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Guillem Quintana, Joaquim Ciurana, Inés Ferrer, Ciro A. Rodríguez

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Sound Mapping for Stability Lobes Diagram Identification in Milling Processes

Guillem Quintana
Department of Mechanical engineering and civil construction
Universitat de Girona
Av. Lluis Santaló s/n
17071 Girona, SPAIN
guillem.quintana@udg.edu

Joaquim Ciurana[1]
Department of Mechanical engineering and civil construction
Universitat de Girona
Av. Lluis Santaló s/n
17071 Girona, SPAIN
quim.ciurana@udg.edu

Inés Ferrer
Department of Business Administration, Management and Product Design
Universitat de Girona
Av. Lluis Santaló s/n
17071 Girona, SPAIN
ines.iferrer@udg.edu

Ciro A. Rodríguez
Centro de Innovacion en Diseño y Tecnología Rutgers University
ITESM Monterrey, Nuevo León, MEXICO
ciro.rodriguez@itesm. mx

[1] Corresponding author, Tel: +34 972 418265, Fax: +34 972 418098

Sound Mapping for the Identification of Stability Lobe Diagrams in Milling Processes

Abstract

This paper deals with milling sound information. In milling operations, cutting edge impacts excite vibrations due to the interaction between the cutter and the workpiece, and because of the system's lack of dynamic stiffness. It is possible to distinguish between free, forced and self-excited vibrations. During a milling operation these three different types of mechanical vibration propagate through the air and generate a sound that intrinsically contains information about the process.

A sound map is a graphical sound level representation of a certain zone or region that is divided into points by means of a mesh. Sound maps have typically been used with social considerations in mind: to determine, for instance, noise levels in cities. The goal of this paper is to determine the stability lobe diagram (SLD) of a milling process by applying sound mapping methodology. Stability lobe diagrams show the stability frontier as combinations of spindle speeds (i.e. the abscissas axis) and radial depths of cut (i.e. the ordinate axis). In this investigation the SLD was obtained from a mesh of 30 spindle speeds per 20 axial depths of cut, resulting in a total of 600 experiments. A data acquisition platform was developed to collect the milling process sound through a microphone placed inside the machine-tool enclosure. Data was analysed off-line in order to recognise chatter frequencies.

A 3D sound map was built by plotting, on each corresponding point of the mesh described above, the sound amplitude at frequencies around chatter frequency. The difference between stable and unstable zones is shown. This is the stability lobe diagram. The extensive experimentation detailed in this work reasserts and confirms the current state of knowledge of the chatter phenomenon.

Key words: audio, chatter, milling, sound, stability

1. Introduction

In metal cutting manufacturing, a blank is converted into a final product by removing extra material through turning, drilling, milling, broaching, boring, and grinding operations performed on machine tools. Metal removal technologies are progressing in parallel with developments in materials, computers and sensors and have become one of the most widely used manufacturing processes to produce the final shape of products [1].

As with the majority of machining processes, milling operations entail different types of vibrations that can damage the machine tool and hinder the process. Among these, chatter is the most harmful because it can produce a poor machined-surface quality, reduce tool life and break tool or machine-tool components. For these reasons, this self-excited vibration has to be avoided as much as possible. However, the phenomenon is highly complex and predicting its occurrence is still the subject of much research, even though the regenerative effect, the main cause of chatter, was identified more than 50 years ago [2].

The first research results appeared in the late 1950s when Tobias [3,4] and Tlusty [5] presented their work regarding the chatter problem. They established the basis of the regeneration mechanism theory, which has become a widely accepted explanation of the most powerful source of self-excitation. Merrit [6] proposed a feedback model to explain chatter as a closed loop interaction between the structural dynamics and the cutting process. These publications have become indispensable references.

Very early on, it was demonstrated that, during a milling process, chatter can arise given certain combinations of spindle speed and axial depth of cut (Figure 1). As a function of these two cutting parameters, the border between a stable cut, without chatter, and an unstable one, with chatter, can be visualised in a chart called a stability lobe diagram (SLD).

Stability lobe diagrams permit decisions to be made regarding specific combinations of axial depth of cut and spindle speed to avoid chatter while increasing the material removal rate. Once the SLD is available, it is possible to select cutting parameters to perform chatter-free cutting operations. This is the reason why a lot of researchers have developed and presented analytical models of the milling process. They have focused on developing methods to make available stability lobe diagrams for certain machine tool, tool holder, cutting tool and workpiece material combinations.

Altintas and Budak [7] developed an analytical method for stability predictions using the zeroth-order Fourier term to approximate the cutting force variation. This method, known as zeroth-order approximation, achieves more accurate SLD predictions for milling operations where the cutting tool has a large number of teeth and the radial cutting tool immersion is considerable. In Manufacturing Automation [1], Altintas details a widely known analytical-experimental method based on the use of an impact hammer instrumented with a piezoelectric force transducer. The structure is excited with an impact hammer and the resulting vibrations are measured with displacement, velocity and acceleration sensors to obtain the transfer functions of the multi-degree-of-freedom (MDOF) system. CUTPRO software simplifies the test and offers automatic predictions of the SLD [8]. Wiercigroch and Budak [9] revised the cutting process mechanics and provided four different chatter mechanisms classified into primary and secondary chatter. Primary chatter is caused by three physical mechanisms, namely friction between the tool and the workpiece, the thermodynamics of the cutting process and the phenomenon of mode-coupling. Secondary chatter, also called regenerative chatter, is the result of the modulated surface that the previous tooth in milling (previous revolution in turning) leaves on the workpiece due to vibrations. Insperger and Stépán [10, 11] detailed the semi-discretisation method which transforms the Delay Differential Equation (DDE) into a series of autonomous ordinary differential equations with known solutions. Regenerative chatter is considered to be the most important cause of instability in the cutting process. Other analytical investigations led to the implementation of bifurcation methods (i.e. Hopf bifurcation and period doubling or Flip bifurcation) to predict stability in milling [12-14].

Milling cutters with irregular pitch angles can be very effective in improving stability against chatter. This method of chatter suppression has been studied by several researchers [15-17]. It is based on disturbing the regeneration mechanism by using cutting tools with irregular spacing, known as variable pitch cutters. Sinusoidal spindle speed variation (S^3V) is another way to disturb the regenerative mechanism that has also been analysed and studied [18]. Investigators have also considered the influence of the helix angle and the consequent phase lag between the forces appearing at different sections of the mill [19-21]. The helix has an important influence on the areas of added lobes (flip lobes), while its influence on traditional lobes (hopf lobes) is insignificant. The milling of thin walled parts with variable dynamic behaviour has also attracted the interest of several investigations [22-24].

In an experimental investigation Ismail and Soliman [25] introduced a method to locate the SLD without stopping the machine based on ramping the spindle speed while monitoring the behaviour of a chatter indicator. Liao and Young [26] proposed an on-line spindle speed regulation method to control chatter when it starts to occur. Current vibration was monitored and the new spindle speed computed and readjusted in real time. Varying spindle speed and tooth passing frequency disturbed the regeneration mechanism, thereby ensuring a chatter free operation.

The milling sound emerging from the mechanical vibrations produced in the interaction zone between the cutting tool and the workpiece has also been used to detect chatter and control its occurrence [27-31]. A microphone is an excellent sensor to use for this purpose, and comparisons with other sensors such as dynamometers, displacement probes and accelerometers have shown good results regarding unstable milling identification [27]. Schmitz et al. [28-30] proposed a method for chatter recognition through statistical evaluations of the milling sound variance with a synchronously sampled signal (one sample per spindle revolution). In order to ensure stable cutting operations the Harmonizer software [32] was developed. Harmonizer scans the sound of the cutting process with a microphone and detects chatter if the energy of the measured sound signal exceeds a certain threshold. To achieve this, it is first of all necessary to capture the ambient noise level of the workshop without the sound of the cut. This permits external noise to be filtered out of the cutting sound emission and the dominant chatter frequency (f_c) to be extracted from the fast Fourier transform. An alternative spindle speed can be calculated using Equation 1:

$$\Omega = \frac{60 \times f_c}{j \times z} \quad (1)$$

where Ω is the spindle speed in (rpm), *j* is the lobe number and so an integer (*j* =1, 2, 3...), *z* is the number of teeth on the cutting tool and *fc* is the identified chatter frequency (in Hz).

This paper deals with a practical approach to construct a stability lobe diagram, which makes it possible to distinguish between stable and unstable cutting parameters, and select optimal chatter-free combinations of axial depths of cut and spindle speeds between lobes to achieve higher material removal rates. A sound, or noise, map is a graphical representation of the level of the sound pressure in a certain zone or region. The area studied is divided into a certain number of points with a grid and the sound map is obtained by taking measurements at defined points in the evaluated area. The rest of the points are calculated by interpolation. With regard to the milling process, the stability lobe diagram is found to be related with regions on a sound map. If the stability lobe diagram is considered as a region it could be divided in several zones with a mesh and stability lobe diagram can be determined applying sound mapping procedure. The proposed approach is validated by comparing the SLD generated with sound mapping with the one generated by means of a hammer test.

2. Building a milling process sound map

In milling operations, extra material is removed from a blank by a rotating cutting tool that translates in the feed direction at a certain speed (Figure2). The impacts of the cutting tool edge excite the machine tool/tool holder/cutting tool/workpiece system modes, thereby producing vibrations. An initial transient stage determines if the process will be stable (i.e. chatter free) or unstable (i.e. with chatter).

When the process is stable, the system is dominated by forced vibrations produced by periodic forces due, for example, to the rotation of slightly eccentric or unbalanced components or to external environmental conditions. If the process is unstable, self-excited vibrations (chatter) arise with all the resultant negative effects. Chatter can occur at low frequencies, normally less than 200Hz, when the machine tool structure modes are excited. At higher frequencies, typically around 2000Hz, chatter occurs with excitation of the system modes related to the spindle, the tool holder and the cutting tool [33].

Forced vibrations can be avoided or reduced when the harmonic excitation that causes them is identified. Engineers can employ various methods to mitigate their occurrence, but self-excited vibrations extract energy from the beginning and increase as a result of the interaction between the cutting tool and the workpiece during the machining process. This type of vibration is the most undesirable and the least controllable, and it is not possible to perform a proper metal removal operation during this unstable stage [2, 4].

During a milling operation where the cutting tool rotates at a constant spindle speed Ω, the number of cutting teeth is *z* and there is a regular pitch between them, the tooth passing frequency *Ft* can be calculated in Hz as shown in Equation 2:

$$Ft = \frac{\Omega}{60} \times z \qquad (2)$$

The periodic impacts of the cutting teeth with the workpiece and the corresponding vibrations that arise due to that generate a sound. This sound is a transmission of mechanical energy that propagates through the air and contains information about the process. Experienced operators can usually extract information from it and correct or modify the cutting parameters. The vibration amplitude increases suddenly when self-excited vibration occurs at the maximum stable depth of cut. This is shown in the work of Tönshoff cited by Dornfeld [34]. Figure 3 shows the vibration amplitude compared with the cutting depth and allows us to observe the frontier between the milling process dominated by forced vibrations and the milling process dominated by self-excited vibrations.

Chatter frequency can be distinguished in the process sound. Insperger et al. analysed the variation of chatter frequencies in milling operations [35]. Chatter arises when there is resonance due to the ratio of the natural frequency of the machine tool structure and the frequency at which excitement occurs, or when there is a loss of stability in the linear time periodic DDE model of the milling process. Depending on whether it is a Hopf case or a period doubling (flip bifurcation) case, it has been demonstrated that chatter frequencies arise at:

$$f_H = \pm \frac{\omega}{2\pi} + n\frac{z\Omega}{60}; \qquad n = \ldots -1, 0, 1 \ldots, \qquad (3)$$

$$f_{PD} = \frac{z\Omega}{30} + n\frac{z\Omega}{60} \qquad n = \ldots -1, 0, 1 \ldots, \qquad (4)$$

where f_H is the secondary Hopf bifurcation in Hz, and f_{PD} refers to the period doubling bifurcation, also in Hz. Although an infinite number of chatter frequencies can be calculated, only positive values have practical meaning; ω is the chatter frequency, Ω is the spindle speed in rpm, and *z* the number of cutting teeth as mentioned above.

Once it has been shown how the milling process vibrations are generated and propagated through the air, thus producing a sound with certain amplitude and frequency characteristics, it is possible to consider how this information can be used to make a sound map.

A sound, or noise, map is a graphical representation of the level of sound pressure in a certain zone or region. Sound mapping is a technique that has been widely used in recent years, especially for social purposes. Governments have been interested in determining the noise levels that citizens have to tolerate because of the various noise sources found near inhabited areas, such as roads, highways, railways, airports, industrial areas, leisure time activities, etc. For example, in Europe, the European Parliament has approved Directive 2002/49/EC relating to the assessment and management of environmental noise. This stipulates that noise maps have to be elaborated in certain regions and locations. In industry, however, sound maps have also been used to determine the sound pressure near machines such as aerogenerators. In the case of milling, as previously mentioned, there have been several investigations where milling sound emission has been used to obtain information about incidents and, in particular, instabilities. However, the authors do not have information about any research that uses the sound map elaboration technique and aims to identify a stability lobe diagram.

Sound maps are currently elaborated by following one of two simple methods: by sampling, through acoustic analyses of sound acquired with microphones or sonometers which are then digitalised; or by simulations that simulate the acoustic situation in a certain zone. These are based on calculations that can be carried out thanks to advances in computers and have the advantages of reducing data acquisition costs and sound map elaboration times.

Sound maps based on measurements are obtained by taking measurements at certain points in the area being evaluated and calculating the rest of the points by interpolation. The points to be measured are usually determined by the vertices of a mesh. The characteristics of the mesh and the separation of the vertices determine the accuracy of the sound map. Portable sonometers have been available since the 1950s, but the first sound maps were not elaborated until the 1970s and always had a social purpose and covered large areas.

In terms of the milling process and focusing on the chatter problem, if the stability lobe diagram is considered as a region and this region is divided into several zones with a mesh, a diagram can be constructed by applying a sound mapping procedure. The diagram shows the stability frontier as combinations of spindle speeds on the abscissas axis and radial depths of cut on the ordinate axis. In this research the SLD was determined from 600 points on a mesh of 30 spindle speeds per 20 axial depths of cut, which meant a total of 600 experiments carried out to obtain the process sound at each of the points of the mesh. The sound pressure was analysed and the chatter frequencies were identified. The method used is presented in Figure 4. A 3D sound map was built by plotting, at each corresponding point on the mesh referred to above, the sound amplitude at frequencies around chatter frequency. On the map it is possible to observe the stability frontier and, consequently, to select combinations of cutting parameters to perform stable cutting operations.

3. Experimental set-up

Labview software was used to develop a data acquisition platform capable of monitoring the sound emission of the metal removal process and collecting data in time domain with a microphone placed inside the machine enclosure. The fast Fourier transform (FFT) of the time-based audio signal was calculated on line to obtain the frequency-domain spectrum of the milling sound. The audio signal was printed on line on the computer screen in time-based and frequency-domain charts while being collected and saved in a file that could be analysed off line. Figure 5 shows the experimental setup for data acquisition purposes.

Experiments were carried out with a Deckel Maho 64V linear 3-axis vertical machine. The cutting tool was a GARANT end mill, 8mm in diameter and with two cutting edges clamped in a thermal cone. The workpiece material was aluminium 5083 with a hardness of 70-80 HB. The audio signal was collected with a sampling rate of 25kHz.

Figures 6 and 7 show the main screen appearance of software used for off-line audio signal analyses.

Figure 6 shows a stable cutting operation and Figure 7 an operation with chatter. The number of teeth and the spindle speed are cutting parameters that have been introduced by the operator and the tooth period has been calculated by the computer application using Equation 1. Figure 6 shows a chatter-free milling operation carried out with a cutting tool with two cutting teeth at a spindle speed of 4,000rpm. This means a tooth period of 133.33Hz which can be observed in the frequency domain plot where an important peak appears at the tooth passing frequency. Figure 7 shows an unstable milling operation carried out with the same cutting tool and spindle speed. In this case, the tooth period does not appear on the frequency spectrum chart because chatter frequency has become dominant and instability is rising with a chatter frequency of 2,121.67Hz. It should be noted that the operations shown in Figures 6 and 7 were performed at different axial depths of cut. It is possible to see in Figure 7 that chatter occurrence is due to excitation in the system consisting of the spindle, the tool holder and the cutting tool. These frequencies are typically around 2,000Hz (2,121.67Hz in Figure 7) while machine tool structure modes are normally less than 200Hz.

4. Results obtained

A total of 600 experiments were carried out, describing a grid over the SLD to collect the milling audio signal and proceed with off-line analyses. There were 30 different spindle speeds. These were increased from 1000rpm to 9700rpm at increments of 300rpm. There were 20 different axial depths of cut, from 0.25mm to 5.00mm with steps of 0.25mm. Feed per tooth was maintained at a constant 0.02mm/tooth. The tool performed raster paths in slotting operations (100% immersion). A three dimensional sound map of the audio signal amplitude within these frequencies was plotted for all the combinations of spindle speed and axial depth of cut, corresponding to the 600 experiments carried out. Figure 8 shows the 3D milling sound map, on which it is possible to detect regions where the audio signal rises suddenly to frequencies between 1,800-2,300Hz. This allows regions of stable and unstable cutting conditions to be distinguished and identified on the stability lobes diagram.

The chart in Figure 9 shows sound amplitude plotted against axial depth of cut for several representative spindle speeds. For lower spindle speeds of 1,300 rpm and 2,200 rpm it is possible to observe the process damping effect. Process damping usually occurs at low spindle speeds and provides stability due to the short undulations left on the part's surface by high frequency vibrations. These surface waves interfere with the cutting tool flank face and dampen the cutting tool vibration. Figure 8 is composed of the sum of slices such as those shown in Figure 9 for the whole range of spindle speeds.

At 3,000 rpm, forced vibrations dominate the milling process until approximately 4.25mm of axial depth of cut, when instability starts. At higher spindle speeds, such as 8,200 rpm or 9,100 rpm, chatter arises at lower axial depths of cut, as can be seen in Figure 9. It is also possible to find a stable speed range around 8,800 rpm. In this case, forced vibrations dominate the milling process and self-excited vibrations do not appear until the axial depth of cut is close to 5.00 mm. These results are in good agreement with Tönshoff's work cited by Dornfeld [33] and allow identification of the frontier between stable and unstable milling operations across the whole spindle speed range on the SLD.

Chatter frequencies were also analysed, and Figure 10 shows where they have been plotted for different depths of cut. It is possible to observe chatter frequency variations with the typical saw tooth shape that normally provides regenerative chatter as revealed by Tobias [4]. This effect is not observable when chatter is caused by other physical events (i.e. friction between the tool and the workpiece, the thermodynamics of the cutting process or the mode-coupling phenomenon). Further information about this was provided by Insperger et al. [34] as noted in Section 2. Frequencies between 1,800Hz and 2,300Hz were analysed and it was observed that chatter occurred at frequencies around 2,100Hz.

If the stability lobe diagram and the chatter frequencies are compared, it can be seen that the stable and unstable zones of the SLD and the chatter frequency charts are in line with each other. For example, the major range of stable spindle speeds is around 5,800 rpm at an axial depth of cut of 5mm. Higher spindle speeds are always unstable because, as can be observed from the chatter frequency chart, all the chatter frequencies of the rest of the unstable intervals are superposed.

5. Impact hammer test validation

Finally, the stability lobe diagram was calculated analytically by performing impact hammer tests to obtain the frequency response function (FRF) of the system, consisting of the cutting tool, the toolholder and the machine tool. This structural dynamic test obtains the frequency response fucntion with the help of an impact hammer instrumented with a piezoelectric transducer, and the use of an accelerometer. A range of frequencies that contains the system's natural modes are excited, resulting in a short impact with the hammer. The corresponding vibration is captured and analysed by the accelerometer [1]. The test was carried out to validate the proposed sound mapping approach. The stability lobe diagram obtained experimentally by 3D sound mapping and the stability lobe diagram obtained analytically are compared in Figure 11. As can be seen, there is good agreement between the impact hammer tests and the sound mapping method. The good fit between the two methods allows us to conclude that the 3D sound mapping approach proposed in this work is a suitable method for removing most of the lobbing effect through construction of an SLD.

6. Conclusions

In machine shops and on production floors, chatter is easily recognised from the loud noise that accompanies it and the visible chatter marks that the cutting tool leaves on the workpiece surface. In this paper, the milling process audio signal information has been analysed to construct a stability lobe diagram.

Experiments were performed varying the axial depth of cut and the spindle speed, in which the feed per tooth was maintained at constant, as happens in the stability lobe diagram. A data acquisition platform was implemented to collect the milling process audio signal, by means of a microphone located inside the machine tool enclosure. The time-based audio signal was analysed off line to identify chatter frequencies and build the sound map of the milling tests, in order to obtain the stability lobe diagram. Milling sound analyses of frequencies and amplitudes, through FFT of the time-based audio signal, produced good results and allowed us to obtain an accurate approach to understanding milling process incidences through vibration occurrence.

The main drawback of this method is that a lot of experiments and, thereafter, time and financial expenditure, are needed to obtain enough data to construct the SLD through the sound map of the milling process acoustic emission. Once the SLD is determined, it is possible to select the appropriate cutting parameters to ensure chatter-free operations. However, with this method, it is not possible to identify chatter on line and or monitor the process. In addition, it should be mentioned that the use of milling sound has usually been considered inadvisable in the industry due to the influence that the noise coming from other machine tools can have on the analysis. In industrial environments, sound from other machines propagating through the workshop could make it necessary to install sound filters so that only the sound that is required for analysis is collected.

The extensive experimentation presented in this work confirms the published findings of numerous investigations, from the first approaches of more than fifty years ago to the present day.

7. Acknowledgements

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Sound Mapping for the Identification of Stability Lobe Diagrams in Milling Processes

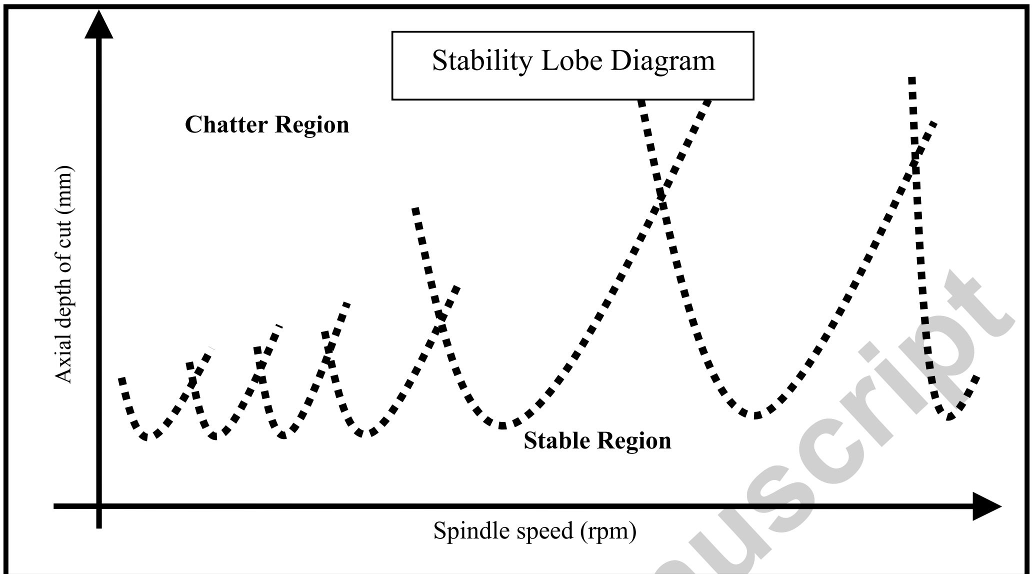
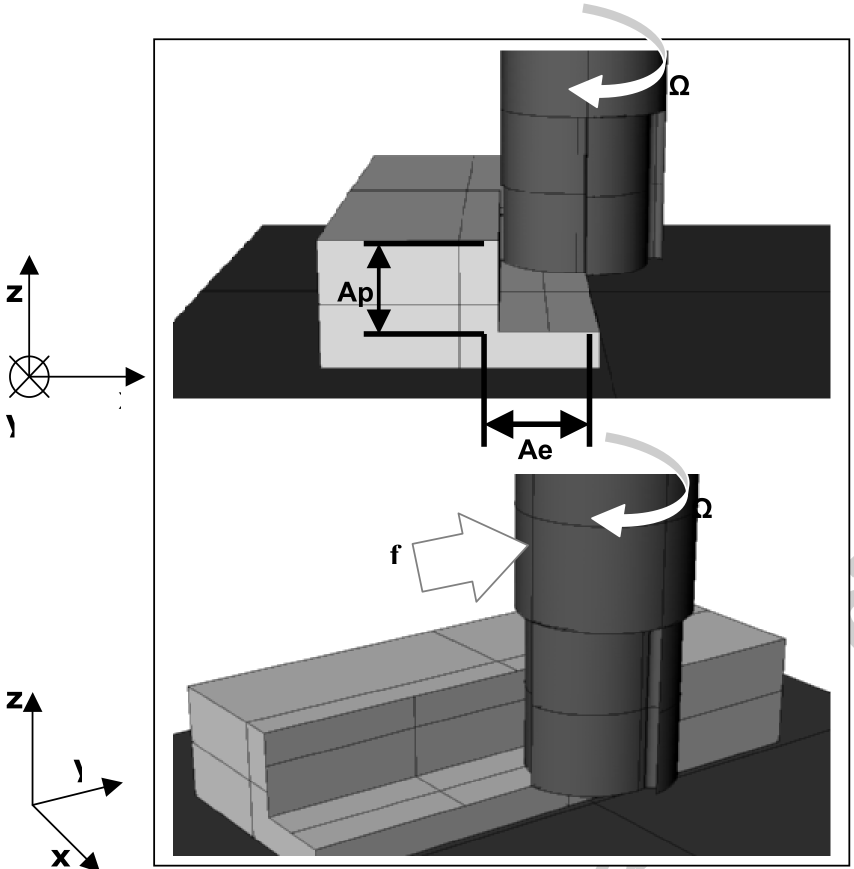


Figure 1: Schematic example of a stability lobe diagram.



Ω: spindle speed
Ap: axial depth of cut
Ae: radial depth of cut
f: feed rate
z: number of teeth

Figure 2: Schematic representation of a milling operation

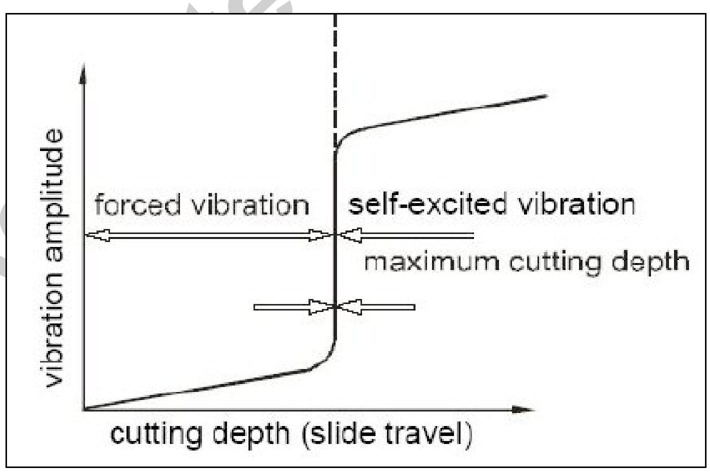


Figure 3: Illustration of the occurrence of forced and self-excited vibrations [34]

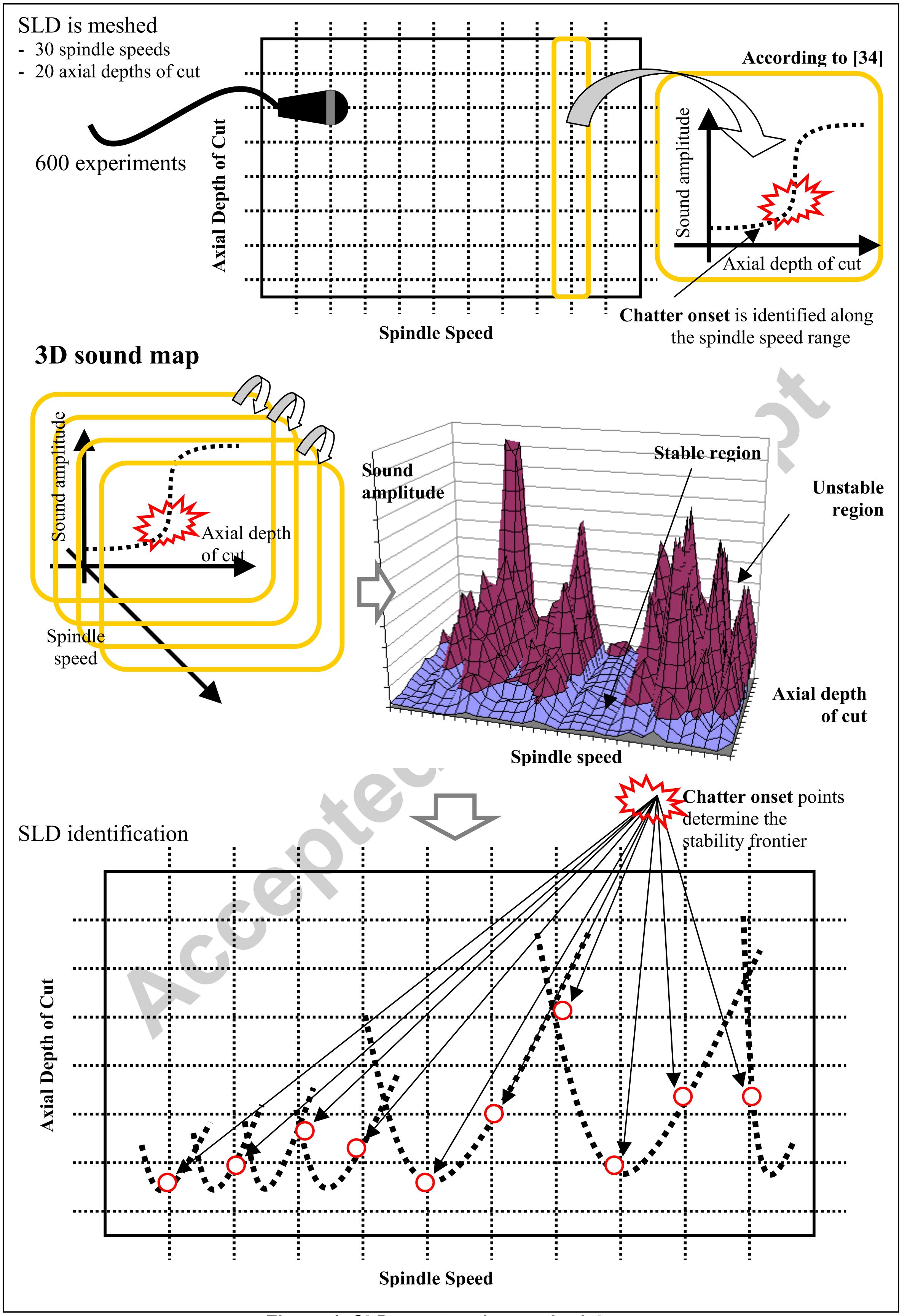


Figure 4: SLD construction methodology

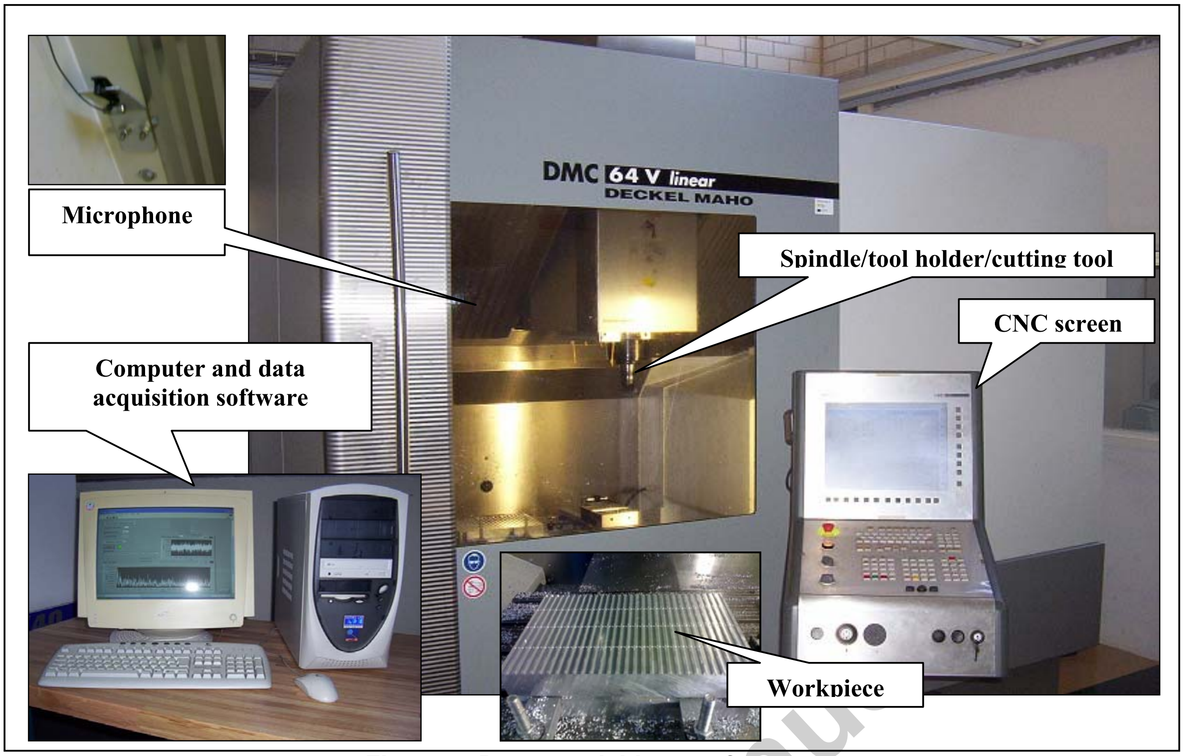


Figure 5: Data acquisition platform setup

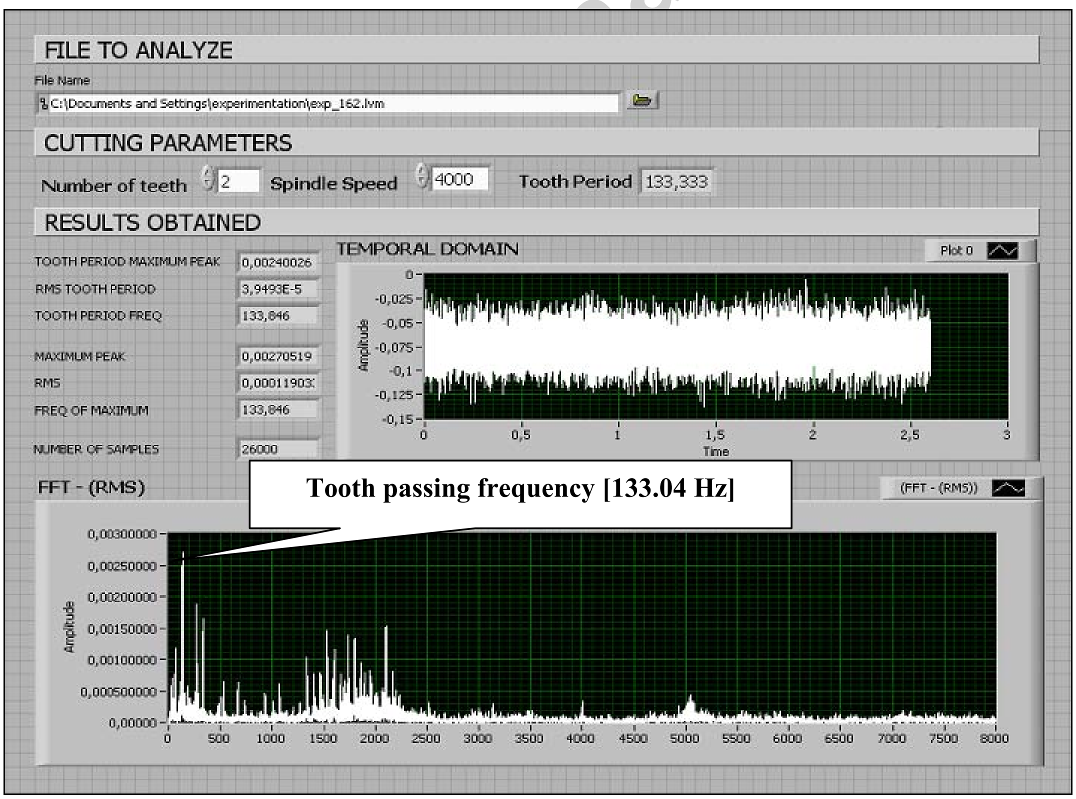


Figure 6: Software appearance: an example of a stable cutting operation

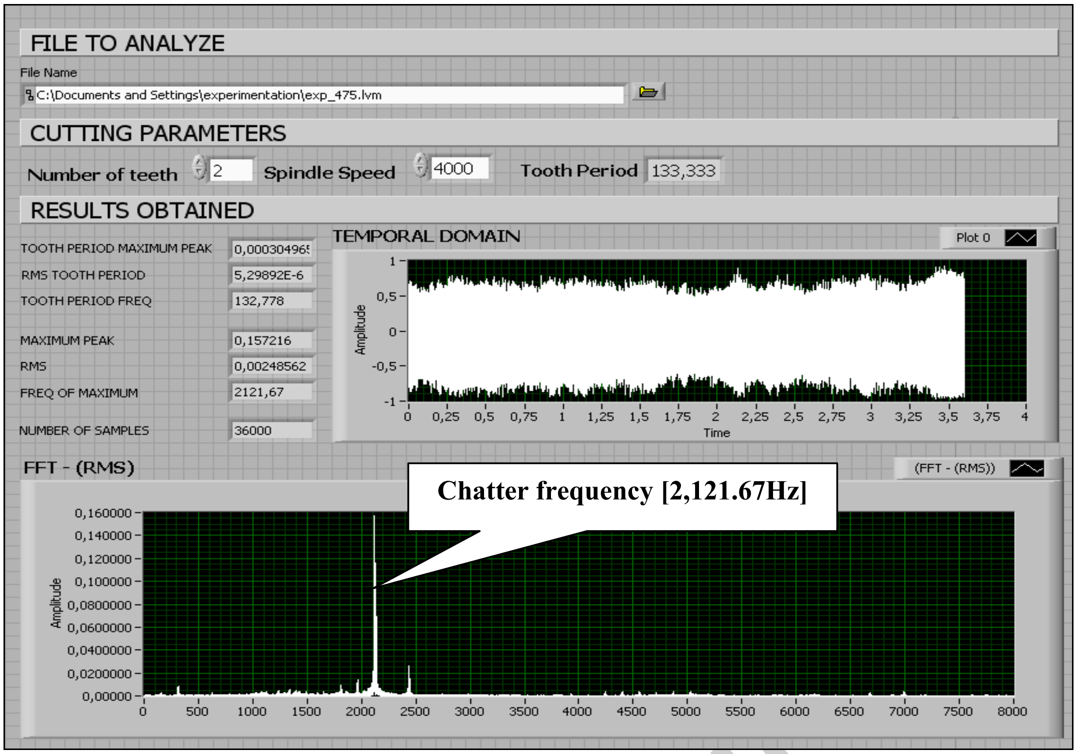


Figure 7: Software appearance: an example of an unstable cutting operation

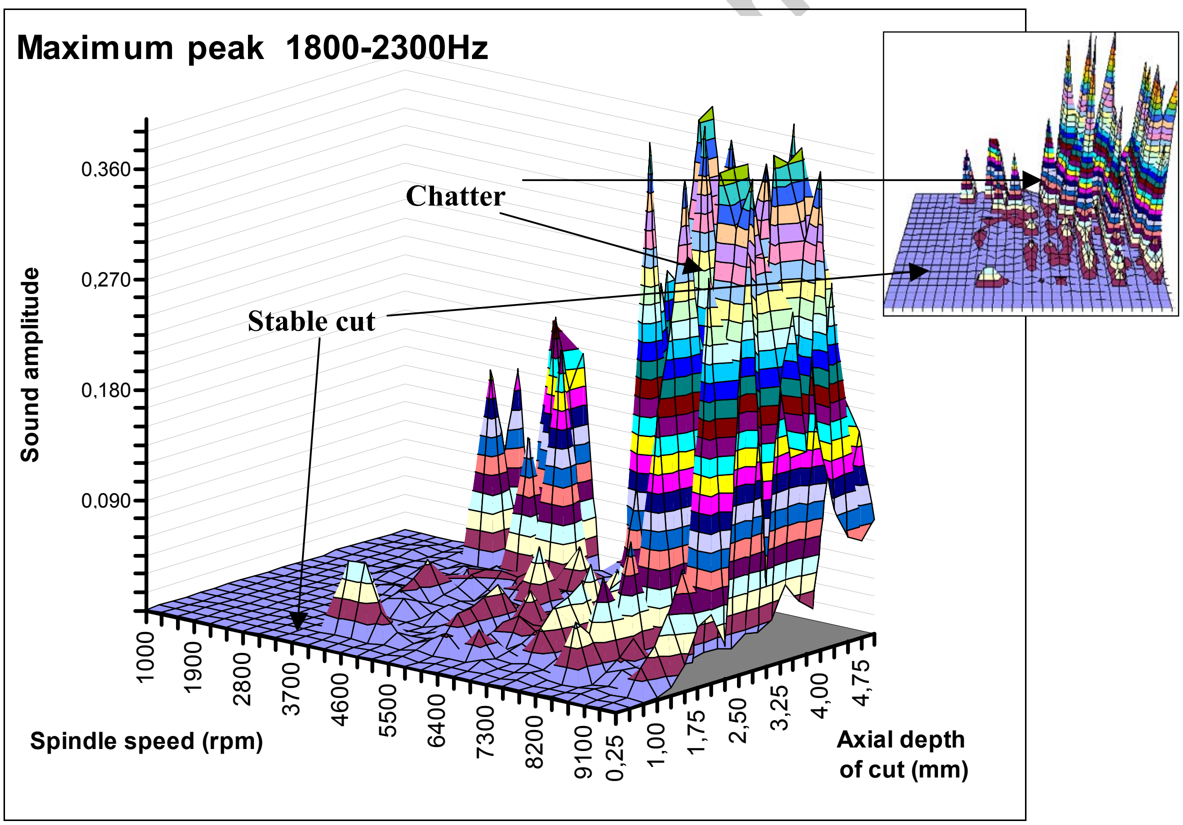


Figure 8: 3D milling sound map

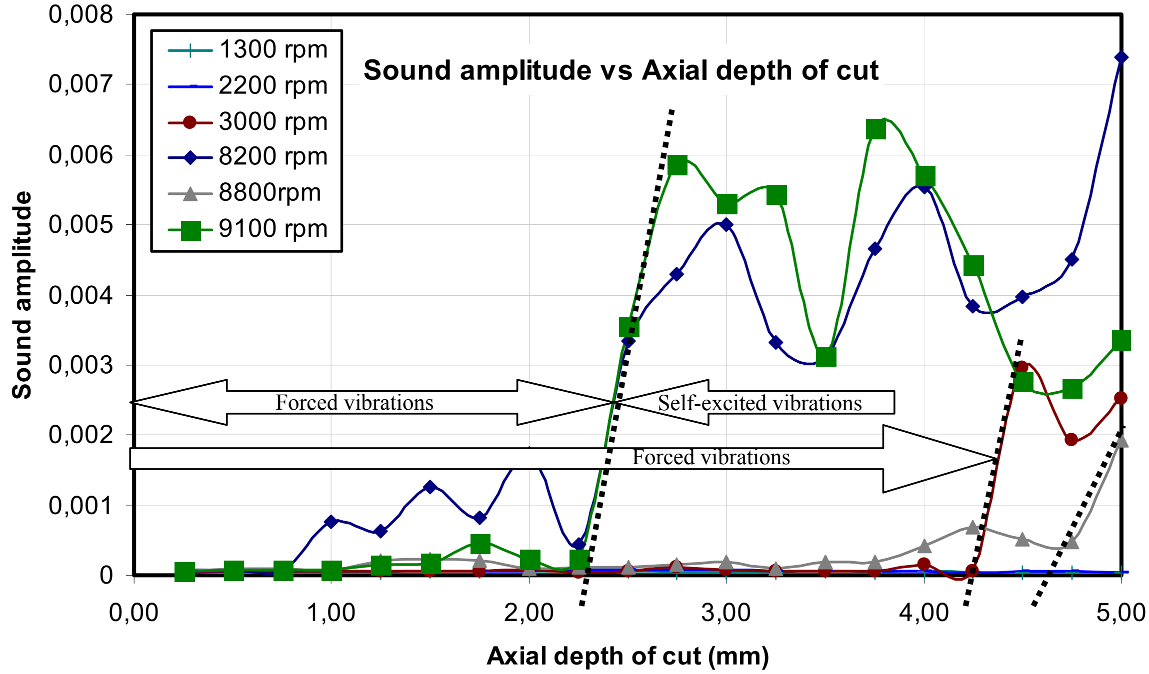


Figure 9: Software appearance: an example of an unstable cutting operation

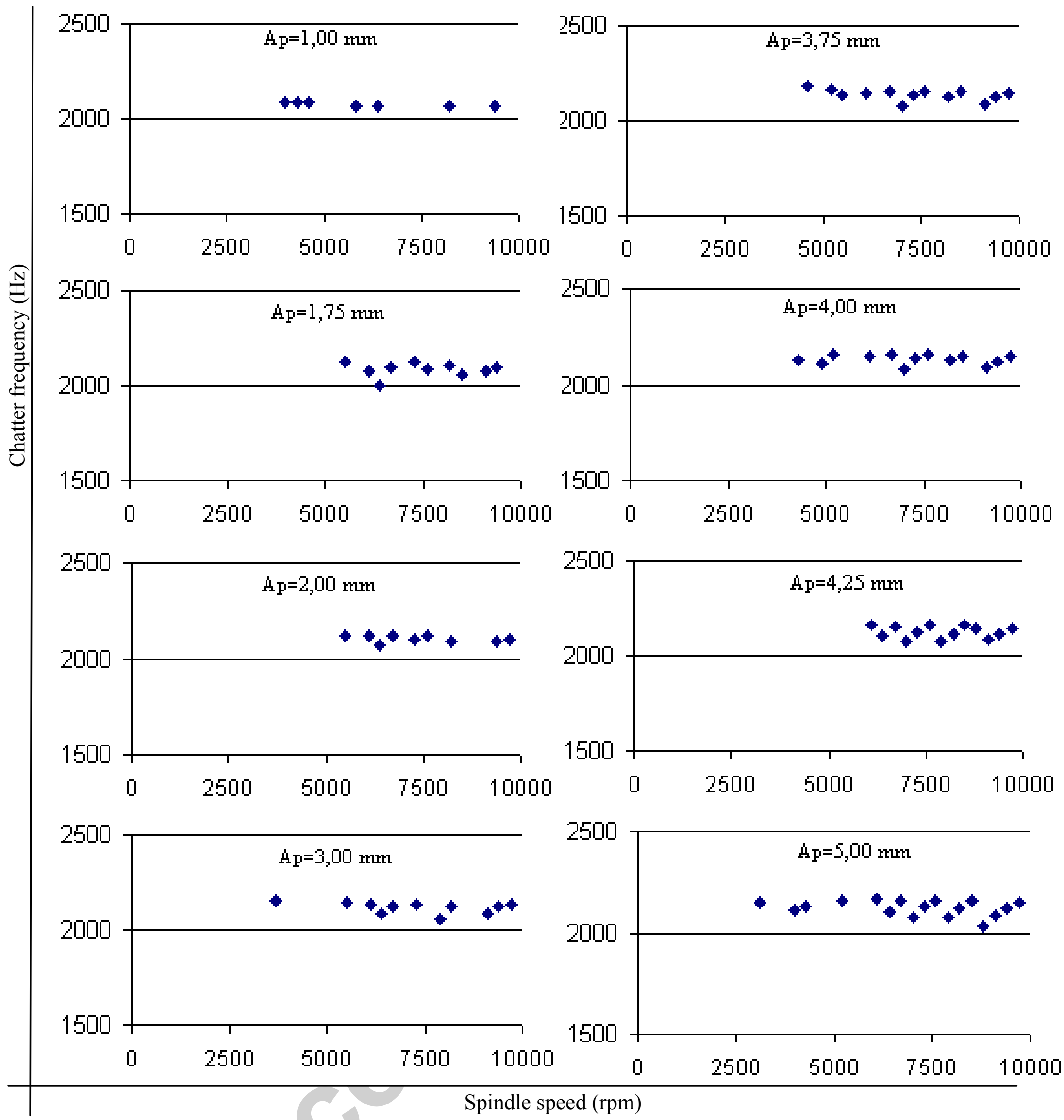


Figure 10: Chatter frequency variations as a function of spindle speed

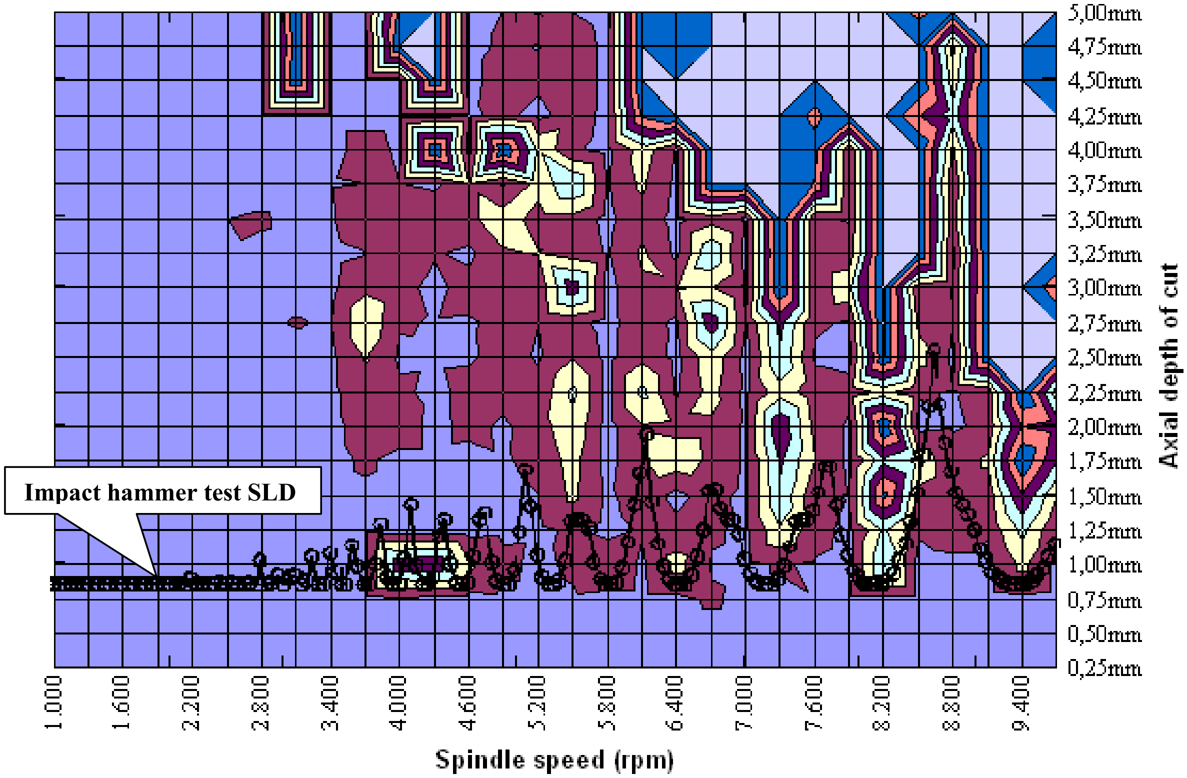


Figure 11: Comparison between the SLD obtained by impact hammer testing and that obtained by 3D sound mapping analyses