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Vibration Based Cutting Tool Path Differentiation by Feature Selection

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***Abstract* – During machining along a complex tool path, it is difficult to connect the change in the amplitude and in the frequency of the recorded vibration signals to the actual state of tool wear. In this article, a method is presented in which the tool wear processes that occur during the machining of a complex geometry (cooling pocket formed on the ceramic coating of the turbine blade) can be evaluated based on the vibration data series recorded during the machining differentiating of some elements of the complex path movement performed by the tool.**

Keywords – micro-milling, ceramics material, vibration, data analysis, Responsible Consumption and Production

I. INTRODUCTION

Vibration analysis is a process that monitors vibration levels and investigates the patterns in vibration signals. It is commonly conducted both on the time waveforms of the vibration signal directly, as well as on the frequency spectrum, which is obtained by applying Fourier Transform on the time waveform [1][2][3].

The time domain analysis, on chronologically recorded vibration waveforms (Fig. 1.), reveals when and how abnormal vibration events occur, by extracting and studying parameters including but not limited to root-mean-square (RMS), standard deviation, peak amplitude, kurtosis, crest factor, skewness and many others based on the original, measured vibration signal. Time domain analysis is capable of evaluating the overall condition of the targets being monitored. Frequency analysis decomposes time waveforms and describes the repetitiveness of vibration patterns, so that the frequency components can be investigated. Additionally, the well-established Fast Fourier Transform (FFT) technique facilitates fast and efficient frequency analysis, as well as the design of various digital noise filters [1][4][5].

Vibration can be measured through various types of sensors. Based on different types of vibrations, there are sensors designed to measure displacement, velocity and acceleration, with different measuring technologies, such as piezoelectric (PZT) sensors, microelectromechanical sensors (MEMS), proximity probes, laser Doppler vibrometer and many others. PZT sensors, the most commonly used sensor, generate voltages when deformed. The voltage signals can be digitalised and translated to represent the vibrations. When selecting suitable vibration sensors, the vibration levels/dynamic range and maximum frequency range/bandwidth should be considered, as well as the other operating environment such as temperature, humidity and pH level.

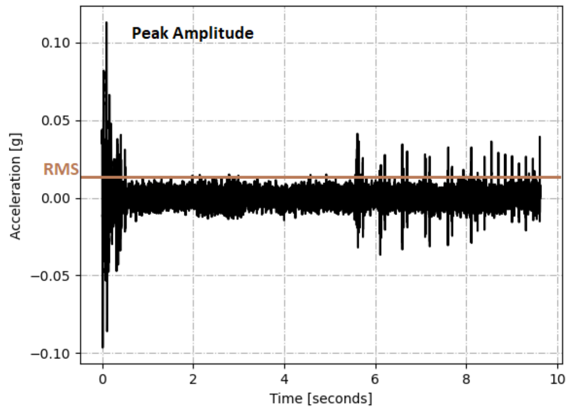

Fig. 1. Recorded vibration signals in time domain [1]

Vibration signals are usually below 20 kHz, except for certain vibration resonances that can reach beyond that. In practice, the sampling rate should be carefully chosen, to make sure that the bandwidth containing frequencies of interest are captured. Additionally, the recording length for one measurement should be at least several periods of the lowest speed of the machines [1][2].

Vibrations can be described both in intensity, by amplitude and in periodicity by frequency.

The time waveform is complicated by its speed-varying movement. Fig. 2 demonstrates the frequency spectrum of the same signal.

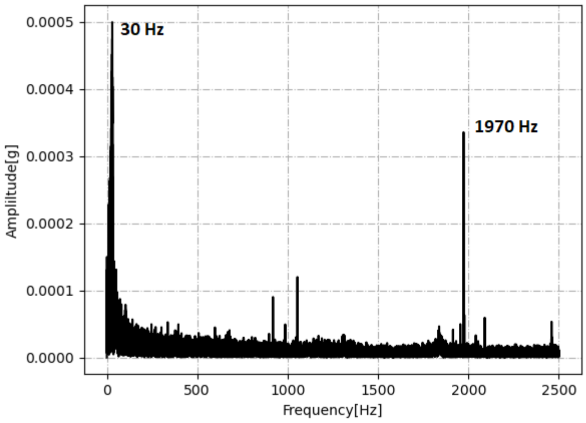

Fig. 2. Fixed vibration signals in the frequency range [1]

Time domain vibration analysis is able to monitor vibration levels. Acceptable operation vibration limits can be pre-defined either through long-term operation and maintenance history or through referring to established standards. If the limit is breached, this could be that the overall health condition of the machine is deteriorating and defects have developed [1][2][4][5].

Frequency domain vibration analysis excels at detecting abnormal vibrating patterns. For instance, a crack that has developed on a roller bearing outer race will lead to periodic collisions with bearing rollers. In time waveform, this information is usually hidden and masked by the vibration from other sources. By studying the frequency spectrum, the periodicity of the collisions can be discovered and thus detect the presence of bearing faults [1][2].

During the ceramics cutting process, when monitoring the lifetime of the tool on the basis of vibration signals, it is examined whether the amplitude and frequency of the resulting vibration changes, and in which direction these vibration characteristics shift during the wearing of the tool. In contrast to traditional evaluation methods, we investigated the machining of complex geometries (pockets, islands) the vibration signals recorded during the formation of individual pockets. It was also analysed what mathematical relationships describe the connection between the wear of the tool and the vibration measurements.

In this article, we present the preliminary preparation steps that had to be taken for the vibration diagnostic solution for monitoring tool wearing of micro-cutting of ceramics.

II. PRESENTATION OF EXPERIMENTAL CONDITIONS

A. Machined geometry

The machined geometry presented in this article is a pocket shape formed in the ceramic coating of a turbine blade for film cooling. During the experiment, the pocket shown in Fig. 3 is continuously produced on a flat ceramic sheet prepared for this purpose. The end of the tool life is indicated by tool breakage or by the complete wearing of the tool geometry.

Fig. 3. Geometric design of manufactured pockets

B. Applied CNC machine

To prepare the cutting experiments, the CncTeamZeg team provided the 3-axis machine tool they developed (Fig 4.).

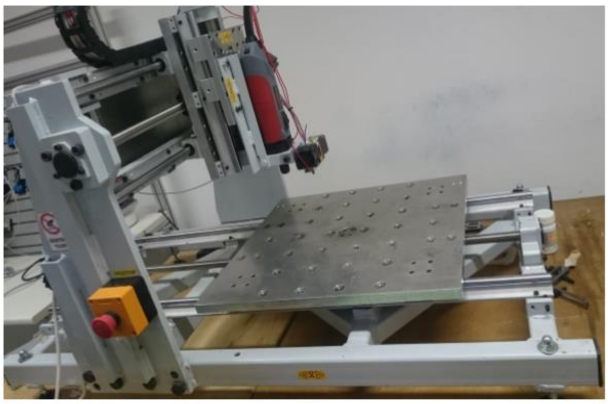

Fig. 4.: Used CNC-controlled machining machine

Technical parameters of experiments:

- Maximum speed: 25000 [1/min]
- Engine performance: 1kW
- Maximum axis feed speed: 1000 [mm/min]
- Machine repetition accuracy: ±15μm

C. Applied cutting tool

A Fraisa-type and TiAlN-coated ball milling tool was used during the experiments (Fig. 5).

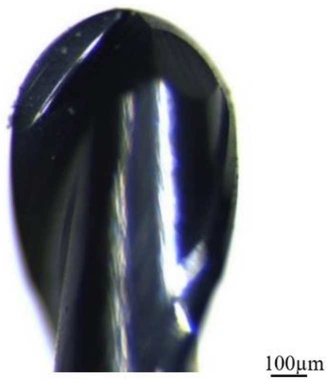

Fig. 5. Applied ball end milling tool

The most important characteristics of the tool applied:

- Type of tool: Ball end milling
- Diameter: 1mm
- Working length: 6mm
- Basic material: Carbide
- Coating: TiAlN

D. Technological parameters used during production

The technological parameters used are the following: speed, n [1 / min]: maximum 25000; feed, vf [mm / min]: maximum 300; axial depth of depth, ap [mm]: maximum 30µm; radial depth of cut, ae [mm]: maximum 30µm. Toolpath types used in the experiment: waveform, trochoidal toolpath (cycloid path), chained toolpath.

E. Applied accelerometer for vibration measurement

A type of TE-CONNECTIVITY accelerometer sensor was used for vibration measurement. The momentary amplitude value of the vibration acceleration is measured with the measuring device in mV. Sensor data:

- Manufacturer: TE-CONNECTIVITY
- Production article number: 805M1-0020-01
- Sensitivity: 100mV/g

The signal from the sensor is transmitted through a custom-built amplifier, through a data collection unit and it was recorded using a National Instruments (LabView) program. The construction of the measuring circuit is shown in Fig.6.

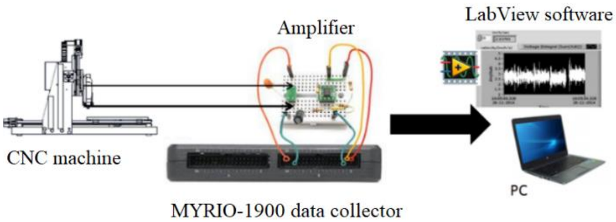

Fig. 6. Schematic structure of the measuring system

F. Applied data collection unit

The signals from the amplifier were recorded with a myRIO-type device. This device was optimized by the manufacturer for measuring tasks, controls, robots and other mechatronic systems, so it was well suited to the task to be solved.

During the measurement, the set sampling frequency was 100kHz.

$$Recommended: f_m > 10 f_{max}$$

Where:

- f_m: sampling frequency
- f_{max}: frequency corresponding to the maximum frequency component of the tested signal

Shannon's rule is: $f_m > 2f_{max}$. The measuring system performed up to an upper limit frequency of 45 kHz.

III. PROCESS OF DATA PROCESSING

The actual positions of the CNC machine axes were exported to a .txt file using a subprogram that can be run in the Mach 3 NC controller. During data collection, the machine continuously chipped along the path shown in Fig. 7. During the machining the vibration data was recorded continuously.

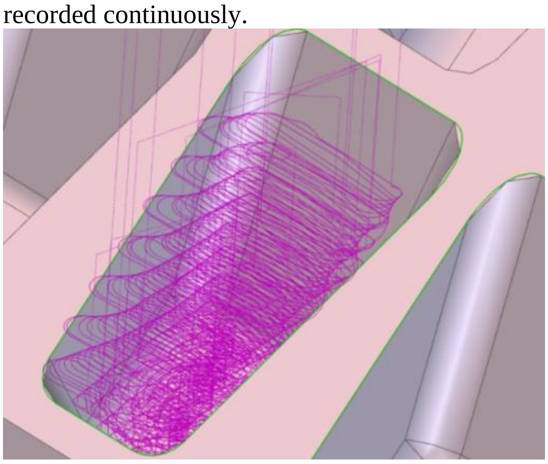

Fig.7. Tool path generated by EdgeCam software

After the pocket was completed, the recorded trajectory indicated further postprocessing steps. During the preparation, the tool's movement point cloud was divided into 2 large groups:

- The first set includes the path sections where the tool works in the X-Y plane (2D movement). Here, the section of the cutting edge running on the tool jacket is loaded *dominantly*.
- The other set includes tooth-picking movements, where, in addition to *the cutting edge, the cross edge is also exposed to a significant* load (3D movements).

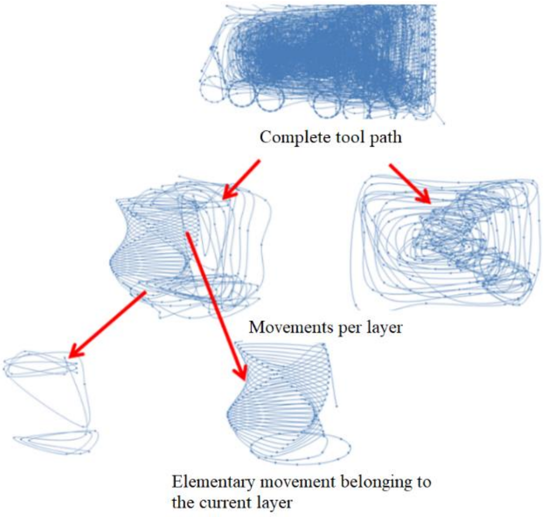

Fig.8. Breakdown of plane motion into elementary components

The (2D) group belonging to x-y movements was again divided into additional two sub-elements (Fig. 8). In the plane movements in the X-Y direction, the first element is when the tool moved horizontally or vertically, so *along a straight line* are separated, and other one where the tool moves *along a circle or other interpolation curve*. During the infeed movement, the tool performed a continuous spiral movement, so there was no need to break the track into additional sub-components.

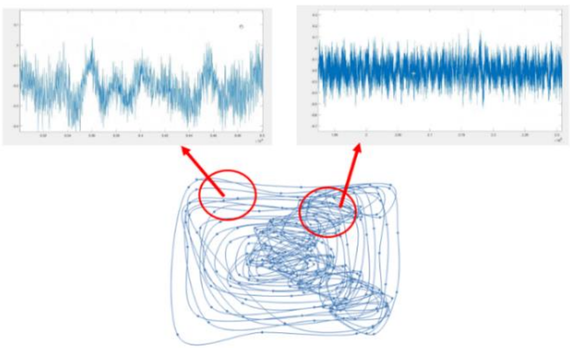

Fig.9. Vibration shapes for the linear and for the curved sections of the track

There are 2 big advantages of the break-down of the track cloud in this direction:

- One is that each path section can be evaluated separately, independently from the other movements (Fig. 9), so that the changes in the signal on the given section of the tool path can also be monitored.

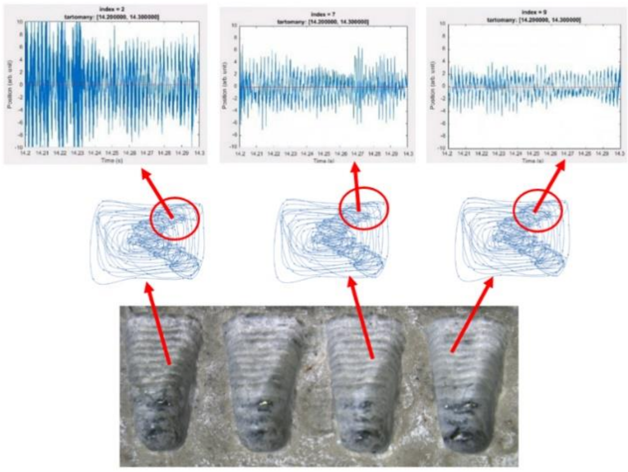

Fig.10. The shape of the vibration occurring in a given section of the track changes depending on the manufactured pocket

- Another big advantage of the break-down is that the track sections that are interesting for the evaluation are comparable for each pocket (Fig. 10).

In order to perform this evaluation, the values of the track (tool path) coordinates must be assigned to the given value of the vibration data series and vice-versa.
For the matching of the data, exact time label must be assigned to the track sections and to the vibration data. This is necessary so that the two data sets start from a common zero starting point. After synchronizing the starting point of the two data sets, the recorded vibration signals can be assigned to the current tool position of the machining, or to the actual tool position vibration data can be assigned.
During the alignment, the two data sets were moved relative to each other along the time axis. The common zero point was at the point where the tool first touched the material. During the matching, the accuracy of the matching was checked at several later points in the data set. The momentary elements generated by the program only in the "Z" (vertical, leaving the ceramics material) direction resulted in the momentary cessation of the vibration signal. The length of this stages without real material removal in time and the length of the time interval for the almost zero vibration signal must be the same. During the inspection, the coincidences of these time cells were checked at several sampling levels. *Based on these iterations, the two signals (tool path and vibration) were completely fitted to each other*.
As a result of this pairing, the amplitude (and frequency) of the vibration occurring there can be analyzed separately for each movement element, this is the main aim of the research presented. The harmonized state of the two times series after pairing with each other is shown in Fig.11.

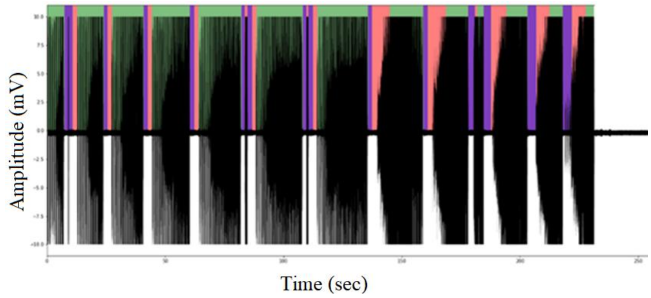

Fig.11. Coordination of vibration data with individual track sections

The black line in Fig. 11. is the vibration amplitude in mV. The black range can be divided into 2 parts:

- The part in which the background area is marked as pink, mirroring the tooth-picking movements. Here, the tool moves in the X-Y-Z direction simultaneously (spatial, 3D movement).
- The area in which the background area is marked as green covers purely X-Y plane movements (plane, 2D movement), so, this is the main range of ceramics material removal by the micro-milling tool.

The areas marked in purple are the tool extractions performed during machining. In these stages, the tool does not perform a cutting movement, so it can be neglected. Before the specific evaluation of the data series, it is important to examine to what extent the vibrations resulting from the idling (without material removal) operation of the machining can influence the characteristics of the vibrations generated during cutting.

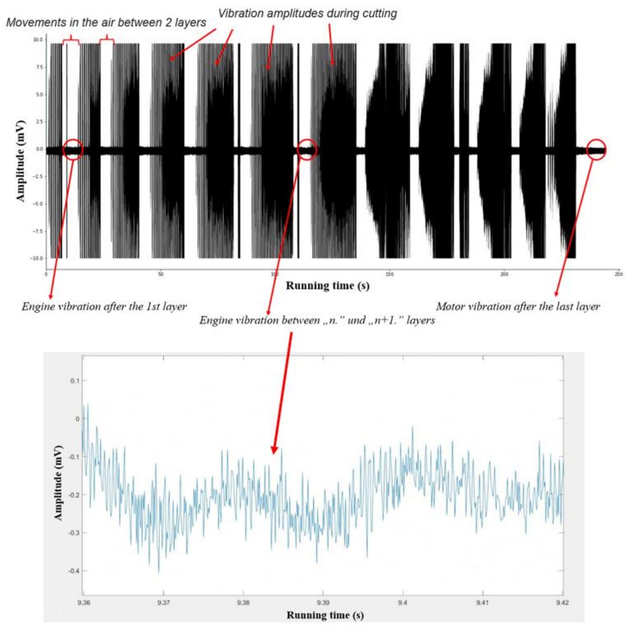

Fig.12. Motor vibration at the first manufactured pocket

Fig. 12 shows that sections where there is no material removal, only the vibrations from the engine rotating with the unloaded tool were recorded. Here, the amplitudes are at least one order of magnitude smaller than the amplitude value of the vibration generated during cutting ("amplitude measured during ceramics removal" instead of 10mV - Value between 0.1; -0.3mV "amplitude measured at idle spindle").

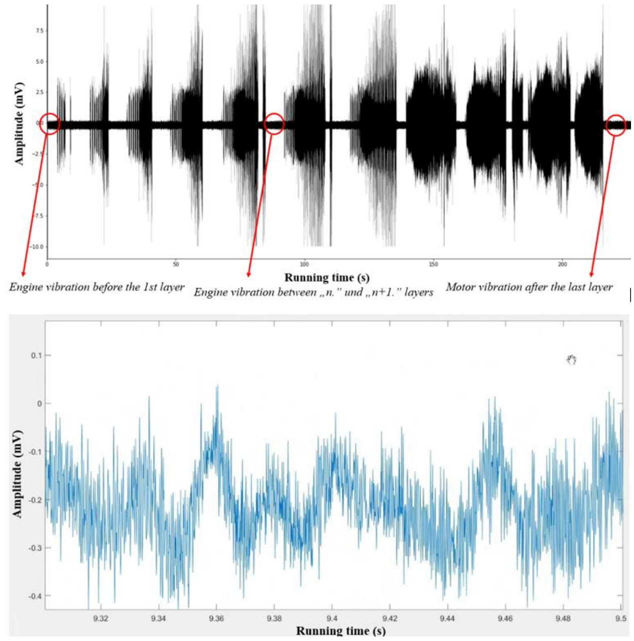

Fig.13. Engine vibration at the last manufactured pocket

This test was repeated for the last manufactured pocket as well, so with a tool having high wearing (Fig.13). The figure shows that even in this case, the amplitude values of the vibrations generated during cutting are orders of magnitude higher than the vibration amplitudes from the engine rotating without load. The magnitude difference between the two signal ranges is also clearly visible in Fig.14.

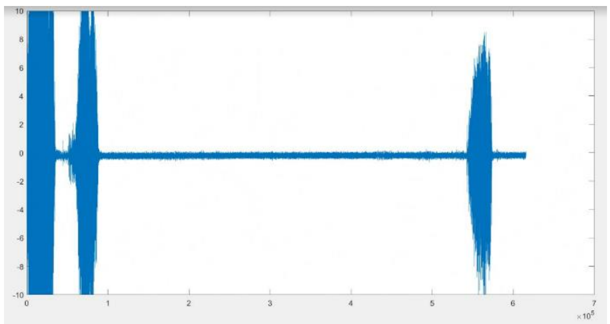

Fig.14. The difference between cutting machine motor and ceramics removal cutting vibration signals

The effect of the vibrations resulting from the rotation of the motor on the cutting is therefore negligible.

IV. SUMMARY

The purpose of the paper is to present a vibration data processing method that is also suitable for evaluating tool wearing along complex cutting toolpaths.

This paper introduced:

- a suggested breakdown of a complex tool path into simple movement elements,
- the tool path broken down into motion elements can be evaluated as elements, and the individual path elements can be compared with each other,
- comparing individual track elements during the successive production of several such pockets the actual state of the tool in the same points can be compared. In this way, it becomes also possible to predict at which point within a given work session the tool will be completely worn out.

In previous research, the so-called Adaptive Hybrid Feature Selection (AHFS) method was used to compare individual pockets with each other [7][8][9][10]. In that research the plane (2D) and spatial (3D) movements were separated but the future research goal is to evaluate the individual tool path elements separately.

V. ACKNOWLEDGMENTS

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