DEVELOPMENT OF VIBRATIONS DUE TO CHANGING SPINDLE SPEEDS DURING MILLING

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The article analyses the problem of measuring and examining the magnitudes of vibration amplitudes at the machining of materials by milling technology. By measuring the vibration parameter on the spindle head of a universal milling machine, the level of the vibration amplitudes magnitude during the milling process was acquired using a piezoelectric vibration sensor. The magnitudes of the vibration amplitudes were recorded during machining when the spindle speed varied between 1200 rpm and 1600 rpm. The measured values were evaluated in the form of FFT spectra, and the information required to design measures to avoid excess vibration amplitudes in such a case was obtained.

KEYWORDS

Material, milling technology, vibration amplitude, frequency analysis, frequency

1 INTRODUCTION

The occurrence of oscillatory motion is an integral part of the operation of production machines and equipment, which are mechanical systems. However, this part of the operation is in most cases undesirable both in terms of the operation of the machine itself and in terms of the working environment - noise and transmission to the structure of the production areas.

Vibrations when machining materials using milling technology arise from two causes. First of all, because the chip is removed intermittently during milling, with the tool teeth being engaged alternately. These are vibrations forced by the action of the tool and are perceived as a normal and easily understood consequence of this method of machining [Parus 2013, Hlavac 2018]. The second cause of vibration in the milling process is that the cutter teeth are machining an undulated surface. In that case, it is considered what happens when the first tooth of the cutter is run into the bore. Due to the cutting force, the entire machine mechanism, including the tool, is elastically deflected to a certain position and then released after chip separation. As a result of the rapid release, the machine oscillates and the next tool tooth entering the cut "copies" these oscillations on the surface of the workpiece. The machined surface is undulated and the next tooth already cuts this undulated surface, whilst oscillating itself against this surface [Zhong 2010]. The undulations on the machined surface and the tool's oscillations are temporally displaced relative to each other, the cross-section of each chip is uneven, it is regularly undulated. The cutting force is therefore also variable according to this cross-section and further induces the oscillations of the machine and the tool [Huang 2010 and 2012]. The whole process is constantly repeated and the oscillations between tool and workpiece are constantly renewed [Svinin 2007]. That is related to self-excited oscillations, i.e. those induced by the cutting process. In rough milling, the depth of cut is large, the cutting force is large and therefore these oscillations increase rapidly and sometimes threaten to damage the tool [Tlust 1963]. In that case, machining must be interrupted.

However, self-excited oscillations also occur in light or finishing cuts, that is, in very small cross-sections of three. They also occur with small machine loads, as long as slender tools are used which are easily oscillated by their own action [Butt 2018]. In addition to the poor surface quality, the intense sound at relatively high frequencies linked by self-excited oscillation is also unpleasant. The self-excited oscillations are maintained or even developed by the fact that the cut surface waves are displaced relative to the oscillations of the instrument and the chip has a periodically varying cross section [Antonialli 2010]. If this cause is removed, the oscillations will disappear. The instructions on how to do this are simple - just synchronise the waves with the oscillations of the tool and thus achieve a constant cross-section of the chip. Because the oscillations are actually caused by the phase Ψ and removing it will suppress the oscillations. In addition to milling stabilizations, it is possible to increase machine stiffness, increase tool stiffness, use a milling cutter with irregular tooth spacing, or reduce chip cross section. Both machine and tool stiffness should always be the highest possible [Rashid 2006 and 2008, Munoa 2015, Moradi 2015, Krenicky 2020 and 2022, Olejarova 2021]. However, it has its limits due to the need to machine in remote parts of the machine work area or the need to machine in narrow gaps between the workpiece walls, i.e. with slender tools. Tools with irregular tooth spacing are very effective in suppressing chatter. On the other side, reducing the chip cross-section increases machining time. Thus, the main aim of this article is to study vibration characteristics during machining of selected materials using the milling technology.

2 MATERIAL AND METHODOLOGY

Experimental methodology:

The experimental measurement of the magnitude of vibration amplitude was carried out on a BMCL 5000VS universal CNC milling machine head (Fig. 1) while machining three types of materials in Kipech Production s.r.o. The material types used were machined by milling technology by combining the parameters namely constant feed rate (150 mm/min) and varying spindle speed (1200 rpm and 1600 rpm).

Figure 1. Universal CNC milling machine type BMCL 5000VS

The HSSCo8 groove milling cutter was used to machine the different types of materials. The technical parameters are shown in Table 1.

Test samples:

During the measurement of the magnitude of vibration amplitudes, three selected types of materials - 11 600 structural steel, duralloy, alkaline polyamide - were machined by milling technology. Non-noble structural steel (Fig. 2) of standard grade with higher carbon content. It is suitable for machine components which are subjected to static and dynamic stresses and do not require weldability. The basic mechanical properties are given in Table 2.

Table 1. Technical parameters of the tool used when machining selected types of materials

groove cutter type HSSCo8	
	
Name	**Value**
Ø d1 = e8	1,00 mm
Brite length	2 mm
Total length	34 mm
Ø of shank d2 = h6	6 mm

Figure 2. Machining of material structural steel 11 600

Duralumin (AlCu4Mg) is an alloy of aluminium copper and magnesium, with a magnesium content of less than 1% and a copper content of 4%. This aluminium alloy is well formable both hot and cold. The machinability of duralloy is given in Fig. 3 and its mechanical are given in Table 2.

Figure 3. Machining of duralumin material

Figure 4. Machining of alkaline polyamide material

Alkali polyamide PA6G is a thermoplastic material that is able to meet most requirements for the use of engineering plastics due to its properties, hardness strength, toughness and low sliding resistance. Fig. 4 shows the machining of the alkaline polyamide material and Table 2 shows its mechanical properties.

Table 2. Mechanical properties of the types of materials used in milling machining

material structural steel 11 600	
Name	**Value**
Tensile strength Rm	590 – 710 MPa
Yield strength Re	min. 325 MPa
Hardness HB	180 – 210 MPa
material duralloy	
Name	**Value**
Tensile strength Rm	380 MPa
Yield strength Re	240 MPa
Hardness HB	90 – 125 MPa
material alkaline polyamide	
Name	**Value**
Density	1,13 g/cm3
Tensile strength Rm	85 MPa
Hardness HB	160 MPa

Description of the measuring device:

A miniature piezoelectric sensor Bruel & Kjaer type 4514-B was used for sensing the magnitude of vibration amplitudes. The sensor technical parameters are given in Table 3. The sensor was attached to the spindle head of a BMCL 5000VS type universal CNC milling machine by using a magnet. The data acquisition was performed using a 4-channel analyser National Instruments NI-9233.

Table 3. Basic technical parameters of the 4514-B sensor

Sensor 45 14-B	
Name	**Value**
Range of measurement	500 - 4900 $m.s^2$
Measurable frequency	32 kHz
Sensor sensitivity	100 mV/g
Input impedance	20 Ω

3 RESULTS AND DISCUSSION

The analysis of the results of the experimental studies was divided into the following phases:

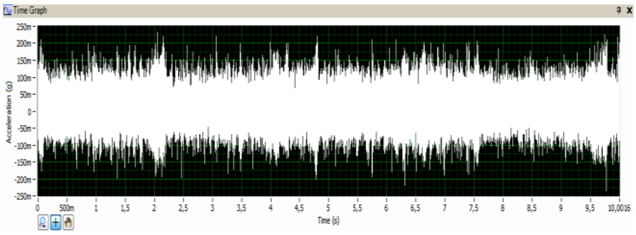
- measured vibration values during machining of the material structural steel 11 600
- measured vibration values for duralumin material machining,
- measured vibration values for machining alkaline polyamide.

Measured vibration values during machining of the material structural steel 11 600

The vibration acceleration amplitudes at spindle head speeds of 1200 rpm and 1600 rpm as a function of time are shown in

Fig. 5. The courses in Fig. 6 show the dependence of the vibration acceleration amplitudes on the frequencies in the range 0 - 10 kHz for the sensed location of the spindle head sensed in the vertical direction during machining at also specified speeds of 1200 rpm and 1600 rpm.

1200 rpm



1600 rpm

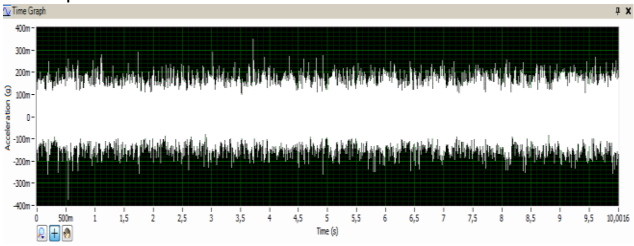


Figure 5. Vibration amplitude versus time when machining material - steel 11600 at 1200 rpm and 1600 rpm

From the waveforms of the frequency spectra of Fig. 6 together for the two examined speeds 1200 rpm and 1600 rpm, it can be seen that there are densely located peaks of amplitudes in the front part when machining at 1600 rpm. Next follows a zone of reduced amplitude values from 1.2 kHz - 4.2 kHz. The middle part of the spectrum contains elevated amplitudes in the 4.3 kHz - 5.5 kHz frequency spectrum. The highest value at 1600 rpm machining speed in this range was recorded at 5.2 kHz with a value of 0.111 mg. However, when machining at 1200 rpm, the highest value of 0.0194 mg was obtained at a frequency of 5.4 kHz.

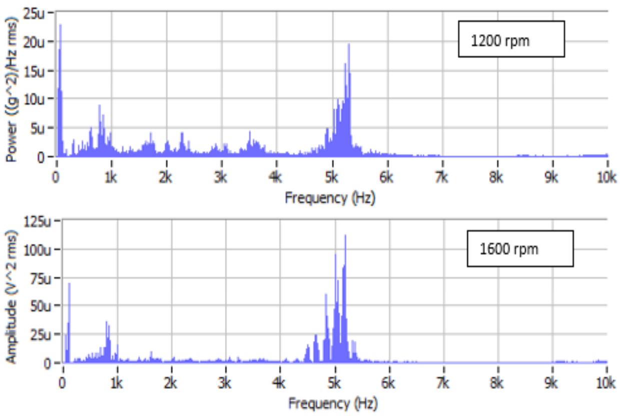


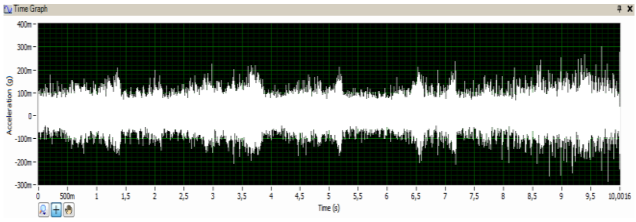
Figure 6. Frequency spectra of vibration acceleration amplitude at frequency for individual speeds when machining material - steel STN 11 600

Further, the spectrum behaves standardly and does not show elevated values, also it can be concluded that the waveforms of both speed curves have similar waveforms. Also, when machining the structural steel material from the set of speeds studied, it is recommended to use a speed of 1200 rpm, as this is the speed at which smaller values of vibration acceleration amplitude were obtained.

Measured vibration values during machining duralumin

The courses of vibration acceleration amplitudes at spindle head speeds of 1200 rpm and 1600 rpm versus time are shown in Fig. 7. The graphs in Fig. 8 show the dependence of the vibration acceleration amplitudes on the frequency in the range 0 - 10 kHz for the sensed location of the spindle head scanned in the vertical direction while machining at the also determined spindle head speeds of 1200 rpm and 1600 rpm.

1200 rpm



1600 rpm

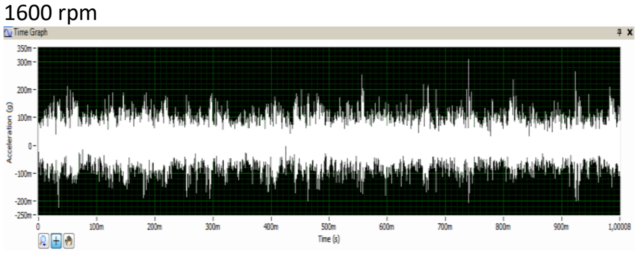


Figure 7. Vibration amplitude versus time during duralloy machining at 1200 rpm and 1600 rpm

From the graphical dependencies of Fig. 8 together for both investigated speeds 1200 rpm and 1600 rpm, it can be stated that the first significant increase in amplitudes is at a frequency of 0.8 kHz when machining at 1200 rpm. At this frequency, a value of 0.00587 mg was recorded. As in the previous case, similarly in the frequency spectrum 4,7 kHz - 5,8 kHz increases in amplitude values were recorded. In the vicinity of 5.2 kHz, the highest increase in values was recorded at both machining speeds used. The highest value was recorded at 5.2 kHz. The amplitude reached a value of 0.0161 mg at 1600 rpm machining speed and a value of 0.0136 mg at 1200 rpm machining speed. Subsequently, the amplitude values in the frequency range 5.8 kHz - 10.0 kHz for both curves decrease. Also, for this case in the combination of input conditions, it is recommended to use 1200 rpm for machining duralumin material from the set of speeds investigated, since smaller values of vibration acceleration amplitude were obtained at this speed.

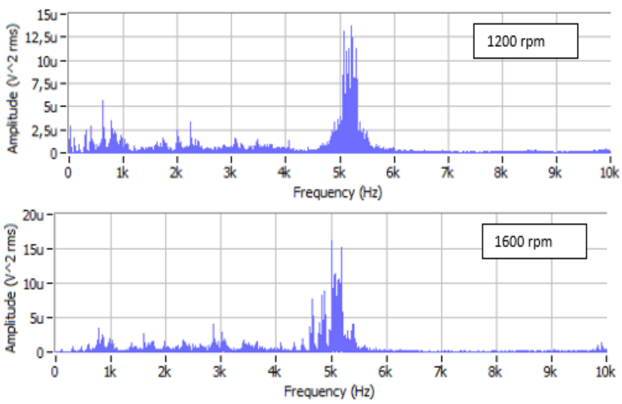


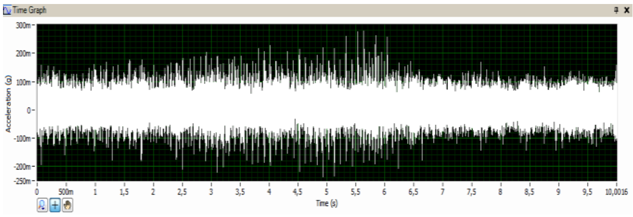
Figure 8. Frequency spectra of vibration acceleration amplitude at frequency for individual speeds when machining material – duralloy

Measured vibration values during machining alkaline polyamide material

The courses of the vibration acceleration amplitudes at spindle head speeds of 1200 rpm and 1600 rpm versus time are shown in Fig. 9. The graphs in Fig. 10 show the dependence of the vibration acceleration amplitudes on the frequencies in the range 0 - 10 kHz for the sensed location of the spindle head scanned in the vertical direction while machining at the also determined spindle head speeds of 1200 rpm and 1600 rpm.

From the waveforms of the frequency spectra taken together for the two studied speeds 1200 rpm and 1600 rpm, it can be said that the first increase in vibration values was recorded in the frequency range 0 kHz - 3.3 kHz, in which there are three increased peaks at frequencies of 1.0 kHz, in the range about 1.8 kHz and 2.8 kHz. This is followed by a range of higher amplitudes, with the highest value in the 4.3 kHz - 5.4 kHz frequency range. The highest value in this frequency range was recorded at 5.1 kHz with a value of 0.0843 mg at a machining speed of 1600 rpm. Higher values were also recorded in this range when machining at 1200 rpm. The highest amplitude was 0,0191 mg at 5,1 kHz.

1200 rpm



1600 rpm

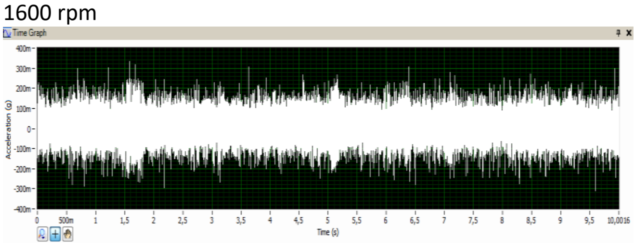


Figure 9. Vibration amplitude versus time for machining alkaline polyamide at 1200 rpm and 1600 rpm

As in the previous cases, it is recommended to use 1200 rpm when machining the silon material from the set of speeds investigated, as lower values of vibration acceleration amplitude were obtained at these speeds.

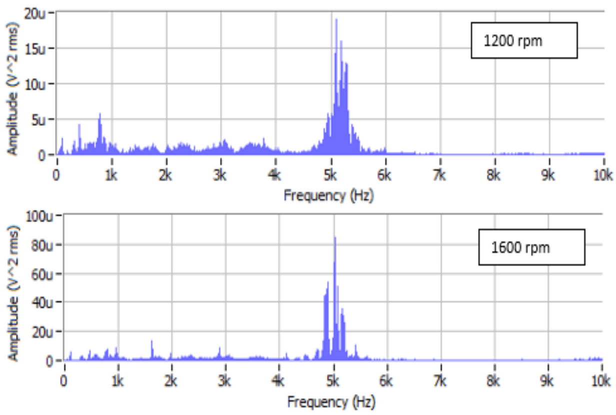


Figure 10. Frequency spectra of vibration acceleration amplitude at frequency for individual speeds when machining material - alkaline polyamide

<u>*Recommendations for measured values of vibration amplitudes*</u>

Vibration in general has an adverse effect on the equipment itself, but also on the material to be machined and of course on the surroundings. By eliminating the adverse factors in our case, the spindle head speed has a positive effect on the process. Using the results obtained from the individual measurements, recommendations can be made for this operation. In Table 4, the maximum experimentally measured values of vibration acceleration amplitudes achieved are clearly presented, followed by the recommended spindle head speed that should be used when machining the material by milling technology.

Table 4. Recommended values of technological parameters for achieving minimum and maximum experimentally measured vibration values

	Type of material	Output parameter	Technological parameter
			Spindle speed
for maximum experimentally measured values	structural steel 11600	vibration acceleration amplitude $a = 1{,}94x10^{-5}$	1200 rpm
for maximum experimentally measured values		vibration acceleration amplitude a = 0,000111	1600 rpm
for maximum experimentally measured values	duralloy	vibration acceleration amplitude $a = 1{,}36x10^{-5}$	1200 rpm
for maximum experimentally measured values		vibration acceleration amplitude $a = 1{,}61x10^{-5}$	1600 rpm
for maximum experimentally measured values	alkaline polyamide	vibration acceleration amplitude $a=1{,}19x10^{-5}$	1200 rpm
for maximum experimentally measured values		vibration acceleration amplitude $a = 8{,}43x10^{-5}$	1600 rpm

4 CONCLUSIONS

The paper deals with the investigation of the influence of selected two technological parameters (spindle speed and feed rate) on the vibration parameter (acceleration amplitude) of STN 11 600 grade steel, duralumin and polyamide samples in a production system with milling technology. The results presented are valid for the exact experimental conditions described in the paper. The obtained results of measurements and analyses allowed to draw the following conclusions:

- using frequency analysis, a shift of the amplitudes to the middle range was found from 4.7 kHz to 5.5 kHz from the whole observed frequency spectrum of 0 kHz - 10 kHz at a speed change of 1200 rpm and 1600 rpm. Using this knowledge, changes in the machining system, such as spindle speed skipping, can be detected.
- it is also recommended that when selecting material, the material is selected to have a positive effect on the machining process itself and the correct tool is used for machining the material. From the material set under consideration, it is recommended to machine the material with the HSSCo8 type duralloy and structural steel grooving cutter tool.
- it can also be said that larger values of amplitudes were recorded on the curves belonging to the speed of 1600 rpm. Therefore, it is recommended to use a lower speed of 1200 rpm for these input parameters for machining of different types of materials.

- using lower speeds will reduce the duration of fault downtime, while increasing the life of the equipment and the economic efficiency of operation.

The results presented in the paper form the basis for further research dealing with the design and streamlining of the control of the material machining process by milling technology. It is therefore necessary to continue this interesting and promising investigation, especially in the context of optimizing the processes used in milling technology for industrial applications. There is a need to focus on the investigation of the different input parameters and their influence on the resulting signal. The latter is taken as a whole and is characteristic of the particular plant on which the individual measurements were made. Further directions of development of this paper may consist, for example, in extending the set of experiments for other types of milling tools. Extend the investigation of selected technological parameters over wider ranges of their values.

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