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Monitoring the Performance of the Drive Mechanisms During CNC Milling

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Abstract: The article deals with a monitoring system designed for the needs of a specific production plant. Its primary purpose is to provide online information about ongoing production processes at monitored workplaces. The system will make it possible to monitor the usability of the machines and the load on individual machine elements to increase production efficiency and prevent machine breakdowns. Furthermore, it will allow to monitor the load on the tool and predict its wear in order to prevent irreversible damage and the production of scrap. To test the applicability of the system on a milling machine, a sample was designed, the elements of which were produced in two ways - HPC and trochoidal milling. With these methods of milling, different manifestations of the tool load were assumed. The experiments proved the functionality of the system. The method of transmission, recording and storage of data has proven to be fully functional. The additional results were knowledge of machine load during both milling methods.

Keywords: signal processing, CNC machine, OPC UA client, HPC milling, iMachining

1. Introduction

The current trend in industrial production is flexibility, manifested by an effort to respond to customer requirements as quickly as possible. Flexibility is a pre-image of intelligent manufacturing, providing personalised products through autonomous manufacturing operations. Intelligent production is based on two basic pillars – the automation of the production process based on a personalized product and the automation of a self-organizing production system. In order to achieve this, a high level of real-time communication between people, machines, equipment and products must be ensured during production [1]. One of the consequences of this development are CNC (Computer Numerical Control) machine tools with control systems supporting wide communication options to ensure the transfer of information.

Collecting information about the state of production and the progress of technological processes makes it possible to significantly improve the level of management, reduce downtime for organizational reasons and thus increase the efficiency of production processes. The information obtained also makes it possible to evaluate the condition of mechanical parts of machines. The recorded data is used for predictive machine maintenance where critical machine wear parts such as bearings, linear guides or ball screws can be identified and replaced before the machine stops due to failure. In this respect, rapid and accurate forecasting procedures are being developed which are particularly suitable for real-time maintenance systems [2].

One of the basic elements of automated machining are tool condition monitoring systems (TCM). Monitoring of the condition of the cutting tool identifies the occurrence of wear, breakage or other loss of functionality. Such an approach leads to

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a reduction in the number of manufactured scraps and to the prevention of possible machine crashes. This also improves the efficiency and economy of the machining process. At the same time, TCM systems contribute to the optimisation of cutting parameters, which leads to an increase of the tool life and the quality of the manufactured part [3]. Predicting the remaining service life is considered more important than monitoring the tool condition [4].

In general, using multiple external sensors can achieve better results than using a single sensor. However, the use of multiple sensors increases noise and increases the difficulty of signal processing. This can lead to a decrease in the accuracy of the results. Miura and Bergs [5] described a method of monitoring cutting power using a device installed on the feed drive motors of a machining centre. The device consists of voltage and current sensors. Cutting power is the product of cutting force (load information) and cutting speed (spindle speed information). The cutting power is monitored by estimating the induced voltage of the drive motor and correcting the motor current. The method was experimentally verified with a milling test and the results were compared with the results obtained with a dynamometer . The result of verification test was that electrically-derived signal, matches the mechanically-derived signal. By smoothing both electrically- and mechanically-derived signals, they were compared in the static domain. In the static domain, the estimated signal also tracks the force-sensored signal.

Brecher et al. [6] designed an application to monitor and control the roughness of the milled surface. The application obtains data directly from the NCK (Numerical Control Kernel) and suggests optimized cutting parameters to the machine operator. Using data from this application, the material removal rate can be increased by 20% and the requirements for manual finishing operations, that represents 15% of total costs in mold industry, can also be reduced . Data from the NCK could also be used to detect vibration, collision, breakage or wear of the tool. Möhring et al. [7] present a machine learning approach that can predict the surface roughness Ra of a milled part based on acceleration data from internal sensors of machine tool. A convolutional neural network was developed and trained to calculate surface roughness.

2. The proposed monitoring system

Data from machine tools can be obtained in various ways. One possibility is to use the built-in function of control systems of machine tools. Since the experiment in this study performs on a machine with a SINUMERIK 840D sl control system, the Trace diagnostic function included in this control system was used. Using this function, it is possible to select any system variable of NC control, PLC control or drives and create a record of it during machining. The recorded waveform is continuously displayed on the machine control panel screen during recording. But when displaying, it is not possible to simultaneously check the status of the running NC program, the current feed rate and spindle speed. The displayed waveform is not very clear, and after the end of the recording, working with the graph using softkeys is not very efficient either. The advantage, on the other hand, is that the data is recorded on the machine's local disk or CF card, which makes it possible to record with a sampling time of 8 ms. A useful option is to export recorded data in XML format and for higher versions of the control system also in CSV format. Thus, the user can view the exported data graphically and further work with them in programs such as MS Excel or Matlab [8].

The communication technology OPC UA (Open Platform Communications Unified Architecture) [9, 10], which complies with international standard IEC 62541, also allows the transmission of data from the machine control system. The OPC UA server is part of newer versions of machine tools control systems. If necessary, the machine without the support of this communication can be equipped with an external device that will ensure it.

To record the machine's internal data via OPC UA communication and display their progress, an application operating as an OPC client was created in the Matlab - App Designer environment. Interface of application allows to select from the list one of the stored machines, where the OPC UA server data is filled in automatically or it is possible to fill data manually. In the second step, the user selects the variables to be recorded after connecting to the server. Since one variable can contain information about several axes, it is necessary to specify the axis for which the progress will be recorded. Before starting the recording, it is possible to set the sampling time by which the selected variables will be read from the OPC UA server. After pressing the Start button, the application waits for the NC program to start on the machine using the NC start button, and then the recording starts. Similarly, depending on the running of the NC program, the record will be terminated. For further analysis, recorded data can be exported in CSV, XLS, XLSX, MAT or TXT format. The interface of this application is shown in Figure 1.

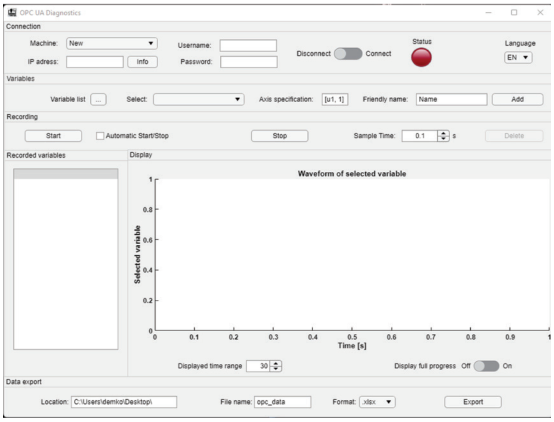


Figure 1: Interface of the monitoring software application

The described monitoring system was developed for deployment in operation with several CNC machine tools (lathes, milling machines, mill-turn machines). The deployment of the system was divided into three phases. In the first phase, experiments were carried out to verify the possibility of using the internal data of the CNC machine for comparison and evaluation of the strategies used in milling. The functionality of data recording via OPC UA communication has also been tested. The aim of the second phase was to verify the functionality and reliability of the system itself, the transmission and recording of the data. In the third phase, a method of online evaluation of the data obtained was proposed. The described experiments were carried out as part of the first phase of implementation of the system.

3. Materials and method

The aim of the conducted experiments was to verify the possibility of using the internal data of the CNC machine for comparison and evaluation of the strategies used in milling. At the same time, the functionality of the designed monitoring system was verified. The experiments were carried out on one of the CNC milling machines included in the monitoring system. Two milling methods were used, which were assumed to load the spindle and feed mechanisms of the machine differently. For the sake of simplicity in the initial experiments, 3-axis milling was chosen.

The following parameters were set in the system for monitoring and recording: the spindle load, the use of the rapid traverse, the current of the drives of the X, Y, Z axis, the power of the drives of the X, Y, Z axis and the drive torque of the X, Y, Z axis.

For the experiment, a sample was designed in the form of a centrifugal pump impeller with five pockets. The SolidWorks CAD system was used in the design. The sample (Figure 2) has a diameter of ø90 mm, the height of the cylindrical part with blades is 23 mm, the depth of the pockets is 20 mm. The material of the sample is medium alloy steel 1.6582, designed for stressed machine parts. The proportion of alloying elements is shown in Table 1. The semi-finished product was a cylinder with a diameter of ø90 mm and a height of 40 mm, prepared by turning.

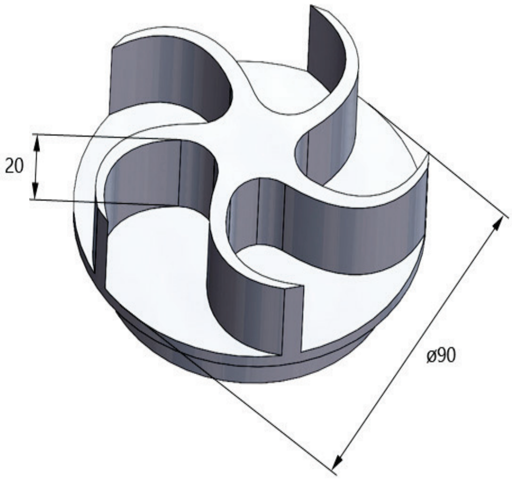


Figure 2: 3D model of the machining test sample

A 5-axis indexed milling machine DMG Mori ecoMill 50 (DMG Mori Corporation, Bielefeld, Germany) with a control system Sinumerik 840D sl V4.5 was used to produce the sample. For the creation of NC programs, the CAM system SolidCAM 2021 with the appropriate postprocessor was chosen. Two milling methods were chosen to machine the pockets, namely HPC (High Performance Cutting) and iMachining. HPC is characterised by a large depth of cut ap and the associated high material

Table 1: Proportion of alloying elements of material 1.6582

Element	C	Mn	Si	P max.	S max	Cr	Mo	Ni
Proportion [%]	0.4	0.4	0.1	0.5	3.6	0.3	0.2	0.15

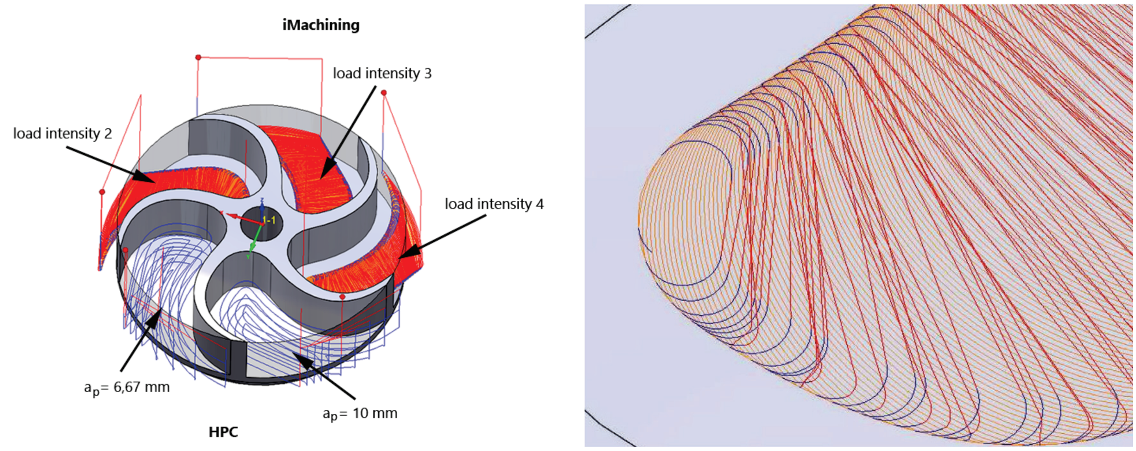


Figure 3: a) Toolpaths for individual pockets. b) Detail of trochoidal shape of iMachining 4 toolpaths (orange)

Table 2: Parameters of the tool [11]

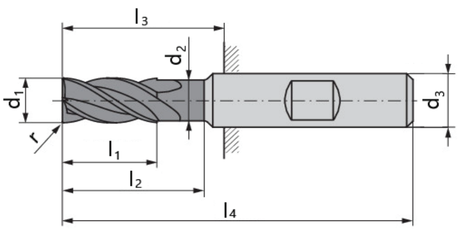
ød_1 [mm]	ød_2 [mm]	ød_3 [mm]	r [mm]	l_1 [mm]	l_2 [mm]	l_3 [mm]	l_4 [mm]	z [-]	γ_s [°]	[°]
10	9.8	10	0.32	22	30	32	72	4	8	36-38
Sketch of the tool										

Table 3: Parameters of the tool [12]

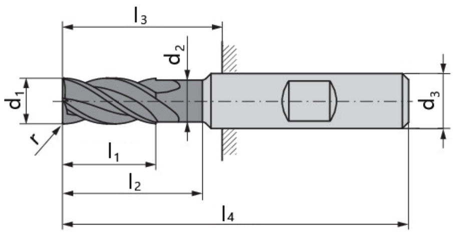
ød_1 [mm]	ød_2 [mm]	ød_3 [mm]	r [mm]	l_1 [mm]	l_2 [mm]	l_3 [mm]	l_4 [mm]	z[-]	γ_s [°]	λ_s [°]
10	9.7	10	0.2	22	30	32	72	6	8	30-31
Sketch of the tool										

Table 4: Cutting conditions for iMachining strategy

Tool load intensity	2	3	4
Cutting speed v_c [m.min^{-1}]	53	72	84
Feed per tooth f_z [mm/t]	0.15	0.15	0.15
Radial depth of cut a_e [mm]	0.076 - 0.212	0.076 - 0.258	0.076 - 0.308

removal rate. The depth of cut ap can reach up to twice the diameter of the tool and the width of the cut can be up to the full value of the diameter. The load on the tool is variable with significant load peaks. This type of milling operation has a high-power consumption and therefore the power of the machine used must be taken into account. The iMachining strategy combines a large depth of cut ap with the trochoidal shape of the toolpaths. The load of the tool has a balanced course without load peaks. The CAM system used allows eight levels of tool load intensity to be set for this strategy.

Two pockets of the sample were made by the HPC method and three pockets by the iMachining strategy. In the HPC method, two cutting depths of 10 mm and 6.67 mm were used. For the iMachining strategy, each pocket was machined with a different load intensity; levels 2, 3 and 4 were used. The depth of the cut was equal to the depth of the pocket, i.e. 20 mm. A separate NC program was generated for each pocket. Toolpaths for all pockets are shown in Figure 3.

For HPC milling, the milling tool PCR-UNI.H-SA.10,0.36°.Z4.HB.L APA72S was used (manufactured by WNT, supplier Ceratizit S.A., Mamer, Luxembourg). The diameter of the tool is 10 mm; its parameters are in Table 2. The cutting speed was set to v_c = 135m.min^{-1}, the feed per tooth was f_z = 0.074 mm/t.
TThe milling cutter CCR-UNI.H-SA.10,0.30°.Z6.HB.K DPX72S was used for milling with the iMachining strategy (manufactured by WNT, supplier Ceratizit S.A., Mamer, Luxembourg). The diameter of the tool is 10 mm, the parameters are given in Table 3. In the CAM system, a cutting speed v_c = 280 m.min^{-1} and a feed per tooth f_z = 0.05 mm/t were defined for the tool. However, the iMachining strategy adjusts the cutting conditions according to the set tool load intensity. The cutting parameters thus adjusted are shown in Table 4.
During the experiments, 8% emulsion Zubora 65 H Extra (Zeller + Gmelin GmbH & Co. KG, Eislingen/Fils, Germany) was used, intended for machining steel, cast iron and aluminum alloys. The manufactured sample is shown in Figure 4.

The data was recorded using the Trace diagnostic function and in parallel also using the OPC UA client. Subsequently, these data were saved in CSV format. Figure 5 shows the application of the OPC UA monitoring system during recording internal machine data.

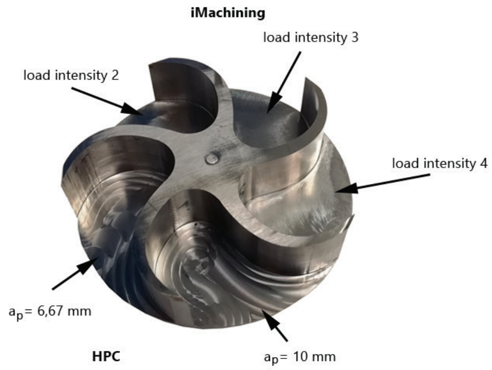


Figure 4: Manufactured sample

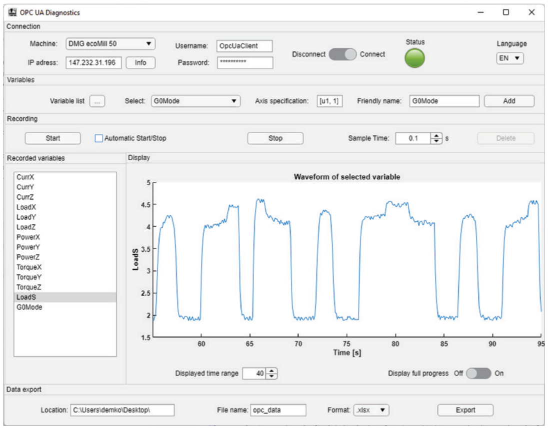


Figure 5: Application during recording

During all the experiments, it was possible to record the course of the required parameters by utilization of the developed application, so the monitoring system was marked as functional at this phase. The graphs presented below were processed in Excel spreadsheet editor. The graphs were based on data obtained using the Trace function, as the aim was to evaluate the milling methods being compared and this function is a built-in feature of SINUMERIK, so the data can be considered reliable.

4. Results

Based on the recorded signals, the graphs in Figure 6, showing machine spindle load versus machining time for all five milled pockets. In all cases, the waveform starts with a significant pulse when the spindle speed is switched on. In HPC milling, there is an area after the initial pulse with no load indicated. During this period of time, the machine movements were slowed down by the operator at the machine control panel to check the tool's entry into the material. In HPC milling, the

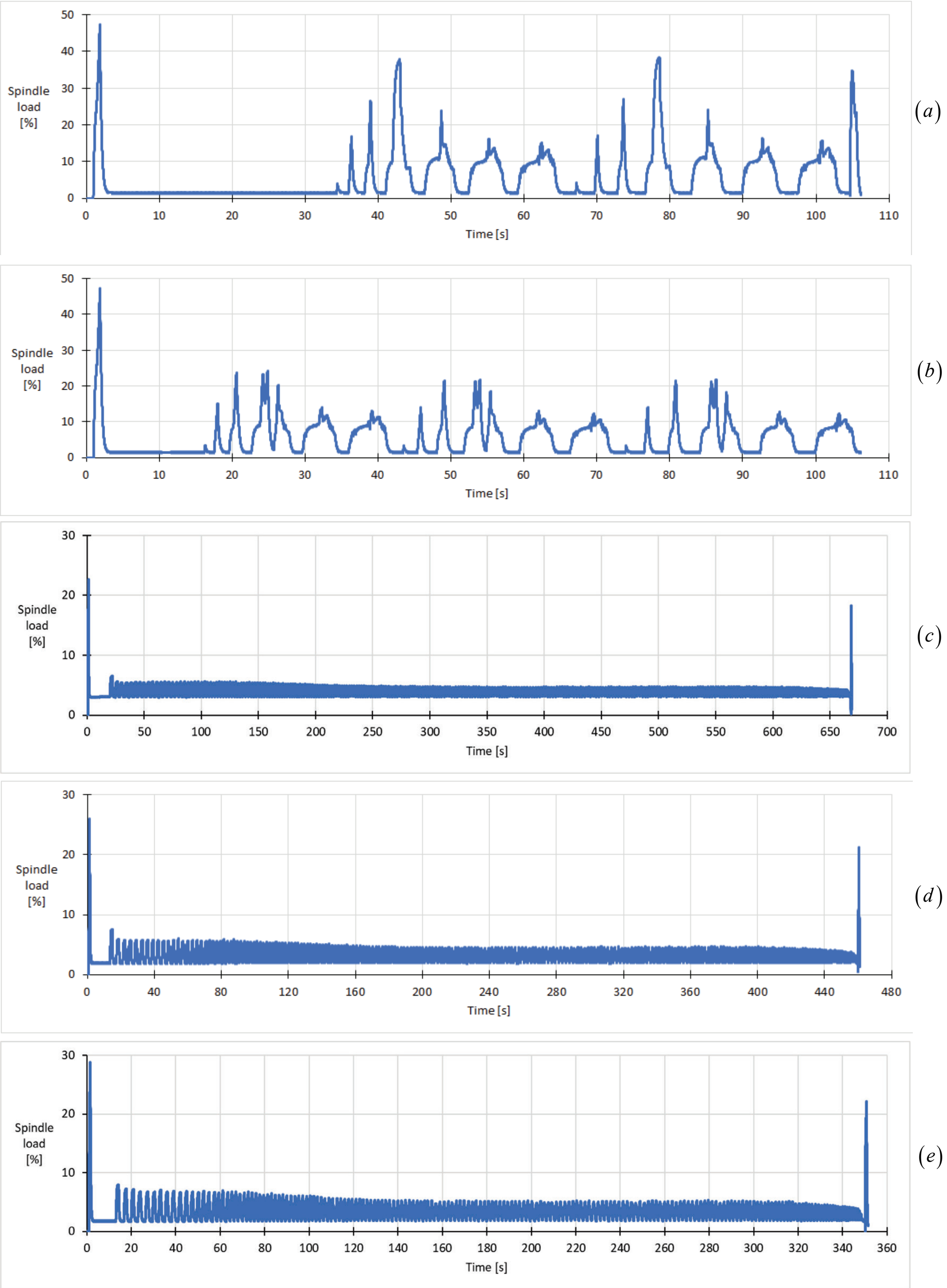


Figure 6: Spindle load flow for individual pocket milling methods
(a) HPC a_p = 10 mm. (b) HPC a_p = 6,67 mm. (c) iMachining 2. (d) iMachining 3. (e) iMachining 4

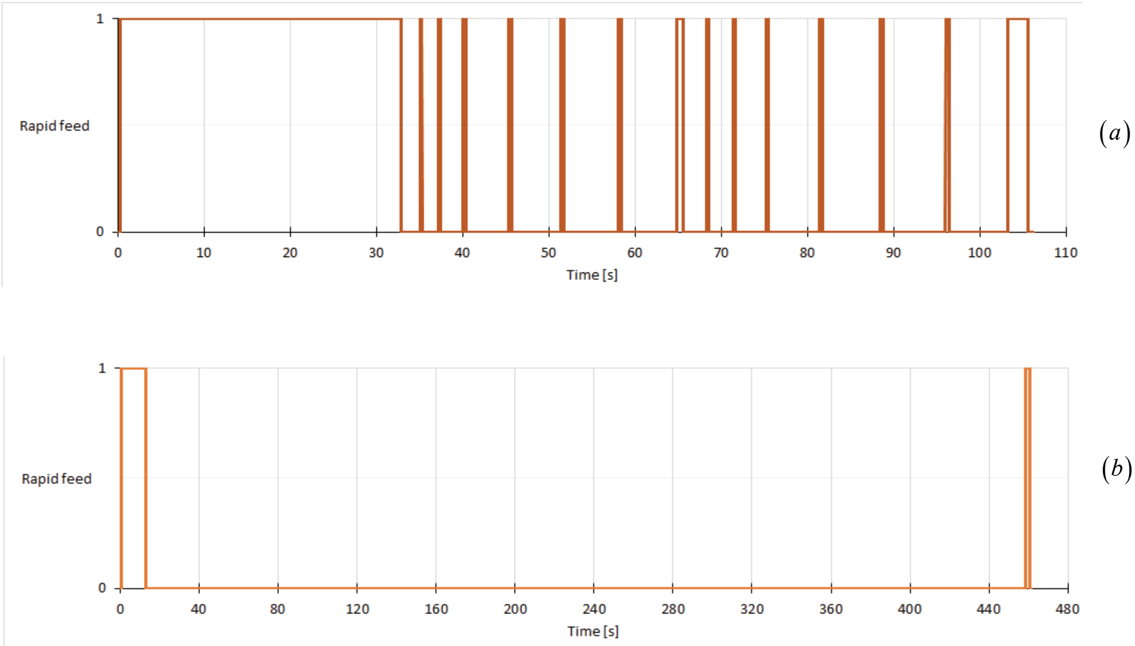


Figure 7: Rapid feed – (a) HPC a_p = 10 mm. (b) iMachining 3

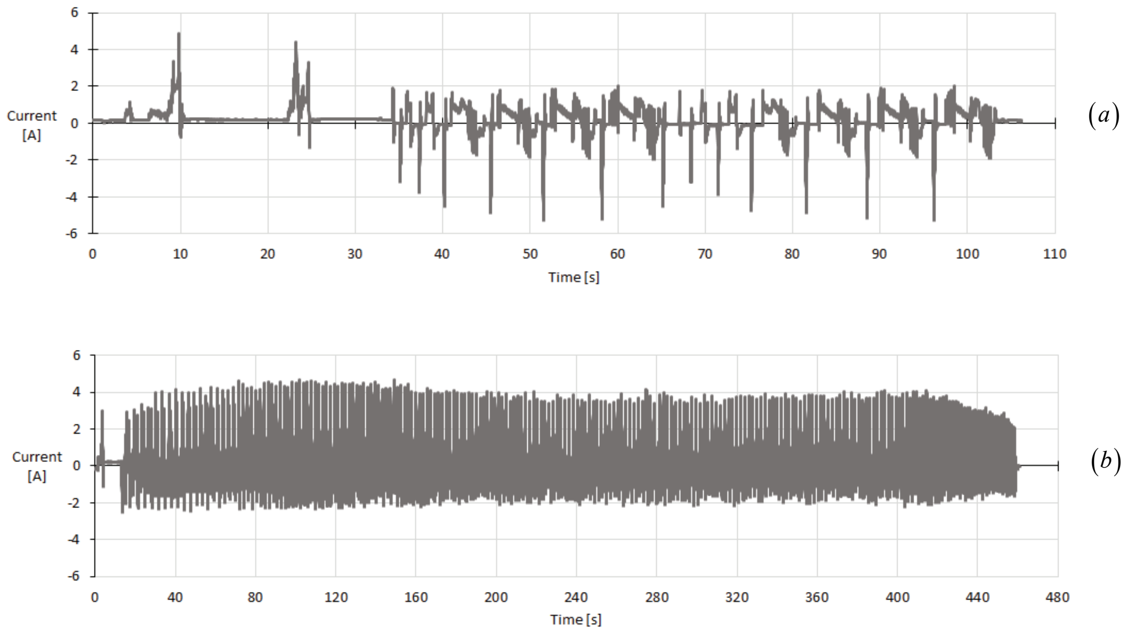


Figure 8: Current waveform for the X-axis drive - (a) HPC a_p = 10 mm. (b) iMachining 3

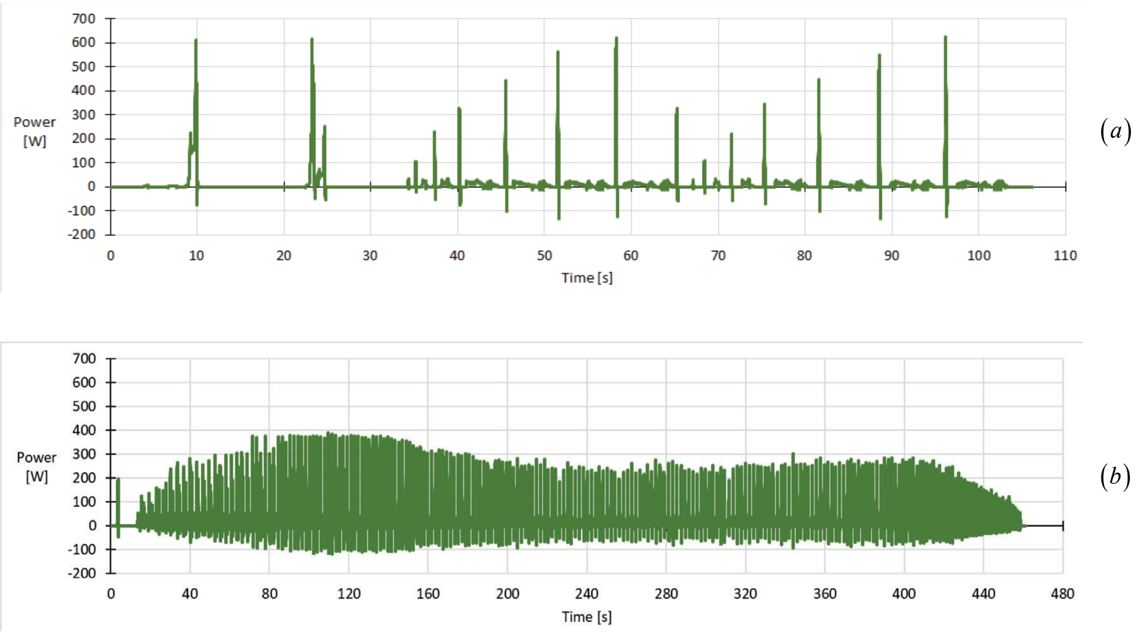


Figure 9: X-axis drive power waveform – (a) HPC a_p = 10 mm. (b) iMachining 3

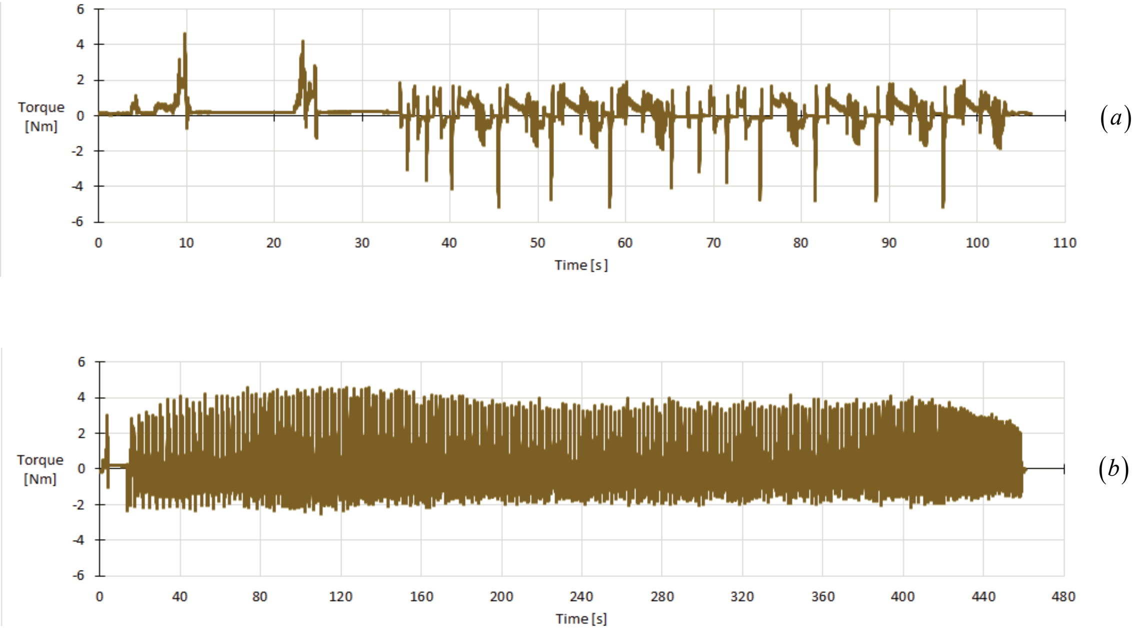


Figure 10: X-axis drive torque waveform – (a) HPC a_p = 10 mm (b) iMachining 3

waveforms are irregular, with significant load peaks. At the depth of cut a_p = 10 mm, the maximum value of the spindle load reached 38.5%, at a_p = 6.67 mm it was 34.8%. With iMachining milling, the waveform is even, with no significant load peaks. The impulse is also significant when the spindle is stopped. The maximum spindle working load reached values of 6.6%, 7.6% and 8% depending on the required tool load intensity set when creating the program in SolidCAM.

Due to the amount of recorded data, in the next part of the text, only the records for HPC milling with a depth of cut of a_p = 10 mm and for iMachining milling at tool load intensity 3 are compared.

In the graphs in Figure 7 records of the use of rapid movements are processed. In part a) of the figure is the record for HPC milling, in part b) for iMachining milling. In the first case, the frequent use of the rapid feed is evident when moving the tool; in the second case, the rapid feed is used only during the initial run-up and final run-out of the tool. The long activation of rapid feed in the initial part of the HPC milling record is due to the already mentioned slowing down of the movements before the tool enters the material.

The recordings of the current values for the X-axis drive is shown in Figure 8. Figure 8 a) shows the current waveform for HPC milling. The current peaks are significant, reaching values of 4.9 A or -5.2 A depending on the direction of rotation of the drive. Because of that the mean and standard deviation were calculated from absolute values. The mean is 0.50 A and standard deviation is 0.60 A. Figure 8 b) of the figure shows the current waveform during iMachining. The waveform is balanced, the maximum values are 4.7 A and -2.5 A. The mean is 0.81 A and standard deviation is 0.66 A. Similar records are available for Y- and Z-axis drives.

Based on the recorded and processed signals, the graphs in Figure 9 were also produced. They capture the dependence of the power of the drive, which ensures the movement of the tool in the X-axis direction, on the machining time. Figure 9 a) shows the drive power waveform for HPC milling. The power peaks are significant, reaching values around 600 W. The average value is 14.2 W and standard deviation 54.6 W. The power waveform for iMachining is balanced, the maximum recorded power is 392 W as shown in Figure 9 b). The mean is 25.2 W and standard deviation is equal to 50.8 W. Records are also available for drives in the Y and Z directions.

The graphs in Figure 10 show the drive torque values for the movement of the tool in the X-axis direction. The torque waveform for HPC milling is shown in Figure 10 a). The peaks are pronounced, reaching 4.6 and -5.1 Nm respectively. The average value and standard deviation are 0.48 Nm and 0.57 Nm. In Figure 10 b) is the torque waveform for iMachining. The waveform is balanced, the maximum values are 4.6 and -2.5 Nm. The mean is 0.77 Nm and standard deviation is 0.63 Nm.

5. Conclusions

In this paper, experiments related to the tests of the monitoring system, developed and employed in the Prototyping and Innovation Centre of Faculty of Mechanical Engineering, TU of Košice were described. Based on the knowledge from the implementation and the course of the tests it is possible to state the following about the proposed system:

– *The system demonstrated the ability to continuously record the specified number of parameters.*

– *The specified number of recorded parameters is sufficient for checking the ongoing process for assessing the condition of the tool and for detecting possible machine malfunctions.*

– *The experiments were performed on one of the workplace's CNC milling machines. The following conclusions follow from the comparison of the two methods of milling:*

– *During HPC milling, the spindle load waveforms are irregular, with significant load peaks. The maximum value of the spindle load is 38.5% at a depth of cut a_p = 10 mm and 34.8% at a depth of cut a_p = 6.67 mm. In iMachining milling, the waveforms are balanced, the maximum spindle working load reached values of 6.6%, 7.6% and 8% depending on the intensity of the tool load.*

– *The strategy for HPC milling often uses rapid feed when moving the tool between cuts, iMachining uses rapid feed only for the initial run-in and final run-out of the tool.*

– *The recorded values of current, power and torque of the drives for the X, Y and Z axes monitored during HPC milling showed significant peaks in these signals compared to the iMachining strategy, which may have an impact on the tool life.*

The proposed monitoring system has demonstrated by experiments the correct functionality and seamless processability of the acquired data. The aim of the follow-up work is to verify its functionality on 5-axis milling machines using all five movements and on milling machines with a different control system (Heidenhain). Later, the functionality will be verified on other types of machines, namely on a lathe with powered tools and on a mill-turn machines. After this verification, the system will be included in the on-line monitoring of production processes with comprehensive use.

Acknowledgments

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