red cross represents a cutting test carried out at a different depth of cut and spindle speed combination.

What are the values of a in table 1 and 2 -with tools 1 and 2.

Table 1 describes used the tool characteristics for the SMFE method test whereas Table 2 describes the cutting conditions employed with each tool. Depth of cut values a_p are indicated in the third column of Table 2.

Consider to use (page 1) "In heavy duty milling with roughing conditions, critical....."; Check again [7,8] if the used workpiece is using channels or slots.

Consider to use "In this work the actual milling force is used....."

Both suggestions have been included in Page 1.

Check the directions of x , y , z in figure 2 left. Is z in the axial direction and not measured for 90 degrees lead angle?

Yes, z represents the axial direction and could be neglected when a 90 degrees lead angle tool is used.

The letter font on all figures is too small.

The font size has been increased in all figures in the manuscript.

What is the use of 1, 2, 3 on figure 2? Any use in the equations for the different coefficients?

1,2 and 3 stands for the different cutting tests used to apply the SMFE method. They have been substituted by "Cutting test #1", "Cutting test #2" and "Cutting test #3" in Fig. 2.

Reviewer #4:

The results presented in Fig. 3 and 4 are unfortunately not definite. The estimated FRFs seem to contain a significant portion of noise (especially Φ_{yy}). What do the corresponding coherence functions look like?

Considering that the SMFE method relies on experimental inputs obtained with the operating machine, the noise level does not seem so high to the authors. It is, of course, higher than in the FRFs obtained through traditional methods in idle conditions but the signal to noise ratio is sufficiently high as it can be deduced from the coherence graphs, which have been added now to Fig. 3. FRF in y direction seems very noisy, but it has this shape due to the high number of modes of the machine at these low frequencies.

Your experiments are a little confusing. We can get better FRF estimation due to the proper linearization, but you used another tool for the stability tests than for the FRF estimation, implying different cutting forces. Moreover, conducting stability tests requires various depths of cut, which implies various cutting forces again. If non-linear behavior is assumed, the FRF is not constant. Thus, various FRFs result from various cutting forces.

When non-linearities of the system affecting the FRF are mentioned, the authors do not refer to non-linear behaviour of the input cutting force itself but to many other effects that can affect the dynamic behaviour. Some examples of these effects are the bearing preload change due to centrifugal forces in rotation, tool and workpiece contact effect, process damping, machine control effect... The cutting force itself could also introduce some kind of non-linearity through the cutting force coefficients and, as the reviewer claims, variable FRFs with the cutting force level should be considered in that case. For the sake of simplification, this cutting force dependency is ignored and a constant FRF is assumed. Therefore, it is also assumed that the FRF obtained through the SMFE method can be extrapolated to different tool geometries from those used for characterisation. This is a crucial assumption, since the great advantage of this method is the possibility of using a single FRF characterisation for every milling tool, since low frequency structural modes are independent from the used tool.

In Fig. 4, the approximation of the chatter frequency based on the FRF measured with hammer seems to be the most appropriate one. Nevertheless, this FRF leads to overestimation of the critical depth of cut. To tell the truth, any of the estimated FRF cannot reliably predict both the critical depth of cut and the chatter frequency in the investigated spindle speed range. It would be preferable to discuss these discrepancies in the results.

The closest approximation is obtained through the SMFE method. The numerical error for both depth of cut and chatter frequency has been quantified and included in section 3: "The average experimental vs. simulation error in depth of cut a with the lobes obtained from the SMFE FRFs is 34%, whereas in the lobes obtained from the standard FRFs the average error grows up to 51%. Regarding chatter frequency f_c error, the average error from the SMFE FRF prediction is 5.4%, whereas the average error from the hammer FRF prediction is 5.6%." As explained in section 1, there are several process nonlinearities that lead to inaccurate prediction. At the end of the conclusions section the sentence "although a slight deviation with respect to the experimental tests still remains." has been added.

Recommendations:

Page 1, Fig. 1: The symbols are not readable in the printed version. The definition of "omega g" is missing in the figure as well as in the text. What physical value is depicted in the figure (e.g. force, acceleration)?

The font size has been increased in all figures in the manuscript. Fig1 caption has been modified to add the meaning of "omega" and "omega g". The caption of the figure has been also changed to specify the measured physical value.

Page 4, Fig. 3 and 4: Using different colors to distinguish different results from each other is not preferable for monochrome printing.

Apart from the difference in colour, a different line type has been used. Moreover, two of the data types have been removed in order to have a more readable picture. Therefore, a single plot for the SMFE method (the one that combines Tool 1 & Tool 2) has been kept. Figure captions have been changed accordingly.

Page 2, Eq. 2: Symbols for complex conjugate values are missing in the equation.

The symbols for complex conjugate have been added.

Page 3, right column: Please define the abbreviation ZOA.

This abbreviation has been defined in the text.

Please, do not hesitate to contact us if further document editing was needed.

Yours sincerely,



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