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Micro milling machine – chosen aspects of diagnostic systems

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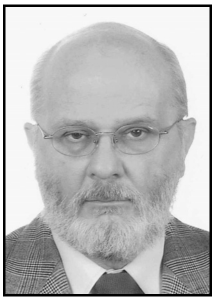

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Abstract

The paper deals with one of designed diagnostic issues for micro milling machine. A short description of the designed and set in motion micro machine for milling is presented. A geometrical construction of the machine is considered. Drive and measurement systems are presented. Moreover capabilities of the machine are compared to conventional ones and advantages of the presented machine are listed. The machine supervisory control system, which is based on an artificial intelligence diagnostic system is described. Conducted in design process deliberations about types and structures of the net and form and source of the signals are discussed.

Keywords: micro milling machine, diagnostic system for micro milling machine, neural networks.

Wybrane zagadnienia diagnostyki pracy mikrofrezarki

Streszczenie

W artykule omawia się wybrane zagadnienia kontroli pracy i diagnostyki mikrofrezarki. Prezentuje się parametry konstrukcyjne zaprojektowanej i uruchomionej w Centrum Mechatroniki ZUT w Szczecinie maszyny SNTM-CM-ZUT-1. Przedstawiono konstrukcję geometryczną maszyny oraz jej systemy pomiarowe i napędowe. Porównano właściwości tej maszyny z rozwiązaniami stosowanymi w konwencjonalnych obrabiarkach numerycznych uwypuklając własności utrudniające precyzyjne nią sterowanie. Opisano system diagnostyki stanu maszyny i nadzoru jej pracy. Stan maszyny określany jest na podstawie pomiarów realizowanych z wykorzystaniem miniaturowych akcelerometrów umieszczonych na korpusie i wrzecionie maszyny. Rejestrowane przebiegi poddawane są przekształceniom FFT w matrycy FPGA a wyniki tych obliczeń wykorzystuje się następnie w klasyfikatorze neuronalnym. Prezentuje się rozważania przeprowadzone w procesie projektowania sieci dotyczące typu i struktury sieci oraz formy i źródła sygnałów. Przedstawia się strukturę i cechy systemu nadzoru pracy obrabiarki oraz formę prezentacji wyników modułu diagnostyki.

Słowa kluczowe: mikrofrezarka, diagnostyka, sieci neuronowe.

1. Introduction

The production of the precise miniature component is stimulated by increasing requests from e.g. aircraft industry, electronic industry or biomedicines [1-3]. Moreover global tendency towards device miniaturization and very fast development of mechatronics cause increased importance of micro machining processes; in particular large interest of the Micro Electro – Mechanical Systems (MEMS) that contain precise mechanic components with high shape ratio, sizes of a few micrometers to a few millimeters and very often are characterized by lack of the axial symmetry [3]. Moreover mechanic components of such systems have to be made of difficulty machined materials such as high alloy steel, ceramic or titanium compounds. Obtaining required precision of manufacturing of such elements is impossible by the use of classical technology as: molding, pressing, hammering, electro or chemical erosion and even laser tooling, but only using micro cutting [3]. That is why, among many techniques of micro components production, there is observed the growing interest in micro cutting, which arises with large potential of that method in the zone of the realization of geometrically complex elements. Especially high rate of adoption of such machines takes place in case of tooling “micro shapes” in the area of micro element.

The micro cutting technique, in case of unitary production, allows for projection of the 3D free face with relatively little cost effort. All that causes a large applicability of micro cutting, for instance in case of micro mold manufacturing [4]. Another advantage of such tooling technique is relatively high efficiency, low harmfulness for environment, relatively low cost of devices and their exploitation.

Nowadays the operations of micro cutting are performed on high precision machines characterized by the high efficient of stiffness equipped with systems for a temperature control [5, 6]. Mainly from the cost reduction point of view, the strong tendency is currently observed to build tooling machines characterized by small dimensions and possibility to move them easily [7, 8]. Unfortunately such constructions are incomparably worst in contrast with conventional precision tooling machines from stiffness, precision and vibration moving by the basis damping point of view. For that reason the development of a new construction of micro machines for tooling is a very important and actual topic. Researches on the micro cutting subject, both in Poland and all over the world, are still pioneering [9]. However, there are brands offering specified commercial solutions of micro cutting machines, which are quite expensive and have rather only individual character.

2. Machine description

The prototype of the described machine for micro tooling was built as an effect of realization of the grant financed by the Polish Ministry of Science and Higher Education. The basis of the machine is composed of specially produced stabile granite corps (Absolute Black Granite) on which an electro-spindle with a controlled rotary velocity (100.000 RPM) and precise system of liner motion are mounted. What is more, the machine is equipped with an air-conditioning system stabilizing temperature of the machine. That micro milling machine has three numerically controlled axes and is equipped with adequate measuring apparatus, such as: a precise multi axes dynamometer for measuring cutting forces, a digital viewing microscope Keyence, model VHX-600ESO with high zoom and acoustic measurement system. The workspace of the machine is limited to the cuboid with size of 100x100x50 mm and the errors of positioning are near the value of 0.5 µm. The rest operation parameters are similar to those of other constructions existing on the market. Nevertheless the expected price is many times lower, due to the use of ready-made modules with made by a control system made by the authors and individual construction of the corps. One of the most important properties of the constructed machine is a monitoring system with diagnostic algorithms based on artificial intelligence. Generally in modern constructions of such machines the monitoring systems are quite rarely integrated with the machine control system.

The design works on the machine were started from selection of a kinematic structure, which has essential influence on the possible technological precision of the machine; it is the mean precision of a relative tool and tooling object motion. For that reason two selected geometrical structures, horizontal and vertical, were taken into consideration.

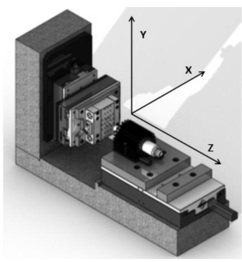

Fig. 1. Project of the milling micro machine with pointed out axes
Rys. 1. Projekt mikrofrezarki z naniesionym układem współrzędnych

The conducted simulations gave the possibility to compare the structure with a vertical and horizontal spindle with respect to the precision of projection of the tool to the tooling object. As a criterion for that comparison the lowest value and dispersion of the volume error were chosen. Finally, all performed analyses led to choosing the horizontal structure as a better one, especially in the view of precision of the projection of the tool and the tooling object relative position. In the machine the spindle moves horizontally along the Z axis and the tooling object could be moved on the surface Y-X. A computer comparative analysis of the machine construction with the others known from literature shows that the chosen construction would meet best all the requirements regarded: stiffness, dynamic and precision of tool position projection due to tooling object.

For the constructions on each line moving axis were used commercial high precision drives of Aerotech, USA: "Y" axis working horizontally based on model ANT95-50-LV, "Z" axis based on model ANT95-50-L; "X" axis based on model ANT130-110-L. The drives work under control of the controller Epaq model EPAQ-S-FPB-XX-/1-MP10MI-MP10M-MP10M-MP10.

The main driven system consists of a commercial electro spindle of type 4015 DC, which was made by SycoTec, Germany, controlled by a controller and supplier e@syDrive 4425. Moreover, that system requires supplying with compressed (0.5-0.8 bar) air of adequate clarity due to protect ceramic bearing from pollutants. Additionally the servo drive of vertical axes uses a pneumatic cylinder actuator for supporting the operations of an electrical linear motor. For that reason there was designed a pneumatic installation for the machine. The main component of that installation is a rotary vane compressor for continuous work, model Gast 74R130-P114H201X, moreover there are air filters, valves and pressure reducers.

One of the most important parameters of the correctly realized process of micro milling is maintaining the constant temperature of the machine and the tooling object. Due to these requirements the machine is installed in a closed cover, inside which the temperature and humidity are stabilized by a maintained-free air conditioner made by Schroff. Summing up, the main features of the micro machine for milling operation are as follows:

- small dimensions,
- very high precisions of tooling,
- very high stiffness and thermal stability,
- high rotary velocity of the tool – high coercion frequency during milling process.

The knowledge about course and character of the micro milling process, obtained from the experiment, was used to make conception of the intelligent diagnostic system. Due to the fact that micro milling process in comparison with classical tooling in macro scale is relatively poorly known and, what is more, is characterized by many specific features, the recorded experimental data and its analysis could be the source of the diagnostic system concept only.

3. Diagnostic system for micro machine for milling

One of the micro tools features is that they can be very easily destroyed, due to their small dimensions, e.g. 0.1 mm. Especially during installation in the spindle the tool can be damaged. For that reason it is very important to validate the state of micro tool after mounting it in the grip of the electro spindle, and before starting the tooling process. The designed, for realizing such diagnostic procedure, system is based on analysis of the measured, with use of miniature accelerometers (model 325B10, PCB) attached to the servo drive corps, spindle vibrations signals. It is assumed that the measurements are made when the proper spindle velocity is achieved. In Fig. 2 the example of time domain signals in the axis "Y", recorded at the speed of 24,000 RPM, for three diagnosed states is presented.

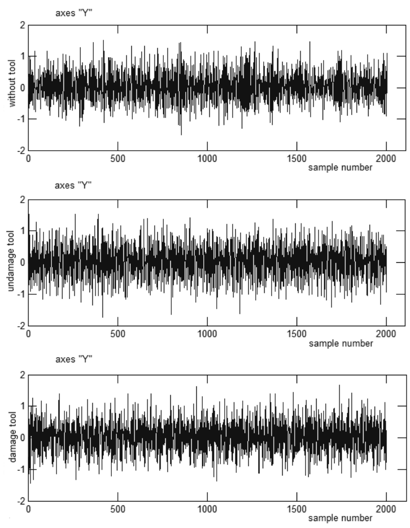

Fig. 2. Time domain signal in the axes "Y"
Rys. 2. Przebiegi czasowe sygnałów w osi "Y"

The proper velocity is related to the sampling parameters, the spread of the FFT window and the expected value of the first harmonic of the vibration signal. Assuming that a tool with 2 edges is mounted in the spindle and the measurements are taken with a sample rate of 51,200 SPS the obtained spindle velocity values are: 96,000 RPM, 48,000 RPM, 24,000 RPM and 12 000 RPM, which guarantees the correct form of the diagnostic signals. For those signal parameters the integer number of samples per period for the first harmonic and the integer number of periods of the first harmonic in the window set up for FFT are obtained. The number of 4096 samples for FFT analysis were chosen in order to guarantee on the one hand the high speed of the working diagnostic algorithm and on the other as to obtain enough thin bands (high enough resolution) in the spectral characteristic. Figure 3 shows the examples of the spectrum charts with a different FFT window spread.

Moreover there was investigated the problem of using the window before FFT. Windows such as Tukey or Taylor, among others, are used for elimination of a negative influence of the FFT algorithm assumptions. All kinds of windows available in Matlab/Simulink environment were checked and it was found that it was enough to use the rectangle kind of window. The spectral characteristics for different types of window are presented in Figure 4.

The diagnostic system uses the information obtained from the results of the performed in advance spectral analysis (FFT). Similar approach to the diagnostic issue is presented for instance in [1]. Such a procedure of analyzing the spectral signals could be carried out not only before starting tooling, but also each time when the micro tool does not have a contact with the tooling object due to the program path. Such a test and analysis could give us a chance to assert if in the grip there is no tool or in the grip is the tool which is undamaged or damaged. The spectral charts for those cases are presented in Figure 5.

To achieve efficiently working diagnostic system recognizing the mentioned above three potential states, it is necessary to collect data concerning different tools existing on the market. To find the best source of diagnostic information, not only the spectra of the recorded signals were taken into consideration but also the signals formed by using the mathematic operation on the elementary, recorded signals. To find the best form of symptoms following signals, there were investigated:

- signal recorded in the "X" axis,
- signal recorded in the "Y" axis,
- signal formed as a result of summing the signals recorded in axes "X" and "Y",
- signal calculated as an amplitude of the resultant vector formed from the signals recorded in the axes "X" and "Y", i.e. $\sqrt{(X*X+Y*Y)}$,
- signal calculated as an amplitude of the resultant vector formed from the signals recorded in the axes X, Y and Z, i.e. $\sqrt{(X*X+Y*Y+Z*Z)}$.

For the mentioned above signals the spectral characteristic were calculated and chosen parameters of that characteristic were used to assemble learning patterns for the process of learning artificial neural networks. What is more, on the basis of the analysis of the shape of many plotted spectral characteristics we state that more efficient neural system could be designed using proportions of the characteristic parameters (integral of specific areas around main harmonics on the spectral characteristic), then just directly parameters. The investigated relations:

- quotients of the area value around the first, second, third harmonic and the sum of the whole chart area (1h/sum, 2h/sum, 3h/sum),
- quotients of the area around the second harmonic and the area around the first harmonic with the quotient of the area around the third harmonic and the area around the first harmonic (2h/1h, 3h/1h),
- quotients of the sum area around the first and third harmonic and the area around the second harmonic with the sum area around the second and third harmonic and the area around the first harmonic ((1h+3h)/2h, (2h+3h)/1h).

For the speed 24.000 RPM the first, second and third harmonics are 400 Hz, 800 Hz and 1200 Hz, respectively. Moreover the analysis of the charts shows that the plots are not constant from window to window. For that reason for the diagnostic system also the average values and deviations calculated for spectral characteristic were taken into account.

Having all the above described assumptions about the form of potentially useful signals, the structures and types of neural networks were chosen. Only forward kinds of nets were investigated. Table 1 presents the list of the researched neural networks.

The listed types and structures of the networks were researched in addition with combination of the previously described form of input signals were investigated when looking for the network capable of correct recognition of the machine state.

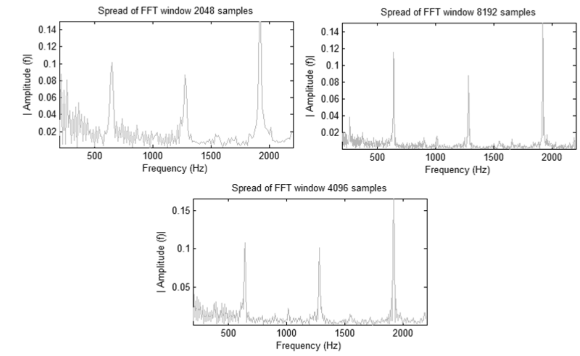

Fig. 3. Spectral characteristic for different spreads of the FFT window
Rys. 3. Charakterystyki widmowe dla różnych szerokości okien FFT

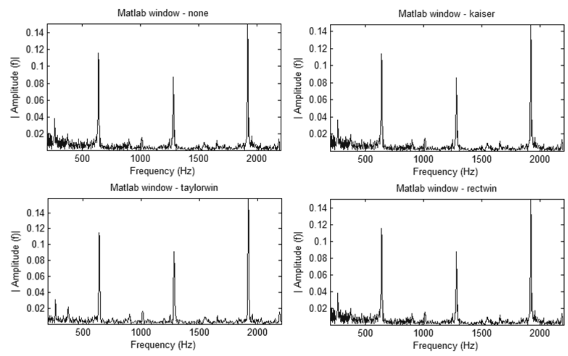

Fig. 4. Spectral characteristics for different types of windows
Rys. 4. Charakterystyki widmowe dla różnych typów okien

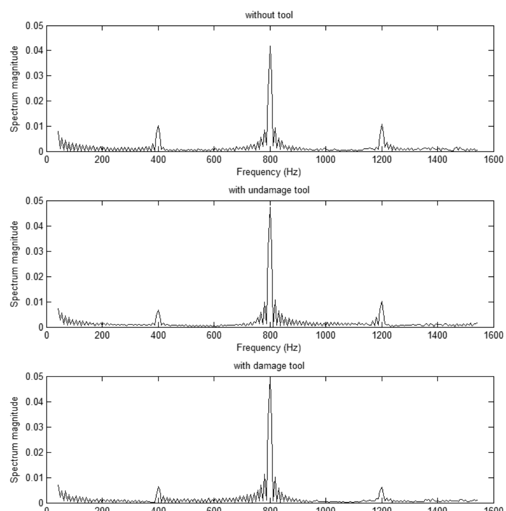

Fig. 5. Spectral characteristics for different machine states
Rys. 5. Charakterystyki widmowe przy różnych stanach pracy maszyny

Finally, as the best kinds of networks, there were calculated the networks:

- with signal at the input:
  - rotary velocity 24,000 RPM,
  - measurement of the acceleration in the „X" axis,
- with operation 2h/1h, 3h/1h (2 dimensional input vector),
- feed-forward type,
- only 1 hidden layer with 3 neurons,
- with outputs coded as -10 / 10.

As a final solution, an advisory diagnostic system, in which the operator will obtain the information from all four networks, is proposed. In case of detecting incorrect operation of the system the operator is supported by a concluding system based on fuzzy logic techniques. Such a diagnostic algorithm was implemented and tested during common operations, which is described in the next subsection in more detail. The main implementation environment for that control and supervisory system is NI LabView.

Tab. 1. List of the examined structures of the networks
Tab. 1. Lista badanych struktur sieci neuronowych

no.	Number of neurons in the layer					
	input	hidden				output
		1st	2nd	3rd	4th	
1	2, 3, 4, 6 due to the set of the signal treated as symptoms	3				3 or 1 3 in case of the network recognizing each of the three states 1 in case of the network recognizing only one state from three
2		6				
3		9				
4		12				
5		15				
6		18				
7		6	3			
8		9	3			
9		9	6			
10		12	6			
11		12	9			
12		15	9			
13		9	6	3		
14		12	6	3		
15		12	9	3		
16		12	9	6		
17		15	9	6		
18		15	12	3		
19		15	12	6		
20		12	9	6	3	

The conducted test using wider (than during learning) sets of signals gave the following results:
- the net recognizing the state "without tool" works with the error equal to 0,
- the net recognizing the state "undamaged tool" works with the error equal to 7,8%,
- the net recognizing the state "damaged tool" works with the error equal to 8,0%,
- the net recognizing all states works with the error equal to 5,2%.

Many more diagnostic problems were also investigated. One of the important issues is, among others, to detect the point when the tool touches the object and the micro milling starts. Another one is to determine before starting the tooling if the program were written accurately and the machine and the tool do not have a path with collisions. Moreover, observation of the actual spindle velocity in contrast with the set up reference signal is the next important symptom of the machine state allowing us to validate the efficiency of the spindle system. The algorithms for diagnosing the mentioned machine states are still under investigation and implementation.

4. Supervision system for the machine

The main tasks of a supervision system are acquisition, monitoring, analyzing and recording data during operation and communication with a control system. The hardware structure was divided into three main parts. The first section, the FPGA module in controller PAC cRIO 9022, is responsible for acquisition and filtering of the signals measured on the machine. That solution gives us a chance to measure very fast changing signals as force and acceleration with sampling rate 51,200 SPS and filtering them in real time. The second section is based on another cRIO 9022 instance working in real time regime. The DMA channels are used to transfer huge amounts of data in short time without charging the controller's CPU. Transition of the data to the third instance is realized using the "Network Streams" protocol. That last instance (PC computer) is responsible for recording all the collected data. That instance is dedicated to data analysis and diagnostic tasks.

The important component of the implemented supervision system is Human – Machine Interface. Such an interface delivers many functions improving comfort of the operator work. It was assumed that HMI would be realized on two wireless panels. To expand supervisory system on remote devices working under Windows operating system, LabView Mobile Module from LabView National Instruments was used. The module supports Shared Variable Engine and cooperates with Data Acquisition devices. As an operator panel tablet Acer Inconia Tab W500 and smartphone HTC HD2 were chosen. Remote HMI systems can be divided into those based on web interface and autonomous, working on mobile devices using WiFi to communicate with the base station controlling the process. While working on a prototype of the numerical micromachining visualization system we focused on the second of these systems. A web-based interface, despite many advantages in our case does not fulfil the tasks put before it. Due to the many hours' time in cut material, the operator should be able to move around the factory floor at the same time having the ability to track and stop a remote process from any place and using any device (HMI implementation).

The interface implemented on PC and operator panel displays results of the diagnostic analysis. The example of such a view is presented in Figure 6.

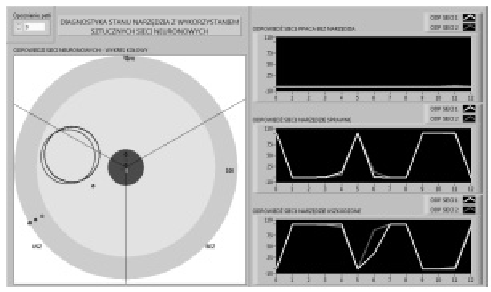

Fig. 6. The view of diagnostic screen
Rys. 6. Widok ekranu diagnostyki obrabiarki

5. Conclusions

Increasing significantly the safety of the process, reducing downtime and increasing the process quality, diagnostics is the most useful feature of the monitoring and visualization systems. As it was described a micro machine for milling was designed, assembled and tested. On the basis on the recorded signals the analysis of the diagnostic procedure was performed. Thanks to that analysis a diagnostic system using neural networks was designed in Matlab and implemented in LabView. The tests shows that the best results are obtained when the decision about the actual state of the machine is made on the basis of combined answers from 4 networks. The remote communication with the operator shows trends in the HMI systems, especially those including the diagnostic system.

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