# ANALYSYS OF THE DYNAMIC STABILITY OF HIGH SPEED FINISHING END MILING AND BALL-END MILLING

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***Abstract.*** *Finishing milling operation is characterized by high interruptions during the cut. The time the tool spend cutting is just a fraction of one rotation period. The phenomena related to the process dynamic are different from those found in roughing operations. The influence of the cutting parameters and the system dynamics (tool, tool holder and spindle) on the stability of high-speed end milling and ball-end milling are investigated in this work. The system dynamics are identified by impact tests. The workpieces are considered to be rigid. The stability evaluation is based on the workpiece texture parameters and the analysis of sound pressure measured during the process. In finishing end milling operations the highest limitation are the regenerative vibrations. Best results are found for the spindle rotations, whose tooth-passing frequency are close but lower than the natural frequency of the most flexible mode. Forced vibrations exert higher influence on the results for finishing ball-end milling. Due to the small machining sections the contact region between tool and workpiece is reduced, and consequently occurs a minimization of the effects of phase difference between the ondulations left by consecutive teeth, and get more importance the periodic excitation of the interrupted cut. Best results are found when the harmonics of the tooth passing frequency have a distance from the natural frequency.*

***Keywords****: high speed milling, end milling, ball-end milling, vibrations.*

## 1. Introduction

In finishing end milling the tool geometry and cutting parameters are chosen in such way to attempt the project requirements related to surface finish and dimensional precision. Endmills are used to finish plane surfaces, while ball-endmills are recommended for finishing of tapered and free form surfaces (Stemmer, 1995). Small radial depth of cuts leads to a condition of smaller engagement between tool and workpiece. This process is characterized by high interruptions during the cut. The time the tool spend cutting is just a fraction of one tool rotation period. The phenomena related to the process dynamic are different from those found in roughing operations (Polli, 2005). The relative vibrations between tool and workpiece, which arise during the operation, may achieve unacceptable levels and deteriorate the surface finish and reduce tool life, especially in situations, that demands the use of tools with high lengths to machine deep cavities, as the ones commonly found in die and mold industries (Tlusty, 1993).

The influence of the cutting parameters and the system dynamics (tool, tool holder and spindle) on the stability of high-speed end milling and ball-end milling are investigated in this work. The system dynamics are identified by impact tests. The workpieces are considered to be rigid. The stability evaluation is based on the workpiece texture parameters and the analysis of sound pressure measured during the process.

## 2. Metodology

Cutting tests were conduced on a high-speed milling center with a 16000 rpm, 15 kW power spindle and maximum slide-speed of 30 m/min. The workpiece material was ABNT P20 steel. Six flutes, 12 mm diameter endmills and four flute, 8 mm diameter ball-endmills were used in the cutting tests. The cutting tool material was cemented carbide with

TiAlN coating. All tests were conducted using fresh tools under dry conditions. The stability evaluation was based on the workpiece surface finish and the sound pressure measured during the process.

The frequency response functions for each tool were obtained by attaching an accelerometer to the end of the tool, striking the tool in the direction of the accelerometer with an instrumented hammer and recording the signals simultaneously by using a signal analyzer.

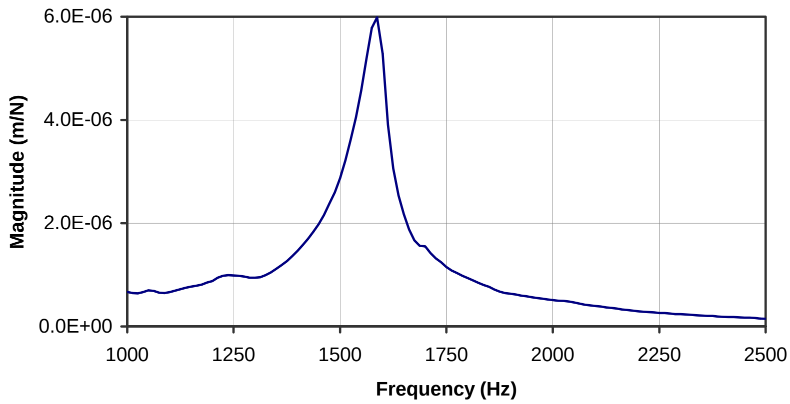
The surface roughness was used as a relative measure for the process stability. A stable process was characterized by a relatively fine finished surface, while an unstable process was associated with a deteriorated one. Measurements were made using the same cut-off (0.8 mm), enabling comparative analysis of the results.

A microphone was chosen as a sensor to detect vibrations during the process because it has an adequate frequency band and it is able to detect vibrations signal from the tool, workpiece or machine-tool. The system used to measure the sound pressure was composed by the following elements: ½" free field microphone, sensor signal conditioner, signal acquisition board, microcomputer and signal analyzer software. The signal acquisition rate was 10 kHz.

## 3. Results and discussion

### 3.1. Finishing end milling

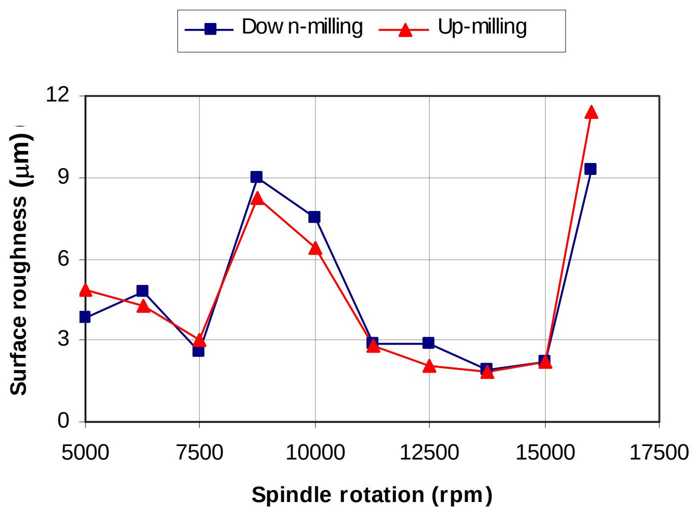
The graph in figure 1 shows a Frequency Response Function (FRF) measured at the end of an endmill. The peak of magnitude occurs in the natural frequency ($f_n$) and corresponds to 1585 Hz.




Tool: Endmill
Diameter (D) [mm]: 12
Length (L) [mm]: 72
Number of teeth (z): 6
Machine: Hermle C800 U

Figure 1. FRF measured at the end of an endmill

Figure 2 shows a graph of the surface roughness parameter $R_z$ as a function of the spindle rotation for down-milling and up-milling cuts.




Workpiece material: ABNT P20 steel

Toll: Endmill
Diameter (D) [mm]: 12
Length (L) [mm]: 72
Number of teeth (z): 6

Axial depth of cut ($a_e$) [mm]: 2.5
Radial depth of cut ($a_e$) [mm]: 0.25
Feed per tooth ($f_z$) [mm]: 0.05

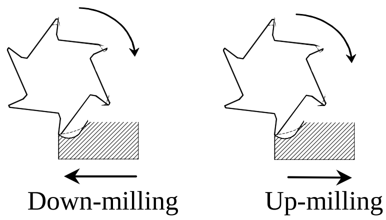



Figure 2. Surface roughness as a function of the spindle rotation

The curves have very close values. There are peaks representing considerably high values for some spindle rotations. These peaks are the result of vibrations during the process. In these cases, the depth of cut used in the tests was greater than the limit for a stable cut.

Figure 3 shows the surface profile for a stable condition (n = 13750 rpm). Due to the tool run-out and the forced vibrations, the distance between the marks observed in the profile corresponds manly to the feed per revolution.

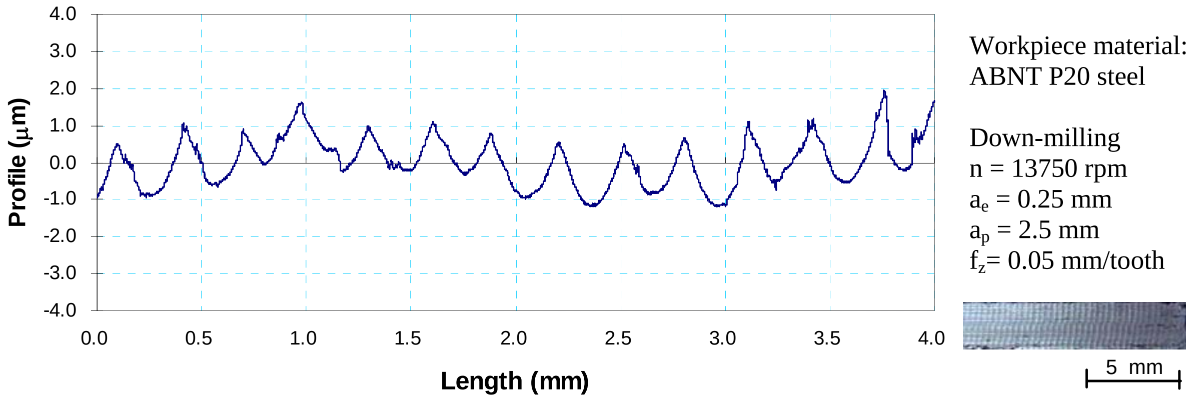



Figure 3. Surface profile for a down-milling stable cut

Figure 4 shows the surface profile for a condition next to the resonance (n = 16000 rpm). The depth of wave is almost 60 µm and the distance between the marks are five times greater than the feed per revolution. The marks tend to be closer a vertical line because the difference between the tool-passing frequency and the regenerative vibration one is small.

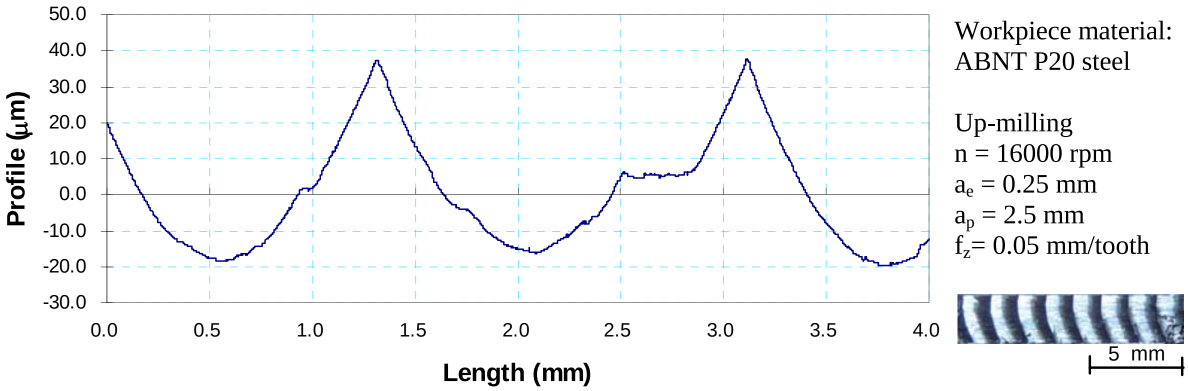
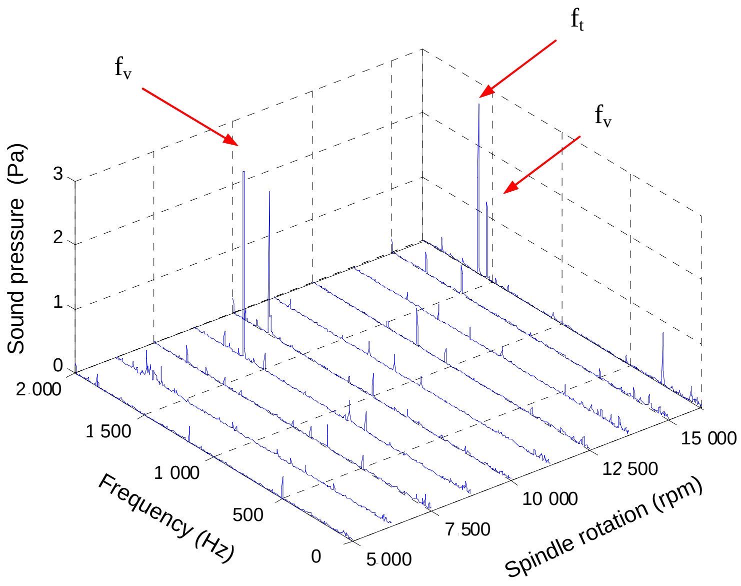



Figure 4. Surface profile for an unstable cut

The graph of figure 5 shows the sound pressure spectra measured during the down-milling cuts.

For stable cuts, which resulted in lower surface roughness values, the spectra are dominated by the tool-passing frequency ($f_t$) and its harmonics that have relative low magnitudes. For unstable conditions, the highest peak does not occur in the tool-passing frequency, but in the regenerative vibration frequency ($f_v$). One exception occurs for n = 16000 rpm, where the magnitude of the tool-passing frequency is higher than the regenerative vibration frequency one.



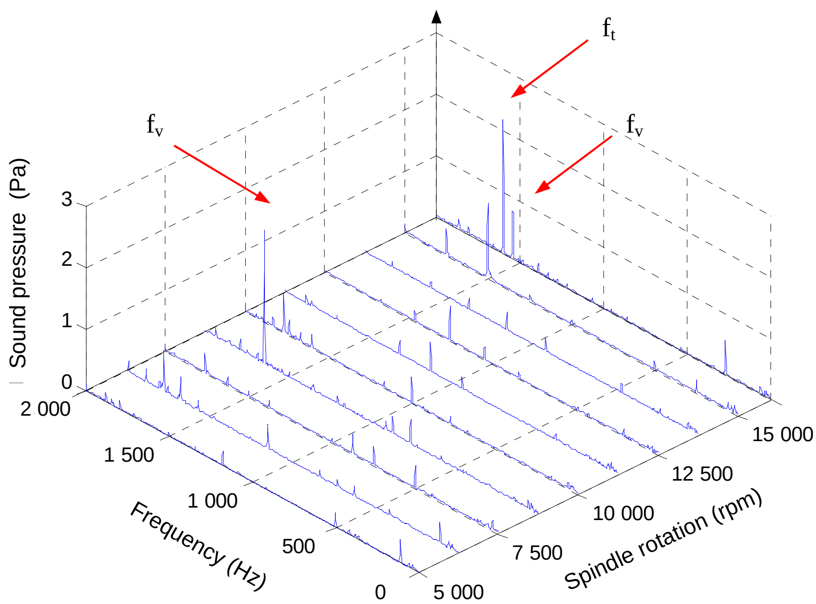

Workpiece material: ABNT P20 steel

Toll: Endmill
Diameter (D) [mm]: 12
Length (L) [mm]: 72
Number of teeth (z): 6

Down-milling
Axial depth of cut ($a_e$) [mm]: 2.5
Radial depth of cut ($a_e$) [mm]: 0.25
Feed per tooth ($f_z$) [mm]: 0.05

Figure 5. Sound pressure spectra for down-milling cuts

The graph of figure 6 shows the sound pressure spectra measured during the up-milling cuts. There are few differences in comparison to the spectra of the down-milling cuts. The peaks of the unstable conditions were less prominent for up-milling cuts. For the stable condition n = 15000 rpm, the peak correspondent to the tooth-passing frequency was higher, but it did not reflected on the surface roughness value. For the conditions n = 5000 rpm and n = 6250 rpm, the magnitude in the regenerative vibration frequency is lower than the magnitudes of the tooth-passing frequency and its harmonics for both cutting directions, what indicates the beginning of the instability. In these cases, the vibrations amplitudes were smaller than the other unstable cases, and they have fewer consequences on the surface finish.




Workpiece material: ABNT P20 steel

Toll: Endmill
Diameter (D) [mm]: 12
Length (L) [mm]: 72
Number of teeth (z): 6

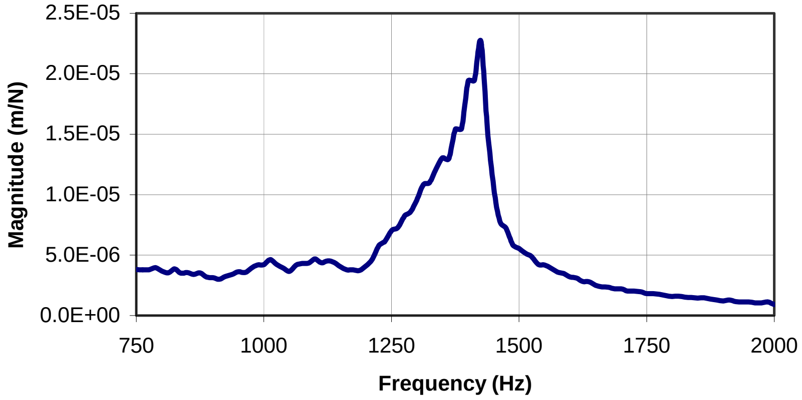
Up-milling
Axial depth of cut ($a_e$) [mm]: 2.5
Radial depth of cut ($a_e$) [mm]: 0.25
Feed per tooth ($f_z$) [mm]: 0.05

Figure 6. Sound pressure spectra for up-milling cuts

Best results were found for the spindle rotations, whose tooth-passing frequencies approach the natural frequency, but do not exceed this value. The same occurred when the tooth-passing frequency approaches the half of the natural frequency. The spindle rotation n = 7500 rpm, whose tooth-passing frequency was close but lower than the natural one, resulted in a stable cut and relative low surface roughness value. While for the spindle rotations n = 8750 rpm e n = 10000 rpm, the cuts were unstable and the surface roughness deteriorated.

### 3.2. Finishing ball-end milling

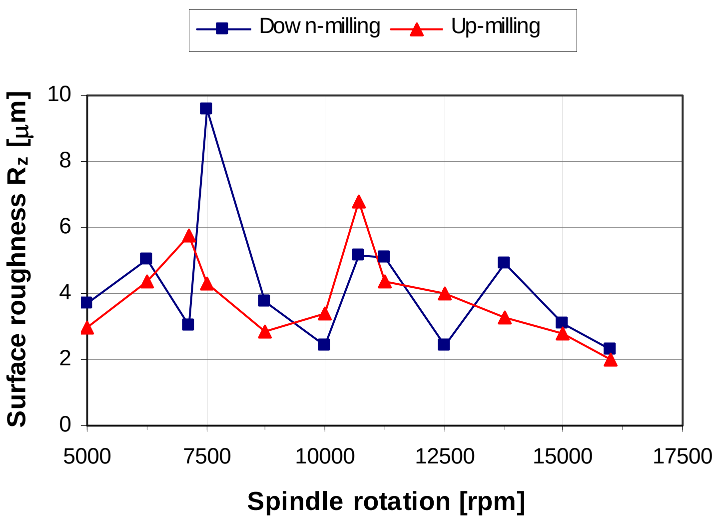
The graph of figure 7 shows the FRF measured at the end of a ball-endmill. The natural frequency ($f_n$) is 1425 Hz.




Tool: Ball-endmill
Diameter (D) [mm]: 8
Length (L) [mm]: 64
Number of teeth (z): 4
Machine: Hermle C800 U

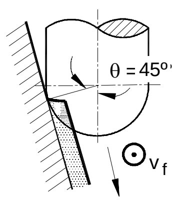
Figure 7. FRF measured at the of a endmill

Figure 8 shows a graph of the surface roughness parameter $R_z$ as a function of the spindle rotation for down-milling e and up-milling for a surface inclination of 45˚.




Workpiece material: ABNT P20 steel

Tool: Ball-endmill
D = 8 mm
L = 64 mm
z = 4 teeth




$\alpha = 45°$
$a_{et} = 0.2$ mm
$a_{en} = 0.2$ mm
$f_z$= 0.05 mm/tooth
Machine: Hermle C800 U

Figure 8. Surface roughness as a function of the spindle rotation for ball-end milling

There are differences between the values found for down-milling comparing to the up-milling ones. However, there are some regions with peaks and other with valleys, in a similar way for both cutting directions. The peaks are related to spindle rotations whose tool- passing frequencies are close to 1/2 or 1/3 of the natural frequency. The lowest surface roughness values are found to the spindle rotation n = 16000 rpm, which permitted the highest peripheral speed and corresponded to 3/4 of the natural frequency.

Figure 9 shows the measured profile for a stable cut. In this case the distances between the marks correspond to the feed per revolution or half of this value.

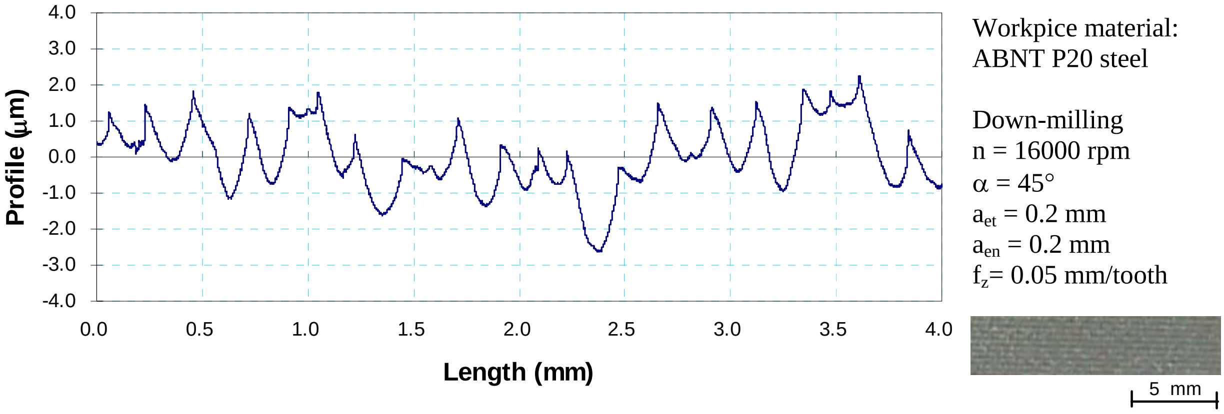



Figure 9. Surface profile for a stable condition

Figure 10 shows the surface profile for an unstable condition, which the tooth-passing frequency corresponded to the half of the natural frequency of the system. Due to the high vibration amplitudes the distance between the highest crest are close to six times the feed per revolution. Marks of the feed per revolution overlapped to the big ones are still visible.

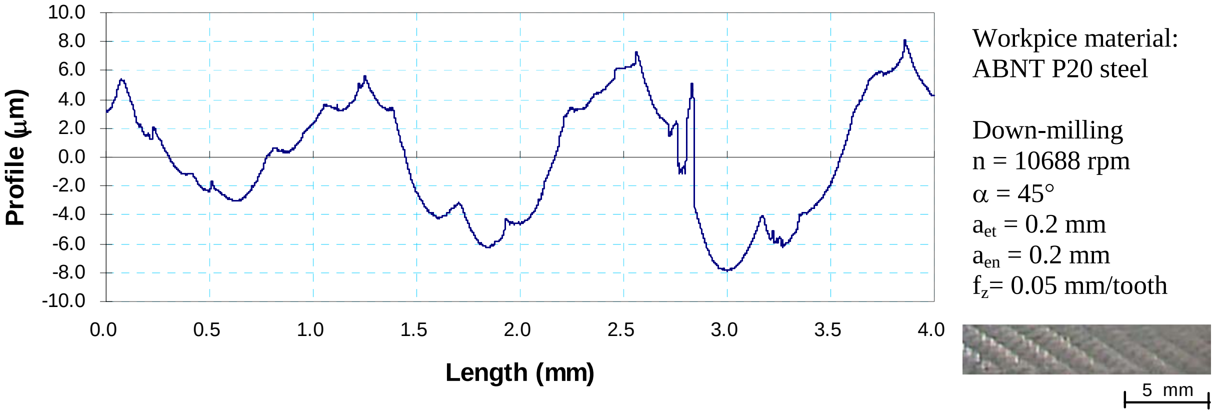



Figure 10. Surface profile for an unstable condition

The graph of figure 11 shows the sound pressure spectra measured during the down-milling cuts. The highest peaks are related to the spindle rotations whose tooth-passing frequencies ($f_t$) were close to 1/2 or 1/3 of the natural frequency ($f_n$). They correspond to the harmonics of the tooth-passing frequency closer to the natural of the system. Hence, the forced vibrations are the major limitation to this process.

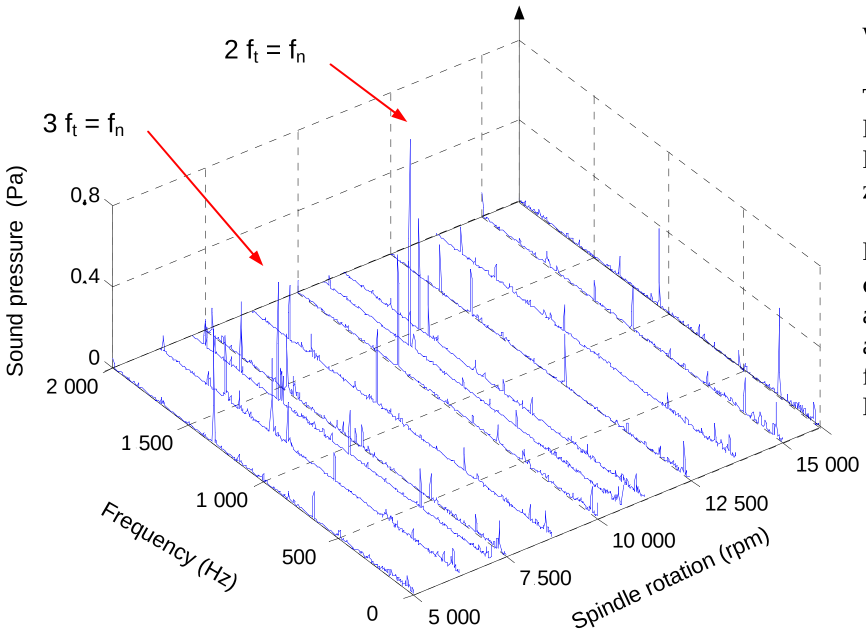



Figure 11. Sound pressure spectra for down-milling cuts

The graph of figure 12 shows the sound pressure spectra measured during the up-milling cuts. The highest peaks are related to the same spindle rotations similarly to the down-milling cuts. Therefore, it is confirmed the presence of the forced vibrations and discarded the regenerative ones. There is no other significant frequency besides the tooth-passing frequency and its harmonics.

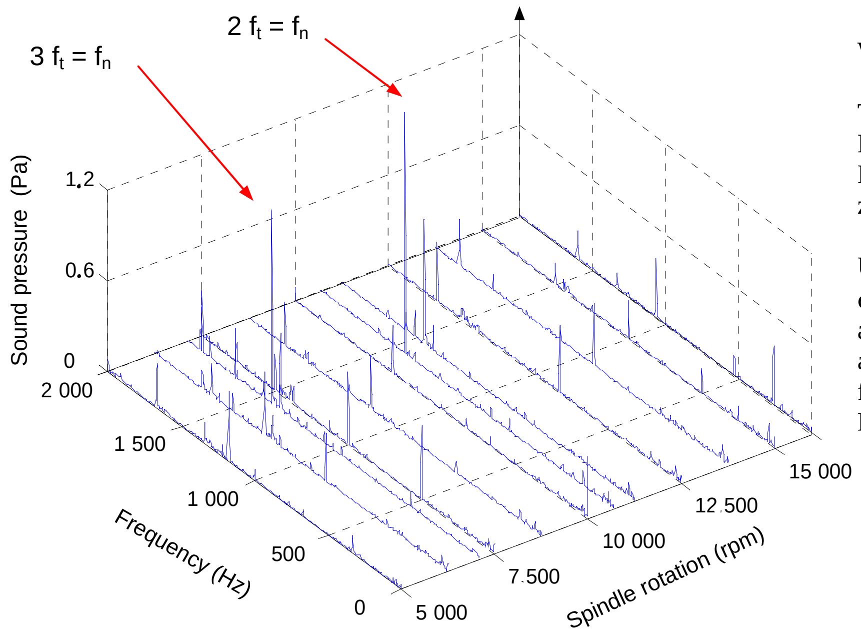



Figure 12. Sound pressure spectra for up-milling cuts

Best results are found for the spindle rotation n = 16000 rpm, whose tooth-passing frequency is close to 3/4 of the natural frequency. This is the condition where the harmonics of the tooth passing frequency have a distance from the natural frequency. Hence, the system has a smaller response to the periodic forces of the ball-end milling process. These results are similar to the ones found by Werner (1992) who made finishing ball-end milling experiments of horizontal and vertical surfaces.

The major difference between the surface roughness values for up-milling and down-milling occurred to n = 7125 rpm, whose tooth-passing frequency corresponded to 1/3 of the natural frequency. Despite the high magnitude in the spectrum for down-milling, the surface roughness value was relative low. However, for a spindle rotation a little bit higher (n = 7500 rpm), the amplitude was high enough to deteriorate the surface finish.

For up-milling, the peaks of the surface roughness curve follow the peaks of magnitude in the spectrum. The values increase for the spindle rotations whose harmonics of the tooth passing frequency are close to the natural frequency, and decrease for those whose harmonics of the tooth passing frequency have a distance from this value.

The fact that the forced vibrations are more critical to finishing ball-end milling is related to its engagement condition. Due to the small machining sections the contact region between tool and workpiece is reduced, and consequently occurs a minimization of the effects of phase difference between the undulations left by consecutive teeth, and get more importance the periodic excitation of the interrupted cut.

According to Janovsky (1996), the phase difference between the excitation force and the displacement which occurs in conditions next to the resonance leads to considerable dimensional errors, mainly to contact conditions where the surface generation occurs in the end of the tool contact.

## 4. Conclusions

In finishing end milling operations the highest limitation are the regenerative vibrations. For unstable cuts the sound pressure spectrum is dominated by the regenerative vibration frequency. Best results are found for the spindle rotations, whose tooth-passing frequency are close but lower than the natural frequency of the most flexible mode. Forced vibrations exert higher influence on the results for finishing ball-end milling. The highest peaks in the sound pressure spectrum are related to the spindle rotations whose tooth-passing frequency harmonics were closer to the natural of the system. Due to the small machining sections the contact region between tool and workpiece is reduced, and consequently occurs a minimization of the effects of phase difference between the undulations left by consecutive teeth, and get more importance the periodic excitation of the interrupted cut. Best results are found when the harmonics of the tooth passing frequency have a distance from the natural frequency.


## 5. Acknowledgements

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