Spindle speed ramp-up test: A novel experimental approach for chatter stability detection

(Article begins on next page)

Accepted Manuscript

Title

Spindle Speed Ramp-up test: a novel experimental approach for chatter stability detection

Abstract

Chatter is one of the most limiting factors in improving machining performances. Stability Lobe Diagram (SLD) is the most used tool to select optimal stable cutting parameters in order to avoid chatter occurrence. Its prediction is affected by reliability of input data such as machine tool dynamics or cutting coefficients that are difficult to be evaluated accurately, especially at high speed.

This paper presents a novel approach to experimentally evaluate SLD without requiring specific knowledge of the process; this approach is called here Spindle Speed Ramp-up (SSR) test. During this test, spindle speed is ramped up, and chatter occurrence is detected by the Order Analysis technique. As result only one test ensures optimal spindle speed identification at one cutting condition, if few tests are performed the entire SLD could be obtained. Results of the method applied to slotting operation on aluminum are provided and a comparison between different measurements devices is presented. This quick, easy-to-use and efficient test is suitable for industrial application: no knowledge of the process is required, different sensors can be used such as accelerometer, dynamometer or microphone.

Keywords: Chatter; Milling; Dynamics; Order Analysis.

1. INTRODUCTION

Milling has a central role in manufacturing industry thanks to its versatility and wide range of metal cutting capability. The increasing use of high-speed milling (HSM) has led to new challenges for the machine tool manufacturers and users. One of the main limitation to productivity increase of such technique is the occurrence of unstable regenerative phenomenon known as chatter that produces poor surface finish, tool wear and breakage [1]. In the last decades chatter has been widely studied [2]. Both predictive models and experimental approaches for identifying, monitoring and preventing chatter have been developed. The main output of predictive approaches is a chart, known as Stability Lobe Diagram (SLD), by means of which optimal machining parameters can be forecasted and hence selected [1-4].

These models are effective because they can predict chatter without performing cutting tests, avoiding time-consuming trial and error approach. However SLD accuracy is strongly affected by reliability of data entries: machine tool dynamics and cutting force coefficients. Extensive investigations on these inputs have been carried out highlighting the main issues related to their evaluation. Tool-tip dynamics is required and generally obtained by experimental impact test. However machine tool dynamics varies changing tool: for each tool a new test has to be performed, increasing the number of tests required [5]. Additionally Tool-tip Frequency Response Functions (FRFs) are evaluated in stationary condition, but could change significantly increasing spindle speed due to thermal effect and ball bearing stiffness under load condition [6,7]. Moreover in some conditions (e.g. thin-wall machining) workpiece dynamics should be also taken into account [8,9], and the main drawback is that it changes during the machining process [10]. Besides cutting forces are influenced by tool geometry [11], type of operation [12], cutting parameters, e.g. cutting speed [13], and working conditions difficult to predict, e.g. vibration effect [14]. Taking these sources of variability into account, in general is not easy to have an accurate identification of FRFs and cutting forces and this could reflect in a wrong prediction of chatter conditions.

To overcome these limits, analytical approaches are hence replaced by chatter detection and prevention methods based on experimental tests [15-19], which use cutting tests to evaluate chatter onset. These approaches are more suitable for industrial application: they are easy-to-use, not directly requiring knowledge of the process and the phenomenon. Two main classes of approaches are presented in literature [2,15-23]: in-process methods and stability limit identification methods.

The first one aims at detecting chatter on-line and tries to avoid it, changing cutting parameters (e.g. spindle speed) during machining operation. These methods generally analyze signals of sensors mounted on the machine: when chatter is detected, cutting parameters are adjusted to reach a stable condition. Different chatter indicators have been developed in order to reliably identify chatter occurrence. Despite the differences almost every indicator is based on the signal frequency spectrum: when chatter frequency amplitude exceeds a certain threshold value, chatter is detected. Different kinds of sensors have been tested: Liao et al. [15] presented an on-line method based on force transducer, Kuljanic et al. [16] a multi-sensors approach using two accelerometer and a dynamometer, but the most interesting sensor has revealed to be microphone because of its simplicity and low-cost: this sensor has shown good chatter identification capabilities [17]. Schmitz et al. [18,19] proposed a chatter detection approach by statistically evaluating milling sound variance. Bediaga et al. [20] developed an algorithm that uses sound signals to detect chatter and suggests alternative machining parameters.

The second class of methods aims at creating a stability experimental map to be exploited for selecting stable machining parameters. This approach is more reliable but more time-consuming than in-process ones. The most used consists in performing cutting tests for each single condition in order to detect the presence of chatter. Identification of chatter is carried out both on the surface finish (checking distinctive marks) and on sensors signals. A large number of tests are thus required to reconstruct SLDs, limiting its application to validation of predictive approaches. In order to extend this approach to industrial context more efficient tests have been proposed: Quintana et al. [21] proposed a new test in which axial depth of cut is increased gradually until chatter is identified: a single test can investigate chatter behavior at one spindle speed. Anyway if a wide range of spindle speed has to be analyzed, many tests should be performed. Ismail and Soliman [22] introduced a different method: in their test spindle speed is increased and chatter is detected thanks to a statistical indicator [23]. They performed a slow ramp of the spindle speed in which feed per tooth is varying working out of the optimal cutting parameters: this leads to some drawbacks in chatter identification. Moreover the use of a statistical indicator instead of a frequency analysis is less reliable: it is not possible to validate chatter occurrence on frequency content of signals and isolate it from other effect (e.g. force vibrations). Method is not able to return chatter frequency values, useful to analyze and understand process behavior.

In this paper a novel experimental method to detect chatter and create an experimental stability map is presented. The proposed test has been called Spindle Speed Ramp-up (SSR). Spindle speed is increased continuously in the test, increasing simultaneously feed in order to keep feed per tooth constant, with fixed depth of cut for each test. Different sensors (accelerometer, dynamometer, and microphone) have been tested and analyzed using the Order Analysis (OA) technique to detect chatter frequencies. As a result a frequency map changing spindle speed has been obtained, and chatter detected checking chatter frequency onset. This very quick test, based on the OA technique, has revealed to be a very efficient way to identify process damping region, and stable and unstable zones for a single depth of cut. Moreover repeating the test with different depths of cut an accurate experimental stability map in the range of spindle speed can be efficiently obtained.

Compared to other experimental detection techniques, in which spindle speed is increased continuously [22], the proposed approach allows to ensure that feed per tooth is kept constant all over the test: this would allow to reduce influence of this parameter on the acquired data. In addition presented approach does not require any statistical indicator (e.g. [23]) to identify chatter onset and thus stability limits. The presented approach, in fact, is based on frequency analysis of measured signal: hence it allows to observe all the vibratory phenomena discerning from forced vibrations and instabilities, returning useful information to ensure accurate chatter identification in all engagement conditions.

2. PROPOSED TEST

SSR test aims at reducing number of tests required to experimentally identify stability limits of a machining operation. The idea is to compress large number of tests at different spindle speed in a single test in which spindle speed is increased in the entire range of interest. Therefore compared to Quintana's test [21] depth of cut is not increased but is kept constant increasing spindle speed instead (figure 1). The main advantage of the proposed method is to obtain exploitable results with just one test: a single SSR test can extract stable cutting parameters for a working condition. This is relevant for industrial context in which could be enough to obtain the optimal spindle speed for a given depth of cut, because this allows to enhance the process without changing the toolpath, which could be a time consuming issue that reduces the possibility to enable an on-line optimization.

Moreover as shown in figure 1, with few tests it is possible to investigate the entirely SLD, drastically reducing the experimental effort usually required.
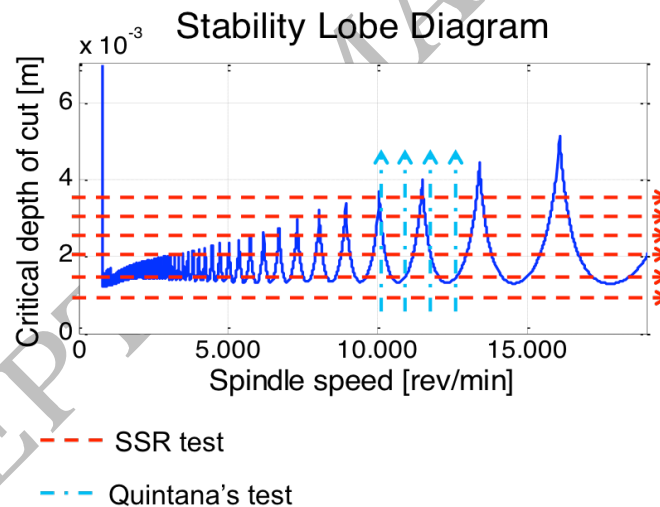

Figure 1. SSR test compared to Quintana's approach [21] for SLD identification

In order to obtain such result some shrewdness should be taken into account. First feed should be simultaneously increased with spindle speed in order to keep feed per tooth constant. In this way suggested cutting parameter for the tool are respected and cutting forces do not vary significantly. Then spindle speed should be increased linearly for mainly two reasons:

- Avoiding chatter growing uncontrollably: a continuous increase of spindle speed does not give time for chatter vibration to become dangerous for tool and machine because a new condition is reached immediately after;

- Easily and properly applying frequency analysis of the signals, as presented in the next section.

These features could be attained thanks to a proper definition of the NC code of the test, where the spindle speed and feed are changed linearly and accordingly.

3. ANALYSIS METHOD

During SSR cutting test sensors signals are acquired and used to identify stable and unstable cutting parameters of the operation. As proposed in other works [15-17,21], chatter vibration characteristic frequency (i.e. chatter frequency) is used to detect instability. Therefore frequency analysis of the acquired signals is required. Due to the continuously changing spindle speed, OA technique [24], usually adopted for rotor-dynamics analysis and health monitoring [25] of rotors, such as turbines [26] or petrol engines, is performed on data.

During a run-up or run-down the structural resonances are excited by the fundamental or the harmonics of the rotational speed: OA allows the separation of rotational and structural noise and vibration phenomena and it is used to investigate critical speeds, resonances and instabilities in rotating machinery. Orders are the normalization of the rotational speed: the first order is the rotational speed, and order n is n times the rotational speed. The goal of this technique is to track sound and vibrations over operating rotational range: signals are collected and post-processed calculating spectrum data based on rpm. Two main methods are generally used: frequency analysis and order-tracking analysis. They differ in sampling frequency: fixed in frequency analysis, in order-tracking it changes with revolution speed. Frequency analysis is thus more focused on frequency but it suffers smearing of frequency content issue especially at high frequency. Order-tracking analysis is suitable for high frequency and focused on orders evolution. In this paper frequency analysis is adopted because the goal is chatter frequency identification. Results of this analysis are spectra of signals calculated at different rotation speeds, generally presented as a 3D waterfall plot (also called Campbell diagram) where amplitudes of signals vibrations as function of frequency are plotted against rotation speed (figure 2a). Harmonic components (i.e. Orders) appear on lines diverging from the origin (0 Hz, 0 RPM) while vibrations phenomena (e.g. resonances) appear on lines parallel to spindle speed axis (constant frequency), as shown in the scheme in figure 2b.
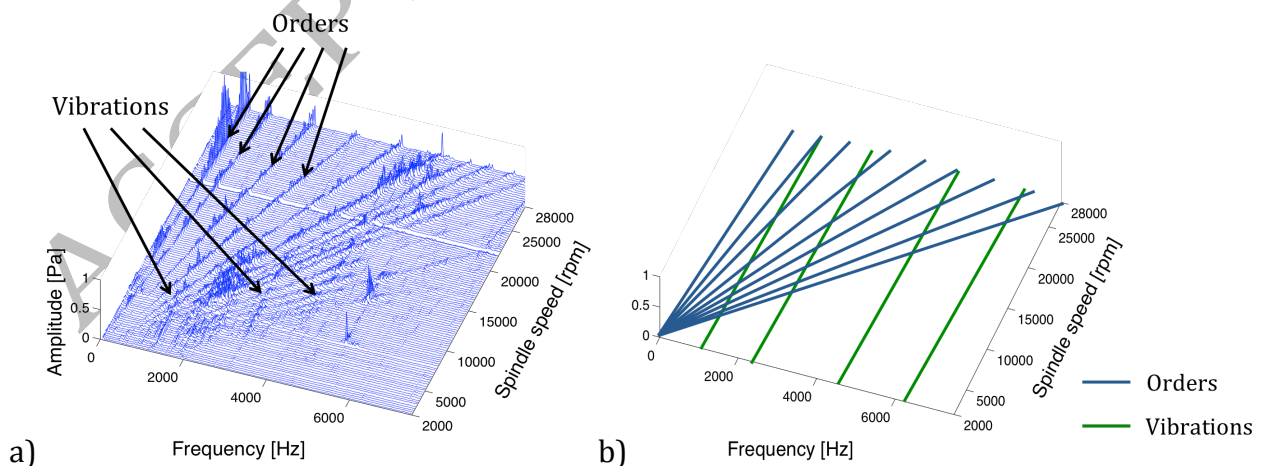

Figure 2. 3D Waterfall diagram example (a) Diagram reading scheme (b)

In machining, order components are related to tooth passing frequency and its harmonics. Frequency contributions of acquired signals should be excited by orders. This is verified until chatter occurs: chatter frequency will appear in the data irrespective of frequency content of forces. Therefore, thanks to this technique, it will be easy to identify stable and unstable parameters at a defined depth of cut by analyzing evolution of the spectrum over spindle speed.

Essential element of OA is rotational speed measurement. If possible, this could be provided by a synchronized tachometer mounted on the spindle or directly by machine tool encoders. Otherwise post processing acquired signals such as sound, vibration or force could return tooth pass frequency and hence identify the instantaneous speed.

OA of the signals can be performed both on-line and off-line on time histories previously collected. During acquisition and further analysis three main parameters have to be set: sampling frequency of the signals, frequency resolution of the spectra, rpm resolution.

Once signals are acquired during SSR test, can be processed in frequency domain. Auto Power Spectrum of the signals is calculated, Fast Fourier Transformation (FFT) analysis is performed every spindle speed interval with the frequency resolution set.

Time-frequency analysis presented in the paper is basically done by performing FFT on a block of data of length ΔT sampled with a fixed sampling frequency (Fs) [27]. Each block of signal is windowed in order to avoid leakage error. Based on spindle acceleration (rpm/s), for each ΔT a Δ rpm can be defined.

$$\Delta \text{rpm} = spindle\_acceleration \cdot \Delta T \tag{1}$$

For each block an average rpm is obtained based on tachometer data: ideally the rpm should not vary within ΔT, so ΔT should be as small as possible, taking into account that smaller ΔT would result in loosing low frequency information. However, the frequency resolution Δf of the FFT corresponds to $1/\Delta T$, even if it can be improved by zero-padding signal elaboration. A compromise on these factors must be found.

In the presented application:
- rpm resolution is important for chatter limits accuracy,
- high spindle acceleration could be useful at high spindle speed to reduce time and material required by the test
- frequency resolution is essential to improve chatter frequency detection and analysis.

On the other hand sampling frequency is defined on the same rule of a stationary FFT, based on Nyquist-Shannon theorem. Sampling frequency should be chosen according with vibrations phenomena to be observed.

Results are presented as waterfall 3D diagram or color map (e.g. in figure 4). In the waterfall spectra on X-axis represents frequency, Y spindle speed and Z amplitude of the spectra. Thereby each calculated spectrum is presented in X-Z plane. In the color map the same information is provided: colors represent amplitude of the spectra.

4. EXPERIMENTAL SET UP

Experimental tests have been performed in order to show method implementation.

Tests have been carried out on a Mori Seiki 5 axis milling machine, a NMV 1500 DCG, equipped with an high speed spindle (40.000 rpm max). A series of SSR tests at different depth of cut in slotting (i.e. full radial immersion) operation has been performed.

The material used for the machining test is a bar of Aluminum 6082-T4 alloy and a two flutes end mill (8 mm diameter Garant 201770) has been used. An optical tachometer able to detect

the spindle speed till its maximum has been installed on the machine. The workpiece has been rigidly clamped to a three-component Kistler dynamometer type 9254 A. The machine has been equipped also with a microphone (Bruel & Kjaer type 4165) installed inside the cutting chamber close to the cutting zone and a 3 axis accelerometer (PCB U356A15) on Z-axis. The signals have been acquired by LMS Scadas III and elaborated in LMS Test.Lab software. Acquisition system performs windowing (Hanning) and anti-aliasing based on the set parameters. Test set-up is presented in figure 3.
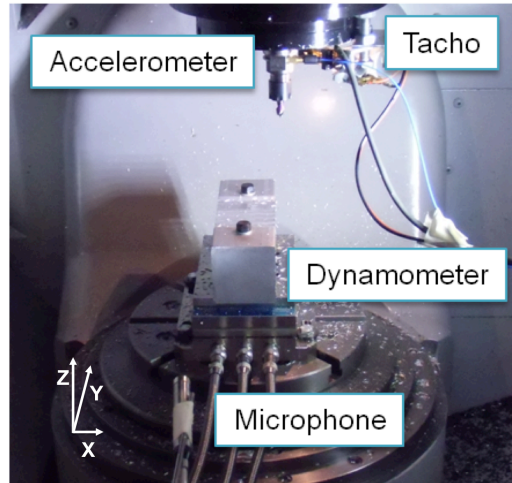

Figure 3. Test set-up

Six different axial depths of cut have been tested, ranging from 1 to 3.5 mm. Cutting parameters are summarized in table1.

Table 1. Cutting and tool parameters

Tool parameters						
Diameter (mm)	8		Helix angle	45°		
Flutes number	2		Material	Carbide		
Surface treatment	TiAlN					
Cutting parameter for chatter						
Spindle speed (rpm)	2.000-28.000					
Feed per teeth (mm)	0.03		Radial depth	Slotting		
Axial depth (mm)	1	1.5	2	2.5	3	3.5

A spindle acceleration of 9000 rpm/s has been set for the tests, two SSR tests for each depth of cut have been performed: from 2000 to 8000 rpm and from 8100 rpm to 28000 in order to avoid the transient due to the power commutation of spindle unit during test. The time history of the spindle speed acquired by the tachometer is presented in Figure4a. SSR test has been performed thanks to a simple NC code. The code has been generated by a Matlab routine, developed on purpose, defining spindle acceleration and feed per tooth: a sample of the code used for this test is presented in Figure 4b.
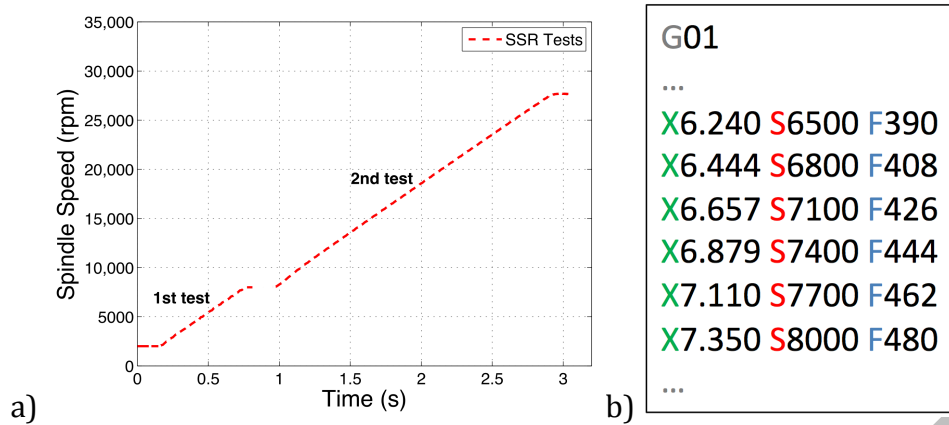
Figure 4. Spindle speed evolution during test (a), extract of NC code of the SSR test (b)

As shown, the proposed test is very time-efficient: each depth of cut can be investigated in about 3 seconds. OA technique has been applied: parameters are listed in table 2 and results are presented in the next section.

In the test case a Δrpm equal to 25 and spindle acceleration around 9000 rpm/s have been used. Each block is about 3 ms long (ΔT), leading to a poor frequency resolution (Δf=360Hz). Frequency resolution has been improved directly in the post-processor (LMS Test.Lab) zero padding the signal till reach 10 Hz resolution. Those parameters are appropriate both for experimentally identifying stable and unstable zones over a wide frequency range with sufficient rpm resolution and providing sufficient accuracy in chatter frequency value identification. Sampling frequency equal to 25.600 Hz has been set to investigate chatter occurrence over 10kHz.

Table 2. Order Analysis parameters

OA parameters			
Sampling frequency (Hz)	25600	Spindle acceleration (rpm/s)	9000
Frequency resolution (Hz)	10	Rpm resolution (rpm)	25

Before performing SSR test impact tests on the tool-tip has been carried out with a Brüel & Kjaer Type 8202 impulse hammer and PCB 352C22 accelerometers (0.4 g) in order to validate and compare results obtained by OA. Frequency Response Functions (FRFs) on both directions (X and Y) are presented in figure 5. Tool-tip FRFs has been reported to highlight machine tool dynamic behavior, focusing on dominant modes that, according to chatter theory, are accountable for instability occurrence. In the reported test case X and Y direction present similar behavior with a dominant mode at around 5100 Hz.
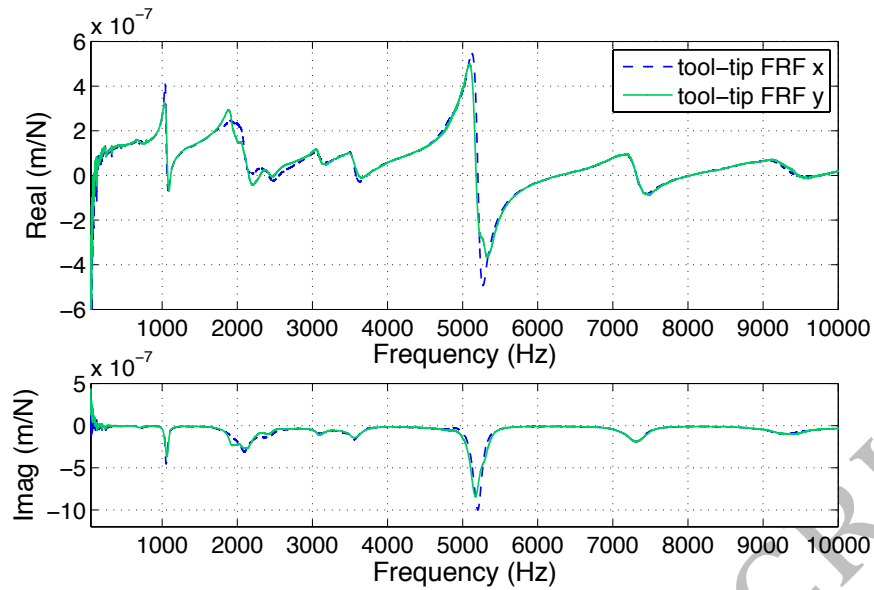
Figure 5. Tool-tip FRFs

5. RESULTS AND EXPLOITATION

5.1 *Chatter detection*

Results of OA for low depth of cut (1 mm) and high depth of cut (3mm) are presented in figure 6 and 7, using as example the Z-axis force signal. Both waterfall and color map are shown.
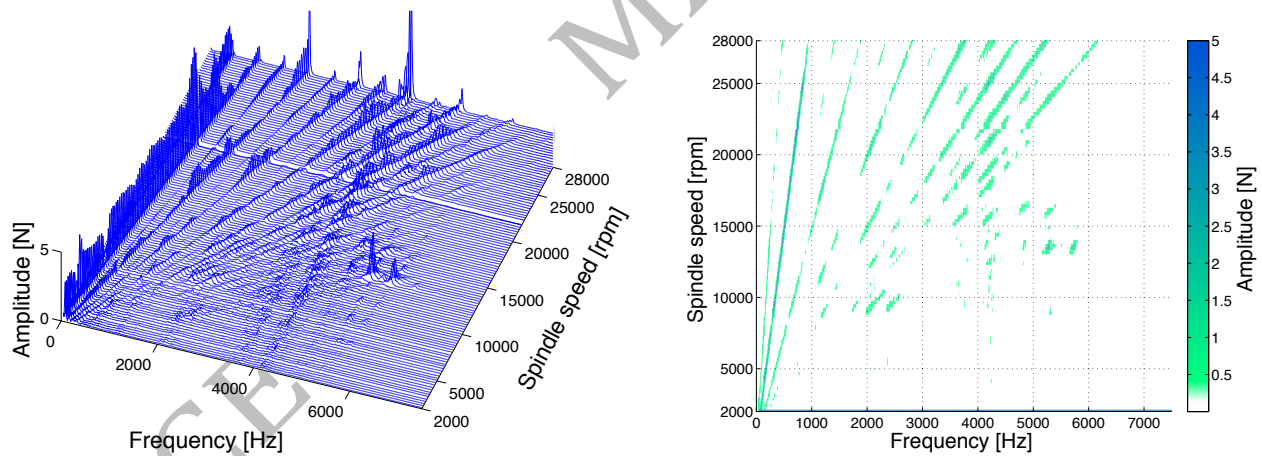
SSR test 1 mm – Force Z

Figure 6. Waterfall diagram and color map for chatter detection (1 mm test Force Z)
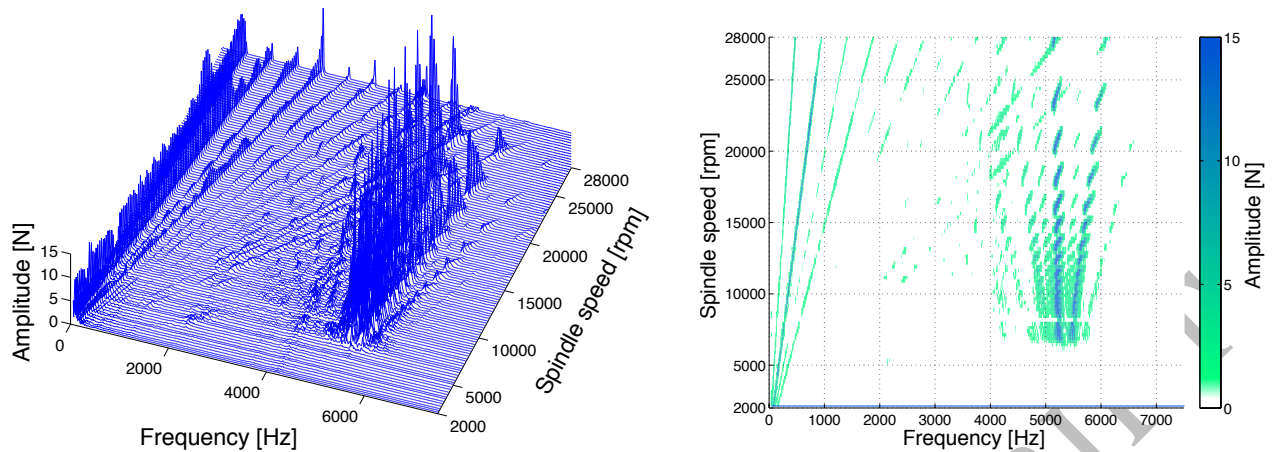
SSR test 3 mm – Force Z

Figure 7. Waterfall diagram and color map for chatter detection (3 mm test Force Z)

As already mentioned, in a stable condition, the main contributions of the frequency spectrum of the sensors signals must be found on frequencies related to the tooth passing frequency and its harmonics. In case of instability, a chatter frequency will appear (becoming dominant) in the spectrum, this frequency is not consistent with the tooth pass frequency or one of its harmonics and remains almost constant varying spindle speed. Detecting chatter stable zones (including process damping) over spindle speed range is hence an easy task: in stable zones no dominant frequency (i.e. chatter frequency) out of tooth pass frequency and its harmonics is present. In figure 6, at 1 mm depth of cut only tooth pass frequency and harmonics (orders) are dominant in the spectra: process is hence stable in the entire range of spindle speed. In figure 7, at 3 mm depth of cut a dominant frequency out of the orders is present at some spindle speeds: at those spindle speeds, chatter will affect cutting operation. Stable and unstable zones are evident using color map: in case of chatter, amplitude of the spectrum at the chatter frequency is very high (blue) becoming low (white) in the stable zones. Therefore analyzing chatter frequency evolution stable and unstable zones can be obtained, as shown in Figure 8 for 3mm depth of cut test. Chatter starts when, for a specific spindle speed, chatter frequency becomes relevant. To evaluate when a chatter frequency becomes relevant it is necessary to use a threshold on its amplitude as proposed in other work [4,21]; for the proposed method the threshold value has been experimentally defined, using some preliminary tests, for which the surface has been studied, as a reference; the defined value for the amplitude of Z force is equal to 2 N. Using this rule it is possible to define chatter free spindle speeds and unstable speeds for each tested depth of cut.
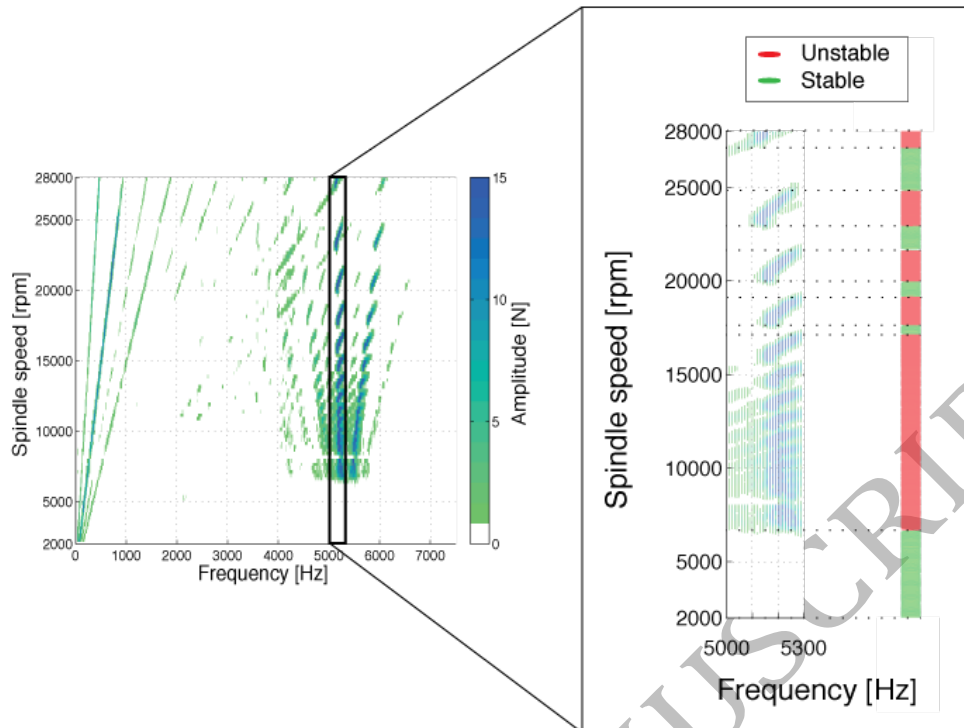
Figure 8. Stable and unstable zones identification (3 mm SSR test)

For example, by analyzing figure 8 one could identify that no relevant chatter frequency contribution is present in the range of around 25000-27000 rpm, this range is thus identified as stable (green in the figure). On the contrary the 23000-2500 rpm range is characterized by evident chatter frequency contribution and is thus identified as unstable (red in the figure).

Presented experimental results are in accordance with chatter stability theory: chatter frequency evolution, and stable and unstable zones alternation are in agreement with SLD prediction models [3]. Moreover, as expected, chatter frequency value around 5200 Hz is close to machine tool dominant mode natural frequency (5100 Hz, figure 5) as chatter prediction theories suggest.

During SSR test no clear chatter marks are identified on the surface, probably because test is too fast to allow chatter grow affecting surface quality, even if chatter is detected, thanks to its characterized frequency, the phenomenon is not fully evolving during the test.

5.2. Sensors comparison

In this section a comparison between signals is presented in order to show the application of the proposed method using different sensors. This investigation has been carried out to highlight the capability of each sensor used for the proposed approach and identify the most suitable one.

Proposed method has been applied to every source acquired. In figures 9, 10 and 11 results for accelerometer, dynamometer and microphone in the 3 mm depth of cut test are presented.
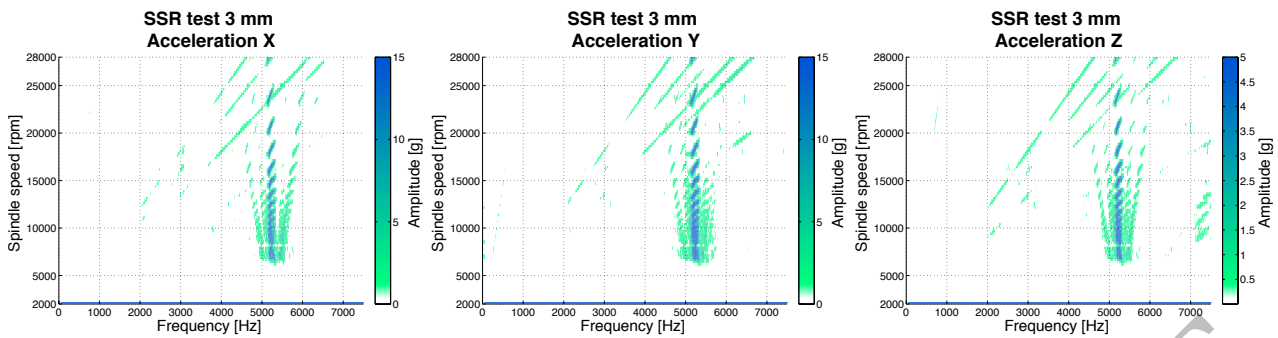
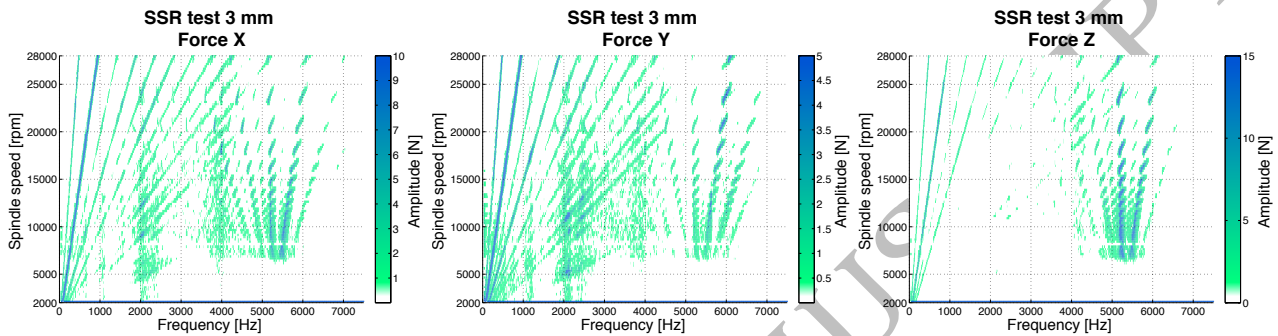Figure 9. Accelerometer signals color maps for 3 mm SSR test

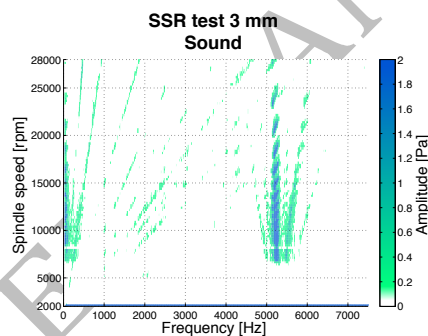Figure 10. Dynamometer signals color maps for 3 mm SSR test

Figure 11. Microphone signal color map for 3 mm SSR test

As shown in the figures 9, 10 and 11 every signal gives similar information: chatter frequency occurrence is detected in the same way from each source. The main differences are:

- X-Y force signals are affected by some noise: this is probably due to influence of dynamometer and surrounding system dynamics on the acquired signal. Amplitude values are not reliable especially increasing frequency: an effective compensation as the one proposed in [27] is required.
- Z force is more reliable than X-Y forces as already pointed out in [16]: on Z direction, influence of dynamometer and surrounding system is less significant, at least in the tested frequency range because of the higher resonant frequency. Signal is suitable both for order identification and chatter frequency detection.
- Accelerometer signals are accurate to detect chatter frequency, but not in identifying orders, that could be used to extract spindle speed values information if tachometer cannot be used.
- Microphone signal returns good results in terms of orders and chatter frequency. However signal is affected by environmental noise.

According to these considerations, Z-axis force signal seems to be the more reliable for both order and chatter frequency detection. Nevertheless accelerometer and microphone are more convenient and easy-to use and could give good results if some precautions are applied (filter for microphone and external tachometer for accelerometer). A sensor fusion strategy for these two sensors could be a promising future development.

5.3.   *Spindle acceleration influence*

One of the main parameter to be set in the SSR test is spindle acceleration. Spindle acceleration determines both operation time of the test and the quantity of removed material. This aspect could become significant when very high spindle speeds are reached: keeping feed per tooth constant, feed rate increases and hence more material is needed to perform the test. Increasing spindle acceleration could reflect in identifying different stable and unstable states , because of inertia between phenomenon occurrence and its detection. In this section the influence of this parameter on the analysis results is presented. This analysis will be limited to Z-force according with previous section considerations, same procedure can be carried out for different signals. Different spindle accelerations (3000, 5000, 7000, 9000 rpm/s) have been tested to discuss the effects on stable and unstable zones detection. Moreover a ramp-down test with spindle speed starting at high speed and decreasing to low speed is proposed. In order to compare results, tests with the same parameters (tool, operation and depth of cut of 1.5 mm) have been carried out and results in terms of identified stable regions are presented in figure 12.

Stable and unstable points have been obtained by analyzing chatter frequency evolution, as presented in the previous section.
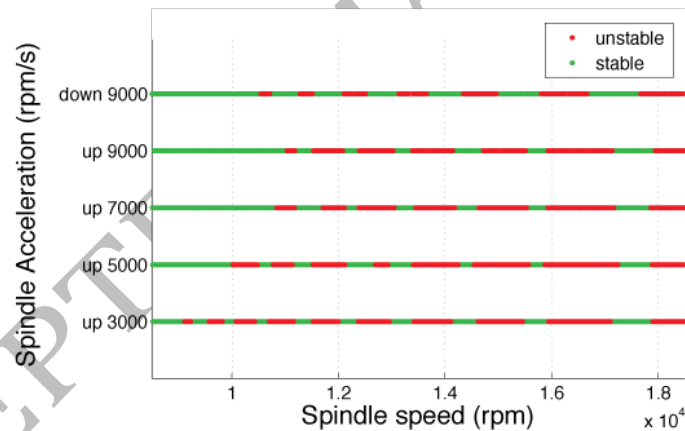

Figure 12. Spindle acceleration influence on 1.5 mm SSR test

Results presented in figure 12 show discrepancies for different spindle accelerations. Particularly accuracy on detection at low speed is reduced increasing spindle acceleration, this is probably due to the inertia of the system entering and exiting unstable conditions. On the contrary at high speed stable and unstable zones are quite the same between the different tests. As shown in figure 12, slightly different results have been obtained even for the test with decreasing acceleration. Comparing the ramp up and ramp down tests for a 9000 rpm/s spindle acceleration we see that stable and unstable zones appear slightly shifted between the two tests. Again the discrepancies are more evident at lower speed.

In conclusion spindle acceleration influences results mainly at lower speeds: in order to improve method accuracy, low acceleration would be needed if lower spindle speed ranges have to be investigated. On the other hand higher spindle accelerations can be adopted for

higher spindle speeds, conditions in which high spindle accelerations are beneficial because of high feed rates.

5.3. Stability experimental map

In order to present method capability of creating an experimental map of stable and unstable zones more depth of cut have been tested. OA has been applied to signals acquired for each depth of cut. In accordance with the main stability theories [3] increasing the depth of cut the process become more unstable: analyzing the signals of the tests chatter frequency becomes dominant in a wider range of spindle speed, as shown in figure 13.
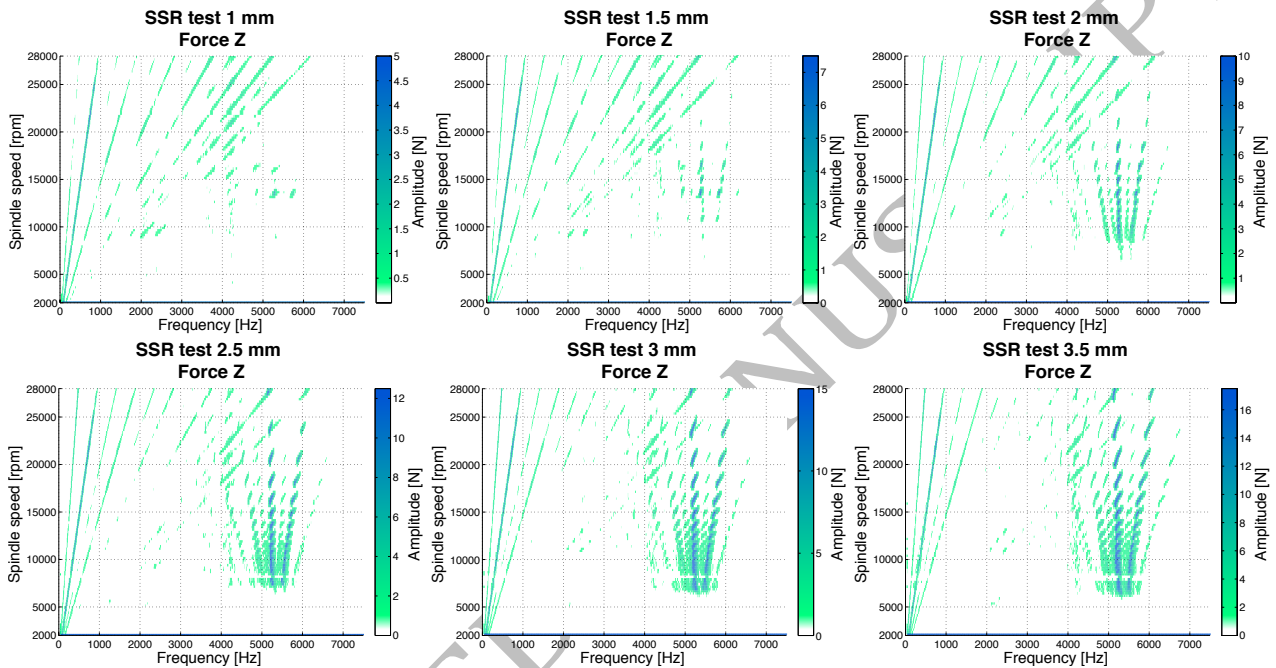

Figure 13. Color maps at different depth of cut

Merging together the results obtained for the different tests is possible to create an experimental stability map, as shown in figure 14. Based on chatter frequency threshold for each depth of cut, stable (green points) and unstable (red points) zones are identified. These zones are then connected together to create chatter limits and reconstruct Stability Lobe Diagram (figure 14).
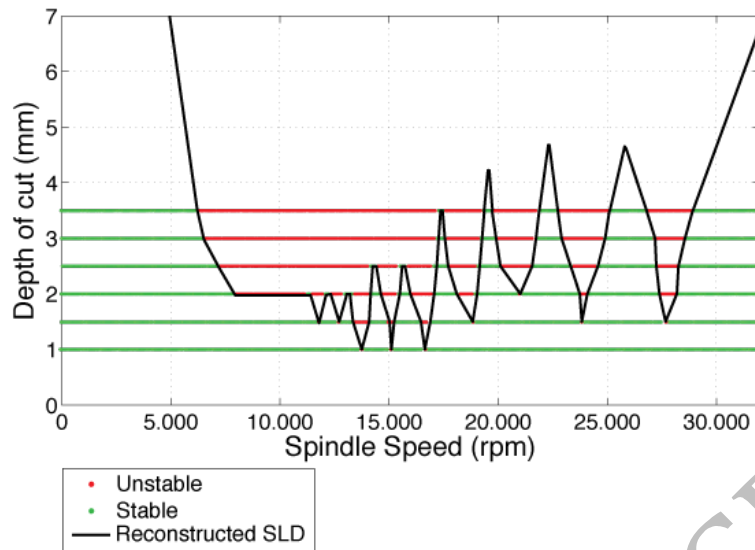
Figure 14. Stable and unstable zones for different depth of cut and reconstructed SLD

In this work this procedure is based on linear interpolation and extrapolation of the data: limit points between stable and unstable zones are connected by linear interpolation, then linear extrapolation has been used to predict zones at higher depth of cut (Figure 15, not experimentally investigated because performing tests at high depth of cut of mostly unstable operations would have potentially damaged the tool and invalidated further tests.
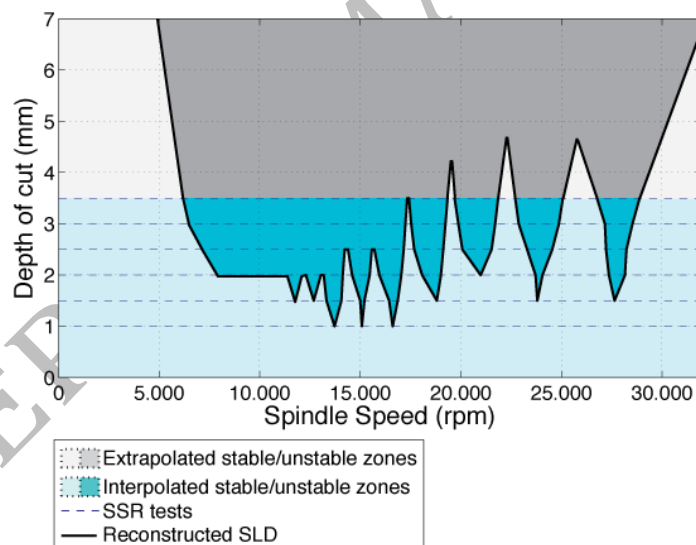

Figure 15. Reconstruction methods for SLD detection

Thanks to few tests an experimental stability diagram can hence be created. In order to validate reconstructed SLD some experimental tests have been carried out with constant parameters (single points in the diagram). Some spindle speeds have been tested, changing depth of cut: chatter occurrence has been evaluated based on frequency signals of sensors and checking distinctive marks on the surface. In particular 59 tests on single configurations have been performed: for each spindle speed depth of cut has been scanned every 0.5 mm (starting from 1 mm), till identifying chatter with at least two tests (red triangle in Figure 16).

Validation of the diagram has been limited to a high spindle speeds range in which, according to previous section, 9000 rpm/s is suitable for chatter identification. Figure 16 shows single tests results compared to reconstructed SLD.
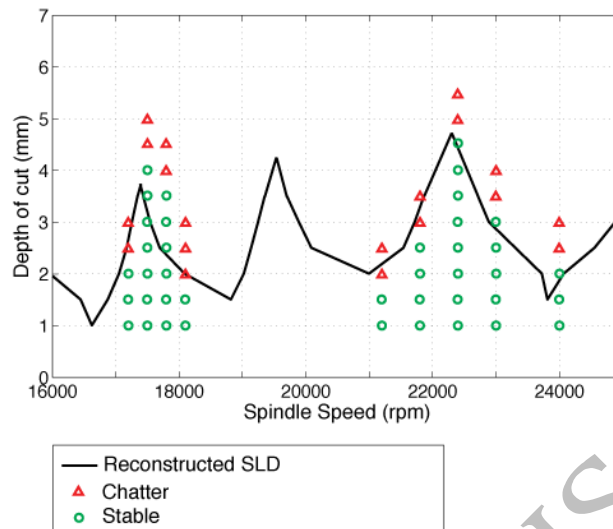

Figure 16. Experimental validation of the reconstructed SLD

As shown in Figure 16 the experimentally reconstructed SLD seems to provide accurate results both in terms of depth of cut limits and positioning of the lobes: only few discrepancies are detected (e.g. 17800 rpm), probably due to inertia of the test, but without resulting in significant inaccuracy.

Proposed reconstruction method here described allows to experimentally obtain the Stability Lobe Diagram with only few tests by defining adequate tests parameters (e.g., spindle acceleration). At higher speeds proposed technique provided good results in terms of reconstruct Stability experimental map, thus it could be useful in identifying optimal cutting parameters (i.e., spindle speed and depth of cut) in an accurate and efficient way.

At low speeds the technique would allow to identify the zone over which chatter does not occur because of process damping. It is thus possible to evaluate process damping effects on chatter stability without the need of modeling it or taking into account other factors.

SLD identified by proposed technique allows to overcome some of the limitations of predictive approaches: given that the experimental map is obtained in operational condition it allows taking into account every possible modification to the process and system including tool-tip FRF and forces changing with spindle speed.

If compared to other experimental SLD identification techniques [20], the proposed method requires fewer tests to obtain the same results.

On the other hand this approach is valid only for the specific operation, tool and workpiece, like every SLD experimental identification technique: a new test is needed for each different set-up.

6. CONCLUSIONS

In this paper a novel experimental method for chatter detection has been proposed.

A simple and fast test, called Spindle Speed Ramp-up (SSR), has been presented to detect stable and unstable spindle speed at a specific depth of cut. The test is carried out increasing linearly the spindle speed but maintaining constant the feed per tooth and the depth of cut. Chatter detection has been performed by frequency analysis of sensors signals thanks to

Order Analysis technique. Method performances have been proven by experimental application to a slotting operation on aluminum. Different measurement devices can be used in the method: accelerometer, dynamometer and microphone have been compared in the paper providing similar results on chatter frequency evaluation.

The proposed test could be proficiently used to:

- Obtain stable cutting parameters for a specific working condition (i.e. maintaining the design depth of cut) with just one test: this is an important advantage for the application in an industrial plant that usually requires a chatter-free spindle speed identification technique that could allow to maintain the programmed tool-path;
- Evaluate experimentally the SLD performing few tests changing depth of cut;
- Validate SLD predictive approaches and investigate process behavior such as machine tool dynamics changing with spindle speed thanks to the analysis of chatter frequency evolution.

The developed test has proven to be an efficient and effective way to experimentally identify stable and unstable cutting parameters, drastically reducing number of tests generally required. In order to achieve this goal, defining the correct spindle acceleration is crucial, since it could directly affect accuracy, especially over lower spindle speed ranges.

Novelty of the proposed method mainly relies on Order Analysis application to chatter identification. This technique allows an efficient use of frequency analysis, supplying an effective tool in investigating frequency content of the different signals and returning information useful to discern chatter frequency from other vibratory phenomena.

In this paper the technique has been tested on slotting operations, providing supporting results. However the technique, as here presented, could be suitable for different operations, even if relevant contributions to the dynamics of the system come from workpiece dynamics (e.g. thin-wall milling). The main issue, in that case, would be to define a suitable test case capable of reproducing engagement conditions and workpiece dynamics. Future works should be carried out to investigate applications of the proposed technique to other operations.

ACKNOWLEDGMENTS

REFERENCES

[1] Altintas Y., Manufacturing Automation: Metal Cutting Mechanics, Machine Tool Vibrations, and CNC Design, Cambridge Uni.Press; 2000

[2] Quintana G., Ciuranab J., 2011, Chatter in machining processes: A review, International Journal of Machine Tools & Manufacture, Volume 51, pp.363-376

[3] Altintas Y., Budak E., 1995, Analytical Prediction of Stability Lobes in Milling, CIRP Annals – Manufacturing Technology, Volume 44, pp. 357-362

[4] R.P.H. Faassen, N. van de Wouw, J.A.J. Oosterling, H. Nijmeijer, Prediction of regenerative chatter by modeling and analysis of high-speed milling, International Journal of Machine Tools and Manufacture 43 (2003) 1437–1446.

[5] Schmitz T.L., Donalson R.R., 2000, Predicting High-Speed Machining Dynamics by Substructure Analysis, CIRP Annals – Manufacturing Technology, Volume 49, pp.303-308

[6] Rantalo M. Non-contact measurements and modelling of milling machine tool vibrations. Ph.D. thesis 2006;ISSN: 1402-1757

[7] Gagnol V, Bouzgarrou B.C, Ray P, Barra C. Model-based chatter stability prediction for high-speed spindles. Int. J. Mach. Tool Manu. 2007;47:1176-1186.

[8] Ratchev S, Liu S, Huang W, Becker AA. An advanced FEA based force induced error compensation strategy in milling. International Journal of Machine Tools and Manufacture 2006; 46 (5): 542-551

[9] K. Kolluru, D. Axinte, Coupled interaction of dynamic responses of tool and workpiece in thin wall milling, Journal of Materials Processing Technology, 213 (2013) 1565-1574.

[10] Scippa A., Grossi N., Campatelli G., FEM based Cutting Velocity Selection for Thin Walled Part Machining, Procedia CIRP, Volume 14, 2014, Pages 287–292

[11] Dombovaria Z., Altintas Y., Stepana G., The effect of serration on mechanics and stability of milling cutters International Journal of Machine Tools and Manufacture Volume 50, Issue 6, June 2010, Pages 511–520

[12] Tuysuz O., Altintas Y., Feng, H.-Y. Prediction of cutting forces in three and five-axis ball-end milling with tool indentation effect, International Journal of Machine Tools and Manufacture, Volume 66, March 2013, Pages 66–81

[13] Grossi N., Sallese L., Scippa A., Campatelli G., Chatter Stability Prediction in Milling Using Speed-varying Cutting Force Coefficients, Procedia CIRP, Volume 14, 2014, Pages 170–175

[14] Scippa A., Grossi N., Campatelli G., Milled Surface Generation Model for Chip Thickness Detection in Peripheral Milling, Porcedia CIRP, Volume 8, 2013, Pages 450-455

[15] Liao Y.S., Young Y.C., A new on-line spindle speed regulation strategy for chatter control, International Journal of Machine Tools and Manufacture, Volume 36, Issue 5, 1996, 651-660

[16] Kuljanic E., Totis G., Sortino M., Development of an intelligent multisensory chatter detection system in milling, Mechanical Systems and Signal Processing 23 (2009) 1704–1718

[17] Delio T., Tlusty J., Smith S., Use of audio signals for chatter detection and control, Journal of Engineering for Industry, 114 (2) (1992), pp. 146–157

[18] Schmitz T.L., Medicus K., Dutterer B., Exploring once-per-revolution audio signal variance as a chatter indicator, Machining Science and Technology, 6 (2) (2002), pp. 215–233

[19] Schmitz T.L., Chatter recognition by a statistical evaluation of the synchronously sampled audio signal, Journal of Sound and Vibration, 262 (3) (2003), pp. 721–730

[20] Bediaga I., Muñoa J., Hernández J., López de Lacalle L.N., An automatic spindle speed selection strategy to obtain stability in high-speed milling, International Journal of Machine Tools and Manufacture, Volume 49, Issue 5, April 2009, Pages 384-394

[21] Quintana G., Ciurana J., Teixdor D.,A new experimental methodology for identification of stability lobes diagram in milling operations, International Journal of Machine Tools & Manufacture 48 (2008) 1637–1645

[22] Ismaili F., Soliman E., A new method for the identification of stability lobes in machining, International Journal of Machine Tools and Manufacture, 1997, Volume 37, Issue 6, pp.763—774

[23] Ismail F., E.G. Kubica, Active suppression of chatter in peripheral milling Part I, A statistical indicator to evaluate the spindle speed modulation method, The International Journal of Advanced Manufacturing Technology, 1995, Volume 10, Issue 5, pp 299-310

[24] I. Bucher, D.J. Ewins, Modal analysis and testing of rotating structures, Philosophical Transactions of the Royal Society of London, Series A: Mathematical and Physical Sciences 359 (2001) 61–96

[25] Al-Khazali H., Askari M. R., Analyzing Rotating Data for Machines Rotor with High Speeds Using the Spectral Map Wizard, International Journal of Scientific & Engineering Research, 2012, Volume 3, Issue 6

[26] Marcin Luczak M., Marcin Firla M., Sporna D., Manzato S., Peeters B., Structural monitoring of the small wind turbine test stand, Proceedings of the 8th International Conference on Structural Dynamics, EURODYN 2011, Leuven, Belgium, 4-6 July 2011

[27] X. Wang, Vehicle Noise and Vibration Refinement, Elsevier Science, 2010.

[28] A. Scippa, L. Sallese, N. Grossi, G. Campatelli, Improved dynamic compensation for accurate cutting force measurements in milling applications, Mechanical Systems and Signal Processing