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Reduction of noise during milling operations

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ABSTRACT

With the increase in performance of machining operations, noise levels have become an occupational health and safety problems. Identification of the main sources of noise emission when milling an aluminium component was analyzed. A machining centre, equipped with microphones, was installed in an anechoic chamber. Testing demonstrated that the part's stiffness is the most critical parameter. Cutting speed, feed and axial depth of cut tend to increase sound pressure level by increasing the impact energy, whereas radial depth of cut is not a sensitive parameter. Moreover the diameter of mills, as well as their unbalance, should be limited.

Introduction

The main challenge for manufacturing plants is to produce parts at low cost. During the last 20 years, manufacturers of machine tools and cutting tools have developed new technical solutions, such as high-speed machine tools, or increased of mechanization, leading to great productivity improvements and reduction of labour costs. In recent years, environment impact has become an additional challenge. Decreased use of chemical products, such as cutting fluids and reduced energy consumption are clear examples.

An additional challenge is to limit the Occupational Health and Safety problems (OHS) impact of manufacturing plants on operators. Among the aggressions undergone by operators in a machining workshop, noise is a critical phenomenon since it affects them daily without any obvious short-term impact on hearing [1]. The long-term consequences, however, are dramatic for operators and costly for companies. Machining of aluminium parts (crankcase, cylinder head, etc.) is a clear example of this, where operators are exposed to high noise levels, especially in big workshops with a large number of machines with limited space between them [2,3]. The European regulation 2003/10/EC indicates two daily noise exposure levels for 8 working hours: (i) below 80 dBA, no protection is recommended, (ii) over 85 dBA, protection is necessary and the company must initiate a programme to reduce noise emission. Between 80 and 85 dBA, the company must offer individual protection to the operators and to test their hearing capacity annually. The critical daily noise exposure level of 85 dBA is often exceeded in the manufacturing industry [1,3].

As a consequence, technological advancements are needed to improve noise emissions of machining. A first solution consists of encapsulating the whole machine, which is not realistic in production system that requires operators. A second solution can consist of adding silencing equipment, which is always costly. A third solution is based on new machine components with passive damping components [4] or active mechanical components [5]. These approaches are valid for new investments but not for current machine-tools, that represent the vast majority of production systems.

So, a more effective strategy may consist in developing new machining strategies that limit noise emission.

Among all the noise sources during a cutting operation in a machining centre, almost any electrical and mechanical components of a machine-tool can generate noise (power supply, hydraulic systems, pumps, chip evacuation, air pressure leakage, etc.) even without any cutting operation [1]. In contrast, the cutting tool and the part can only generate noise when the cutting operation is in progress. Static components such as the fixturing and the mechanical structure can also generate noise due to the mechanical excitation of mechanical components induced by the cutting process.

In the case of machining an aluminium crankcase, preliminary research [6] showed that among all the cutting operations employed in the manufacturing of a crankcase in a plant, milling operations generate the highest sound pressure level (commonly higher than 100 dBA at a distance of 40 cm from the cutting zone – Fig. 1). Other processes such as drilling, tapping and reaming

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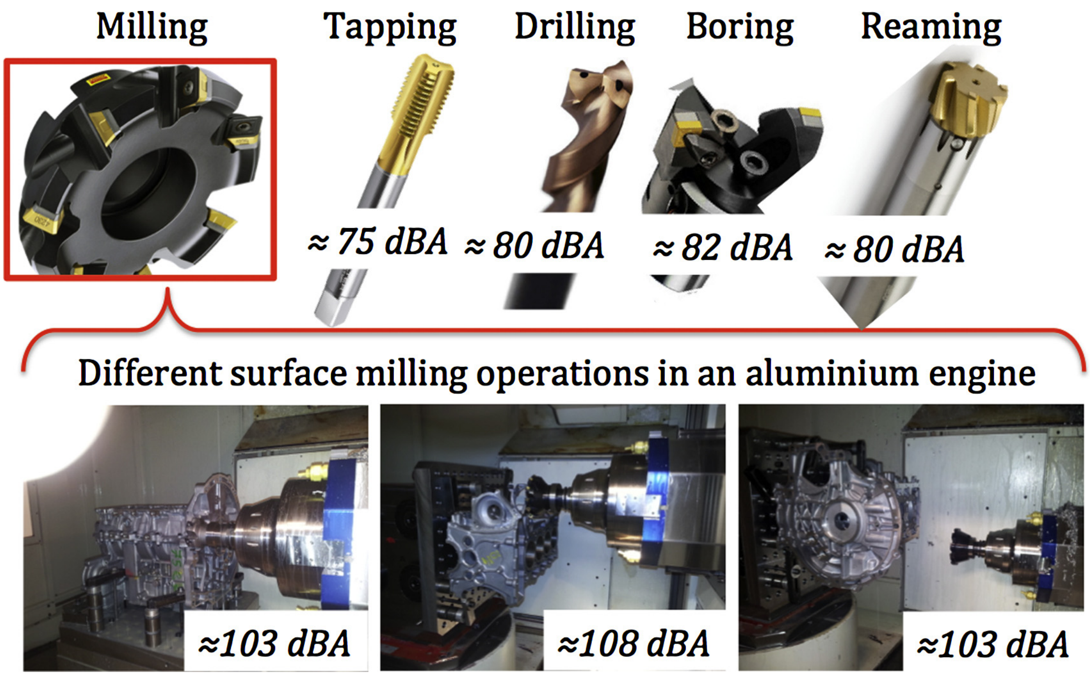

Fig. 1. Comparison of average sound pressure level emitted by various cutting technologies during the machining of an aluminium crankcase.

generate a sound pressure level of around 80 dBA. So, to reduce the noise emission in a workshop, it is necessary to focus on the milling process.

Most of the research carried out in machining or cutting to date has not considered the reduction of noise as the main goal. Several articles dealing with the monitoring of cutting tool wear [7–9] can be found in the literature, but unfortunately, most of them only consider high acoustic frequencies (>100 kHz), which are outside the range of human hearing (max. sensitivity between 1 and 5 kHz). Some authors also use sound emission analysis in order to detect chatter vibrations [10–12], but again they do not pay attention to relationship between sound pressure level and human hearing, nor do they consider the legal threshold.

This paper identifies the parameters that most influence noise emissions in a milling operation of aluminium parts. Then new milling strategies to reduce noise levels are proposed.

Development of an anechoic chamber

The characterization of noise emitted by a machining centre located in a workshop can be difficult since the all the equipment in the vicinity disturb noise measurements. Moreover, even if all the equipment is switched off, the enclosures and the walls of the buildings reflect noise, which disturb measurements [4]. For this reason, it is necessary to make such measurements in an anechoic chamber. An anechoic chamber with a hard floor was specially designed and built around a PCI METEOR 5 machining centre. The machining centre is a 4-axis horizontal machine typically used to produce aluminium parts in automotive machining plants. The dimensions of the chamber are presented in Fig. 2. The inside walls are built from ROCKFON® stone wool acoustics ceiling (ISO11654 absorption coefficient α_w in the range 500–5000 Hz) so as to avoid noise reflection and transmission from outside. In contrasts the outside walls consist of metallic cladding so as to facilitate external noise reflection.

It is worth mentioning that the cooling pump and its climatization system have been located outside the anechoic chamber. Indeed, in most industrial machining workshops, there is a single hydraulic system for the entire workshop. This equipment is usually installed far from the machining centre, which cannot induce noise disturbances for operators close to the machining area.

A data acquisition system was installed to collect milling process sound through two ½″ condenser microphones. One was placed inside the machine-tool enclosure (Fig. 2, micro 1 at 40 cm away from the cutting zone) and the other where operators are commonly installed to check cutting operations in front of the CNC system (Fig. 2, micro 2). Sounds were analyzed by sampling the signal of the microphones with a frequency up to 48 kHz. The signals were post-processed with a A-weighted filter in order to estimate the noise level in dBA within the range of the response to sound of the human ears. Finally, a spectral analysis was performed using the Fast Fourier Transform (FFT) algorithm to identify dominant frequencies.

Sensitivity study of sound pressure level

A sensitivity analysis was carried out to evaluate the most critical parameters of noise emission in the following machine states:

- First set of experiments: Switching on and off the machine tool (without milling).
- Second set of experiments (without milling): Rotation speed, tool diameter and tool balancing.
- Third set of experiments (in milling): Cutting speed, axial depth of cut, radial depth of cut and feed per tooth, part stiffness ratio.

Noise emission of the machine switched on and off

The first set of experiments analyzed the noise emission when the machine tool was switched off and on, without milling.

When the machine and air pressure admission were switched off, the sound pressure inside the anechoic chamber in the operator's zone (Fig. 2, micro 2) was around 42 dBA, whereas it was only 39 dBA in the cutting zone (Fig. 2, micro 1). As the sound in the operator's zone was higher, it means that the idling sound comes

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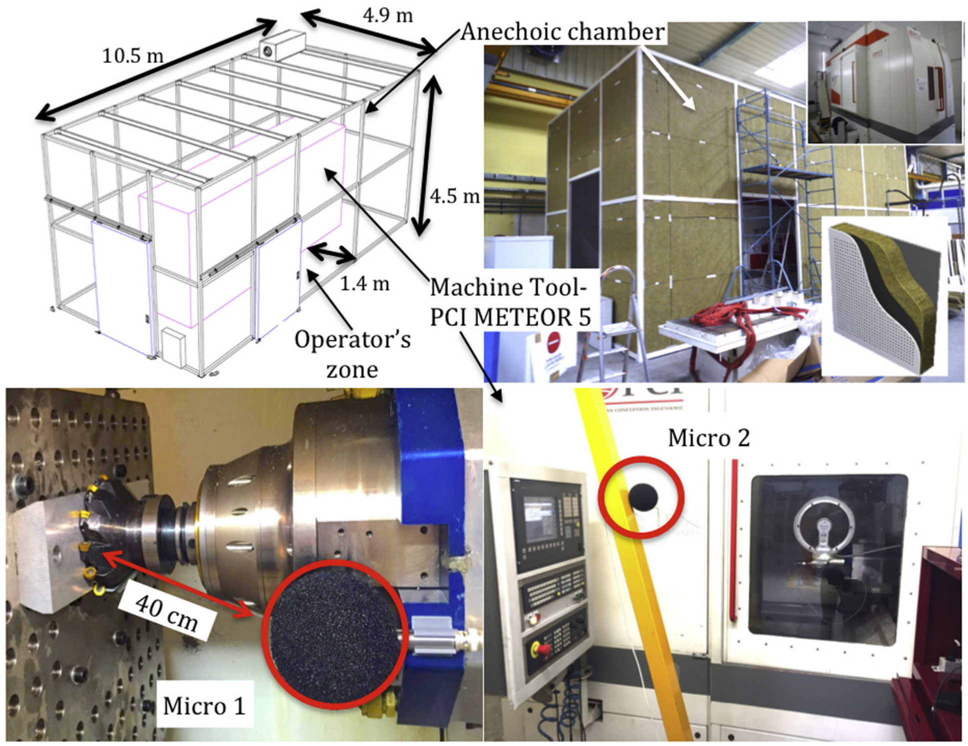

Fig. 2. Design of an anechoic acoustic chamber around a machining centre.

from the ambient of the anechoic chamber. In all cases, the ambient sound levels recorded were very low – comparable to those of a quiet office. This indicates that the anechoic chamber was correctly designed and significantly reduced external sound pressure levels (roughly 70 dBA).

When the machine was switched on (idling configuration, electrical systems and air pressure), the sound pressure level increased from 39 to 71 dBA in the cutting zone and from 42 to 52 dBA in the operator's zone. It was observed that air pressure leakage was clearly responsible for the great majority of this increase. In this case, noise in the cutting zone became 19 dBA higher compared to the operator's zone, which shows that the machine tool enclosure provided efficient insulation to protect operators. Therefore, pressurized air leakage should be avoided in machining centres.

It is important to note, that according to Eq. (1), an increase of the sound pressure level in the operator's zone from 42 to 52 dBA corresponds to a 3.1 times higher pressure on eardrum. However, this 10 dBA change is perceived by human ear as twice as loud.

$$Lp = 20 \cdot \mathrm{Log}\frac{P}{20 \times 10^{-6}} \qquad (1)$$

where Lp is sound pressure level (dBA) and P is the sound pressure (Pa).

Note that, for human hearing to perceive an increase in noise, a difference of 3 dBA is necessary.

Noise emission without cutting

The second set of experiments characterized the noise emitted by the spindle and a tool in rotation without milling. The effect of tool diameter (6 and 125 mm) and of tool balance (6–95 g mm for the surface mill and 2–80 g mm for the solid end mill) depending on the rotational speed was studied (Table 1). Each experiment was replicated five times in order to evaluate the maximum uncertainty in noise measurements, which was estimated to ±2 dBA (the graphs will be plotted with this value).

Fig. 4 plots the evolution of sound pressure level inside the machine enclosure versus the rotational speed. By comparing the noise emitted by the machine without any movement (micro 1 ≈71 dBA) and the machine in rotation (micro 1 average value ≈79 dBA), it was observed that the spindle rotation induced a significant increase of noise emission compared to an idling configuration (machine switched on, electrical systems and air pressure on), even for very low rotation speeds (lower than 4000 rpm). The reason for this was the aerodynamic noise which increases the sound pressure levels. In this low range of rotation speed, noise emission is mainly controlled by the components of the machine (spindle, motors, air pressure leakage), which explains the weak influence of the tool.

From rotational speeds of 6000–12,000 rpm, the noise emission of the surface mill (diameter 125 mm) increased steadily reaching 98 dBA at 12,000 rpm, whereas the solid end mill reached a value of 82 dBA. The characteristic frequencies of the machine and of the

Table 1
Tested parameters in the second set of experiments.

Parameter			Refer.	Range
Without milling	Balancing (g mm)	Mill 1: diam.: 125 mm–12 inserts	95	6 & **95**
		Mill 2: diam.: 6 mm-2teeth	2	**2**–20–40–60–80
	Rotation speed (rpm)		4000	1000–2000–**4000**–6000–8000–10000–12,000

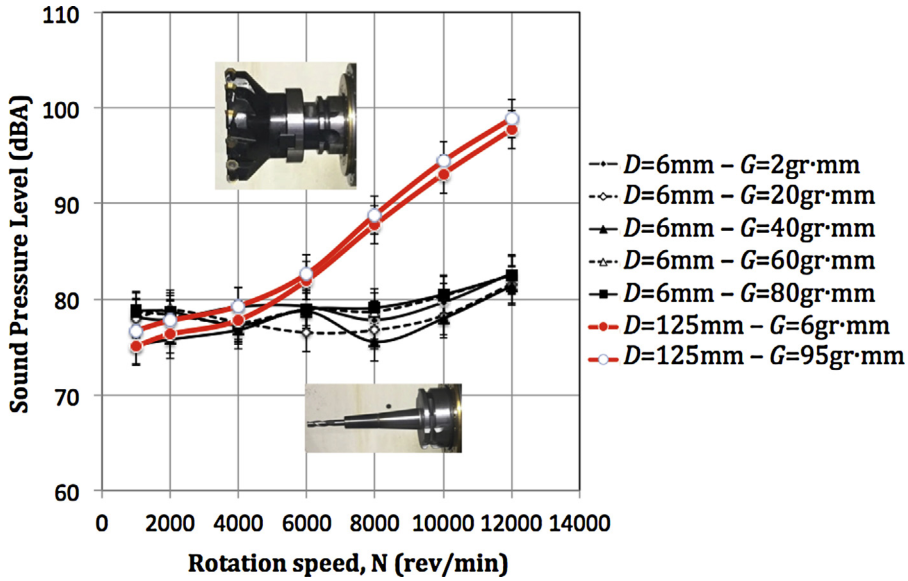

Fig. 3. Influence of rotation speed, tool balance and tool diameter on noise emission without milling.

spindle rotation at 12,000 rpm disappeared and a broadband noise appeared. This behaviour is typical for aerodynamic noises [13].

Regarding the influence of the tool balance, Fig. 4 demonstrates that the sound pressure level can be increased on average by 1–2 dBA with an unbalanced tool. This small increase was due to the higher radial force supported by spindle bearings.

To sum up, it was observed that the diameter of the tool is a key parameter for noise emission at high rotational speed, whereas tool balance is a secondary order parameter.

Noise emission in milling

The third set of experiments analyzed the noise emission depending on the Cutting speed, axial depth of cut, radial depth of cut and feed per tooth, part stiffness ratio. The machined samples had a "*L*" shape (Fig. 4), where the machined width defined the radial depth of cut (a_e), and together with the height (H), the stiffness ratio. The material was a common $AlSi_7$ die casted aluminium alloy employed in crankcases. The reference conditions and the range of variation for the experimental plan were chosen in accordance with industry experience (see Table 2).

Fig. 5 plots the evolution of the sound pressure level measured by the microphone outside (operator zone, lighter colours) and by the microphone inside (cutting zone, darker colours) depending on parameter values for milling conditions. The legal threshold of 85 dBA, over which individual protection is mandatory (only operator microphone), is plotted as well.

It was observed that for the reference milling conditions (v_c = 1571 m/min ⇔ 4000 rpm, surface mill) a very high sound pressure level of 92 dBA was obtained. The sound pressure level of the same mill in rotation without milling was only 79 dBA (Fig. 4). Milling generated an increase in sound pressure level (Lp) of 13 dBA, which corresponds to 4.5 times higher pressure. Moreover, by comparing the idling sound pressure of the machine in the operator's zone (71 dBA) and the sound pressure level in milling (92 dBA), the sound pressure was 10 times higher. Such a difference indicates that the noise of the machine in milling is dominant.

Fig. 5 also shows that milling sound pressure level increased from 84 dBA to 94 dBA when cutting speed v_c was varied from 500 to 2500 m/min for the 125 mm surface mill (rotation speed: 1273–6329 rpm). In Fig. 3, it can be observed that part of this increase is due to aerodynamic noise. Moreover, by observing the frequency domain (Fig. 5) for the reference milling condition an important peak can be observed. This corresponds to the tooth passing frequency (4000 × 12/60 = 800 Hz) together with its corresponding harmonics. So the increase of the sound pressure level in parallel with increased cutting speed can also be attributed to the increase in impact energy provided by the spindle. In fact, the cutting power in milling can be expressed by the following equation [14]:

$$Pc = \frac{a_p \cdot a_e \cdot f_z \cdot Z \cdot K_c \cdot v_c}{\pi \cdot D \cdot 60} \quad (2)$$

Fig. 5 also shows the evolution of the sound pressure level for a range of feed per tooth (0.05–0.2 mm/rev), for a range of axial depth of cut (0.5–2 mm), for a range of radial depth of cut (20–95 mm) and finally for a range of stiffness ratio (0.08–4).

It was observed that when increasing the feed per tooth, the sound pressure level increased from 88 to 95 dBA. This may be due to the increase of the cutting force applied to the mechanical system (tool + spindle + machine-structure + fixturing + part). The

Table 2
Tested parameters in the third set of experiments.

	Parameter	Refer.	Range
In milling Mill1: diameter: 125 mm–12 inserts	Cutting speed (m/min) (rotational speed (rpm))	1571 (4000)	500–1000–1250–**1571**–1750–2000–2250–2500 (1273–2546–3183–**4000**–4456–5092–5729–6366)
	Feed per tooth (mm)	0.15	0.05–0.075–0.1–**0.15**–0.175–0.2
	Axial depth of cut (mm)	1	0.5–0.75–**1**–1.25–1.5–1.75–2
	Radial depth of cut (mm)	95	20–24–40–50–65–75–**95**
	Stiffness ratio (a_e/H)	1	0.08–0.17–0.33–**1**–2–2.5–4

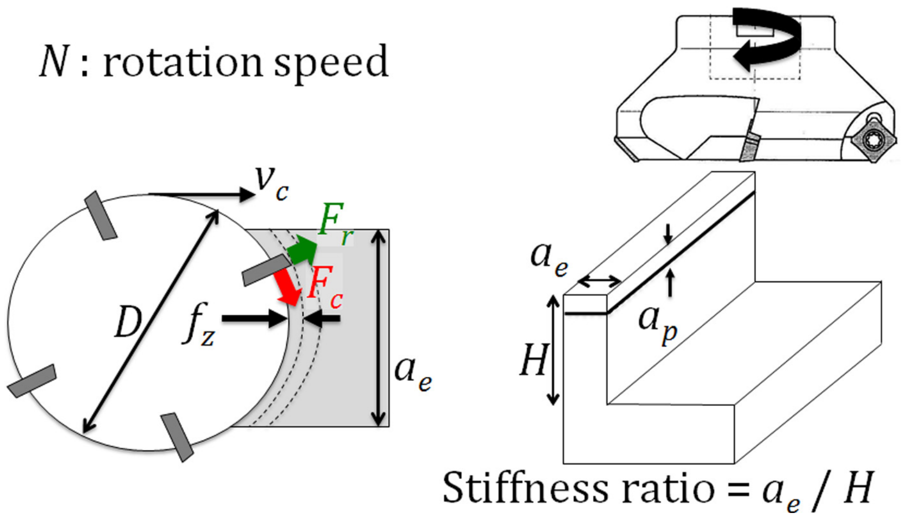

Fig. 4. Cutting parameters in surface milling.

cutting force can be estimated by the following equation [15]:

$$Fc = a_p \cdot f_z \cdot K_c \quad (3)$$

When axial depth of cut was increased from 0.5 to 2 mm, the sound pressure level increased from 91 to 100 dBA. This observation may also be as a result of the increase of the cutting force applied to the mechanical system as shown by Eq. (3).

In the case of radial depth of cut, this parameter appeared to have less sensitive influence on noise emission when reduced from 20 to 95 mm. In fact, radial depth of cut does not significantly influence cutting force. It mainly influences the duration of the contact between the cutting tooth and the part, which has limited impact on sound emission.

When analysing the sound pressure level depending on the stiffness of the part, it was observed that for stiffness ratios of 1 and

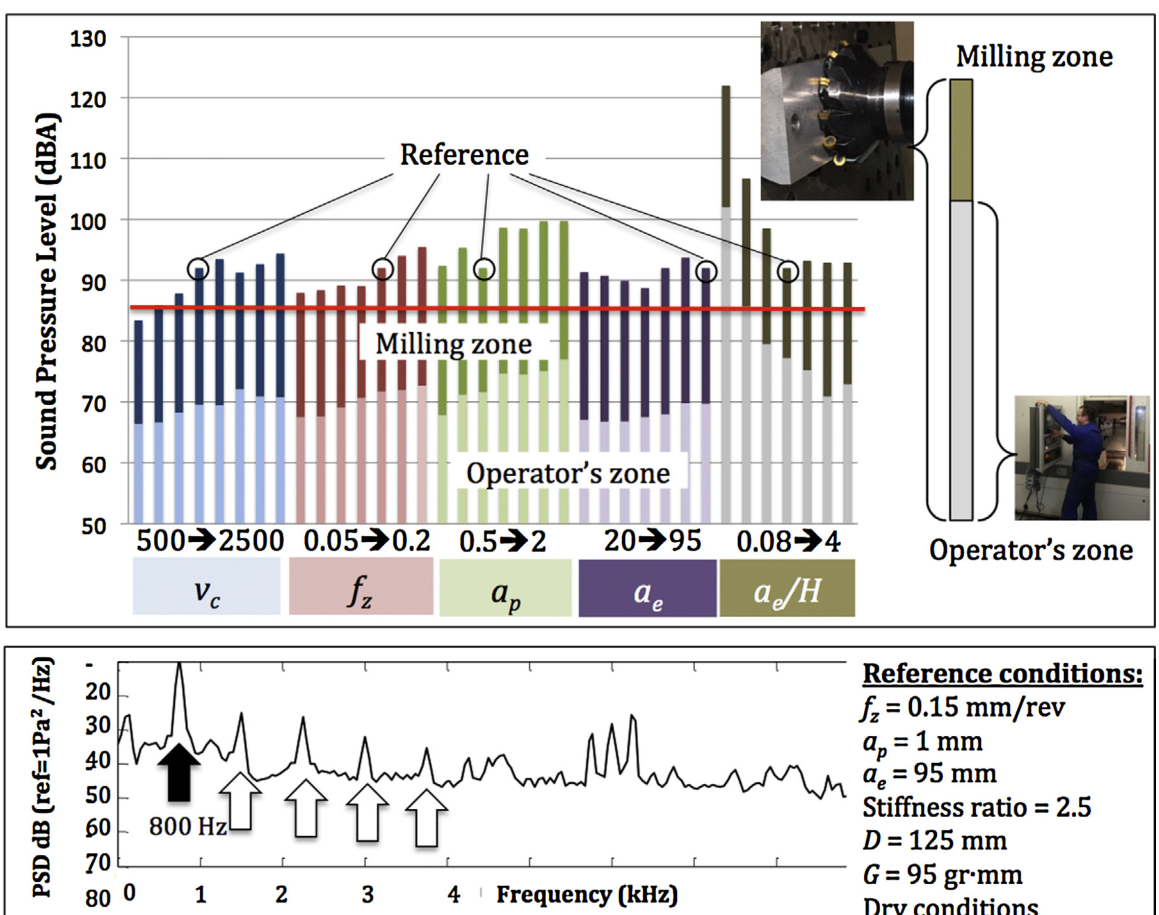

Fig. 5. Synthesis of the sensitivity study.

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higher, the sound pressure level was not significantly influenced, being 92 dBA (inside). However, when the stiffness ratio was lower than 1, the sound pressure level increased dramatically reaching values of 122 dBA (inside) and 102 dBA (outside). This is due to the fact that the milling operation becomes unstable with a flexible part causing the chatter to become dominant. Thus the stiffness of the part can increase sound pressure level by more than 30 dBA (sound pressure 31 times higher) compared to a rigid configuration.

The noise level of 122 dBA exceeds the legal threshold acceptable for 8 working hours. The European regulation specifies that the daily exposure duration to a level over 102 dBA must be limited to 10 min. With a flexible part, the milling operation becomes unstable and the chatter becomes dominant.

Thus to summarize the influence of cutting parameters, the results indicate that stiffness ratio, cutting speed, feed per tooth and axial depth of cut tend to increase the sound pressure level. This is due to the increase of the impact energy transmitted to the mechanical system, which responds by vibrating and therefore radiating structure-borne noise. Indeed milling induces mechanical impacts at the contact between each cutting edge and the workpiece. Then the vibration propagates through the mechanical components (tool + spindle + machine-structure + fixture + part). In the present work, the weak element of these components was the part itself, but it can also be the tool or any other components. For instance, by selecting a small diameter mill, industry can face similar problems. So, a compromise has to be found between a small diameter that limits sound emission due to air turbulences and a large diameter that limits chatter.

As a consequence, when facing severe noise emission, industry has first to develop original clamping systems that increase part's stiffness or that damps vibration efficiently, for instance by active damping as proposed by [5].

Conclusions

As the machining industry pay serious attention to workshop noise levels, and their impact on occupational health and safety, an original anechoic chamber containing a 4-axis horizontal spindle machining centre was designed and validated in order to investigate noise emission in machining. Testing in this experimental set-up, highlights that new machines will need to be designed so as to limit noise emission, especially air leakage, and to dampen noise with appropriate enclosures.

The results demonstrate that, among cutting operations performed on a machining centre, milling is by far the most critical process. The work also shows that:

- The stiffness of the part ratio is the most critical parameter leading to an increase of more than 30 dBA of the sound pressure level.
- Without milling, spindle noise dominates at relatively low rotation speeds but aerodynamic emissions dominate at highest speeds.
- In machining, cutting speed, feed per tooth and axial depth of cut induce an increase of sound pressure level due to the increase of impact energy, when cutting teeth come in contact to the part.
- Radial depth of cut only slightly influences noise emission.
- Mills with a small diameter and with a good balance are preferred in order to avoid air turbulences that are responsible for excessive noise.

Acknowledgement

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