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FRF Estimation through Sweep Milling Force Excitation (SMFE)

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Abstract

Inaccurate machine dynamics characterization is thought to be one of the main sources of errors in current cutting stability models. For this reason, traditional dynamic characterization procedures have been called into question. A new method for frequency response function (FRF) estimation using the real milling force as the input excitation is proposed. It consists of exciting the structure through several cutting tests at increasing or decreasing spindle speed while measuring its response. This sweep milling force excitation (SMFE) procedure allows obtaining the FRF under real cutting conditions. The results obtained have improved stability prediction with respect to conventional impact tests.

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

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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

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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 (12-42Hz 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.

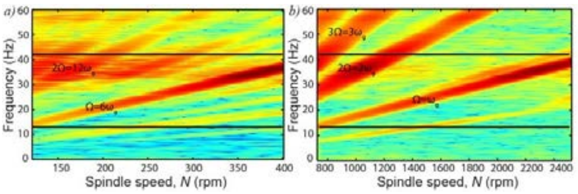

Fig. 1. Spectrogram of the vibration acceleration signal in the SMFE method for 2 different tools: (*a*) *D*=125mm, *Z*=6; (*b*) *D*=32, *Z*=1. Ω: tooth passing frequency; ω_g: rotation frequency.

2.2. Test plan definition

The frequency response function Φ(*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:

$$\Phi_1 = \frac{G_{rF}}{G_{FF}}, \tag{1}$$

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:

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

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.

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

As there are nine unknowns to solve, at least three different cutting tests must be performed in order to solve the system. If a 90º lead angle tool is used, the axial force *Fz* 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 *Fx*, *Fy* and *Fz*. 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:

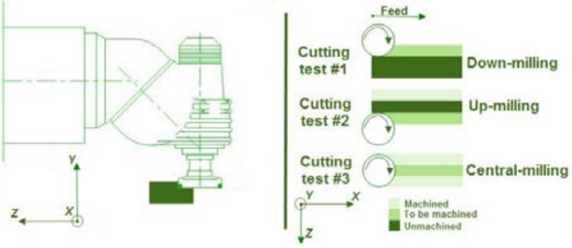

Fig. 2. Cutting tests outline. Three different cutting tests are performed in order to obtain the 9 terms of [Φ] matrix: down-milling cut, up-milling cut and central-milling cut.

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 [Φ] matrix:

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

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 [Φ] 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:

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

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)*	*fz (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.

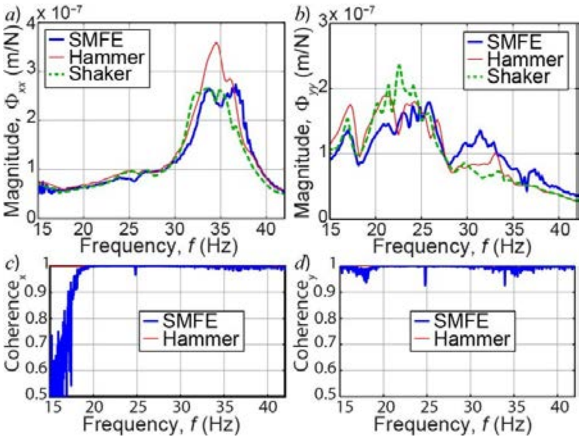

Fig. 3: Comparison of the SMFE FRFs with traditionally obtained FRFs: SMFE FRF with tool 1&2, hammer FRF and shaker FRF. *a*) Φ_{xx}; *b*) Φ_{yy}, *c*) Coherence$_x$; *d*) Coherence$_y$.

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. 3*c* and Fig. 3*d*.

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%.

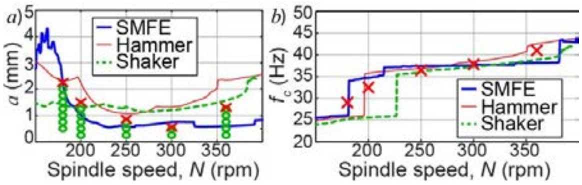

Fig. 4. Comparison of lobes obtained from SMFE FRFs with lobes obtained from standard FRFs: lobe from SMFE FRF with tool 1&2, lobe from hammer FRF and lobe from shaker FRF. *a*) chatter frequency f_c; *b*) depth of cut *a*. Experimental stable tests (green circles) and unstable tests (red crosses).

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.

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