Embedded Systems for Real-time Predictive Diagnostic

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Abstract: - The article discusses using embedded systems for diagnostic and maintenance planning. There is described design and using of two embedded systems with different digital signal processors, their advantages and disadvantages. There are described applications of embedded systems for diagnostic and maintenance planning for machines, drives and ventilators. There is practice demonstration of the signal filtration and Fast Fourier transformation FFT in the real-time. These tasks are very important for diagnostic and maintenance planning in industry and engineering.

Key-Words: - embedded system, diagnostic, real-time systems, signal processing, vibration, microcontroller

1 Introduction

The using of embedded systems for the process diagnostic and maintenance planning (for machines, drives, buildings and others) is very important and useful. These systems are smallness, powerful and low-cost and extend real-time applications in this area. It is possible use various types of microcontrollers. For diagnostic systems, where are measured vibrations, rotation speed and noises, are used digital signal processors (DSP's) and signal and control theory. These measured signals contain information about technical state of equipments, their wear and tear, and others.

In practice application is DSP use for handle signals and control system based on signal measurements. Most of DSP applications solve computing problems like FFT signal analyzing (Fast Fourier Transformation), signal filtering (low-pass, high-pass and band-pass) and others signals processing for industry control and engineering areas.

Digital Signal Processor (DSP) is developed for measurement, signals processing and control systems. They are often used in embedded systems. Advantages of DSP are doing more then one instruction in one clock cycle of processor, and their design for controlling and handling of signals. New digital signal processors are suitable for using in real time applications.

2 Diagnostic systems and maintenance

The reliability and safety of products technological processes is possible increase using the real-time predictive diagnostic. There are requirements on the measurement of various values and prediction of their changes under the character of monitored processes. The real-time diagnostic systems on the high level are in the area of vehicles. There are tens of embedded systems for diagnostic and control functions. Communications between parts of diagnostic and control systems are realized through industrial nets. In some cases is used the wireless communication between mobile parts.

The diagnostic of vibrations is important for the safety of machines, devices and systems, where vibrations set in the running. The proper design of diagnostic system increases the reliability and safety of running processes and equipments. The diagnostic system is generally closely associated with the system of maintenance. The correct control of the maintenance guarantees good stability and economy of product systems and equipments [1], [2].

The mechanical vibrations are measured and analyzed. Vibrations are measured by accelerometers. The acceleration signal is filtered and converted by means of integration on the speed (power) of vibration. Vibrations are measured on various locations of the equipment, in one or more axes.

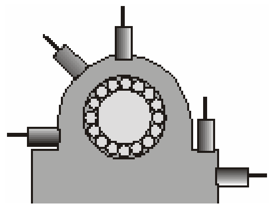

Fig. 1: Locations of sensors for the vibration measurement.

The diagnostic system includes:

- Detection of the defect

- Identification of the defect in the system.
- Reporting of the defective or defect-free state.

- Localization of the defect – determination of the defect location in the system.

The diagnostic system modes are following:

- The on-line diagnostic mode is running in real-time. The complex diagnostic system includes usually the processing of measured values, theirs analysis, defects monitoring and controls the response on these defects. These systems are possible to use as predictive diagnostic systems. These systems are realized as embedded systems.
- The off-line diagnostic mode is realized in two steps. In the first step values are measured and saved in the memory. The second step is realized later no in the real-time, when the data are transferred into the computer for their processing.

Among the current defects and mistakes belong the critical wear, change of geometry, deformation, change of mechanical characteristics, change of forces, change of load and mechanical break.

The analysis of the signal, which is received from the relevant sensor, is realized in two ways:

The time analysis of the signal depends on the whole time interval of vibrations. It means that the vibrations are monitored in the whole frequency spectrum. The last measuring with the existing measuring is compared. The critical values which may not be exceeded are set. The advantage is the low price of the system but the disadvantage is the way of the defect localization, in case that it occurred.

Frequency analysis of the signal is more accurate and has also further advantages. The defect can be localized and it is possible to find out why it has occurred. It is possible to obtain the amplitude and phase spectrum of the signal. The phase spectrum is important for indication of the non-balance indication. The monitoring in the real time enables to detect the frequency characteristics, trend of the machine functionality, start characteristics and stopping of the machine, state of the machine etc. In case that the signal is the periodical one, it is possible to utilize the quick Fourier's transformation (FFT) for transfer of the signal from time into the frequency domain.

DSP measures and processes the discrete values of the signal. The calculation of the quick FFT represents an important integral part of the measuring and controlling systems for analysis of the signals. For FFT with the discrete values of the signal the length of the record is given by the number of samples *A*, where the single samples scanned with the regular sampling frequency are indicated by indexes $k = 0, 1, ..., N-1$. The length of the record N of samples, in most cases, is equal to $N = 2^m$. The maximum frequency complies with the Shannon's sampling theorem where the sampling frequency has to be two times higher than the maximum harmonic frequencies (the Nyquist's frequency) and it is given by the relation $f_{max} = f_{vz} / 2$. For FFT the following relation is valid

$$X(k) = \frac{1}{N} \cdot \sum_{n=0}^{N-1} x(n) \cdot W_N{}^{nk} = \frac{1}{N} \cdot \sum_{n=0}^{N-1} x(n) \cdot e^{-\frac{j2\pi nk}{N}},$$

in which the *twiddle* factor is defined, and namely by the relation

$$W_N{}^{nk} = e^{-\frac{j2\pi nk}{N}}$$

2.1 Vibration diagnostics

The equipment units which measure and analyze the vibrations are called diagnostic systems of vibrations. The mechanical vibrations are very good indicator of the equipment state. With the help of the diagnostic systems we can measure the vibrations of machines and equipment, buildings and structures, res. also the vibrations from the viewpoint of work hygiene. The parameters and limits of vibrations are determined by standards and laws. If it comes to exceeding of the limits the machines can be destroyed, damaged, it can come to the damage of human health or death. This vibration diagnostics is very important for reliability and safety of equipment, and so also their structure, and, further for their operation economics and health of their service personnel. The measuring of vibrations can inform accurately about the internal states of components, about place and source of defect and the entire state of the system. For instance, the noise in rotation machines, gear boxes, couplings etc. can be measured.

The conversion of the mechanical amplitude on electrical signal is carried out in case of diagnostic measuring. The vibration measuring is the measuring of periodical components of the signals. Characteristics of the following values are evaluated for a determination of vibrations:

- Deviation. The sensors scan the changes of the position and distance of the object for some reference point. For vibration diagnostics are used induction, capacity and magnetic sensors. Most frequently, the induction sensors are used; they work in the frequency band 0 to10 kHz.
- Speed. The sensor measures the speed of deviation of signal changes. Frequently, the

cheap accelerometers are used where the speed value is obtained by the integration of acceleration. The electrodynamics sensors are used, which are limited by the frequency maximum 3 kHz.

- Acceleration. The sensors scan the acceleration of the signal deviation. The sensors for measuring of acceleration are integration strain tensors or capacity accelerometers, electrodynamics speed sensors with the derivation unit or piezoelectric accelerometers. The piezoelectric accelerometers are used most frequently because their frequency range makes 0,01Hz up to 20 kHz, they have small dimensions and weight, and, they do not tend to the parasite magnetic field.

2.2 Noise diagnostics

For the diagnostic measuring of noise are used special microphones. The measured noise can include information about the technical state of system. The noise measuring can be carried out in the frequency range from 20 Hz up to 20 kHz, what is sufficient for analysis of the system state. The parameters of the noise diagnostics are as follows: the effective acoustic pressure value, selected characteristic values of frequency band and total frequency spectral analysis.

The noise can be measured in rotary machines, drives, gear boxes, transformers, ventilators, etc. The noise is composed of discrete and continuous elements. The noise is evoked by the microscopic forces, impulses e.g. by internal friction in contact points of two parts. The main problem of noise diagnostic is location of sensors. Frequently, there are more noise sources. Further, the noise interference and reflections are included into the analysis.

The measured data are analyzed by microcontrollers or digital signal processors. It is possible to determine the state of measured system after a signal analysis.

2.3 Design and realization of diagnostic system

We realize the monitoring system of ventilators technical state for the predictive maintenance of ventilators. The goals of application are analyzing of running conditions, optimizing of embedded system and realization of monitoring system. The first goal was selected the propriety diagnostic method for the technical state monitoring of ventilators during their continuous operation. The one part of running conditions is the ventilation pipelines analyze. The pipelines are very complicated; it was reason to measure only the suction on the input of ventilator. The suction is only the auxiliary quantity for a determination of working conditions in pipeline. Desired attributes of embedded diagnostic system are simplicity, suitability and low-cost.

On the higher level then the embedded system is PC for the continuous monitoring of ventilators states. This system prepares data for the predictive maintenance of ventilators, which will realize the higher level of maintenance system. This application use mathematic methods and models for optimizing and prediction of maintenance actions. The block diagram of diagnostic system for the one ventilator is presented on the figure 2.

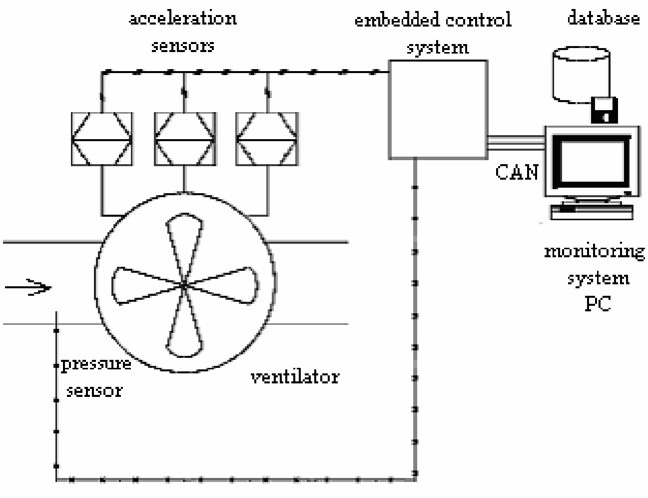

Fig. 2: The block diagram of diagnostic system.

3 Hardware development

3.1 Microcontrollers

We used for embedded control systems microcontrollers (Motorola- MC68HC08, MC68HC12, MC68332 and PowerPC, Atmel and Microchip) and signal processors DSP (Analog Devices - ADSP 21065L SHARC EZLITE, ADSP 21535 BLACKFIN EZLITE and Motorola - 56F803EVM, 56F805EVM).

DSP's are used frequently for the signal processing in embedded control systems (control of high speed modems, adaptive pulse modulations, coding, digital wireless communication systems, MPEG compression, signal conversions, etc.). DSP's are also used for the realization of real-time applications. The programming languages for DSP are mostly assembler or version of the C language with the special libraries for the DSP functions. The disadvantages are represented by the limits for real-time mode where the calculations must be carried out during one sampling period and where the AD and DA converters must be sufficiently quick.

We tested two types of microcontrollers. The first one was MC68HC08 with CAN bus. The signal processing was executed on the higher level (PC). This solution is useful when the diagnostic system consist tens of ventilators. Embedded systems communicate with the higher level via CAN bus; also it is possible used wireless communication. The second solution is using DSP when the signal processing is executed in the embedded system. We tested the DSP56F803 which is member of the DSP56800 family of DSP's. They combine, on a single chip, the processing power of a DSP and the functionality of a microcontroller with a flexible set of peripherals to create an extremely cost-effective solution for the signal processing.

The instruction set is highly efficient for C compilers to development control applications. Major features of the DSP core include the following:

- Efficient 16-bit engine with dual Harvard architecture
- As many as 40 MIPS at 80 MHz core frequency
- Parallel instruction set with unique DSP addressing modes
- Efficient C compiler and local variable support
- JTAG/OnCE debug programming interface

Used peripheral blocks of application specific memory & peripherals:

- Two pulse width modulator modules (PWMA & PWMB) with current sense and fault inputs. Both with centre- and edge- aligned modes.
- 12-bit analogue to digital converter with synchronisation with PWM modules.
- Two quadrate decoders (Quad Dec0 & Quad Dec1) each with 4 inputs (or two additional Quad timers A & B).
- Two serial communication interfaces (SCI0 & SCI1).
- External reset pin for hardware reset.
- JTAG/On-Chip emulation (OnCE™) for unobtrusive, processor speed-independent debugging.

3.2 Sensors

Acceleration sensors were prepared on the base of IC MMA1260D (Motorola Micromachined Accelerometer). The encapsulation of sensors was implemented from the plastic case. The sensitivity of sensor is in the direction of Z-axis.

The type of pressure sensor was selected the Huba Control 696 with silicon membrane for measurement of low-level pressures (range 0 to 3 kPa). This sensor is resistant in the aggressive medium.

4 Software development

On the present, the standard development of software is in the higher language. Also in control applications the assembler was replaced by the C language. With the respect of the fact that the optimum way of control of this system is searched for and it is necessary to carry out the whole number of simulations of the whole control system it is advantageous to use the development system enabling the replacement of recording of the C-code by automatic generation of the C-code on the basis of the model set up.

This possibility enables to pay attention to the main problems and it need not deal with the implementation details. For development of software of the distributed system the Unified Modeling Language – UML was used which enables, for the system designer, to work on analysis and proposal with one consistent language for specification, visualization, construction and documentation of software system, same as in modeling of other non-software systems [3].

The implementation of the language UML Rhapsody from the company I-Logix was used. For embedded systems the version Rhapsody in Micro C (RiMC) is suitable which implements some tools defined in UML but makes use of some further tools for the real-time tasks [5]. UML has the corresponding output for servicing the requirements and analysis of models on higher level of abstraction.

RiMC is the graphic software proposing and implementation tool which supports the development including tuning and testing (both in an interactive mode). The output is represented by compact and readable C code with the support of local extensions of the C standard, including automatically generated documentation of the proposal. The code is generated on the basis of the graphic model which represents the fully functional application. Four basic graphic tools are used for the application definition: State charts, Activity charts, Flow-charts, Truth tables. Each graphic tool has its relevant graphic language allocated, and namely for proposal which enables for designer to be very precise in defining of functional importance of each graphic element. The graphic elements can be supplemented by set up user's supplement of C code or code in assembler or by both.

The last step is the testing on real environment. For the generation of source code is used the Metrowerks CodeWarrior for the Motorola processors. The communication between the host development system and target system is realized by the integrated development environment for embedded microprocessor systems. The tuning enables more the language tuning in assembler, C or C++. It enables the simulation in real-time and simulation of the hardware proposed (e.g. the mainboard with the processor or the I/O circuits).

4 FFT application

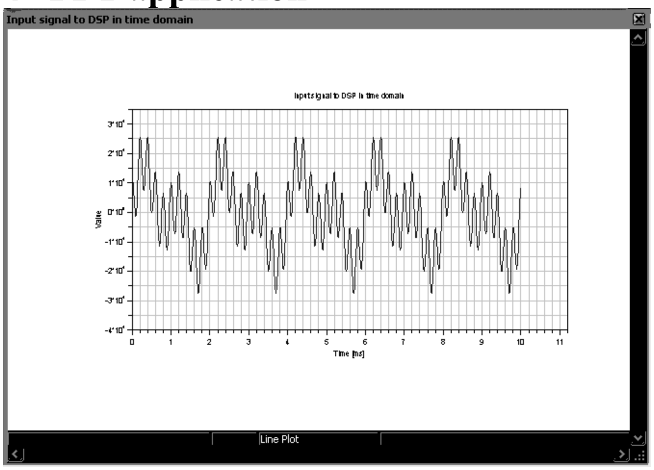

Fig. 2: The graph from MATLAB, there is the signal in the time domain and Fourier spectrum.

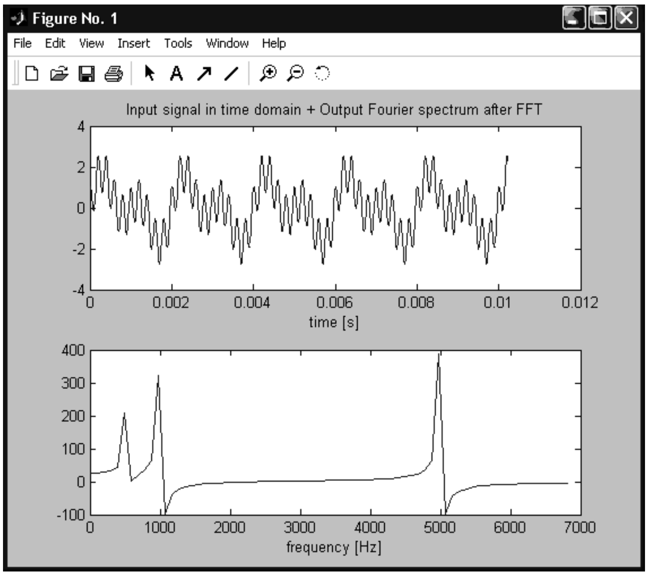

Fig.3: The graph from the Visual DSP++, there is the input signal to DSP.

In diagnostic and maintenance systems are the characteristics in the frequency domain very important. We used DSP for the FFT analysis. As an example the processing of periodic signal composed from three harmonic ones is given on figures 3 to 6 - $\sin(2.\pi.f_1.t)$ f_1 = 500Hz, $\sin(2.\pi.f_2.t)$ f_2 = 1000Hz, $\cos(2.\pi.f_3.t)$ f_3 = 5000Hz. For the simulation in MATLAB: input = sin(500*(2*pi*t))+sin(1000*(2*pi*t))+cos(5000*(2*pi*t)).

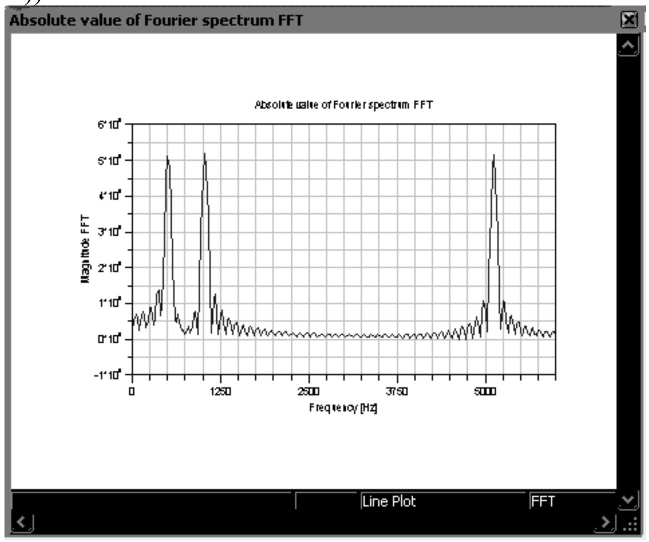

Fig. 4: The graph from the Visual DSP++, there is transformed the output signal from the DSP presenting spectrum FFT in the frequency domain.

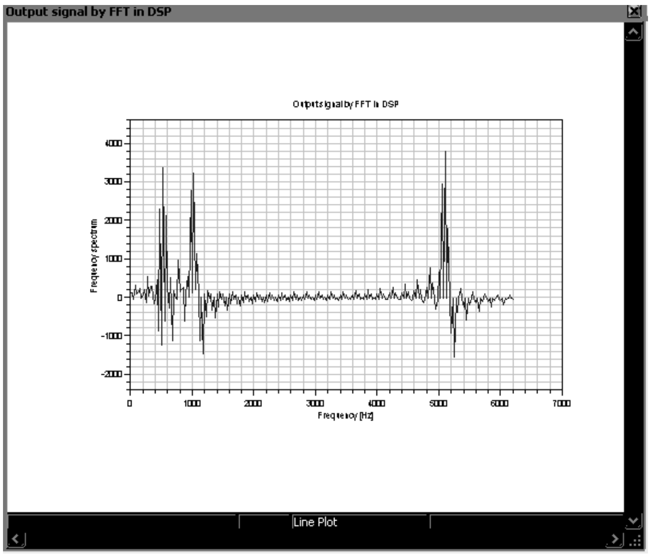

Fig. 5: The graph from the Visual DSP++, there is transformed the output signal from the DSP absolute spectrum FFT in the frequency domain.

5 Conclusion

The increasing of safety and reliability is very important for technological and product processes and products. At present high level products include the diagnostic system as the part of control system. Embedded control systems are running in most of electromechanical and electronic home products. Cars are products with one of the best diagnostic and control systems. There are sensors and embedded systems connected on the CAN bus, which realized communications between them. Some of sensors use also wireless communications. The example is the measurement of pressure and temperature in tyres, where sensors and wireless communication module are integrated in the one IC. Sensors in cars measure great part of values, which are necessary for the real-time diagnostic system. There is also the predictive maintenance system, which recommends to users appropriate maintenance actions in the forthcoming period. The diagnostic system like this is the good example for all systems from all area of the human activity.

The mentioned diagnostic system of ventilators predictive maintenance assumed following contributions after its implementation:

- optimizing of existing maintenance system,
- cost reduction of maintenance system,
- security system for emergency situations.

The digital signal processors were tested as the integral part of embedded control systems. These processors are used in the whole number of applications in control systems. Their speed and reliability are high. Their using is in the industrial area and in other spheres of human activity.

We use DSP's in the diagnostic and maintenance application where their using was very successful. The credibility and accuracy of diagnostic system depends on the good knowledge of system running and experiences of system maintenance. This knowledge is used at the definition of data processing algorithm and predictive functions.

The basic processing of the signal and its transformation from the time into the frequency domain with the help of FFT is presented in this article. There are also compared the accuracy of calculations from DSP with the results from the software system MATLAB. On the basis of these calculations the extreme and characteristic values are analyzed and, in this way, it is possible to detect or predict the system defects.

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