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Methodology of Algorithms Design and Methods Using in Predictive Diagnostic System

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Abstract – A paper deals with analysis and development of complex methods and algorithms for evaluation designed and measured signals of predictive diagnostic system. The design and the solution of system are original and an embedded system with a digital signal processor DSP is important control unit. The paper is composed of suitable algorithms design for measured signal processing. The developed system is designed for education and development at Department of measurement and control, VSB-TU Ostrava, further the system is available for a commercial industrial utilization. By described methods and algorithms implementation to the system, there is arisen unique instrument for predictive diagnostic of monitored mechanical devices.

Keywords: embedded system, predictive diagnostic system, signal analysis, digital signal processing

I. INTRODUCTION

Today, signal processing and signal analyses in embedded systems are a much evolved and interesting research area. There are many methods and possibilities for utilizing this theoretical and practical knowledge. Signal processing applications and development are affected by modern computers and electronics. A modern automated diagnostic and maintenance system is one of a sphere, where we can utilize new signal processing and computer possibilities. The modern automated diagnostic and maintenance system guarantees and increases stability and the economic efficiency of monitored devices.

II. SPECIFIC AUTOMATED DIAGNOSTIC SYSTEM DESIGN

Specific automated predictive diagnostic and maintenance system is developed for improvement of today's instruments for diagnostic of mechanical devices. This system manner is based on the data of the real states of monitored devices. So this allows the predicting of possible system events and problems. The diagnostic system executes signal measuring, diagnostic methods and signal analysis for the detection of real states of monitored devices or for the detection impending danger failures or device damage. The automated diagnostic system is composed of sensors, which scan mainly device vibrations and device noises, rotation speed, movement values, device temperatures, fluid states and other areas. These measured data and signals are analyzed by a user or automatically. Monitored devices are controlled pursuant to analysis results of system states. The predictive diagnostic system is composed of these basic function parts:

- Automated user system
- Embedded system
- Sensors
- Monitored mechanical devices

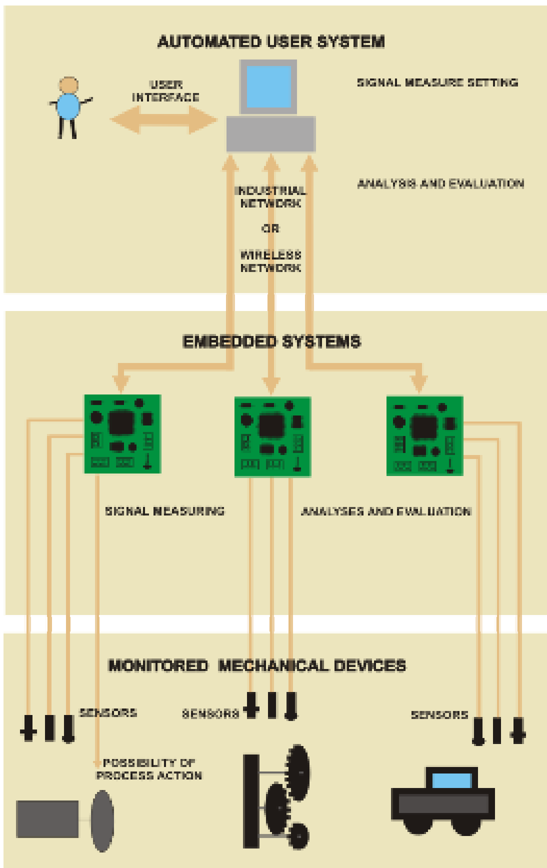

Fig.1. Automated system function blocks

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The automated user system is basically used for visualization, state monitoring, data transfer, the user interface, and connected embedded system control. This system is created in the programming environment Delphi 7. The program runs on the personal computer. This comfortable user environment of the developing system is designed for various embedded control systems. It enables selectable system parameter possibilities. The automated user system is created like a operating user program. This program is customized for comfortable user control and it is very well suited for data measuring and the analysis from embedded systems. The communication with embedded systems has to be fast enough and very safe. For real-time data computation communication is a very important and indispensable problem. This automated diagnostic system is customized for serial RS232 and wireless communication. The industrial communication can be very easily implemented to this automated user system, because communication protocol is able to edit and customized. The programs basic screen is composed of these easy common user components:

- **user menu** – is placed on the top of the program screen. There are selectable parameters of data measuring and analysis obtained from the embedded system. The selectable parameters appertain to peripheries, communication protocols, data sequences, sensors, limits and alarms, system reactions, signal analyses, computations, prediction, and files. Furthermore, there are program help and the finish item.

- **rapid icons** – are often used, and important data parameters settings. There are placed under the user menu. These icons make easier and faster user control.

- **graphical sheets** – are several sheets with one, two or three graphs. Inside of graphs are measured or computed data, which are sent from the embedded control system. They are placed in the middle of the program screen.

- **graphical setting items** – are for user data graph definitions. These items are placed on the right side of the program screen. The program user can define the name of the graph sheet, the number of the graph, data from the sensor, data computation, characteristic and analysis, the alarms and limits, the defined interconnection. So, all these user settings are determined for the displayed graph.

- **parameters of displayed data** – are placed under the graphical setting items. Information about just active graphical sheet is displayed. The information is about the graphs of the active sheet. There is information about the sensors, the data computations, the data characters, the alarms, the limits and prediction methods.

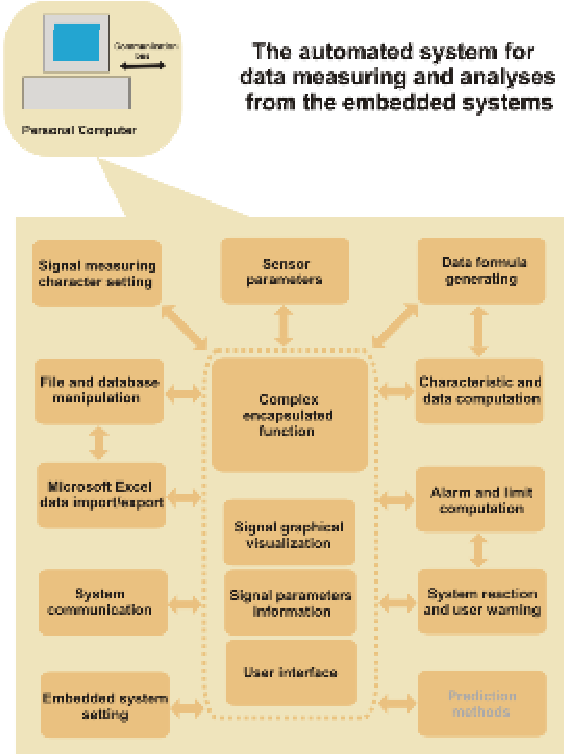

Fig.2. Automated user system function blocks

An embedded system is control system for fundamental calculations and algorithms execution. The embedded system is special purpose computer system, which is encapsulated and housed on a single microprocessor board. This system performs pre-defined tasks and it has specific requirements. It is of a contrary character to personal computers. The embedded systems often obtain a memory, a slower processor and needed interfaces. It guarantees lower cost and smaller power consumption. Programs often have to run with real-time and application-specific integrated circuit limits. Designers use assemblers, compilers, debuggers to develop the embedded system.

In developing a project, the embedded system contains a DSP digital signal processor for process and signal computation. This new improvement of the diagnostic system design is very powerful and it could control devices better and faster than the old ones. Thanks to this embedded system, we can automatically monitor values, execute, analyze, monitor the equipment state, and react to system operation. For modern applications, it is necessary to process complex computations in a very short time (RT - real time). So for processing, the digital signal processor DSP is mostly suitable.

DSP is a Harvard architecture processor with special features. The architecture enables using a more system buses for the data and instruction transfer inside processor. DSP is RISC (Reduce Instruction Set Computer) processor type. One of DSP special features is Pipe-lining. It means, they process more instructions in the one instruction cycle. It enables using special MAC instructions for filtering.

For this project is used the digital signal processor MOTOROLA DSP 56F805. Maximum core frequency is 80MHz, and 8MHz crystal. The program memory is internal FSRAM 64K x 16 bits and 64K x 16 bits is a data memory. It is 16 bit processor with a sufficient performance and a number of peripheries. For programming, there is the development software - Code Warrior - transparent and comfort programming in C and Assembler languages.

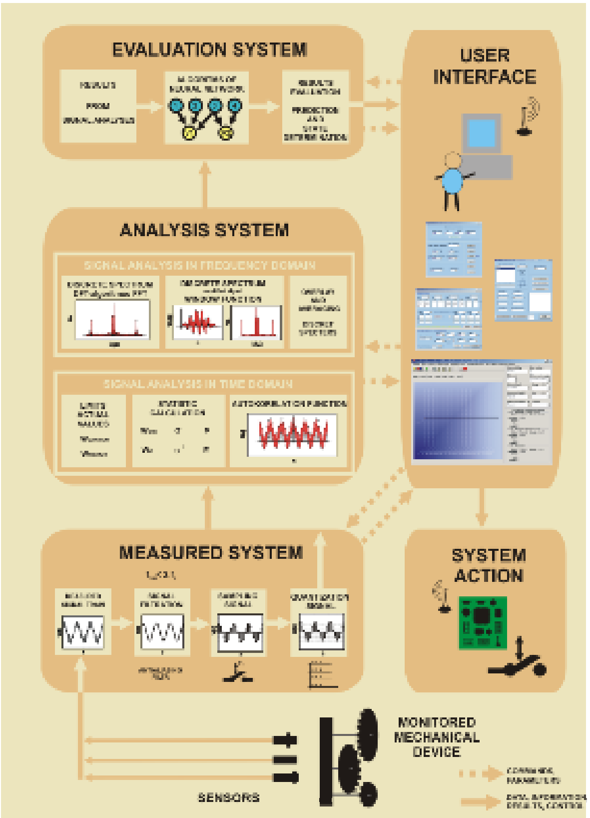

Fig.3. Diagnostic system structure of analysis and signal evaluation

III. ALGORITHMS AND ANALYSES FOR MEASURED SIGNAL DIAGNOSTIC

Algorithms and analysis methods are used for signal diagnostic. This signal is measured on the monitored mechanical device. Results from these analyses are used for mechanical device state detection and for prediction of impending failures. Analyses of signal are computed in time and frequency domain. Measured signals are scanned from the monitored devices in the real-time. These values can be processed by various analysis methods to the applicable results. There are used statistical analyses and computations, too. The analyses methods enable the performance these basic functions in the developing diagnostic system:

- determine impending failures
- detect part of a device, where is failure
- estimate the average time of failure starting
- inform about real system states
- predict device states problems

The measured continuous-time signal is filtering by an Antialising filter for a correct data conversion. Modified signal is sampled to discrete-time signal *w[n]* for following computer processing. The last operation with signal is quantization. The data from signal are moved to the embedded system after the signal modification.

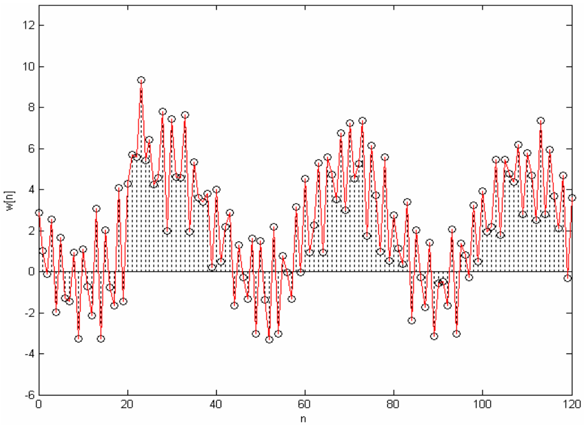

Fig. 4. Example of the measured signal in time domain

The data representing measured signal are processing by algorithms and analysis methodology in the embedded system. The analyses methods usable for this developing automated diagnostic and maintenance system are:

- **time domain signal analyses**
  This analyses type depends on the whole signal bandwidth in a time domain. The time signal analyses are much easer then frequency signal analyses. A results evaluation is almost based on specified critical values, which have not to be exceeded. The time signal analyses are:

  - **immediate signal value** – detection of maximal or minimal values in a signal *w[n]* train. Limit transcendence can detect the monitored device states.

$$w_{MINIMUM} \leq w\left[n_i\right] \leq w_{MAXIMUM} \qquad (1)$$

  - **statistical algorithms** – detection of statistical values of signal *w[n]*, where N is a number of samples. These algorithms are used for computation of these parameters of the measured signal:

Mean value $$w_{str} = \lim_{N\to\infty} \frac{1}{N} \sum_{n=-N/2}^{N/2} w[n] \qquad (2)$$

Effective value $$w_{ef} = \sqrt{\lim_{N\to\infty} \frac{1}{N} \sum_{n=-N/2}^{N/2} w^2[n]} \qquad (3)$$

Dispersion $$\sigma^2 = \lim_{N\to\infty} \frac{1}{N} \sum_{n=-N/2}^{N/2} \left(w[n] - w_{str}\right)^2 \qquad (4)$$

Mean power $$P = \lim_{N \to \infty} \frac{1}{N} \sum_{n=-N/2}^{N/2} w^2[n] \quad (5)$$

Function utilizing of the statistical algorithms in a time domain analysis is an Autocorrelation function R[κ]. The Autocorrelation function describes coupling signal values in a time. This function is used for a signal noise removing and a harmonic and periodic signal elements emphasis. Information about phase of the signal harmonic elements is lost.

$$R[\kappa] = \lim_{N \to \infty} \frac{1}{N} \sum_{n=-N/2}^{n=+N/2} w[n]\, w[n+\kappa] \qquad (6)$$

$$\kappa = \ldots, -2, -1, 0, 1, 2, \ldots$$

Time domain diagnostic methods usually used for monitoring of the mechanical devices are:

- Crest factor – the rate of effective signal value (PEAK) and maximum signal value (RMS) – PEAK/RMS. This analysis is sensitive to the mechanical failures already in the beginning.

- Curtosis factor – a statistical signal analysis of normal Gaussian distribution and the value of acuteness observation.

- **frequency domain signal analyses**
  This analyses type is more precise. We can observe just a part of the signal bandwidth in a frequency domain. By this analysis, the fault can be located and it can be specified why it was happened, the phase and amplitude spectrum of the signal can be also traced, of course, if there is used a complex signal transform. In the case that some part of the signal is periodic, the Fast Fourier Transform (FFT) is used for converting the signal from the time to the frequency domain. Of course, these analysis methods are more sophisticated and it obtains more advantages but it is more the time consumption compares to the time analysis methods.

Discrete Fourier Transform (DFT) converts discrete-time signal *w[n]* from a time domain to a frequency domain. Result of transformation is N complex coefficients W_k of Fourier series, which represent frequency domain of the signal. Relations of direct and inverse Discrete Fourier Transform are:

$$W_k = FR\{w[n]\} = \sum_{n=0}^{n=N-1} w[n] \cdot e^{-j2\pi n \frac{k}{N}} \qquad (7)$$

$$w[n] = FR^{-1}\{W_k\} = \frac{1}{N} \sum_{k=0}^{k=N-1} W_k \cdot e^{j2\pi n \frac{k}{N}}$$

$$n = \langle 0, N-1 \rangle$$

$$k \in \langle 0, N-1 \rangle$$

An amplitude spectrum is even function. It is composed of coefficients W_k by relation:

$$^{FR}|\mathrm{W}| = \{|W_k|\} = \left\{\sqrt{\mathrm{Re}\{W_k\}^2 + \mathrm{Im}\{W_k\}^2}\right\} \qquad (8)$$

Relation between samples and frequency of the signal is equal:

$$f = \frac{k \cdot f_S}{N} \qquad (9)$$

Where *fs* is sampling frequency of the time-discrete signal and N is number of the signal samples used for Discrete Fourier Transform computation.

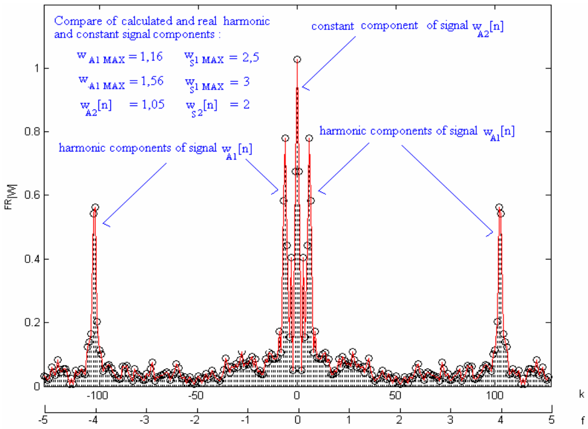

Fig. 5. Example of analysed signal in frequency domain

A phase spectrum is composed of coefficients W_k and it is odd function. The phase spectrum is defined by relation:

$$^{FR}|\theta| = \{\theta_k\} = \left\{ arctg \frac{\mathrm{Im}\{W_k\}}{\mathrm{Re}\{W_k\}} \right\} \qquad (10)$$

A power spectrum is composed of coefficients W_k by relation:

$$^{FR}P = \{|W_k|^2\} = \{\mathrm{Re}\{W_k\}^2 + \mathrm{Im}\{W_k\}^2\} \qquad (11)$$

Fast Fourier Transform (FFT) algorithm is used for faster analysis computation compare to Discrete Fourier Transform (DFT). Number of the signal samples has to be choose by relation $N=2^m$, where m is integral positive number. Transformation from time to frequency domain and its inversion is given by numbers of multiplications and additions used for transfer:

DFT for N samples of discrete-time signal *w[n]* – N^2 additions and N^2 multiplications.

FFT for $N=2^m$ samples of discrete-time signal *w[n]* – $m.N$ additions and $\frac{m \cdot N}{2}$ multiplications.

Windows Function (weight function) damps inaccuracy of the frequency signal spectrum computation. Good localization of a measured signal *w[n]* in time interval accordant with samples number N raises accuracy of the results. Modified signal $w_A[n]$ by Windows function $w_O[n]$ is equal:

$$w_A[n] = w_O[n] \cdot w[n] \qquad (12)$$

Basic used widows functions are:

- Rectangular Windows function

$$w_O[n] = \begin{cases} 1 & 0 \le n \le N_O - 1 \\ 0 & n < 0 \cup n > N_O - 1 \end{cases} \qquad (13)$$

- Hanning Windows function

$$w_O[n] = \begin{cases} 1 - \cos\left(\dfrac{2\pi n}{N-1}\right) & 0 \le n \le N-1 \\ 0 & n < 0 \cup n > N-1 \end{cases} \qquad (14)$$

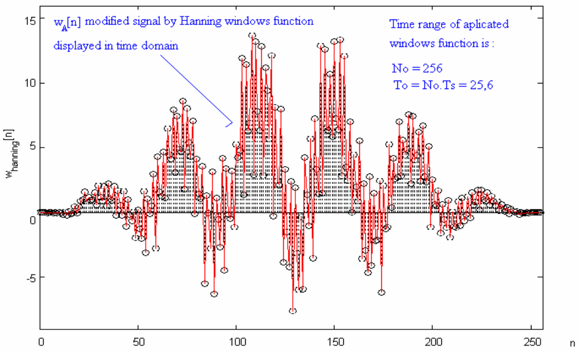

Fig. 6. Example of modified signal $w_A[n]$ in time domain

- Flat-Top Windows function

$$w_O[n] = \begin{cases} 1 - 1{,}98\cos\left(\dfrac{2\pi n}{N-1}\right) + 1{,}29\cos\left(\dfrac{4\pi n}{N-1}\right) & \\ -0{,}388\cos\left(\dfrac{6\pi n}{N-1}\right) + 0{,}0322\cos\left(\dfrac{8\pi n}{N-1}\right) & 0 \le n \le N-1 \\ 0 & n < 0 \cup n > N-1 \end{cases} \qquad (15)$$

Improvements of the frequency signal spectrum results can be obtain by the frequency signal spectrum modification. One of the improvement possibilities is **Frequency Spectrum Averaging**, which is equal with relation:

$$W_{k,K} = \frac{1}{K} \sum_{i=1}^{K} W_{k,i} \qquad (16)$$
$$k = \langle 0, N \rangle$$

The second of the improvement possibilities is **Frequency Spectrum Overlaying**, which is completion of the Frequency Spectrum Averaging. Overlaying of the frequency spectrum improves results and failures eliminates by signal damping at the edge of measured data records. The Frequency Spectrum Overlaying is defined by percents of spectrum overlaying 50%,66.7%,75%.

$$\frac{N_P}{N} \cdot 100\% \qquad (17)$$

Frequency domain diagnostic methods usually used for monitoring of the mechanical devices are:

- HF High Frequency Emission method – the energy of vibrations in high frequencies is increasing as early as beginning failure of the monitored device.

- LIN – a signal analysis is based on a wide frequency bandwidth 0,8Hz-16kHz. This analysis is very simple and computed quickly.

- LF Low Frequency Emission method – a vibration speed signal analysis in a frequency bandwidth between 10 – 1000 Hz.

- Envelope analysis – the complex method enables a very detailed detection and analysis. By this diagnostic method there is possible to dedicate part, type of failure, state failure. Theoretically every segment of a rotation device part and every other segment could be analyzed separately, because relative rotation speed of every part is different. The failures can be proved by different frequencies in measured vibration signal. Energy of an analyzed signal is increasing with failure execution especially in high frequencies. In this method, there are measured vibration impulses on a monitored device. The input measured signal is modified by a band-pass digital filter algorithm. Then it is possible to use the Fast Fourier Transform (FFT) for the failure type recognition. The vibration impulses in a signal aren't of a harmonic character. Usually they are modulating the other harmonic components with failure components in a signal on a carrier frequency.

IV. EVALUATION ALGORITHMS

The evaluation algorithms enable determine actual state of monitored mechanical device and likewise it allows estimate impending monitored device states and failures. Parameters of the evaluation algorithms are set by user in the automated user system. The results of the signal analysis methods and the signal algorithms are an input data for evaluation algorithms. The developed evaluation algorithms are composed of Neural Network algorithms. The parameters of the Neural Network algorithms are adjustable by user and some parameters are set by studying signal analyses results from monitored device in diagnostic system learning state. Weight of the inputs and limits of neurons in the Neural Network are set by a training user. The presumption of the correct parameters setting of the Neural Network is to user's knowledge about monitored mechanical device behaviors and the possible device states. Likewise user has to know an estimate time to start device failure or some state from the first problems signifies.

V. CONCLUSION

The specific automated diagnostic and maintenance system application has been developed for real-time and short time data measurement, communication, analysis, and reaction with the use of an embedded system. One of the major research targets is a system upgrading more accurate and faster diagnostics and maintenance computations. The solution of this problem could be predictive or improved control methods implementation. This is a very interesting and formidable task. It is necessary to use a complex mathematical theory and joint it with digital signal processing. For this, we will use a mathematical programming environment – Matlab Simulink and helpful Matlab toolboxes. This program runs on a personal computer PC. The signal processing toolbox is very helpful for Fast Fourier Transformation, various filters, correlation, statistical and other signal computations. By simulation in Matlab Simulink, we can verify measured and calculated real diagnostic system data with simulating data. By these computations, we could recognize the best methodology for the control and the diagnostic of a monitored device. Additionally, we can transfer these pieces of knowledge to the developing embedded system, to the developing program for the diagnostic and maintenance system. The evaluation algorithms allow automatically decide about actual monitored device state and allow automatically predict potential device states.

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