Minimization of chatter in machining by the use of mobile platform technologies

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ABSTRACT

The risk of vibration in machining can be estimated by identification of the transfer functions of the system. Traditionally the transfer functions may be identified through the use of an impact hammer and a force transducer. This technology needs wiring and therefore cannot be easily used in a production environment. Through the use of the sound that is picked up from the running process, the simplified stability diagram of the system can be deduced. Mobile platforms, like phones and pads can be used to record the sound of the process. The computational capability of these devices are now enough to render the possibility to include the theory and modelling into these devices to make it possible to analyze the process in question as it is running and from that give recommendations to modify the process for minimization of the chatter vibrations. The paper outlines the theoretical considerations and strategy employed to make it possible to develop a useful solution for end-users on the shop floor.

Keywords: vibration, chatter, machining, milling

1. INTRODUCTION

Vibration is not uncommon in everyday life and range from trivial, like car tire imbalance to destruction of bridges, like the Tacoma Narrows. In machining, vibration may be detrimental both to the quality of the workpiece, the performance and life of the cutting tool or the life of the machine tool. Vibrations in machining arise from flexibility in the workpiece, the machine tool, the fixture or a flexible tool system, or combinations of these. This makes every setup unique and it is therefore difficult, on a global level, to solve all vibration problems in machining. Two different types of vibration are generated in in machining, forced vibration and chatter. Regenerative chatter occurs from the difference in vibration phase between the current cut and the previous cut through the waviness of the surface to be machined. When the two vibrations are out of phase, chatter occurs. On the shop floor, the common way to solve chatter issues is to reduce the speed and/or depth of cut. This approach has the drawback of reducing the productivity and is not taking use of the full capability of the process. Vibration risk can be estimated by identification of the transfer functions of the system using e.g. an impact hammer and a force transducer. This technology needs wiring and therefore cannot be easily used in a production environment. A more simplified and practical solution is therefore needed in order to optimize metal cutting processes for productivity while minimizing chatter vibration.

2. THEORETICAL CONSIDERATIONS

Chatter starts as a self-excited phenomenon in the closed loop of dynamically flexible machining structure and the machining process (Figure 1) where vibrations change the cutting forces and oscillatory cutting forces create vibrations between the tool and the workpiece. Vibrations between the tool and the workpiece damages the surface finish (Figure 2), increase cutting forces dramatically and ultimately lead to tool breakage and damages to the machine tool. The phase difference between the vibration marks left on a freshly cut surface, which is reflected on the outside of chips, and vibration at the moment of cutting, that makes the inner side of a chips (swarf), produces an oscillating cutting force at the frequency of the vibration and contributes to the existing vibration, leading to the possibility growing vibration amplitude and vibration regeneration as discussed by Doi and Kato [1] and others [2, 3].

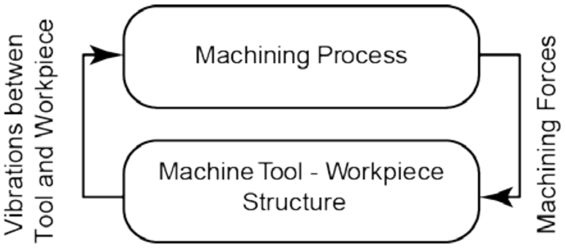


Figure 1: The closed loop between machining process and machining structure

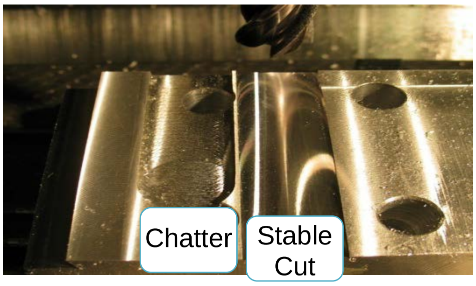


Figure 2: Surface finish in stable cut compared to the surface finish in chatter

The phase difference ψ between inner and outer vibrations depends on the frequency of the vibration (ω_c) and delay (τ), the time between subsequent passes of the cutting tool over the machined region, and it controls the regeneration:

$$\boldsymbol{\psi = \tau\omega_c} \tag{1}$$

An additional parameter, the tooth passing frequency (ω_t) could be calculated from the delay as:

$$\boldsymbol{\omega_t = \frac{2\pi}{\tau}} \tag{2}$$

$\psi/_{2\pi}$ controls if the subsequent waves are parallel or out of phase; if $\psi/_{2\pi}$ is close to 0.5,1.5,…, $k + 0.5$, ($k \in \mathbb{Z}$) the regeneration force would be maximum as shown in Figure 3 (a). On the other hand, when $\psi/_{2\pi}$ becomes close to an integer, the inside and outside waves become parallel and the effect of regeneration is minimized as shown in Figure 3 (b).

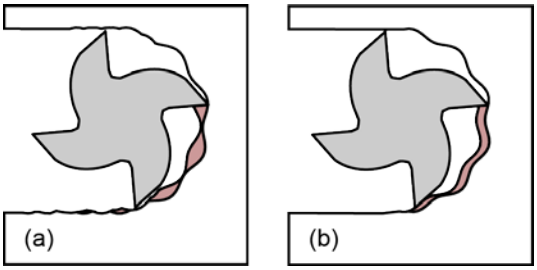


Figure 3: Effects out of phase (a) and in phase (b) vibrations on dynamic chip thickness

$\psi/_{2\pi}$ is equal to the ratio between the chatter frequency ω_c and the tooth passing frequency ω_t and as shown here:

$$\boldsymbol{\frac{\psi}{2\pi} = \tau\frac{\omega_c}{2\pi} = \frac{2\pi}{\omega_t}\frac{\omega_c}{2\pi} = \frac{\omega_c}{\omega_t}} \tag{3}$$

The time between subsequent passes (τ) depends on the spindle speed (n) and number of cutting edges or flutes on the cutting tool (N_z):

$$\boldsymbol{\tau = \frac{60}{nN_z}} \tag{4}$$

The chatter frequency (ω_c) is close to (but not exactly the same as) the dominant natural frequency (ω_n). The ratio between the natural frequency and the chatter frequency is calculated according to the chatter theory of Altintas and Budak [4] in Figure 4 for a special case with a workpiece that has a flexible mode in the feed direction. In this special case, the chatter frequency could be 50% higher than the natural frequency for certain ω_t/ω_n ranges.

An earlier approach [5] approximates the natural frequency as the chatter frequency from one single measurement, and proposes an optimum spindle speed based on this approximation. Since the stability charts are strongly affected by the errors in estimation of natural frequencies, as demonstrated in Figure 5, such approximations may not lead to optimum spindle speeds. The system developed for the mobile platform, considers chatter frequency measurements from multiple cutting experiments and arrives to a more accurate estimation of the natural frequency, and proposes a spindle speed with a higher margin of stability. This algorithm is compared to the one proposed by Smith and Tlusty [5] in Figure 6.

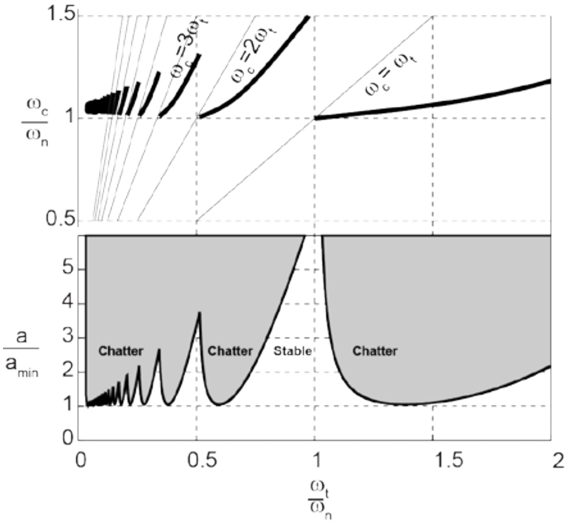


Figure 4: Ratio between the chatter frequency and natural frequency and stable depth of cut versus ratio between the tooth passing frequency and the natural frequency

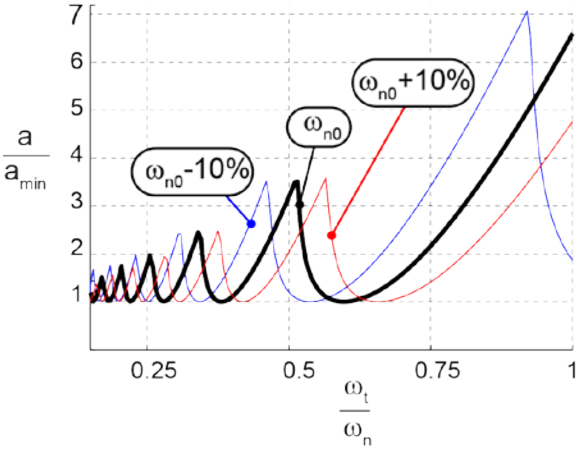


Figure 5: Changes in Stability lobe due to different natural frequency calculation

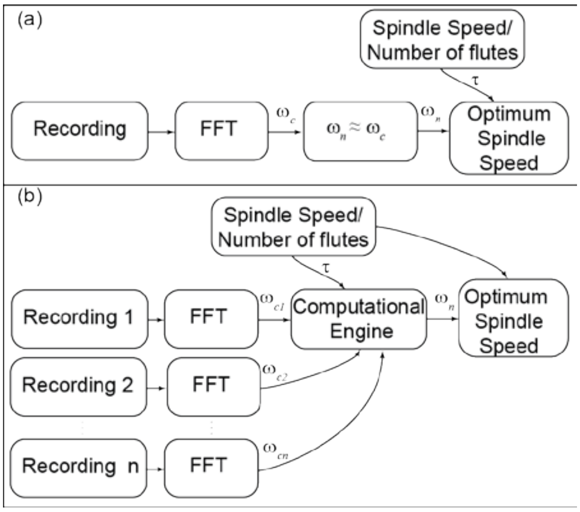


Figure 6: Algorithms for calculation of optimum spindle speed (a) as discussed in [5] and (b) developed for the mobile platform

3. CHATTER ANALYSIS SOLUTION FOR MOBILE PLATFORMS

The risk of vibration can be estimated by identification of the transfer functions of the system. Traditionally the transfer functions have been identified through the use of an impact hammer and a force transducer. The sensitivity of the impact and the need of wiring for the use of this technology make it less useful in a production environment.

Through the use of the sound that is picked up from the running process, the simplified stability diagram of the system can be deduced. Mobile platforms, like phones and pads can be used to record the sound of the process. The computational capability of these devices are now enough to render the possibility to include the theory and modeling into these devices to make it possible to analyze the process in question as it is running and from that give recommendations to modify the process for minimization of the chatter vibrations. By using the theory outlined above the following tool have been developed and introduced into mobile platforms such as iPhone and iPad to facilitate the easy use of vibration theory on the shop floor to solve chatter problems in machining. Below is given the general process and the features of the developed tool. This tool is dedicated for milling operations.

With the software (iCut) a sound track of a machining operation is recorded and the dominant sound frequency is used to propose a new spindle speed.

This process has following steps.

a. Setup
b. Recording
c. Preview
d. Spectrum plot
e. Optimization

Each step is presented in a view accessed by the "Tab bar" (a black ribbon with icons, Figure 7).

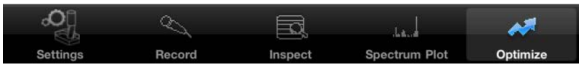
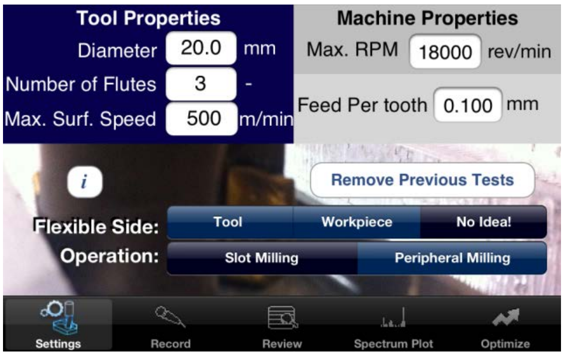


Figure 7: Tab bar

In many cases, more than one cut is needed to reach to a good cutting condition. Therefore, after reaching to step 5 operator must to go back to the step 2 and record the machining in the proposed cutting condition. Repeating this cycle multiple times would lead to a better cutting condition by gathering more information about the machine and the tool at different spindle speeds.

a. Setup


Tool Properties
Diameter 20.0 mm
Number of Flutes 3 -
Max. Surf. Speed 500 m/min

Machine Properties
Max. RPM 18000 rev/min
Feed Per tooth 0.100 mm

Flexible Side: Tool | Workpiece | No Idea!
Operation: Slot Milling | Peripheral Milling

Figure 8: Settings page

In the setup page (Figure 8), the critical information about machining is given to the software.

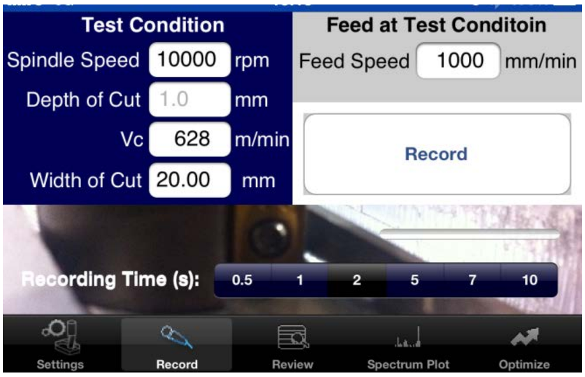
This information include (Number of flutes, tool diameter, maximum cutting speed and maximum spindle speed and feed per each flute). Optimization procedure for one specific machine tool and cutting tool combination will be based on all recordings stored in the program. Therefore, when the app is going to be used for a new machine or tool, it is necessary to remove previous test done on another machine or tool.

Tools with different number of flutes have different responses to the spindle speed change; therefore it is important to give the system information about this parameter.

Based on the tool diameter, either maximum possible cutting speed (that affects the tool life) or maximum spindle speed (which is determined by spindle and tool holder's design) is limiting the spindle speed. These speeds are given to the software in order for the proposed optimum not to violate these restrictions.

b. Recording

In the recording page, some of the cutting parameters will be recorded. User could input either spindle speed or cutting speed. (Feed speed will be calculated and displayed and could be used in setting up the CNC program). Depth of cut could also be modified before recording.



Test Condition
Spindle Speed 10000 rpm
Depth of Cut 1.0 mm
Vc 628 m/min
Width of Cut 20.00 mm

Feed at Test Conditoin
Feed Speed 1000 mm/min

Recording Time (s): 0.5 1 2 5 7 10

Figure 9: Recording view

c. Preview

In the preview (inspect) page, Figure 10, it will be possible to review the recording. If machining time was shorter that the recording time, it will be possible to select a section of the recording for the frequency range analysis. A special recording could be selected by clicking the "All Recordings" button on the top left corner which brings a new view (Figure 11). Ft indicates the tooth passing frequency.

Recording: 060711_084914
Recording Duration 2.00
Spindle Speed 3000
Depth of Cut 2.00

Figure 10: Preview page

All Recordings

8000RPM, 2.50mm 1065 Hz
Ft = 400Hz

7000RPM, 2.50mm 1237 Hz
Ft = 350Hz

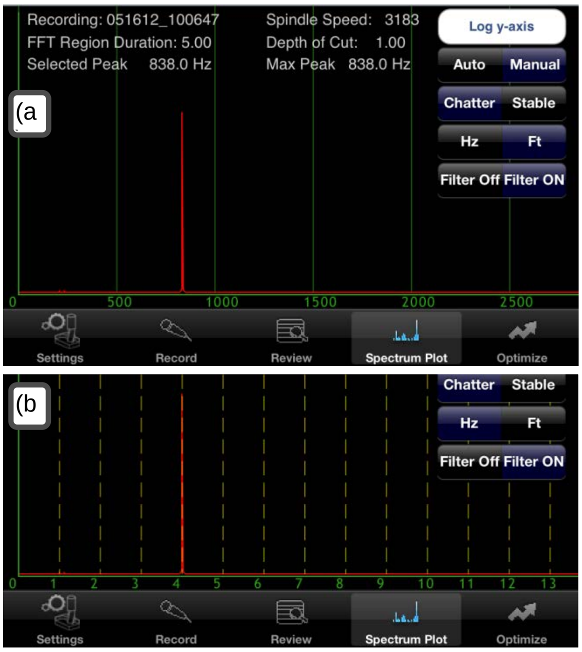
6500RPM, 2.50mm 1090 Hz
Ft = 325Hz

Figure 11: "All recordings" selection page

In all recordings page, it is possible to select a recording. An unwanted recording could be deleted using "edit" key in the top right.

d. Spectrum Plot

In the spectrum plot (Figure 12) the dominant frequency of the vibration will be detected automatically, but it is also possible to alter this selection by selecting the manual key. If one decides that the machining operation was stable, he could select the "stable" key. It is possible to switch the unit of the horizontal axis to the multiples of tooth passing frequency (Figure 12 b) instead of Hz. Odd integer multiples of half of the tooth passing frequency indicate flip bifurcation (period-doubling) instability [6] in low immersion milling; while regular multiples of the tooth passing frequency is expected due to the interrupted nature of the milling operation, present even in a stable cut.

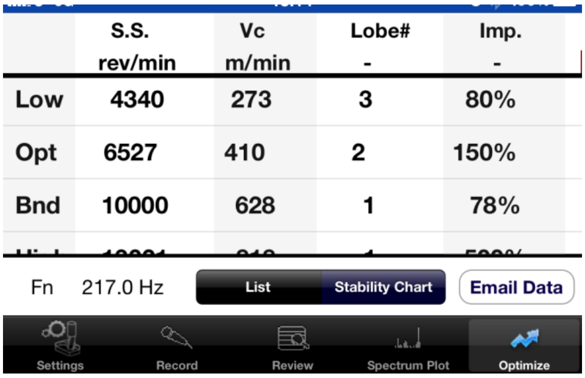


Recording: 051612_100647
FFT Region Duration: 5.00
Selected Peak 838.0 Hz
Spindle Speed: 3183
Depth of Cut: 1.00
Max Peak 838.0 Hz

Figure 12: Spectrum Plot; (a): Frequency in Hz, (b): Frequency in harmonics of tooth passing frequency (Ft)

e. Optimization

In the optimization page optimization is performed and optimum spindle speed is proposed in a list, Figure 13 and also in the form of a stability improvement chart (Figure 14). Fn indicates the estimated natural frequency which is calculated from multiple tests.



	S.S. rev/min	Vc m/min	Lobe# -	Imp. -
Low	4340	273	3	80%
Opt	6527	410	2	150%
Bnd	10000	628	1	78%

Figure 13: Optimization Page (Listing of suggestions)

At the second line (Opt.) the optimum spindle speed is proposed along with the corresponding feed speed and cutting speeds along with an estimate of possible stability improvement and the lobe number. Low, Opt, Bnd, and High points are shown in the stability chart in Figure 15. In first and third lines (Up and Down from Opt.), alternative cutting speeds are proposed, one at a higher speed (that passes either the maximum spindle speed or maximum cutting speed) and one at a lower than the optimum one (which usually has a lower potential for improvement). Also, the conditions at the boundary are also presented.

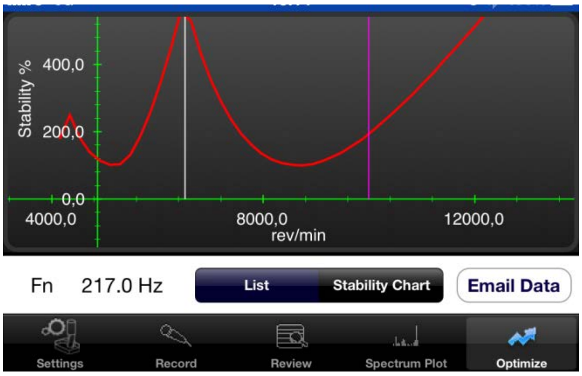


Figure 14: Optimization Page, Stability Improvement Chart

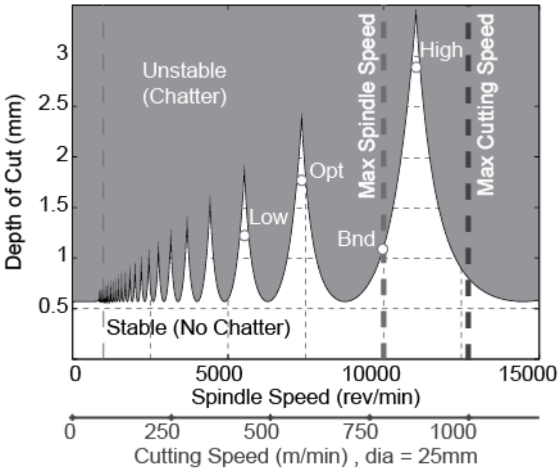


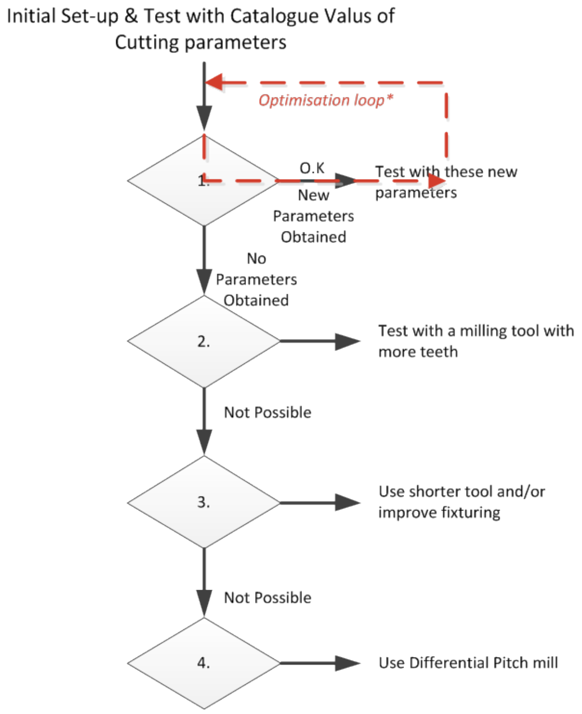
Figure 15: Low, Opt, Bnd and High points in stability chart

After selecting the optimum speed, it is recommended to do a test machining to verify the proposed speed. If this speed is not satisfactory (as it could be the case with only one measurement), the new measurement could be used to fine tune the optimum speed and repeat the machining. When speed modifications can't lead to any speed improvement, a decrease in the depth of cut should be considered to avoid chatter.

By selecting the stability chart from (instead of the list), stability chart will be displayed. The vertical axis is the improvement in stability, and the horizontal axis is the spindle speed.

4. FIELD EXPERIENCE

In order to evaluate the capability of the developed method and tool, a series of field test at different companies have been performed. The companies where test have been performed are a major tool steel manufacturer, two cutting tool manufacturers and a machine tool manufacturer. Conclusions from the field test can be divided into two major points. First, the developed process has, when compared to current available methods, proved to perform at least on an equal level as those methods and tools. The method described in this work being a more easy to use method and can be conducted while the process is running. Second, the need for a more complete methodology, especially when there is no recommendation for new parameters obtained, became evident. The methodology developed as an answer to this, is presented in Figure 16.



* Optimisation is conducted by a interative process where the axial deapth of cut is increased in incremental steps and followed by a frequency analysis in order to find the best cutting velocity until no such soulutions is to be fund. Then the optimisation is finished

Figure 16: Work procedure for using iCut Mill

5. CONCLUSIONS

Chatter vibration in machining may be detrimental to both the quality of the workpiece, the performance and life of the cutting tool or the life of the machine tool. The source of these vibrations may stem from flexibility in the workpiece, the machine tool, the fixture or a flexible tool system, or combinations of these. Every setup unique and to, on a global level, solve all vibration problems in machining is therefore difficult. A simplified solution, through the use of the sound that is picked up from the running process, to deduce a stability diagram of the system has been developed. The algorithm is based on chatter theory and has been adopted for mobile platforms, like phones and pads. The tool has proven to give recommendation for adjusted parameters taking both vibration risk and productivity into account.

The information obtained from sound signals has some limitations compared to the information from impact hammer tests. Since in an impact hammer test it is possible to obtain both the dynamic stiffness and the natural frequency of the flexible modes. In a sound recording, only the natural frequency is obtained. It means that to determine the admissible depth of cut an iterative approach should be employed.
The microphone on conventional phones are designed to capture frequencies higher that 100Hz, therefore an alternative method should be used when the chatter occurs at frequencies lower than 100Hz.

Engineers involved in testing of the program have had problem with staring the recording at the moments when chatter occurs during a long cutting process; it was suggested to allow a very long time of recording for further selection of unstable sections.

Noise from other machinery may affect the sound signals. A solution for this problem could be recording of the ambient sound, and subtracting the frequency spectrum corresponding to the ambient sound from the later measurements of the cutting processes (this approach is not implemented yet).

An interrupted cutting may generates sounds at harmonics of tooth passing frequency.

6. REFERENCES:

[1] S. Doi and S. Kato, "Chatter vibration of lathe tools", Transactions of the American Society of Mechanical Engineers 78 (5) (1956) 1127-1134.

[2] J. Tlusty and M. Polacek, "The stability of machine tool against self excited vibrations in machining", International research in production engineering, ASME, (1963) 465-474.

[3] S.A. Tobias and W. Fishwick, "A theory of self-excited chatter", The engineer (1958).

[4] Y. Altintaş and E. Budak, "Analytical Prediction of Stability Lobes in Milling", CIRP Annals - Manufacturing Technology 44 (1) (1995) 357-362.

[5] S. Smith and J. Tlusty, "Stabilizing Chatter by Automatic Spindle Speed Regulation", Annals of the CIRP 41 (1) (1992) 433-436.

[6] M.A. Davies, J.R. Pratt, B. Dutterer, and T.J. Burns, "Stability Prediction for Low Radial Immersion Milling", Journal of Manufacturing Science and Engineering 124 (2) (2002) 217.