Journal of Machine Engineering, 2019, Vol. 19, No. 3, 5–16
ISSN 1895-7595 (Print) *ISSN 2391-8071 (Online)*

Received: *22 December 2018* / Accepted: *05 July 2019* / Published online: *25 September 2019*

sound pressure level, machine enclosure,
noise transmission,
acoustic grid

Friedrich BLEICHER[1]
Christoph REICHL[2*]
Felix LINHARDT[3]
Peter WIMBERGER[2]
Christoph HABERSOHN[1]
Stephan KRALL[1]

INVESTIGATION OF NOISE TRANSMISSION OF A MACHINE TOOL ENCLOSURE

Machine tools are highly integrated mechatronic systems consisting of dedicated mechanic design and integrated electrical equipment – in particular drive systems and the CNC-control – to realize the complex relative motion of tool towards work piece. Beside the process related capabilities, like static and dynamic stiffness as well as accuracy behavior and deviation resistance against thermal influence, safety aspects are of major interest. The machine tool enclosure must fulfill multiple requirements like retention capabilities against the moving parts of broken tools, lose work pieces or clamping components. In regular use, the noise emission have to be inhibited at the greatest possible extent by the machine tool enclosure. Nevertheless, the loading door and the moving parts of the workspace envelope are interfaces where noise transmission is harder to be avoided and therefore local noise emissions increase. The aim of the objective investigation is to analyse the noise emission of machine tools to determine the local noise transmission of a machine tool enclosure by using arrays of microphones. By the use of this measuring method, outer surfaces at the front, the side and on the top of the enclosure have been scanned. The local transient acoustic pressures have been recorded using a standard noise source placed on the machine table. In addition, an exemplary manufacturing process has been performed to analyse the frequency dependent location resolved sound emissions.

1. INTRODUCTION

The occurrence of chattering in mashing operations can be regarded as one of the major effects resulting in work-piece defects and instable machining operations [1]. Chattering is a self-excited vibration caused by the cutting forces [2]. Existing examinations like [3] and [4] show, that chattering can be detected using sound emission analysis. However, besides the investigation of the process stability the influence on the human hearing should be taken into

---

[1] Institute of Production Engineering and Laser Technology, TU Wien
[2] Austrian Institute of Technology, Center for Energy, Sustainable Thermal Engineering, Wien
[3] Department of Geography, Earth Observation and Modelling, Kiel University, Germany
[*] E-mail: bleicher@ift.at
https://doi.org/10.5604/01.3001.0013.4076

account, too. By increasing the machining parameters of a milling process like cutting speed, feed per tooth or axial depth of cut, the sound pressure level rises due to a higher impact energy of the tool on the work-piece. This effect occurs particularly in milling processes with discontinuous cutting tooth engagement. Investigated sound pressure measurements e.g. in [5] depict, using a plane milling operation, a sound pressure level above 80 up to 100 dBA at a distance of 40 cm from the cutting zone. In fact, this exceeds the permitted value for noise emissions of machining equipment. With respect to the above mentioned research work, a plane milling process was set up to generate a noise emission by machining cooling fins of aluminum type EN AW 6060 T66. In order to achieve a deeper knowledge about the sound absorption potential of a machine tool enclosure experimental investigations have been performed focusing on the frequency dependency of the sound impedance. Due to long and thin ribs of the work-piece specimen, a cooling body, the selected geometry shows a significant chattering behavior. All investigations were performed on a conventional 5-axis machining center of type DMG MORI Seiki DMU75 monoBLOCK. The used measuring method to map the sound emissions of the machine tool enclosure consists of 60 microphones placed in front of the different machine surfaces (cf. [6–7]). Firstly, a broad band reference sound source is placed on the machine tool table, where the work-piece is normally mounted (cf. [4, 8]). After that, a sample manufacturing process is mimicked by cutting the aluminum test specimen [9–10]. Sound pressure levels and frequency spectra are compared for the machine enclosure surfaces for both setups [8]. With the proposed method, the sound encapsulation of the machine tool is characterized showing inhomogeneity in part of the outer shell as well as at the vicinity of door interface. However, by using microphone arrays it is possible to access correlated spatial and time resolved data from a real time dependent manufacturing process, the frequency dependent sound absorption of the machine enclosure can be used to predict the efficiency of the machine tool enclosure for damping the sound level for a defined cutting process.

2. RESEARCH METHOD

Sound pressure levels are recorded using calibrated measurement microphones positioned in front, at the side and on top of the machine enclosure of the machine tool (see Fig. 1). Up to 64 MICW M215 Class 1 measurement microphones have been connected to an 8 channel amplifier OctaMic XTCs via XLR cables. The OctaMics amplify the analog signal and convert them to a digital signal, which is transmitted via optical link (MADI) to the HDSPe MADI FX interface cards, which are synced via Word Clock signal. The setup is used for synchronous recording of the 64 signals with a sampling rate of 192 kHz and a resolution of 24 bits. The audio data is routed to Reaper via ASIO. The reaper is a digital audio workstation, originally capable of producing, mixing and mastering music. Reaper was chosen as recording software, because of its high customizability, scripting support and good VSTi - implementation allowing for easy evaluation of the audio data in real-time using FFT algorithms and spectrogram-visualizations. All microphones are calibrated by a Bruel & Kjaer calibrator (1000 Hz, 94 dB).

Fig. 1. Vertical microphone grid for measurements of the front machine side (left), of the right machine side (middle) and horizontal microphone traverse for top measurements placed in front of the machine (right)

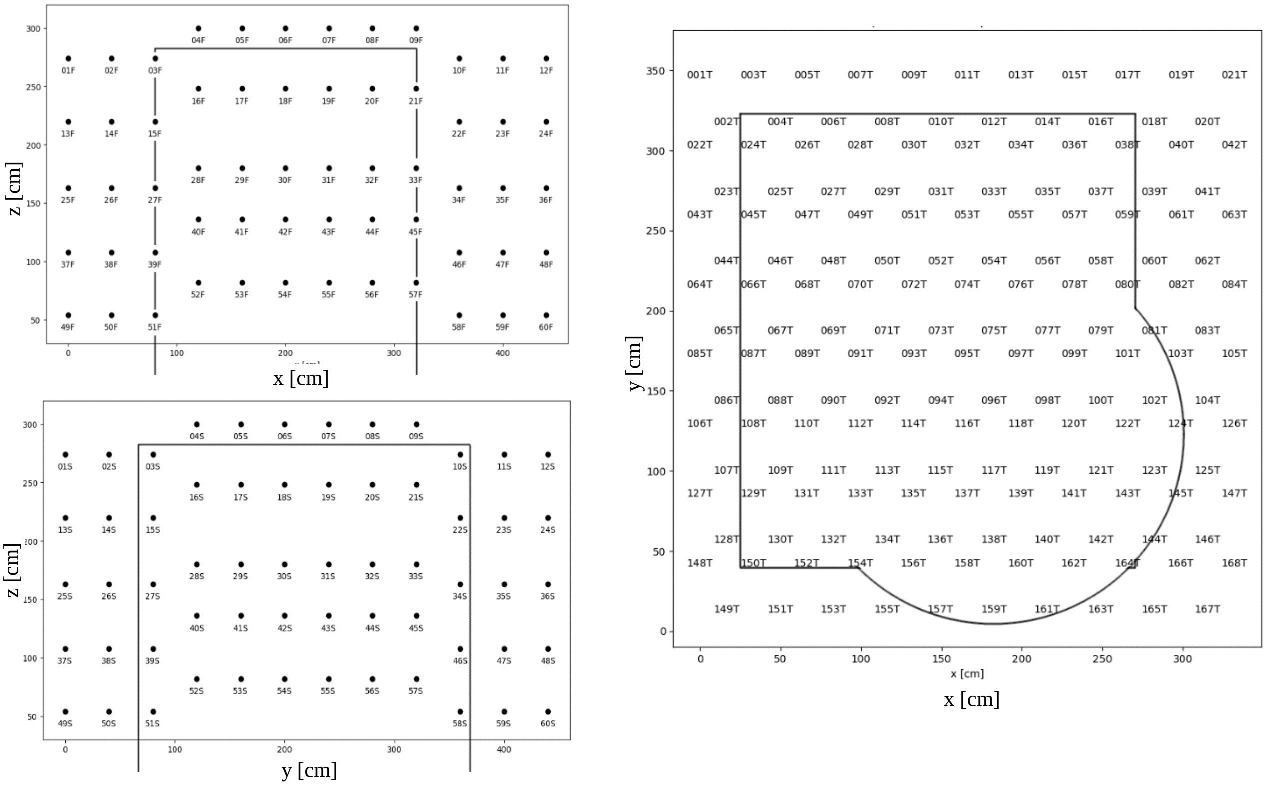


Fig. 2. Numbering of the microphone grid for front (upper left), side (lower left) and top (right), the machine contour is depicted as a solid line

For the side and front (see Fig. 1) measurements of the sound pressure level 60 microphones have been mounted in a vertical plane using a moveable metal rig. The numbering is shown in Fig. 2 using 01F–60F (front) and 01S–60S (side) as microphone numbers. In this, the bold line is showing the outer contour of the machine tool. For the horizontal surface above the machine a different approach has been selected. One traverse with 21 microphones (see Fig. 1) has been built and moved from the front to the back of the machine along the *y*-axis. As a result of this, a sound mapping of the entire enclosure planes of the machine tool can be created. The microphone positions are numbered from 001T to 168T (see Fig. 2). All microphones have been placed in a distance of 40 cm in front of the machine enclosure (nearest distance). As a reference signal, additionally one microphone (numbered) was placed inside the enclosure (see top right side of Fig. 3).

3. EXPERIMENTAL SETUP

3.1. STANDARD NOISE SOURCE MEASUREMENTS

A reference sound source NorSonic Nor278 has been placed on the machining table (see Fig. 3) and its sound emissions have been recorded on the front, side and top measurement planes. The reference sound source produces an uniform A-weighted sound power output of approximately 94 dB(A). Weighting is commonly introduced in acoustic data post processing to account for the relative loudness perceived by the human ear as defined in the international standard IEC 61672:2003. Independently from the sample manufacturing process which is characterized by distinct frequency ranges, this allows a broad band analysis of the sound transmission from the enclosure to the surrounding.

Fig. 3. Noise source placed on the work piece table
and inside microphone #64 on the top right side

In Fig. 4, the un-weighted sound pressure levels are shown with the corresponding microphone number (compare to Fig. 2). Sound pressure levels in the front of the machine range from 69.7 dB at the sides to 73.6 dB in the mid center in the vicinity of the floor. On the right side of the machine levels range from 70.0 in the upper left area (front part) to 77.9 dB again in the vicinity of the floor at the back of the machine. The levels measured above the machine are significantly higher and range from 71.9 dB (right front) to 79.0 dB at a spot in the left front center of the machine enclosure. Thus a difference of 7 dB between the front of the machine tool in typical hearing height (30F) compared to the maximum above the machine (112T) can been observed.

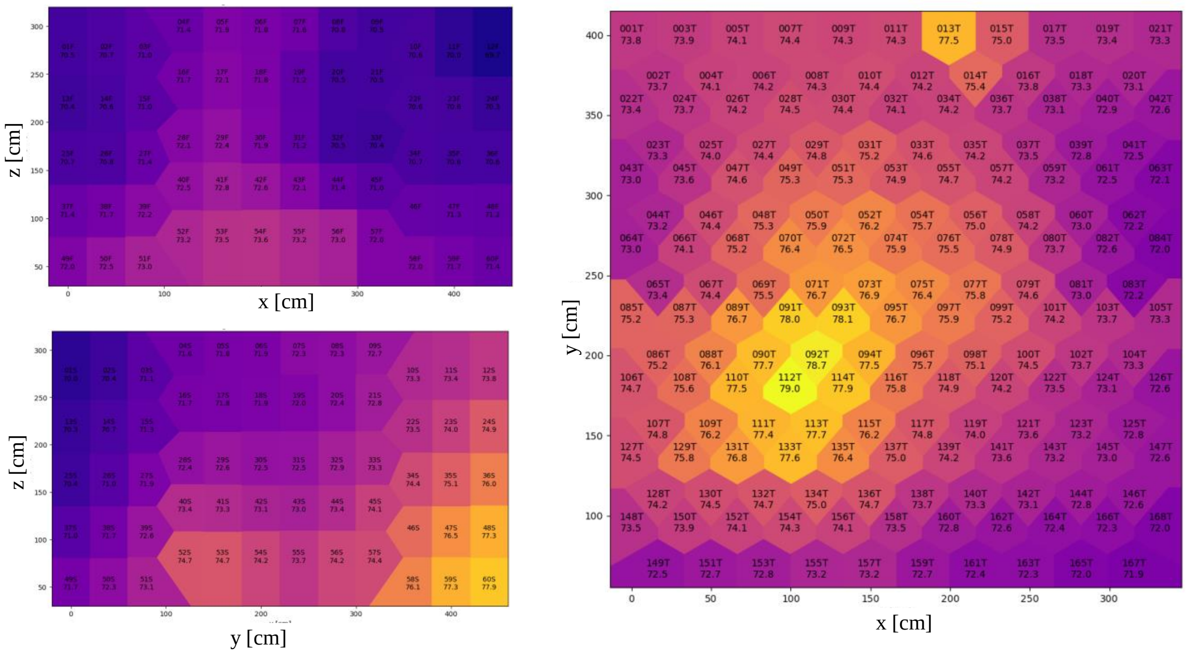


Fig. 4. Un-weighted sound pressure level in dB for the front (upper left), side (lower left) and top (right)

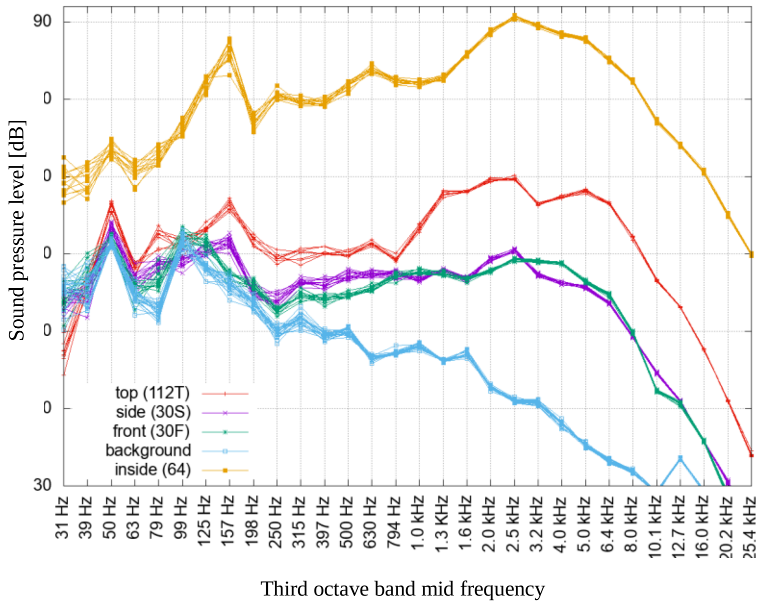


Fig. 5. Unweighted frequency spectra of the standard noise source at 3 selected microphone positions compared to the background sound pressure level and the measurement inside the enclosure. Several two second analysis periods are plotted for each microphone position

For selected microphones in front (30F), at the side (30S) and at the top side of the machine (112T) unweighted sound pressure frequency spectra are calculated. The results depicted in Fig. 5 are compared to the background signal and the sound pressure level spectra inside the enclosure (64).

In the low frequency range (less than 125 Hz) the machine contribution to the sound pressure level outside of the enclosure is very small. At higher frequencies, the directivity of the sound emissions is clearly visible, the upper sound path being especially pronounced between 1 kHz and 10 kHz. The data is also presented using the A-weighting in Fig. 6 (top).

The sound emission to the top significantly depends on the position above the machine. Fig. 6 (bottom) shows the frequency spectra for microphones parallel to the *y*-axis and visualize a range of 10 dB(A).

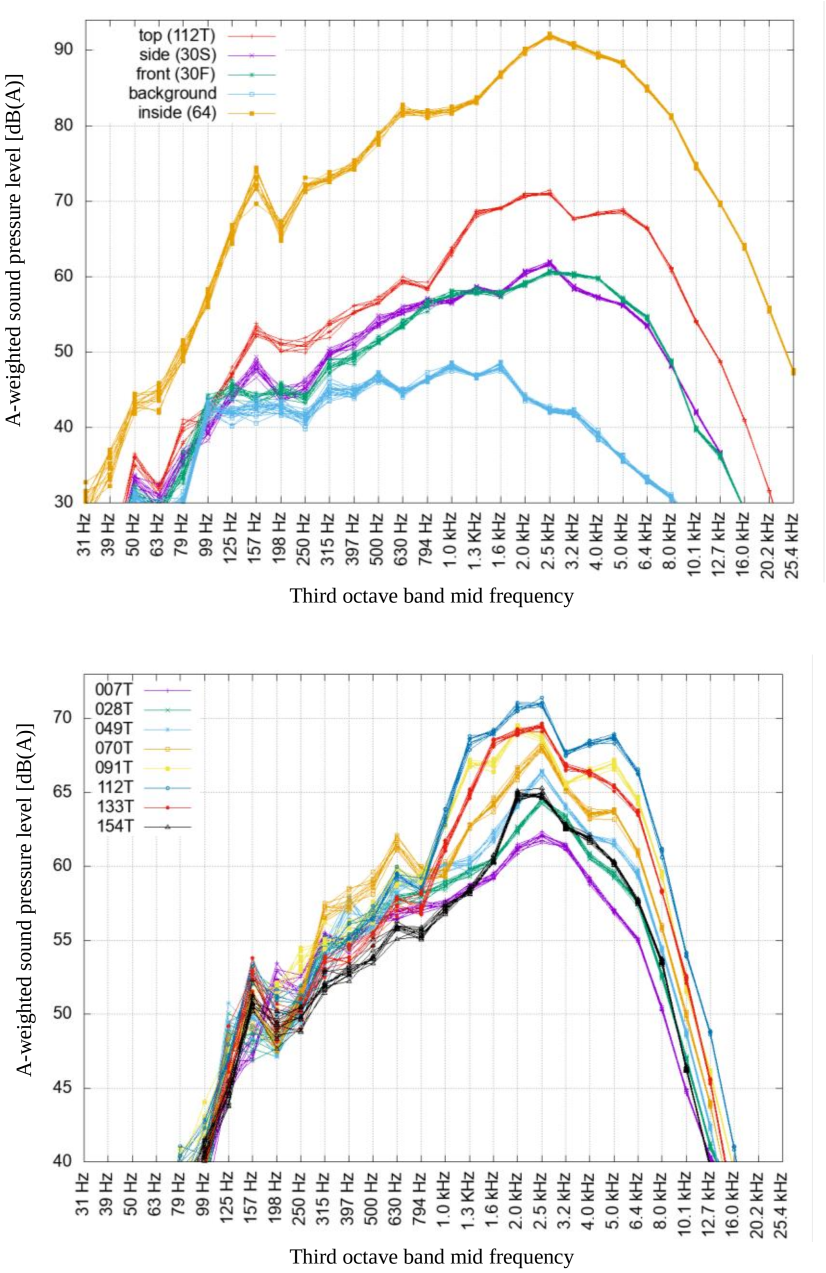
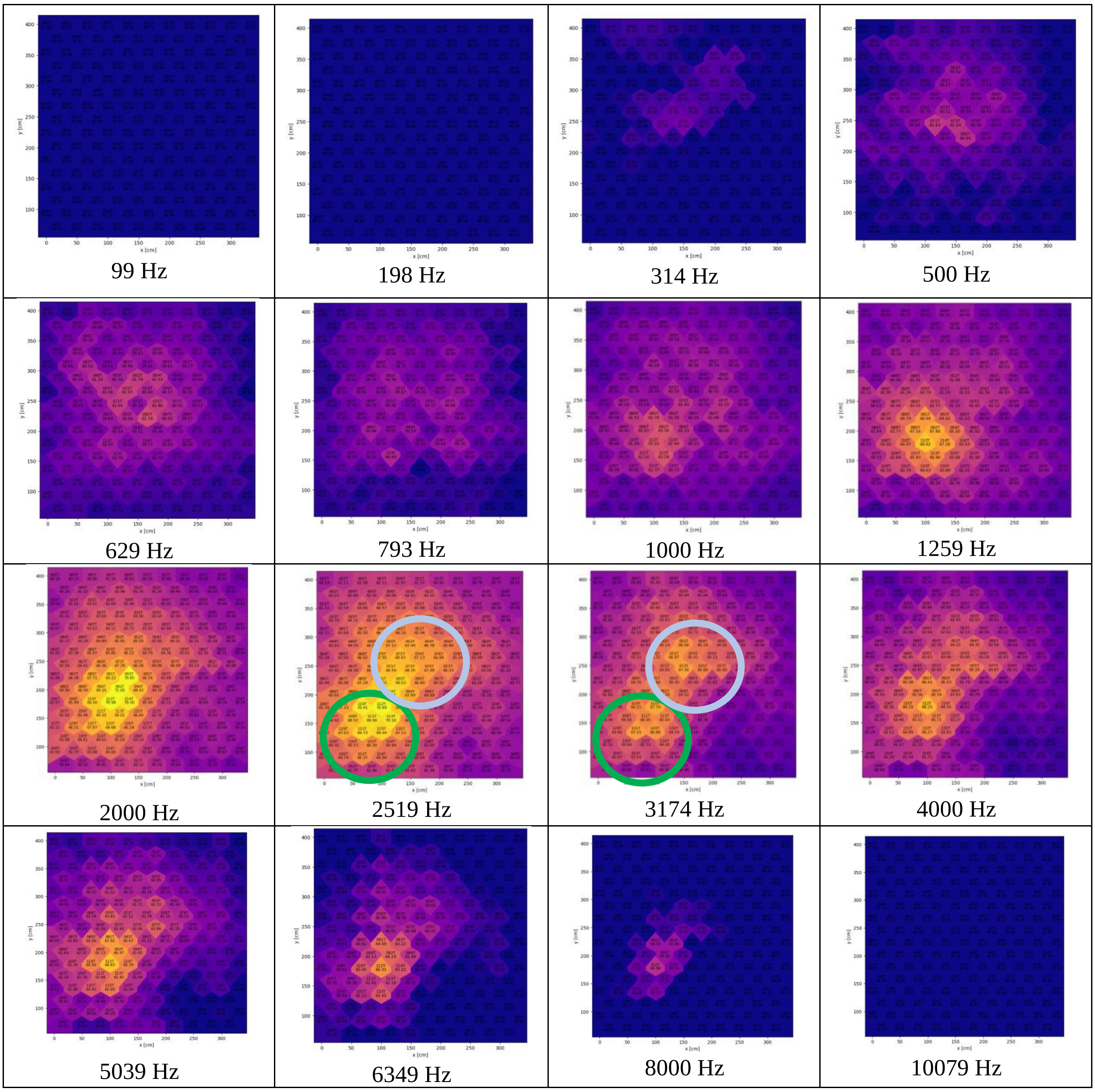


Fig. 6. A-weighted representation of Fig. 5 for reference (top); A-weighted sound pressure level at various positions along the *y*-axis at the horizontal measurement plane (bottom), (microphone numbers placed see Fig. 2)

Figure 7 depicts the A-weighted sound pressure level on top of the machine tool for different frequencies. As it can be seen by the frequency 2519 Hz and 3174 Hz, two different spots of high transmission can be identified. The green coloured spots has also higher transmission in different other frequency ranges. The blue coloured spots appear as significant only at the mentioned frequency ranges.

Another advantage of measurements using the standard noise source is the possibility to assess the noise transmission coefficients of the machine tool enclosure. This can be realized by scanning all surrounding surfaces and calculating the respective sound power level compared to the known directional independent value for the standard noise source. As it can be seen in Fig. 8, there is an absorption gab around 1500 Hz at the top of the machine tool, which causes an unwanted noise emission of the cutting process.



99 Hz | 198 Hz | 314 Hz | 500 Hz

629 Hz | 793 Hz | 1000 Hz | 1259 Hz

2000 Hz | 2519 Hz | 3174 Hz | 4000 Hz

5039 Hz | 6349 Hz | 8000 Hz | 10079 Hz

Fig. 7. A-weighted sound pressure level in dB at the top for different frequencies

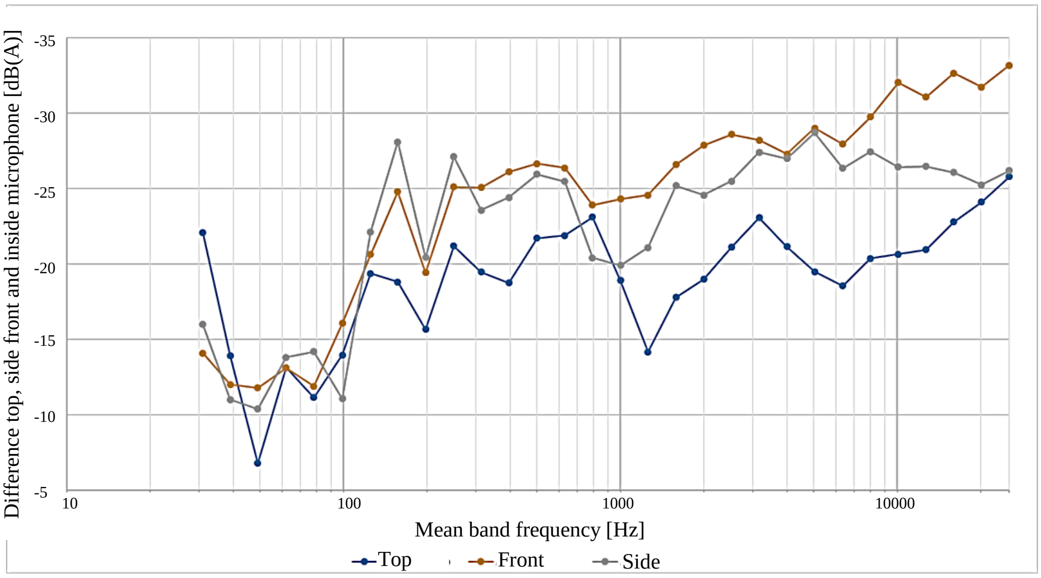


Fig. 8. A-weighted sound absorption in dB for front, side and top for different frequencies

3.2. EXEMPLARY MANUFACTURING PROCESS MEASUREMENTS

Whereas the reference sound source provides a broad band noise, real machining processes are characterized by the sound emission at distinct acoustic frequencies like the tooth-pass frequency of a milling tool. Thus, a test work-piece geometry, an aluminum profile for a cooling body type SK92, consisting of the material EN AW 6060-T66 is machined (see Fig. 9 and Fig. 10) using a face mill shell cutter with 6 cutting inserts with a diameter d = 80 mm. The process parameters like the feed rate was set to v = 1000 mm/min using a cutting depth of a_p = 1 mm, a spindle speed of s = 1000 U/min and a cutting speed of v_c = 250 m/min. The tool path is shown in Fig. 9.

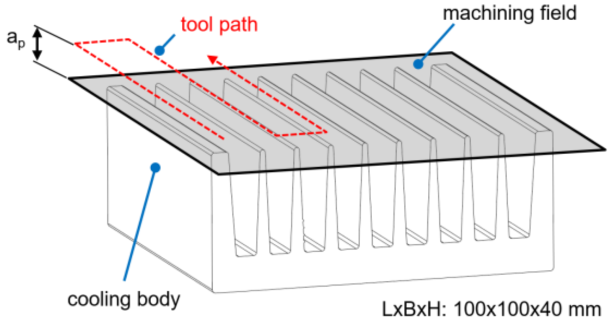


Fig. 9. Sample manufacturing process showing the machining area and the path of the tool (red)

Fig. 11 depicts the transient A-weighted sound pressure level during the machining process for three selected microphone positions compared to the levels recorded inside of the enclosure. As noted above, the reference sound source causes a difference of about 7 dB between front and top sound emissions.

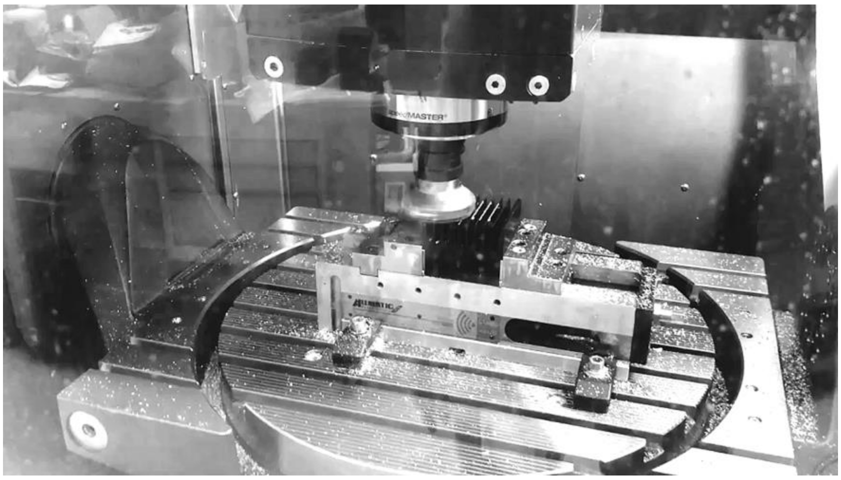


Fig. 10. Experimental setup for the sample manufacturing process, work-piece arrangement and the tool cutting through the test work-piece

Using a Fast-Fourier-Transformation (FFT) the time signal is transferred into the frequency domain. Typical sound emissions of the experimental manufacturing processes have been calculated and their results are recorded by Fig. 12. They vary depending on the machined volume as well as the position of tool.

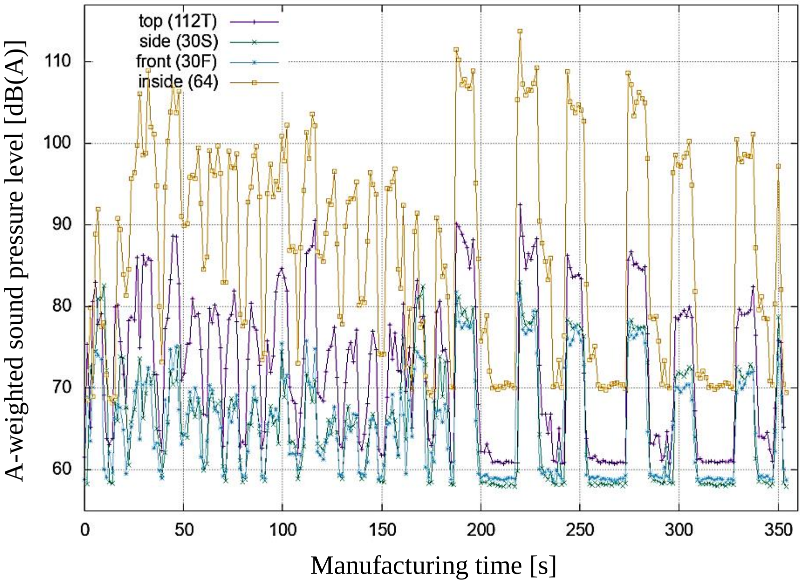


Fig. 11. A-weighted sound pressure level at 3 selected microphone positions compared to the measurement inside the enclosure during the machining test

As it becomes obvious by Fig. 12, well visible acoustic patterns can easily be distinguished. The frequency content for the top microphone 112T (hot spot in the measurements above the machine) is followed in a time period of 50 s in Fig. 13. The spectrum varies corresponding to the progress of the sample manufacturing process showing a sound pressure level range of more than 30 dB(A).

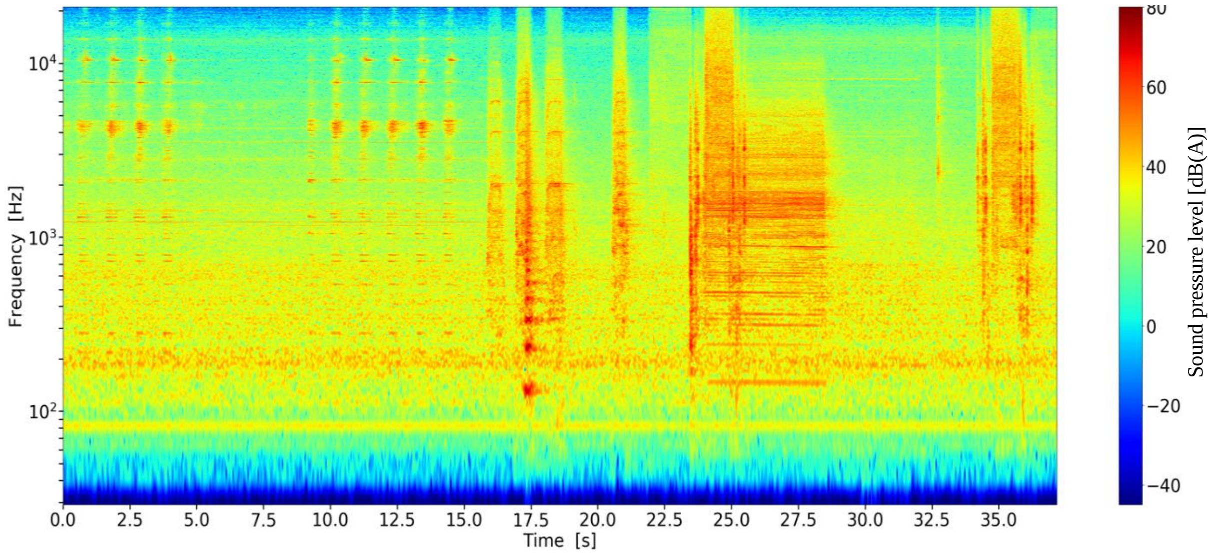


Fig. 12. Waterfall visualization of the top microphone position 112T starting from time 103 s in Fig. 11

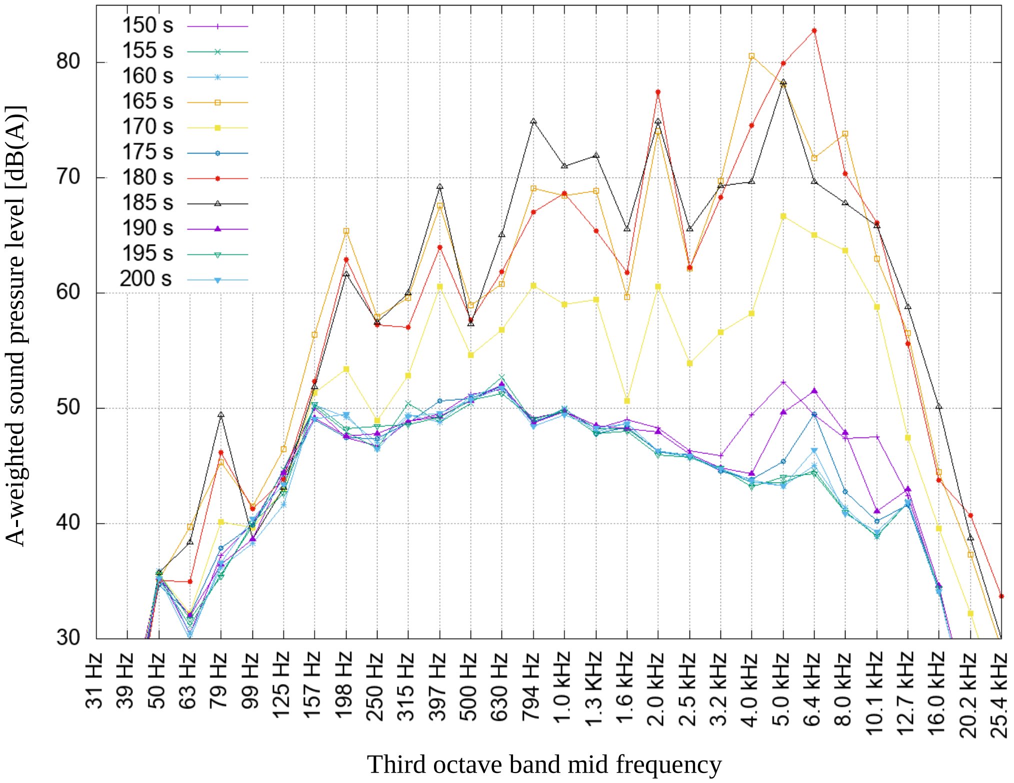


Fig. 13. A-weighted sound pressure level spectra at top microphone position 112T at different times during the sample manufacturing process

The time-dependant evolution of the A-weighted sound pressure level for selected microphones with high, mid and low sound pressure levels at top, side and front are finally compared in Fig. 14. Again, it can be observed that the sound pressure levels differ by 30 dB(A).

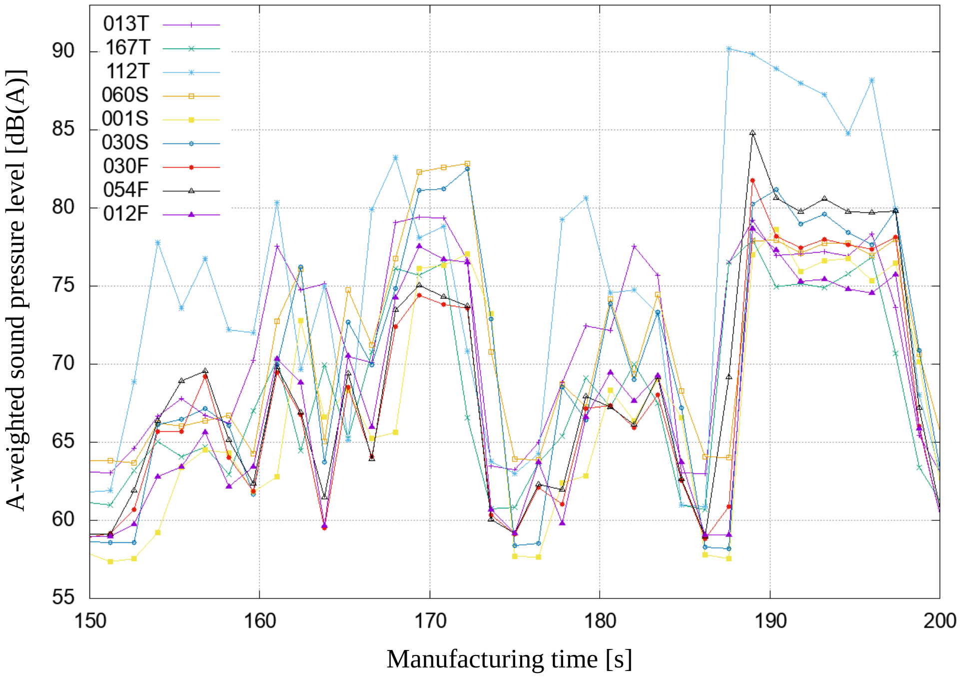


Fig. 14. A-weighted sound pressure level at selected microphone positions with low, intermediate and high values at the front, the side and the top

4. CONCLUSION

The machine tool enclosure is designed to inhibit noise emissions. The measurement methodology presented in this work is able to map the sound emission with high accuracy. This can be achieved by using a reference sound source inside the machine tool compared to values e.g. obtained in front of the particular surfaces. Differences between the emissions to the front of the machine (where the operator is mainly working) to the values on top of the machine tool can achieve up to 7 dB in this objective experimental setup. In addition, a machining process was Performed and the sound emission have been measured. Conventional sound measurements using a single measurement device would require a high number of repetitions (~230) to obtain a similar overview of weak areas of the machine tool enclosure. Beside that, the exact time correlation of each single signals would be lost. Microphone arrays allow to acquire time resolved data. The changes in sound pressure levels during the machining process are easily accessible exhibiting a range of 30 dB(A). Visualizing the frequency content of the sound emissions and by the use of the local resolved measuring data allow to identify areas in the machine enclosure, where acoustic shielding is imperfect. In this particular case, the interface of the machine tools loading door and parts of the roof shielding have been identified as promising areas for improvements. Due to acoustic reflections, particularly the emissions on top of the machine tool can lead to higher sound pressure levels compared to the area in front of the machining center.

Furthermore the frequency-response characteristic can be used to adapt the noise absorption characteristics of the machine tool enclosure according to typical sound emissions of the cutting processes. As a consequence, resulting from the measurements performed in this work the adaption of the spindle speeds and feed rates can be used to generate sound emissions in the range of frequencies with higher sound absorption values.

REFERENCES

[1] FU Q., RASHID A., NICOLESCU C.M., 2013, *Improving Machining Performance Against Regenerative Tool Chatter Through Adaptive Normal Pressure at the Tool Clamping Interface*, Journal of Machine Engineering, 13/1, 93–105.

[2] GROSSI N., SCIPPA A., SALLESE L., MONTEVECCHI F., CAMPATELLI G., 2018, *On the generation of chatter marks in peripheral milling: A spectral interpretation*, International Journal of Machine Tools and Manufacture, 133, 31–46.

[3] TEKINER Z., YESLYURT S., 2004, *Investigation of the cutting parameters depending on process sound during turning of AISI 304 austenitic stainless steel*, Materials and Design, 25, 507–513.

[4] SARRADJ E., 2010, *A fast signal subspace approach for the determination of absolute levels from phased microphone array measurements*, Journal of Sound and Vibration, 329, 1553–1569.

[5] RECH J., DUMONT F., LE BOT A., ARRAZOLA P.J., 2017, *Reduction of noise during milling operations*, CIRP Journal of Manufacturing Science and Technology, 18, 39–44.

[6] MUELLER T., 2002, *Aeroacoustic Measurements*, Springer.

[7] SIJTSMA P., 2009, *Clean based on spatial source coherence*, Int. J. Aeroacoustics, 6, 357–374.

[8] KOLLMANN F., SCHOESSER T., ANGERT R., 2006, *Praktische Maschinenakustik*, Springer, ISBN-10 3-540-20094-0.

[9] PRIME Z., DOOLAN C., 2013, *A comparison of popular beamforming arrays*, Proceedings of ACOUSTICS 2013,Victor Harbor, Australian Acoustical Society, 1–7.

[10] LACHAT E., MACHER H., MITTET M., LANDES T., GRUSSENMEYER P., 2015, *First experiences with Kinect V sensor for close range 3D modelling*, ISPRS, International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XL-5/W4, 93–100.