Concept of tool condition diagnostic system for micromachining

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Abstract: The paper deals with part of diagnostic system for micromilling machine. The short description of designed and set in motion micromachine for milling is presented. The machine supervisory control system, based on artificial intelligence diagnostic system is described. Conducted during design process, deliberations about types and structures of the neural nets and form and source of the signals are presented. The last part of the paper includes conclusions and final remarks.

Keywords: micromilling machine, diagnostic system, neural networks

The production of precise miniature components is stimulated by increasing demand from different industry trades. It is especially important for construction of devices that contain precise mechanic components characterized by high shape ratio, sizes of a few micrometers to a few millimeters and very often by lack of axial symmetry. What is more, such systems very often have to be made of the difficult-to-machine materials such as high alloy steel, ceramic or titanium compounds. Obtaining required precision of manufacturing of such elements using classical technology as molding, pressing, hammering, electro or chemical erosion and even laser tooling is impossible [1, 2, 10, 11]. That is why there is observed the growing interest of microcutting.

The micro cutting technique, in case of unitary production, allows for projection of the 3D free face with relatively little costs effort. 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 microcutting are performed on high-precision machines characterized by the high coefficient of stiffness and equipped with systems for temperature control [3– 5]. Mainly from the cost reduction point of view, the strong tendency is actually observed to build tooling machines characterized by small dimensions and possibility of easy transfer to another location [6–9]. Unfortunately such constructions are significantly worse in comparison to conventional precision tooling machines from point of view of stiffness, precision and vibration transmission by basis. For that reason, the development of new constructions of micromachines for tooling is very important and actual topic. Research activities concerning the microcutting subject, both in Poland and all over the world, are still of the pioneering kind [12].

The paper is organized as follows. In Section 1 a micromilling machine is presented. The machine diagnostic system is described in Section 2. Supervisory system and its hardware solution are presented in Section 3. Brief conclusions are drawn in the last section.

1. Machine description

Presented prototype of machine for micromilling was built as an effect of realization of the Grant No. N R03 0050 06/2009 entitled "Construction of a prototype system for testing micromachining – researches and modeling of process" financed by the Ministry of Science and Higher Education of the Republic of Poland.

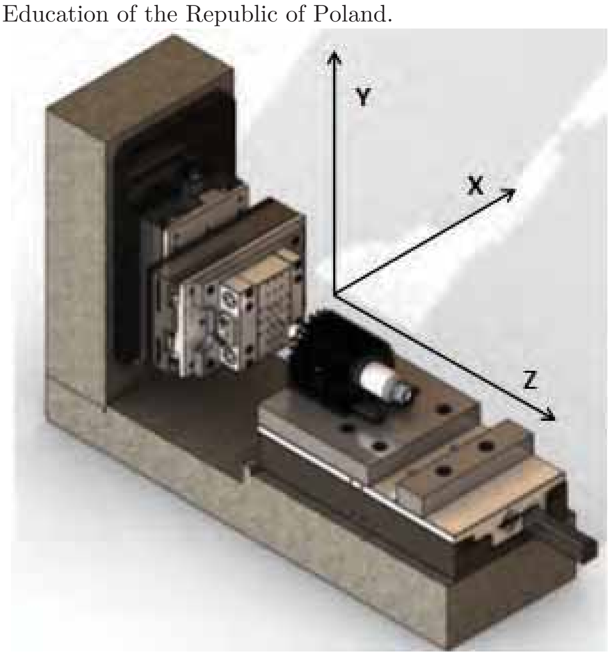

Fig. 1. Project of the milling micromachine with marked axes of coordinate system

Rys. 1. Projekt mikrofrezarki z naniesionymi osiami układu współrzędnych

The basis of the machine consists of specially produced stabile granite foundations on which the electro-spindle with controlled rotary velocity and precise system of three numerically controlled axes for linear motion are mounted. Moreover, machine is equipped with appropriate measurement apparatus, among others: precise multi-axes dynamometer for measuring cutting forces, Keyence digital viewing microscope, and acoustic measurement system. The workspace of such designed machine is limited to cuboid with size of 100 × 100 × 50 mm and the error of positioning is near the value of 0.5 µm. Although the remaining operation parameters are similar to other constructions existing on the market, expected price is many times lower, due to using ready-made modules with made by us control system and construction of the foundations. One of the most important properties of the constructed machine is monitoring system with diagnostic algorithms based on artificial intelligence. Generally, in contemporary constructions of such machines, monitoring systems are quite rarely integrated into machine control system.

All conducted analyses lead to choice of the horizontal structure of machine as the better one especially in view of precision of the projection of the tool and relative position of a tooling object. In the machine, the spindle is horizontally moving along the Z axis and the tooling object can be moved on the surface Y-X.

In construction of each linear moving axis were used commercial high precision drives of Aerotech, USA. The main drive system consists of commercial electro-spindle made by SycoTec, Germany.

Main features of the presented machine are:

– 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.

For that machine the control and supervision system were designed and implemented. The scheme of the system is shown in the fig. 2.

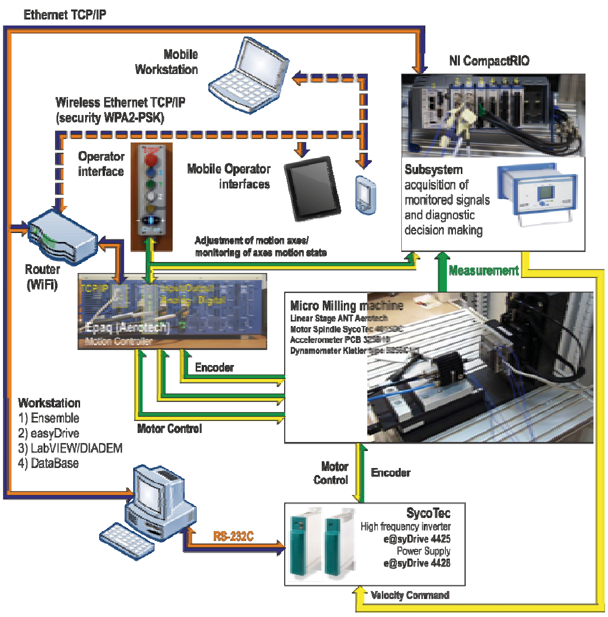

Fig. 2. Structure of the machine control and supervising system
Rys. 2. Struktura systemu sterowania i nadzorowania maszyny

The knowledge about the course and character of the micromilling process, acquired on the way of experiment, were used to develop conception of the intelligent diagnostic system. Noting that micromilling process, in comparison with classical tooling in macro scale, is relatively poorly known, and additionally that it is characterized by many specific features, one concludes that only the use of recorded experimental data and its analysis could be the source of the diagnostic system concept.

2. Diagnostic system

One of the microtools 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 microtool after mounting it in the grip of electro-spindle, and of course before starting the tooling process. System designed for conducting such a diagnostic procedure is based on analysis of measured, by means of miniature accelerometers attached to the servo drive housing, spindle vibrations signals. It is assumed that the measurements are made, when the proper spindle velocity is achieved. In the fig. 3, an example of time domain signals in all axes, recorded at the speed of 24 000 RPM, for the three diagnosed states are presented.

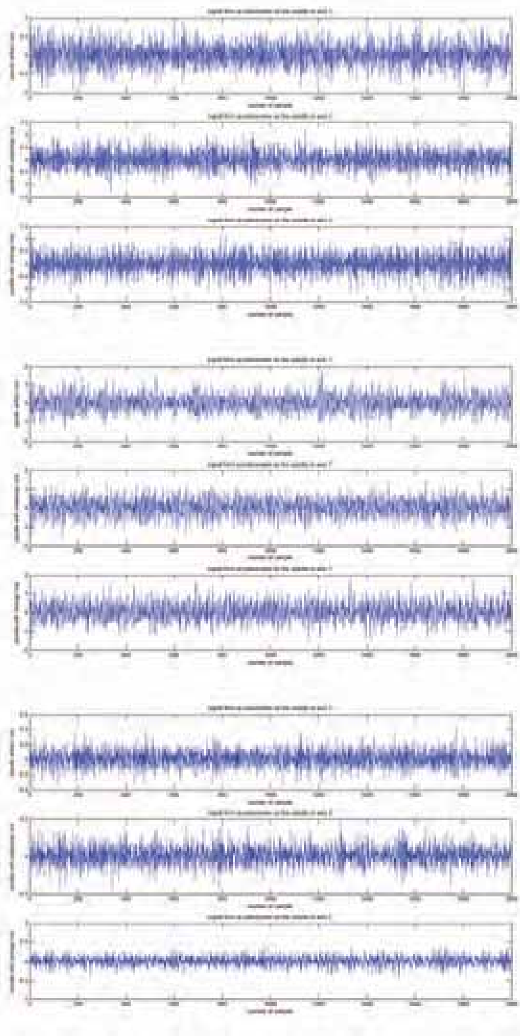

Fig. 3. Time domain signals in the “X” , “Y” and “Z” axes
Rys. 3. Przebieg w czasie sygnałów w osiach „X”, „Y” i „Z”

The proper velocity is related to the sampling parameters, the spread of the FFT window, and expected value of first harmonic of the vibration signal. Assumptions that in the spindle is mounted the tool with 2 edges and the measurements are conducted with sample rate of 51 200 SPS (samples per second), resulted in calculating the spindle velocity values of 96 000 RPM, 48 000 RPM, 24 000 RPM and 12 000 RPM as guaranties of correct form of the diagnostic signals. For those signals' parameters the integer number of samples per period for first harmonic and integer number of periods of first harmonic in the window set up for FFT are obtained. The value of 4096 samples for FFT analysis was chosen to guarantee on the one hand the high speed of working of diagnostic algorithm and on the other hand as that one which allows to obtain enough thin bands (high enough resolution) in spectral characteristic. The fig. 4 presents examples of the spectrum charts with different FFT window spread.

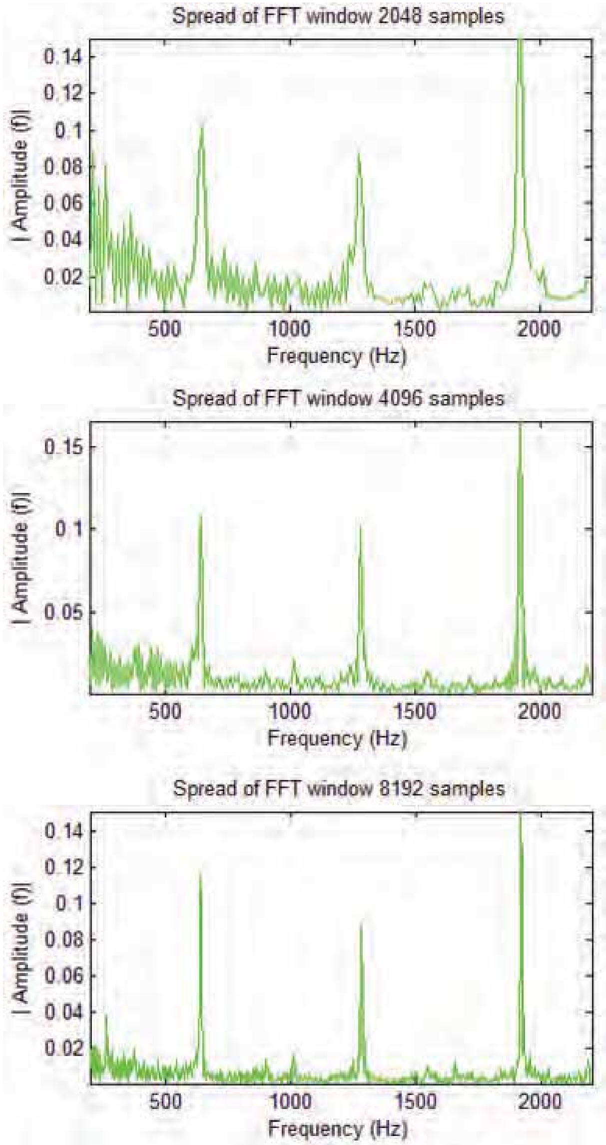

Fig. 4. Spectral characteristic for different spreads of the FFT window

Rys. 4. Charakterystyka spektralna dla różnych rozpiętości okien dla analizy FFT

Moreover into investigation was taken the issue of using window before FFT. Windows such as Tukey or Taylor among others are used in case of elimination of negative influence of FFT algorithm assumptions. All kinds of windows available in MATLAB environment were checked and it was found that it is enough to use the rectangle kind of window. The spectral characteristics for different types of windows are presented in fig. 5.

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 procedure of analyzing the spectral signals can be conducted not only before start of tooling, but also each time when the microtool does not have contact with the tooling object, as it follows from the programmed path of the tool. Such test and analysis can give us a chance to state if in the grip there is no tool, the tool is undamaged or damaged.

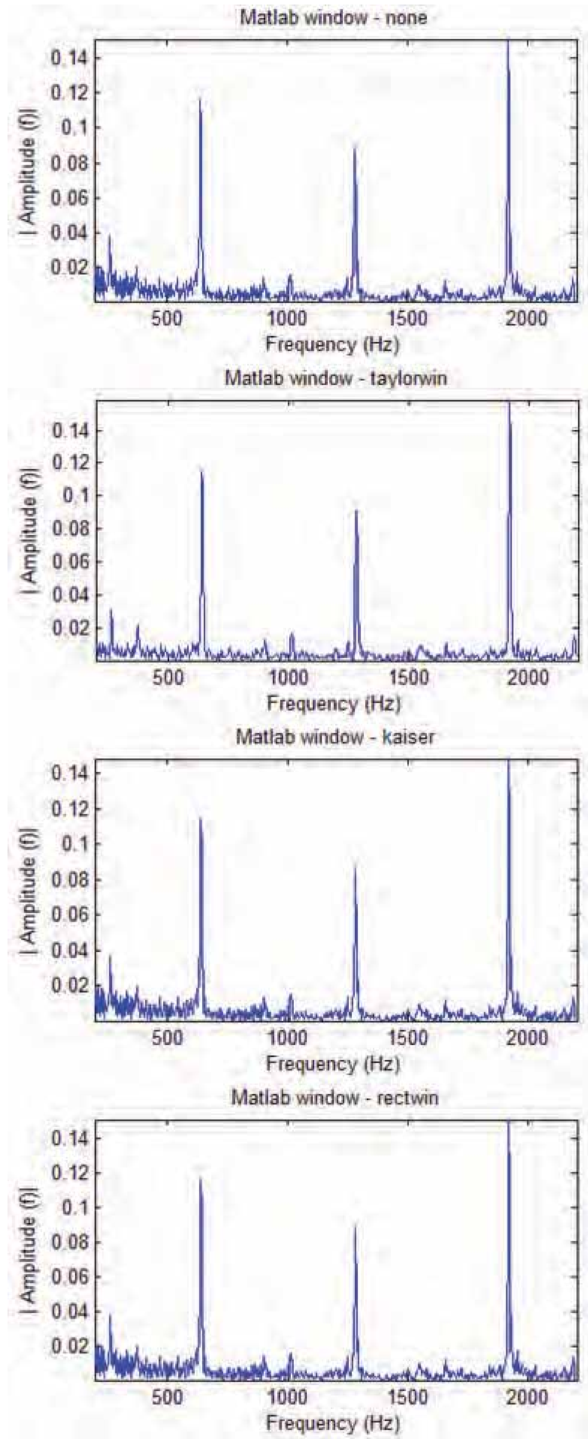

Fig. 5. The spectral characteristics for different types of windows

Rys. 5. Charakterystyki spektralne dla różnych typów zastosowanych okien

The spectral charts for those cases are presented in fig. 6. To achieve efficiently working diagnostic system recognizing mentioned above three potential states it is necessary to collect data reflecting different tools occurring on the market. In order to find the best source of diagnostic information not only spectra of recorded signals were taken into consideration, but also signals formed by using the mathematic operation on the elementary, recorded signals. To find the best form of symptoms, following signals were investigated:

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

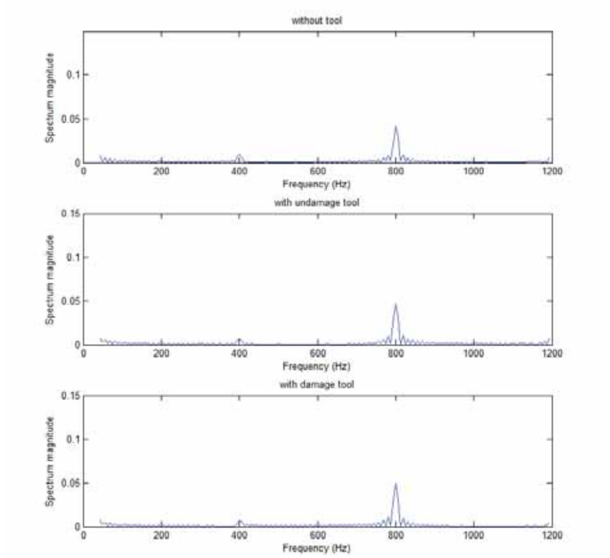

Fig. 6. The spectral characteristics for different machine states
Rys. 6. Charakterystyki spektralne dla różnych stanów maszyny

For mentioned above signals spectral characteristics were calculated and chosen parameters of that characteristics were used to prepare learning patterns for the process of artificial neural networks learning. What is more, analysis of the shape of many plotted spectral characteristics leads us to the view 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), than just directly the parameters. The investigated relations:

– quotients of area value around first, second, third harmonic and the sum of whole chart area (1 h/sum, 2 h/sum, 3 h/sum),
– quotients of area around second harmonic and area around first harmonic with quotient of area around third harmonic and area around first harmonic (2 h/1 h, 3 h/1 h),
– quotients of sum area around first and third harmonic and area around second harmonic with sum area around second and third harmonic and area around first harmonic ((1 h+3 h)/2 h, (2 h+3 h)/1 h). For the speed 24 000 RPM the first, second and third harmonic are 400 Hz, 800 Hz and 1200 Hz, respectively.

Moreover, analysis of the charts shows that the plots are not constant from window to window. For that reason for diagnostic system also average values and deviations calculated for spectral characteristic were taken into account.

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

Tab. 1. The list of examined structures of the nets
Tab. 1. Zestawienie badanych struktur sieci

<table>
<tr><th rowspan="3">no.</th><th colspan="6">Number of neurons in the layer</th></tr>
<tr><th rowspan="2">input</th><th colspan="4">hidden</th><th rowspan="2">output</th></tr>
<tr><th>first</th><th>second</th><th>third</th><th>fourth</th></tr>
<tr><td>1</td><td rowspan="20">2, 3, 4, 6

due to the set of signals treated as symptoms</td><td>3</td><td></td><td></td><td></td><td rowspan="20">3 or 1

3 in case network recognized each of the three states

1 in case network recognized only state one from three</td></tr>
<tr><td>2</td><td>6</td><td></td><td></td><td></td></tr>
<tr><td>3</td><td>9</td><td></td><td></td><td></td></tr>
<tr><td>4</td><td>12</td><td></td><td></td><td></td></tr>
<tr><td>5</td><td>15</td><td></td><td></td><td></td></tr>
<tr><td>6</td><td>18</td><td></td><td></td><td></td></tr>
<tr><td>7</td><td>6</td><td>3</td><td></td><td></td></tr>
<tr><td>8</td><td>9</td><td>3</td><td></td><td></td></tr>
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<tr><td>20</td><td>12</td><td>9</td><td>6</td><td>3</td></tr>
</table>

Looking for the net capable of correct recognition of the machine state, above listed types and structures of the nets were examined in addition to combination of also previously described forms of input signals.

Finally, as the best kinds of nets were calculated nets:

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

Conducted test using wider than during learning sets of signals gave the results:

- the net recognized state “without tool” with error equal to 0,
- the net recognized state “undamaged tool” with error equal to 7.8 %,
- the net recognized state “damaged tool” with error equal to 8.0 %,
- the net recognized all states with error equal to 5.2 %.

As a final solution, advisory diagnostic system is proposed in which machine operator would be presented with information from all four nets. The operator in case of detecting malfunction of the system is supported by inference system based on fuzzy logic techniques. Such a diagnostic algorithm was implemented and tested during common operations, what is described in the next paragraph with more details. The main implementation environment for that control and supervisory system is LabVIEW by National Instruments. The example of realization of neural networks in LabVIEW is presented in fig. 7.

Fig. 7. Neural network in LabVIEW environment

Rys. 7. Realizacja sieci neuronowej w środowisku LabVIEW

Another diagnostic issue was connected with the state of increasing temperature of the electro-spindle above boundary, observed during operation. For that reason the information system for operator was designed. That system delivers to operator hints connected with maintaining the spindle cooling system. Due to actual spindle temperature, operator obtains information, if the intensity of cooling of the spindle should be increased or decreased. The solution of that hints system is based on fuzzy logic. The system calculates output taking into account the value of spindle temperature and its derivative. The operator obtains hints in the form: “Heat”, “Cool”, “Do nothing” or “Observe”, and in the form of percentage probability of the decision correctness. To design the fuzzy system of spindle temperature diagnostics in LabVIEW environment, the Fuzzy Designer Tool was used. In the fig. 8 there is a screenshot of the tool, and in the presented “overlaps”, definitions of linguistic variables are shown.

Many more diagnostic issues were also investigated. Among others, one of the important issues is to detect the point when the tool tip touches the object and the micromilling starts. Another one is to determine, before starting the tooling, if the program was written accurately and the machine and the tool do not have path with collisions. Moreover, observation of actual spindle velocity in contrast with set up is next important symptom of the machine state that enables us to validate the efficiency of the spindle system. Algorithms for diagnosing mentioned machine states are still under investigation and implementation.

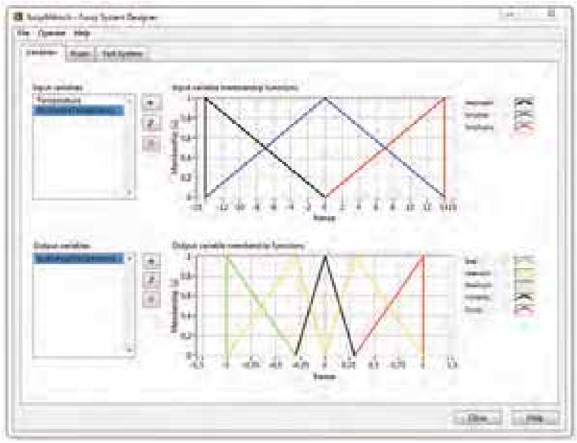

Fig. 8. Fuzzy System Designer in LabVIEW – definitions of linguistic variables

Rys. 8. Narzędzie projektowania systemu rozmytego w LabVIEW – deklaracja zmiennych lingwistycznych

3. Supervision system

Main tasks of supervision system are acquisition, monitoring, analyzing and recording data during operation and communication with control system. The hardware structure was divided into three main parts as shown in fig. 9.

The FPGA module in controller PAC cRIO 9022, the first part, 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 like force and acceleration with sampling rate 51 200 SPS and filter them in real time. The second part is based on another cRIO 9022 instance working in real time regime. The DMA channels are used to transfer large amounts of data in short time without charging controller’s CPU. Transfer of data to the third instance is realized using “Network Streams” protocol. That last instance (PC computer) is responsible for recording all collected data. That instance is dedicated to data analysis and diagnostic tasks.

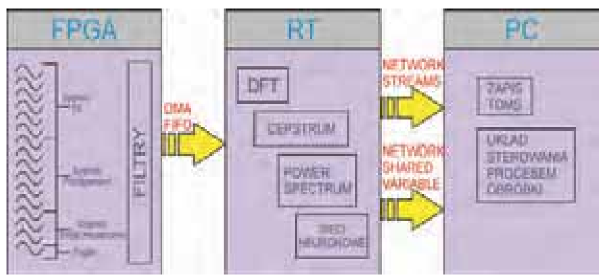

Fig. 9. Hardware structure

Rys. 9. Struktura sprzętowa

The important component of implemented supervision system is Human–Machine Interface. Such an interface delivers many functions improving comfort of operator’s work. It was assumed that HMI will be realized on two wireless panels. In order to expand supervisory system onto 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 operator's panels tablet Acer Iconia Tab W500 and smartphone HTC HD2 were chosen.

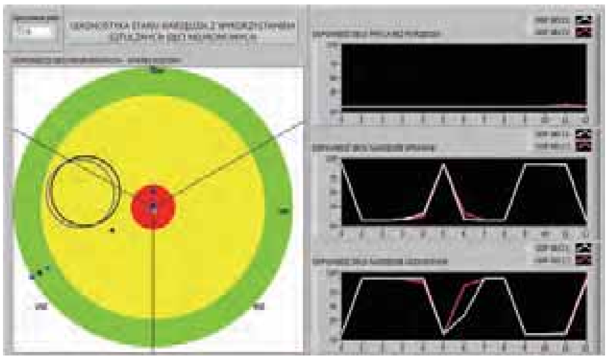

Fig. 10. The view of diagnostic screen
Rys. 10. Widok ekranu diagnostycznego

The interface was implemented on PC and operator's panel displaying results of diagnostic analysis. The example of such view is presented in the fig. 10.

4. Summary

As it was described, a micromachine for milling was designed, assembled and tested. On the basis of the recorded signals, analyses of diagnostic procedure were done. Relying on those analyses, diagnostic system using neural networks was designed in MATLAB and implemented in LabVIEW. Tests show that the best results are obtained when the decision about actual state of the machine is made on the basis of combined answers from 4 nets.

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Koncepcja systemu diagnostycznego stanu narzędzia dla mikroobrabiarki

Streszczenie: Artykuł stanowi opis części systemu diagnostycznego mikrofrezarki. W artykule przedstawiono ponadto opis projektu maszyny oraz jej wykonany i uruchomiony egzemplarz. W artykule zaprezentowano bazujący na sztucznej inteligencji system diagnostyczny zaprojektowany specjalnie dla tej maszyny. Opisano struktury i typy przebadanych sieci neuronowych i wskazano najskuteczniej działające. W ostatniej części artykułu przedstawiono wnioski dotyczące działania zaprojektowanego i przetestowanego system diagnostycznego.

Słowa kluczowe: mikrofrezowanie, system diagnostyczny, sztuczne sieci neuronowe

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