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VIBRATION ANALYSIS OF A MANUFACTURING DEVICE

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Abstract: This article introduces the instrumental vibration analysis of a large-sized manufacturing device for face-milling rectangular aluminium ingots. Firstly, potential vibration sources of the machine and its environment were counted and their frequency territory and characteristic frequency values were assessed. With the help of the appropriately placed vibration sensors, oscillations from different conditions of the equipment were sampled, on the score of generated spectrums, the assumed vibration sources were tried to identify, furthermore their ponderosity in spectrum and exerted influences on machine were estimated.

Keywords: *vibration sources, measuring instruments, exciting frequencies*

1. INTRODUCTION

The instrumental vibration analysis of a large-sized face-milling device is detailed in this article. This machine is applied for the improvement of the surface quality of aluminium ingots manufactured by face-milling. This operation is required by the high demands made on the multi-layered rolled aluminium products from the side of the automotive industry. The remanent surface roughness however, as the result of the face-milling process, often brings forth problems in the forms of bubbles, inclusions during the subsequent multi-layered rolling procedure. To eliminate this problem, several technological experiments, investigations and modifications had been carried out and implemented, the surface roughness of the ingots, however, still have not been approved enough, and not always met the requirements. In summary, some 50% improvement of the surface quality had been achieved as the result of the technological investigations [1–3]. Besides these improvements, which still have turned out to be unsatisfactory in several cases, investigations have revealed additional concerns. The theoretical surface roughness for example, which comes purely from the geometry of the cutting inserts, the feed rate and the depth of cut, still has not been able to be achieved, hence some other sources of the surface errors need to be searched for, which might come from the dynamic properties of the manufacturing device. These vibration sources are to be revealed by both experimental and theoretical means. This paper is to give some overview on the steps carried out during the experimental investigations.

2. THE GOAL AND THE METHOD OF ANALYSIS

The main objective of the instrumental vibration analysis is the exploration of those vibration sources, which influence the face-milling operations and occur in the device or its environment, just as the introduction and estimation of the induced oscillations' effects to the surface waviness. Thereunto by the help of appropriately chosen and placed vibration sensor and beside of properly adjusted sign-conditioning parameters, the evolving vibration samples will be recorded, then with the means of secondary signal processing (the spectrum-analysis of recorded samples), the previously considered vibration-sources and their weigh in spectrum are identified and from these factors, the exerted influences on the surface quality were inferred.

3. THE POTENTIAL VIBRATION SOURCES

In the factory – due to activities carried out there – several vibration sources are present, independent from the milling-device, of which the oscillation – propagating partly in the ground, partly through the air – can get into the workspace of the equipment. Such sources, but not limited to them, might come from the bridge crane passing over the equipment from time to time, the fork-lift carrying heavy weight rolled plate products, the high voltage electric induction of heating furnaces, the raw aluminium ingots hitting the ground following transport, the vibrations of other machines' auxiliary equipment (pumps, fans, hydraulic units) located in the factory. These sources summary are called the environmental sources, and their synergies are considered. During registering the environmental vibrations, the milling-device is at resting condition and off.

Derived from ingot-milling instrument, deemed more relevant excitations may be:

- imbalanced rotary weights,
- eccentrically rotary weights,
- driven (deformed) shafts,
- uniaxial error,
- different errors of the gear drive,
- mechanical clearances, gaps related errors,
- errors derived from cutting process.

Identifying of the vibration sources listed above is accomplished by the spectrum-analysis of vibration diagrams adopted from sensors. The necessary vibration diagrams are recorded in idle and during cutting process too. As there are three rotary units operating at constant rotational speed within the instrument (2 pieces of motor-shaft and the milling tool-spindle unit), thus frequencies of the certain vibration sources – in the course of spectrum-analysis – were correlated to either of these two different rpms, as basic frequencies.

The rotational frequency of electro-motors is $f_m = n_m/60$, the spindle is $f_o = n_o/60$, where $n_m = 1500$ [min^{-1}] and $n_o = 530$ [min^{-1}] are the rotational speed of

motors and spindle. Based on these, $f_m = 25\,[Hz]$ and $f_o \approx 9\,[Hz]$ are yielded to the rotational frequency. L_{f_m} and L_{f_o} indicate the level values for the rotational frequencies. The *Table 1* below contains the typical frequency-rates and levels of the milling-device's vibration sources.

Table 1
Considered relevant vibration sources of the ingot milling machine [4] [5]

Vibration-source	**Occurrence**	**Characteristic frequencies [Hz]**
Unbalanced rotary weights	Inductors of electro motors	$1 * f_m$
	Shafts of the input gears	$1 * f_m$
	Spindle + milling disk	$1 * f_o$
Eccentrically rotary parts	Inductors of electro motors	$1 * f_m$
	Shafts of the input gears	$1 * f_m$
	Spindle + milling disk	$1 * f_o$
Bended, deformed shafts	Shafts of the input gears	$1 * f_m$, $2 * f_m$, where $L_{1*fm} > L_{2*fm}$
Uniaxial error	Eccentrically connecting units	$1 * f_m$, $2 * f_m$, where $L_{1*fm} < L_{2*fm} \cong 1{,}2 \dots 1{,}3 * L_{1*fm}$
	Angular setting error: eccentricity of the axle head bearings	$1 * f_m$, $2 * f_m$ where $L_{1*fm} > L_{2*fm}$
Gear drive errors	Eccentric gear tooth connection	$3 * f_Z$ + adjacent channels
	Flank wearing	
	Increase of the gear toothing load	
	Gear gaps	
	Gear tooth breakage	$1 * f_m$, $1 * f_o$
	Repetition error	$f_1 = \frac{Z_m}{Z_m x Z_o} f_m$, $f_2 = \frac{Z_o}{Z_m x Z_o} f_o$, $2 * f_1$, $2 * f_o$
Mechanical clearances, gaps	Foundation, Bolt connections, bearing clearances	$n * f_m$, $n * f_o$, where $n = 15 \dots 20$
Bearing errors	Cage frequency	These frequencies are proportional with the rotational speed and depend on the installed bearing's geometrical parameters.
	Inner ring frequency	
	Extern ring frequency	
	Rolling unit frequency	
	Rolling unit rotational frequency	

Vibration-source	**Occurrence**	**Characteristic frequencies [Hz]**
Errors derived from cutting process	Catch stepping of the cutting edges	$N * f_o$, where N is the numbers of cutting-edge
	The milling disk	The disk's self-frequency

4. THE DEVICE SYSTEM OF THE INSTRUMENTAL VIBRATION TEST

The oscillation state of the milling machine was tested by vibration pick-up sensors which were placed on the machine's specific points. The positions of measuring points were selected in such a way, that all vibrations from the listed sources in *Table 1* can reach at least one of the sensor with due measurement. Important consideration was composed, that the sensors must been placed directly on the machine frame, ribbing or nearby of that – not on the plating, plate-like parts, bars or servo-mechanism – as close as one of the reviewed oscillation sources, so been supported due efficiency detection of vibrations.

In the course of tests – properly unto the certain vibration sources – displacement and acceleration of vibration diagrams were registered in the following sensor-distribution:

- 1 piece of shift vibration sensor laser interferometer made by Panasonic-SUNX, with $10\ kHz$ sampling frequency and $4\ \mu m$ resolution. By the help of this sensor, partly the environmental vibrations, partly the idling axial direction shift vibrations of the spindle-milling-disk assembly were identified;
- 1 piece of inductive principle seismic sensor made by HBM, which is sensitive along horizontal plane with $1\ \mu m$ resolution and $20-120\ Hz$ frequency range. By the help of this sensor, the feeding-direction horizontal vibrations were determined partly from the environment, partly from the idling state of the equipment, in the first place from imbalance, from the eccentrically rotating machine parts, the deformed shafts, the uniaxial errors and the machining process (*Figure 1*, H);
- 1 piece of inductive principle seismic sensor made by HBM, which is sensitive along vertical plane with $1\ \mu m$ resolution and $20-120\ Hz$ frequency range. By the help of this sensor, the vertical direction shift vibrations caused by excitations were identified from the imbalance, the vertical direction gaps, the machining process and the machine foundation errors (*Figure 1*, V);
- 3 pieces of PIEZO-CUBE g-sensor made by KISTLER, which are sensitive along one axis with $0-8\ kHz$ frequency range. By the help of these sensors, the acceleration of vibrations were determined from the imbalance, shape and position error, the gear connection, the accidental bearing errors, gaps and the machining process (*Figure 1*, 338, 339, 340).

The figure below *(Figure 1)* shows the placement of sensors on the machine frame.

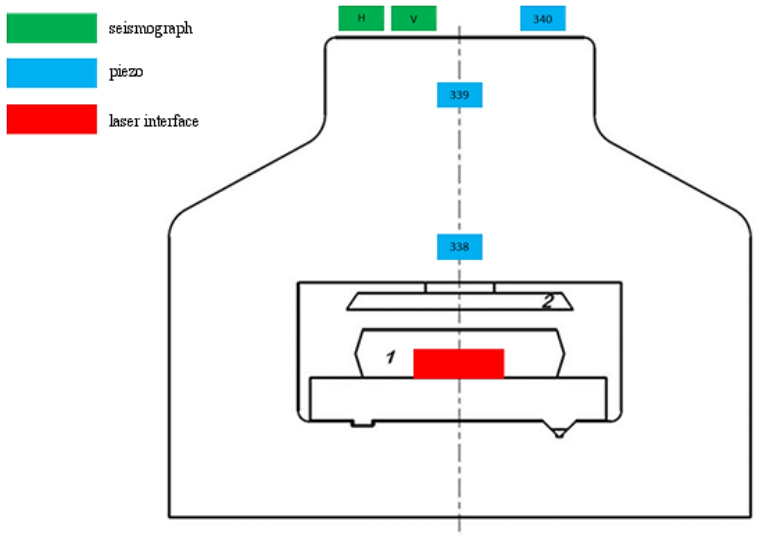


Figure 1. The placement of sensors

5. EXAMINATION OF THE ENVIRONMENTAL VIBRATIONS

In doing so, the synergy of environmental oscillations were registered, during measurements, all the sensors worked, the milling machine and its auxiliary units were off. The diagram of *Figure 2* sets an example for the negligible quantity influence of the environmental vibration, which was registered by the horizontal plane sensitive seismograph that was placed on top of the milling-tower and shows the feeding-direction vibration.

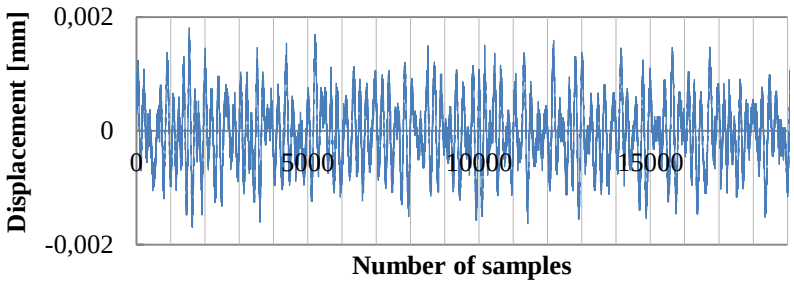


Figure 2. The feeding-direction vibration of horizontal seismograph (standing)

Other sensors detected similar negligible vibration level, so it could be pronounced that the influence of the environmental vibrations are not significant, approach in negligible quantity to the oscillation state of the equipment during machining process.

6. IDLE CONDITION

In this state the auxiliary equipment of the milling machine are working, the main spindle with the milling head are running at a given speed, the sledges are not moving and there is no work piece in the working area. With this test we revealed the vibration conditions resulting from eccentrically turning masses, spindle setting, eccentric connections, unbalance, mechanical looseness, unbalance and faults of gears.

6.1. Eccentric parts

Three parts of this kind can be found in the machine: the main spindle, parts turning together with the main spindle and the two driving motor spindles and parts turning together with them. Typical frequencies are $1\times f_m$ and $1\times f_o$ *(Table 1)*. The relevant low band vibration and spectrum diagrams can be seen in *Figure 3*.

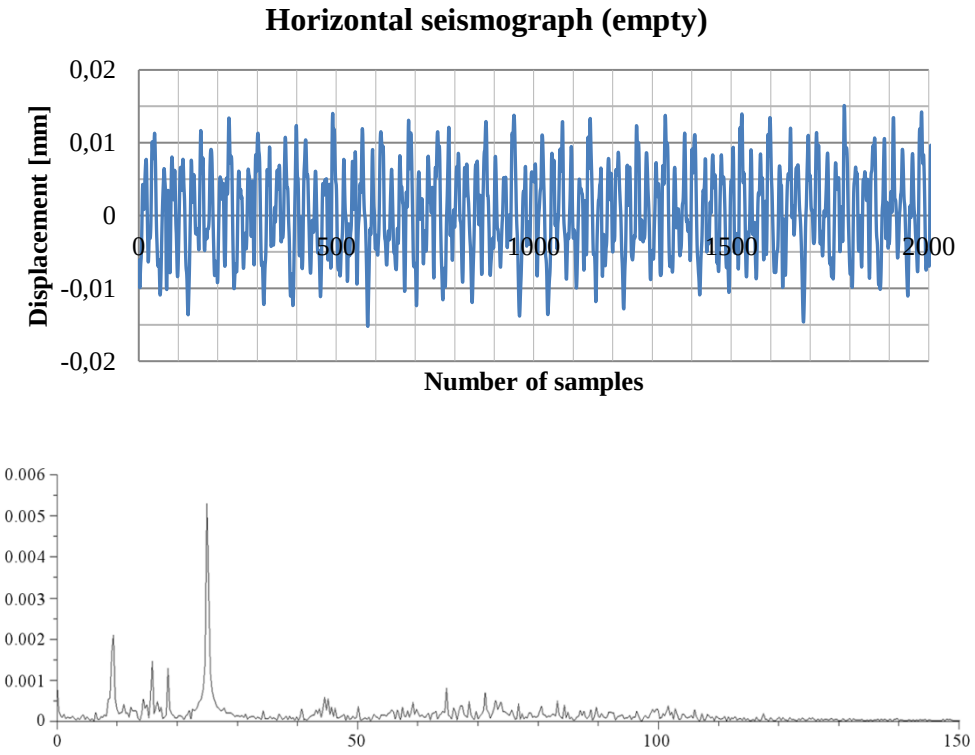


Figure 3. Vibration and spectrum diagrams

On the low band spectrum diagram we can see that high values appear at the frequencies of the main and driving spindles ($9\ Hz$, $25\ Hz$), therefore excitation from eccentric rotating parts may be present in the machine.

6.2. Deformed spindles

This vibration source can be originated form the deformity of the driving and main spindles caused by gear connection between the spindles. Typical frequencies are $1\times f_m$, $2\times f_m$, where $L_{1\times f_m} > L_{2\times f_m}$. Looking at the previous diagram *(Figure 3)* it can be clearly seen that $2\times f_m$ can be found in negligible amount, thus it slightly influences the machine's condition.

6.3. Eccentrically connecting turning parts

This kind of excitation can be originated from the clutch connecting the spindle of the electric motor and the end of the spindle driving the main spindle. Typical frequencies are $1\times f_m$, $2\times f_m$, where $L_{1\times f_m} < L_{2\times f_m} \approx 1{,}2...1{,}3\times L_{1\times f_m}$. This relation cannot be found in the spectrum diagram *(Figure 3),* therefore this factor is unimportant.

6.4. Unbalanced turning masses

Typically appears in the spectrum at equal rotational frequencies equal to revs additively and inseparatively from the presented errors before. Due to the sampling in the low band frequency range we get a result freed from high frequency noises *(Figure4).*

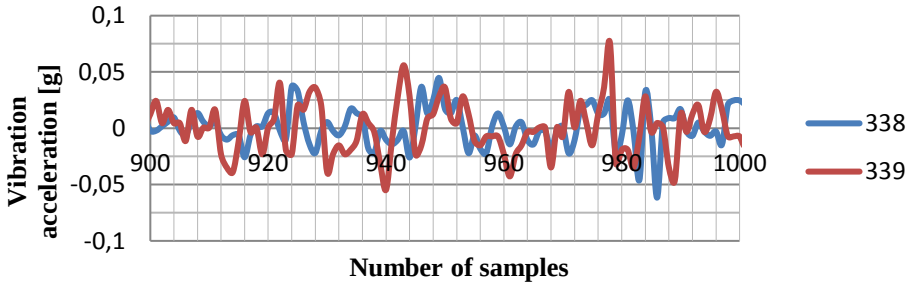


Figure 4. Spindle imbalance

The diagram shows the transmitted signals of vibrations from the accelerometers marked 338 and 339 *(Figure 1),* which were placed at the upper and lower bearings of the main spindle. It is noticeable that the signals run in phase or opposite phase alternatively. This can be allude to floating phenomenon, which can be originated from the processing movement of the main spindle which acts like pendulum with high moment of inertia. It forecasts some types of bearing defects (gaps, wearings). The sources of errors described in *chapters 3.1–3.4* are inducing on frequencies maximum twice as the speed-frequencies present in the machine. These frequencies, except $2\times f_m$, appears on the spectrum in *Figure 3,* but their absolute signal

level – because of the low band sampling – not so informative. The next diagram shows a much wider – 1200Hz – spectrum range.

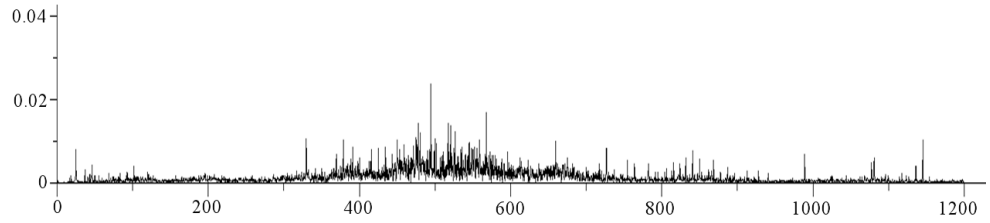


Figure 5. Spectrum diagram

It is clear from the diagram that the 0–1200Hz band signal levels of the spectrum are low compared to the lines in the midrange which are likely bearing noises. So the effect of vibrations from sources of errors described in *chapters 3.1–3.4* does not looks significant to the machine condition.

6.5. Vibrations caused by gear defects

These defects – eccentrically connecting gear pairs, excessive loads on some tooth, gaps between teeth – comes from excited vibrations of the connecting gears of the machine. Typical frequencies $3\times f_z +$ (the sidebands of the rev. speed of gears), contact frequency: $f_z = z_o \times f_o = z_m \times f_m$, where z_o, z_m the number of teeth on the main and motor spindle. In our case the $z_o = 92$, $z_m = 34$, so the contact frequency is $f_z = 34 \times 25\ Hz = 850\ Hz$, which second harmonics is $3\times f_z = 2550\ Hz$. The related spectrum diagram *(Figure 6)* was recorded by the closest piezo electric accelerometer – marked 339 – to gears, sensitive in the radial direction to the gears.

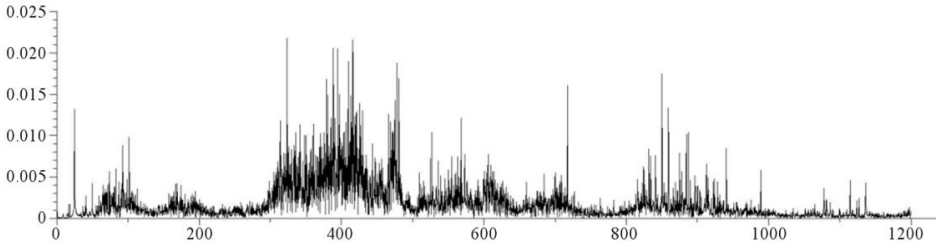


Figure 6. Spectrum diagram

Around $f_z = 850\ Hz$ and $3\times f_z = 2550\ Hz$ the typical striped lines modulated by the speed frequency of the main spindle can be noticed, which can occur from the increased gap between the teeth of the gears caused by wear of the gears.
Spectrum lines of other gear defects (breakage, repetition error etc.) cannot be found in neither on the recorded vibration diagram, nor it's spectrum *(Figure 6).*

6.6. Mechanical looseness, fitting gap

This vibration error appears as a result of the loose fitting of bearing elements in this machine. Spectrum lines emerge at the rotational frequency and its multiples of the specific bearing and results in the characteristic fishbone pattern *(Figure 7, Figure 8).*

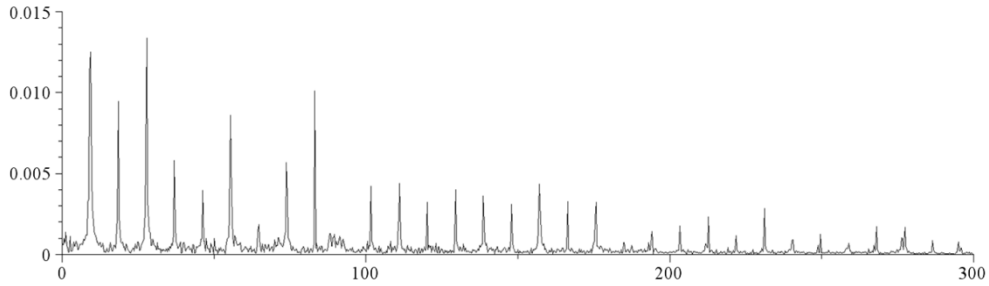


Figure 7. Fishbone patterns of spectrum diagram

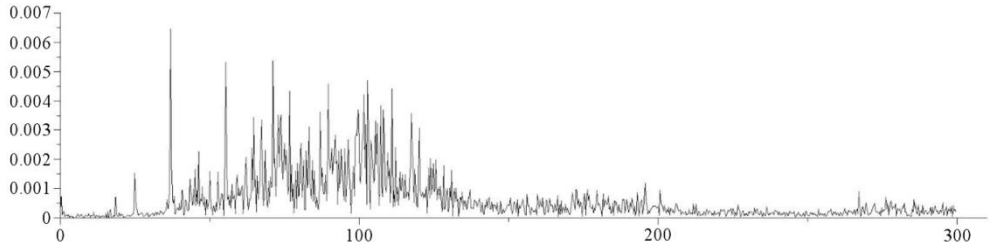


Figure 8. Spectrum diagram

For the recording of these, we used a laser interferometer *(Figure 7)* placed under the milling head targeted to the middle of the cross-section, and piezoelectric accelerometer – marked 340 *(Figure 8)* placed axially on the portal structure. The characteristic fishbone pattern can be observed on both diagrams, which refers to significant axial displacement, verifying the gap in the thrust bearing from constructional reasons. The vibration diagram recorded by the laser interferometer shows 0,08–0,1 mm idle displacement of the main spindle – milling head assembly.

From the spectrum diagrams we think that the axial vibrations caused by the 0,3–0,4 mm prescribed gap for the bearings of the main spindle, have significant impact on the waviness of the surfaces of the aluminium ingot.

7. ANALYSIS OF VIBRATIONS COMING FROM MANUFACTURING

In this chapter we review the effect of machining on the machine-vibration condition. During machining tests we analysed the displacement-vibrations of the top of the machine portal (*Figure 1,* H, V) and the noises of bearings and gears (*Figure 1,* 338, 339, 340) together with the effect of axial bearing gap (*Figure 1,* 340). The

test was conducted at several cutting conditions, we represent our result with the usage of 6000 mm/min feedrate and 8 mm axial depth of cut.

The diagram below *(Figure 9)* shows the displacement-vibrations of the top of the machine structure in feed direction.

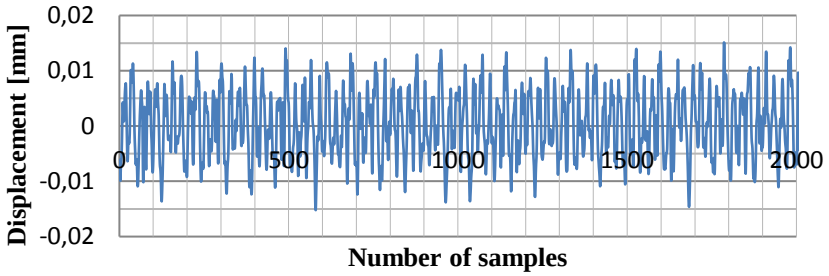


Figure 9. Displacement-vibrations of horizontal seismograph (empty)

Comparing this with the vibration diagram in *Figure 3* it is clear that the examined point of the machine structure doesn't have significant displacement during machining, because the vibrations in the feed direction only slightly increased. We can declare the same about the vertical **v**ibrations of the tower. One likely reason is the gyroscopic stabilizing effect of the main spindle and milling disc assembly, which has a great angular momentum.

Take a look on the recorded vibrations of the "338" piezo electric sensor which was attached near to the lower bearing of the main spindle *(Figure 10).*

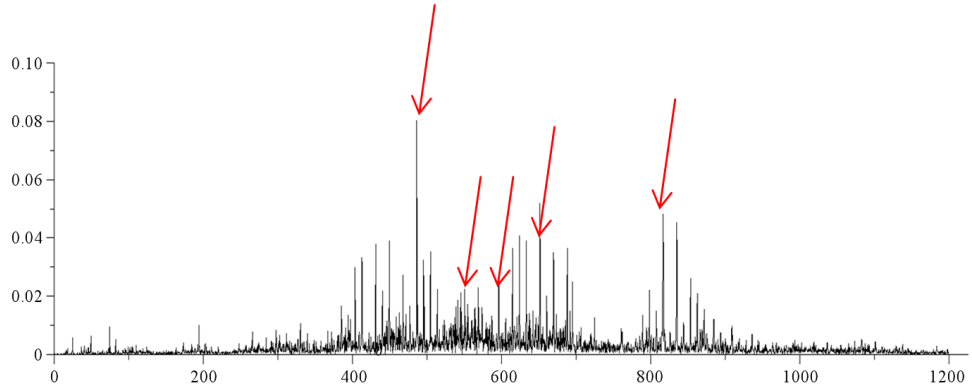


Figure 10. The recorded vibrations of the "338" piezo electric sensor

Comparing this with the idling spectrum diagram of the same sensor, it is obvious, that the spectrum lines of the noises of the lower bearing marks out, which error frequencies can be calculated by knowing the bearing characteristics and by the help of it can be easily identified *(Table 2, Table 3).* The highlighted frequencies are marked with red arrows in the diagram. The bearing noise – based on the dia-

gram – contributes in a notable way to the vibration condition of the machine during machining, which can prognosticate the significant wear of the affected bearings.

Table 2
Defect frequencies and harmonics of FAG 49/500 NNU type, double row, cylindrical roller bearing

Defect frequency and harmonics [Hz]	1x	…	3x	4x
Rotational frequency	9.083	…	27.249	36.332
Cage frequency	4.265	…	12.795	17.06
Rolling Element Frequency	74.178	…	222.534	296.712
Inner ring frequency	183.11	…	549.33	732.44
Outer ring frequency	162.056	…	486.168	648.224
Rolling frequency	148.355	…	445.065	593.42

Table 3
Defect frequencies and harmonics of FAG 7511-type, angular contact ball bearing

Defect frequency and harmonics [Hz]	1x	2x	…	6x	…	12x
Rotational frequency	9.166	18.332	…	54.996	…	109.992
Cage frequency	4.58	9.16	…	27.48	…	54.96
Rolling Element Frequency	67.6	135.2	…	405.6	…	811.2
Inner ring frequency	192	384	…	1152	…	2304
Outer ring frequency	192	384	…	1152	…	2304
Rolling frequency	135	270	…	810	…	1620

In *Figure 7* we can see the effect of excitation coming from the bearing gap to the machining, which already has been identified during idle run tests. For this observe the spectrum diagram of the “340” accelerometer which was attached in the direction of the main spindle *(Figure 11).*

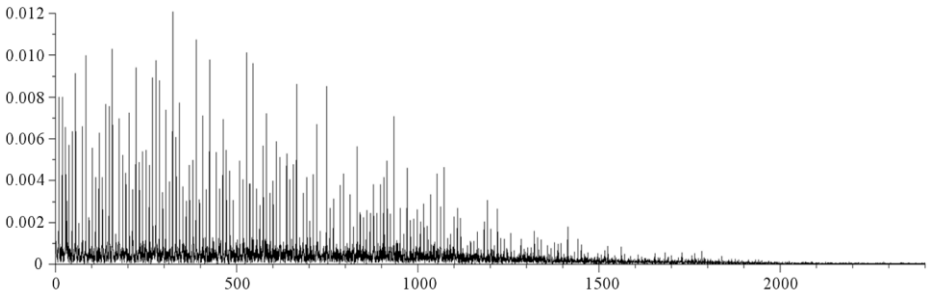


Figure 11. Spectrum diagram

This diagram compared with the idle state spectrum on *Figure 7* shows a typical equidistant, so-called fishbone texture, which obviously refers to the presence of the bearing gap during machining and the clashes from the vertical vibrations of the main spindle.

8. CONCLUSION

From the time and spectrum diagrams of the vibrations recorded during machining, we can draw the conclusions as follows:

- The displacement- vibrations recorded by the seismographs (*Figure 1,* H, V) are slightly increased between idle and machining runs
- The rise of the vibrations recorded by the "338" piezoelectric accelerometer by 100% is due to the increased bearing and gear noises – based on the frequencies – and the excited frequencies of the cutting (primarily from the milling head, like a flexible disc)
- Significant noise is generated by the lower radial cylindrical roller and angular bearings of the main spindle *(Table 2 and 3)*
- The diagram in *Figure 10* suggests that during both idle and machining runs the main spindle assembly has vibration in axial direction with significant amplitude. The detection of the numerical values of this vibration – respect our toolkit – can be conducted with the laser interferometer, but we could only take measurement during idle run by pointing on the appropriate point of the main spindle. During machining we could not use this equipment, so we could only verify it relying on the "340" piezoelectric accelerometer.

On the whole we presume that the 0,3–0,4 mm gap between the lower angular bearings of the main spindle has a major role in the creation of axial vibrations, which are responsible for the increased waviness of the ingot's surface during machining. We describe the theoretical investigation and verification in another article.

ACKNOWLEDGEMENT

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