

Original scientific paper

EMBEDDED SYSTEMS FOR VIBRATION MONITORING

UDC 62-135:534.1

**Miloš Milovančević¹, Aleksandar Veg¹, Aleksandar Makedonski²,
Jelena Stefanović Marinović¹**

¹Faculty of Mechanical Engineering, University of Niš, Serbia

²Faculty of Machine Technology, Technical University Sofia, Bulgaria

Abstract: *The purpose of the research presented in this paper is the development of the optimal micro configuration for vibration monitoring of pumping aggregate, based on Microchip's microcontroller (MC). Hardware used is 10-bit MC, upgraded with 12-bit A/D converter. Software for acquisition and data analysis is optimized for testing turbo pumps with rotation speed up to 2000 rpm. This software limitation is set for automatic diagnostics and for individual and manual vibro-diagnostic; the only limitation is set by accelerometer performance. The authors have performed numerous measurements on a wide range of turbo aggregates for establishing the operational condition of pumping aggregates.*

Key Words: *Micro Configuration, Vibration Monitoring, Microcontrollers*

1. INTRODUCTION

The development of non-invasive methods of monitoring has enabled the transition from preventive to predictable maintenance. There are various indicators of machine condition (temperature, pressure...); however, the method of using vibrations for determining machine operating conditions has proved the best. A MC-based monitoring system is developed because vibrations-based monitoring has been used in a large number of cases in which the machine condition has been determined. This system is created to meet certain demands: monitoring platform based on the use of common PC, a low cost of device, mobility, 12-bit resolution and appliance on rotational machines. The microcontrollers application in industry is a new research topic, based on fundamental research [13] as well as on industrial application [14, 15].

Received May 06, 2014 / Accepted July 3, 2014

Corresponding author: Miloš Milovančević

Faculty for Mechanical Engineering, University of Niš, Aleksandra Medvedeva 14, 18000 Niš, Serbia

E-mail: milovancevic@masfak.ni.ac.rs

2. USE OF MC IN MONITORING

Microcontrollers (MC) are electronic components designed for developing electronic systems for digital command and control. With the use of such systems it is possible to control several electronic devices and systems and to collect and process various electric and non-electric quantities. Digital systems based on microcontrollers are programmable to perform distinct processing depending on the condition of control circuit, and to perform command in circuit by using the results obtained from the processing.

The main difference between microprocessors and microcontrollers is that the latter are designed to incorporate a complete digital computer in one chip, because, besides the processor, they also contain memory and peripheral units. This results in the desired system having a minimal number of components as well as realizing savings in space and the time needed for device designing. There are several microcontroller manufacturers at present, having very diverse MC families in their production range. Most important are Intel, Motorola and Microchip. There is a very wide range of microcontroller usages because they can be programmed, depending on the desired usage, to obtain the type of behavior of the digital device we design [1].

With the intention to determinate an analysis of pumping aggregate operating condition, the authors of this paper have designed special MC developing environment, whose description is here given in brief.

The optimal micro configuration for vibration monitoring is designed based on axiomatic design regarding electronic components selection.

The basic idea in the optimal micro configuration design is to meet the frame conditions that are required for pump aggregates vibration monitoring.

In order to define all components of the micro configuration it is necessary to define functional requirements of the system and the conditions in which the system will be tested.

Considering micro systems for vibration monitoring the signal characteristics determine system accuracy and vibration monitoring quality in general. Selection of the microcontroller that serves as a base for micro system has been done primarily by taking into account economic aspects of new-developed system that is PC (personal computer) dependant [2]. Microchip, a company that has been producing microcontrollers for more than a decade, and microcontroller PIC16F877A have been developed as symbioses of microprocessor (CPU), memory and periphery, with PIC as acronym for (*Peripheral Interface Controller*) [3]. This microcontroller is based on CMOS technology with RISC architecture and implemented FLASH and EEPROM memories. Thus, PIC16F877A represents the best compromise between price and technology. The main signal characteristics that have been chosen as the main requirements for design of optimal micro system are: resolution, stability and repeatability of signal. In order to meet the requirement of resolution an A/D converter is added, since the microcontroller has 10-bit resolution, a MCP3204 12-bit A/D converter is connected via SPI connection protocol [4].

3. SIGNAL REPEATABILITY ANALYSES

The analyses of the main selected signal characteristics have significant influence in an optimal micro system selection. A significant signal resolution has been obtained by introducing MCP3204 12-bit A/D converter and stability is ensured by selecting leading

electronic components manufactures and implementing their components. Thus, testing signal repeatability in laboratory conditions, on signal generators *Tektronix 3102* and *Tektronix dpo 4034*, is a method for selecting an optimal micro configuration. The following diagrams represent part of intensive signal repeatability testing of the selected optimal micro configuration.

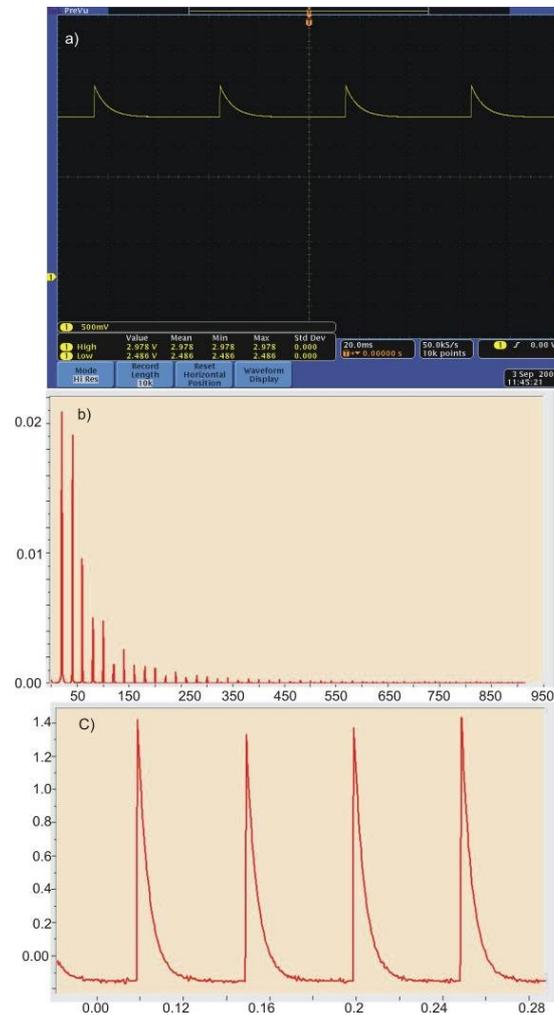


Fig. 1 Diagrams of signal repeatability testing by exponential signal

Signal repeatability has been tested by two types of complex signals: exponential and triangle. Exponential signal in repeatability testing is presented in Fig. 1 in the following order: a) original signal screen shot of referent testing signal, b) fast furrier transformation (FFT) diagram of collected signal from tested configuration, c) collected signal from tested configuration without transformation.

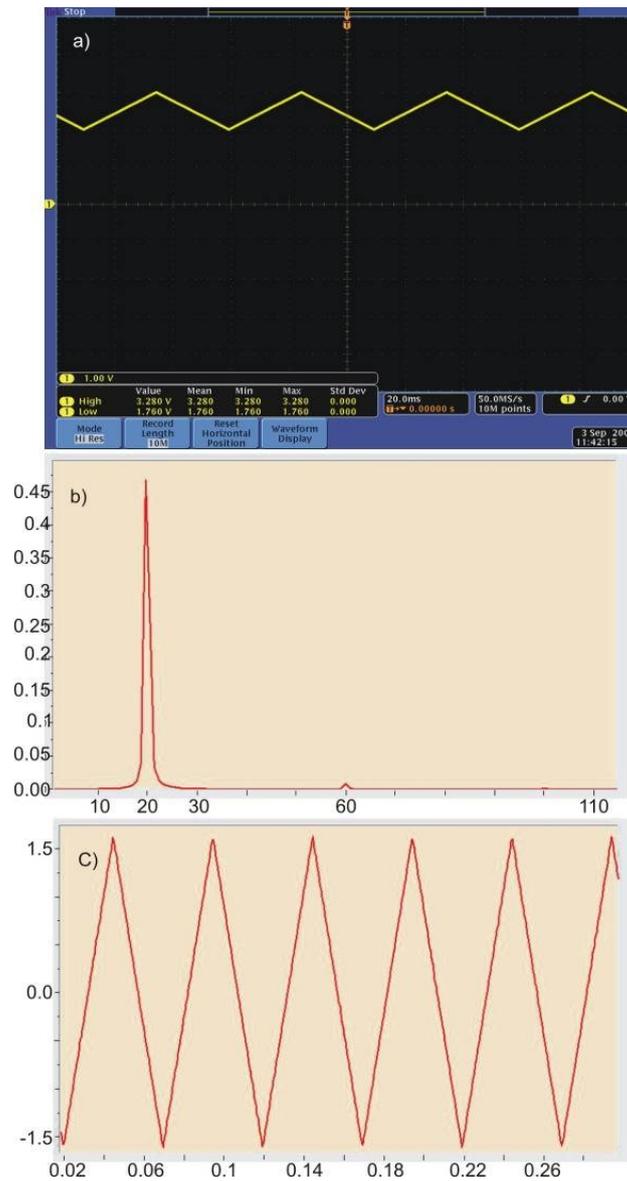


Fig. 2 Diagrams of signal repeatability testing by triangle signal

Triangle signal in repeatability testing is presented in Fig. 2 in the following order, a) original signal screen shot of referent testing signal, b) fast furrier transformation (FFT) diagram of collected signal from tested configuration, c) collected signal from tested configuration without transformation. This testing has proved that the selected optimal micro configuration for vibration monitoring based on microcontroller has suitable performance regarding signal characteristics.

4. IDENTIFICATION OF PUMPING AGGREGATE VIBRATION PARAMETERS

It is necessary to provide several measures of supervision to assure the correctness of turbo pumps operating conditions. The control of vibrations and their measuring via electric means is considered the very basis for supervision. The primary objective of all the supervision measures is timely recognition of critical operating conditions. The operation of centrifugal pumps is accompanied by two undesirable side effects: vibrations and noise. The intensity level of vibrations and noise characterize the perfection of pump operation, its construction and pump condition during exploitation period, as well as cavitation phenomenon in the pump. More about all these effects of the emitted noise as a side effect of centrifugal pumps is given in [5, 6, 7].

The source of centrifugal pumps vibrations are mechanical, hydraulic and electrical processes caused by the pump construction, operating regime, exploitation and manufacturing technologies used.

Due to the blade passage frequency (BPF) with frequency $f_z = z\omega / 2\pi = zn$, where z is the number of impeller blades and n is the rotational speed in rps.

Unbalance of rotational masses of rotor is caused by oscillation with frequency $j_1 = \omega / 2\pi$.

Vibrations from the collisions of parts in the contact are produced in bearings, gear box, couplings and connected shafts of pump and driver. Rolling bearings may produce vibration with frequency often lower than 30 kHz [8].

Disturbance force is generated by connecting of pump and driver shaft to the geared coupling, with frequency $j_2 = z_s \cdot \omega / 2\pi$, (z_s – number of coupling teeth). Electromotor vibrations are caused by disturbance forces generated by variations of electromagnetic field, with frequency for this case: $j_E = \omega \cdot z_w / 2\pi$, (z_w i– number of motor poles).

Mechanical vibrations of pumps are the subject of numerous research projects [9]. The analysis of the obtained results leads to the conclusion that the level of vibration can be lowered by respecting certain instructions and recommendations for balancing of rotational masses, selection of bearings, couplings, eccentricity between the shaft axis of pump and driver, etc.

5. RESULTS

Horizontal pumps have a significant role in water transportation. It also defines the importance of providing flawless work. The electro motors of horizontal pumps are extremely burdened from the aspect of continuous exploitation for maintaining a permanent operation. An adequate choice of measuring point at pump aggregate of horizontal pump can indicate the condition of operation for electromotor bearings and rotor, the pumping aggregate bearings and coupling, and complete aggregate construction likewise.

The following measuring points are chosen:

- First measuring point is chosen for diagnosing the operational condition of the first bearing at electromotor.
- Second measuring point is defined to diagnose the condition of the driving electromotor second bearing

- Third measuring point is determined in such a manner that it is possible to diagnose both the condition of the pump first bearing and the elastic coupling.
- Fourth measuring place is defined to diagnose the condition of the pump second bearing.

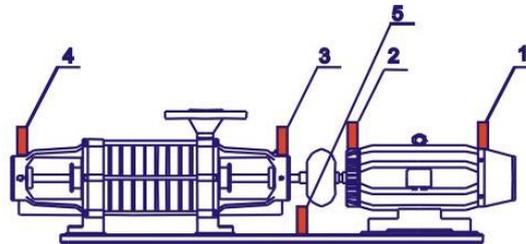


Fig. 3 Measuring point at horizontal pump aggregate CVNR 5-3, No.1

The measured result analysis is generated by means of frequency spectra. The presented diagrams are created from FFT algorithm, adapted for pump aggregate diagnostics.

Measuring point 1, Fig 4. a), horizontal and vertical acceleration not passing the 1 m/s^2 can be observed, indicating the electro motor (EM) bearing proper operating condition. Likewise, there are no vibrations in frequency range 700-900Hz which indicates that the motor fan is installed correctly.

Measuring point 2, Fig 4. b), high acceleration amplitude at frequency at 310Hz is manifestation of an incorrect coupling working condition; the second electromotor bearing is in a good operating condition.

Measuring point 3, Fig 4. c), based on the acceleration, the correct bearing operation can be concluded, while, an incorrect coupling operating condition can be based on analyzing previous diagrams.

Measuring point 4, Fig 4. d), a satisfactory operating condition of second bearing of pump can be concluded.

Diagram presented in Fig. 4 (a, b) points to the following facts: for electro motor it is possible to determine bearing malfunction as well as other mechanical defects as an incorrect coupling operating condition. Diagram presented in Fig. 4 (c, d) present pump bearing malfunction but also a high frequency range is appearing as a result of hydrodynamic processes in a pump.

- First measuring point is chosen for diagnosing the operating condition of the bearing at the upper part of electromotor
- Second measuring point is defined to diagnose the condition of the driving electromotor lower bearing
- Third measuring point is determined in such a manner that it is possible to diagnose both the condition of the pump bearing and the elastic coupling
- Fourth measuring place is defined to enable a diagnosis of the vibrations caused by nonlinear oscillations of the complete pump aggregate.

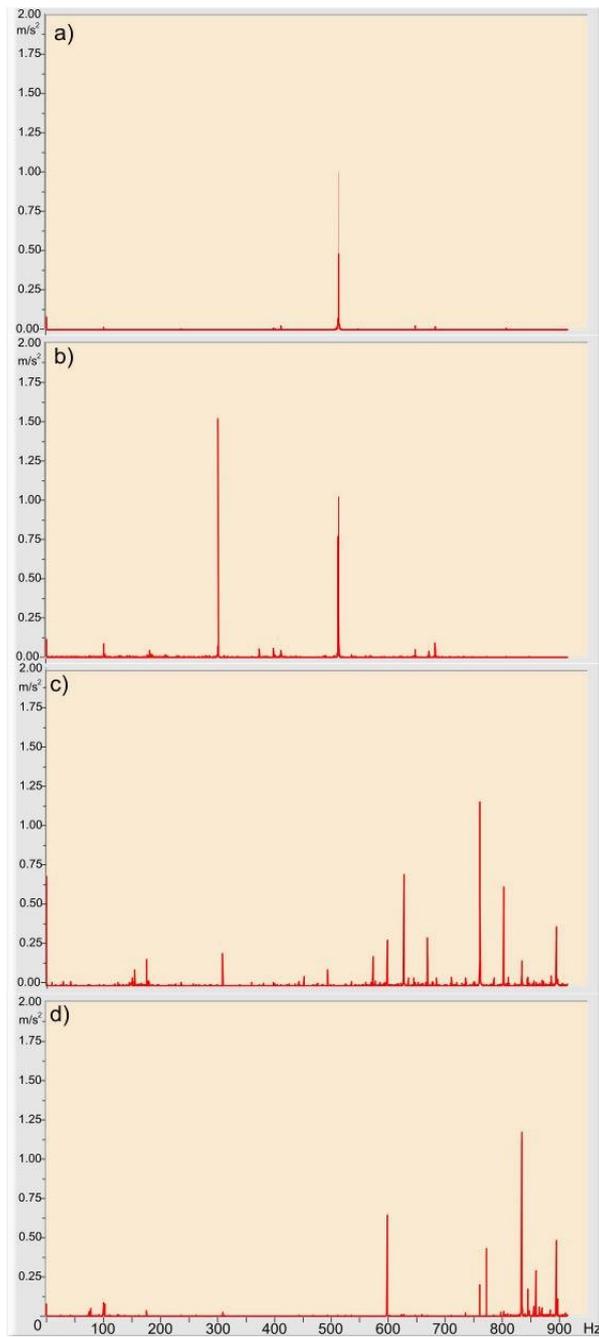


Fig. 4 FFT diagrams for horizontal pump aggregate CVNR 5-3, No.1 at measuring points (MP), a) MP 1, b) MP 2, c) MP 3, d) MP 4.

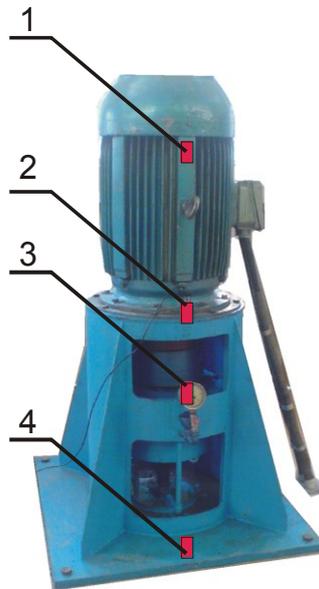


Fig. 5 Measuring points at well pump aggregate BP 350-3G, No. 1

3.2.1. Result analysis of pump aggregate measurement

Measuring point 1, Fig. 6. a) based on diagram, the correct EM bearing operation can be concluded but there are some vibrations on high frequencies which are product of fan vibrations.

Measuring point 2, Fig. 6. b) based on diagram, the correct EM bearing operation is concluded; there are vibrations on frequencies in the range of 400-700Hz that are caused by an incorrect coupling connection between the shafts.

Measuring point 3 Fig. 6. c) based on diagram, the correct bearing operation can be concluded; coupling connection vibrations are increased by the pump aggregate body vibration induced by a loose connection between aggregate and ground.

Measuring point 4 Fig. 6. d) based on diagram, intensive vibrations in the rage of 300-500Hz can be concluded by a loose connection between aggregate and ground.

In order to understand the results previously presented, it is necessary to emphasize that the frequency amplitude diagrams that are presented, are the result of several years of work in order to determine the operating condition for most of the pump aggregates used in industry.

The data presented is a small segment of the research. Over 230 pump aggregates have been analyzed in order to improve the mathematical apparatus and software for vibration analysis. The Table gives absolute values of acceleration; bold values are marked as analyzed in the previous diagrams. The Table is part of the project report and the starting point is in the analysis of operating condition.

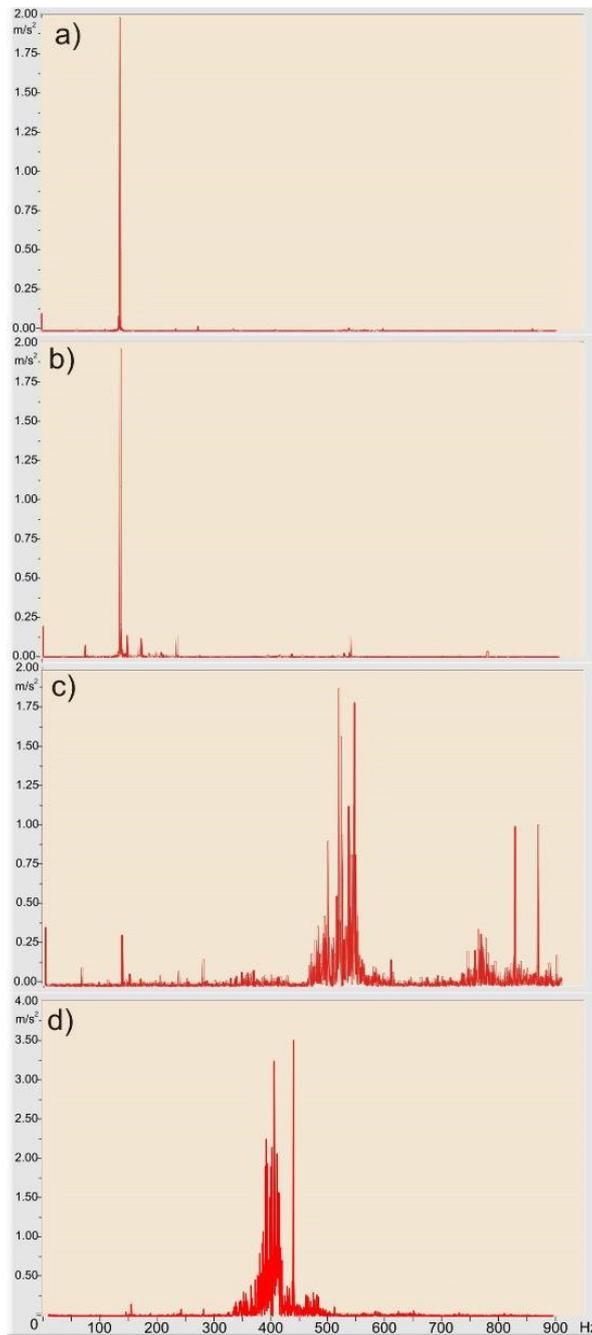


Fig. 6 FFT diagrams for well pump aggregate BP 350-3G, No. 1 at measuring points (MP), a) MP 1, b) MP 2, c) MP 3, d) MP 4.

6. CONCLUSIONS

The examination of pumps vibration phenomenon provides the data about the vibration magnitude and its frequency components as well as their change with respect to operating parameters. On the basis of the obtained results the safety level for the pump and the whole plant is evaluated. Besides the mentioned ones, in most cases it is necessary to determine the cause of non-stationary occurrences. The operating ranges that should be avoided are determined in many cases. The primary sources of vibrations at centrifugal pumps are mechanical, hydraulic and electric processes caused by the design of a pump, its manufacturing technology, operating regime and exploitation condition.

It is possible to eliminate mechanical and electrical sources, partially or completely, thus lowering the level of vibrations.

However, hydraulic vibrations are hard or almost impossible to avoid [12]. Hydraulic processes which happen in pumps are complex and non-stationary as a rule. For description of such processes it is possible to form mathematical models whose evaluation is performed after very comprehensive, expensive and long-lasting research projects.

For these reasons such models have not been taken into consideration in this paper – given are the experimental results obtained by new-developed embedded system, based on the new generation of microcontrollers. In the diagnosis of pumping aggregate malfunctions, frequency spectrums have a crucial role in defining the causes of failure. The created monitoring system has significant results in frequency vibration analyses regarding mechanical defects detection of the pumping aggregate.

REFERENCES

1. Matic, N., Andrić, D., 2000, *PIC mikrokontroleri*, Mikroelektronika Beograd.
2. Milovančević, M., Cvetković, M., 2009, *Application of new microcontroller generation for pump aggregate working condition analyses*, Journal Research and Design in Commerce & Industry, 23/24, pp. 35-41.
3. Milovančević, M., Cvetković, M., 2009, *Applicative approach to vibro-diagnostic model optimization for turbo pumps*, Journal Research and Design in Commerce & Industry, 25, pp. 41-48.
4. Milovančević, M., Veg, A., 2009, *Application of axiomatic design on vibro-diagnostic system*, 9th International Conference "Research And Development In Mechanical Industry" RaDMI, pp. 295-301, Serbia.
5. Čudina, M., 2003, *Detection of cavitation phenomenon in a centrifugal pump using audible sound*, Mechanical System and Signal Processing, 17(6), pp. 1335-1347.
6. Čudina, M., Prezelj, J., 2008, *Use of audible sound for safe operation of kinetic pumps*, International Journal of Mechanical Science, 50(9), pp. 1335-1343.
7. Čudina, M., Prezelj, J., 2009, *Detection of cavitation in operation of kinetic pumps. Use of discrete frequency tone in audible spectra*, Applied Acoustics, 70(4), pp. 540-546.
8. Milovančević, M., Stefanović Marinović, J., Andelković, B., Veg A., 2010, *Embedded condition monitoring of power transmission of a pellet mill*, Transactions of Famena 34(2), pp. 71-79
9. Grjanko, L. P., Papir, A. N., 1975, *Lopastine nososi*, Mašinstroine Leningrad.
10. Milenković, D., 1988, *Nestabilno strujanje kroz kola turbomašina izazvano globalnim gubitkom stabilnosti*, 18. jugoslovenski kongres teorijske i primenjene mehanike, Vrnjačka Banja, pp. 320-326.
11. GOST 13731—68 (State all union standard), *Mechanical vibration, vibration characteristics control* 12.1.003-76.
12. Milovančević, M., Milenković, D., Troha, S., 2009, *The optimization of the vibrodiagnostic method applied on turbo machines*, Transactions of Famena, 33(3), pp. 63-71.
13. Danković, D., Vračar, Lj., Prijić, A., Prijić, Z. 2013, *An electromechanical approach to a printed circuit board design course*, IEEE transactions on education, 56(4), pp. 470-477.

14. Prijić, A., Danković, D., Vračar, Lj., Manić, I., Prijić, Z., Stojadinović, N., 2012, *A method for negative bias temperature instability (NBTI) measurements on power VDMOS transistors*, Measurement science & technology, 23(8), 085003.
15. Vračar, Lj., Prijić, A., Vučković, D., Prijić, Z., 2012, *Capacitive pressure sensing based key in PCB technology for industrial applications*, 5th IEEE Sensors journal, 12(5), pp. 1496-1503.

EMBEDDED SISTEMI ZA MONITORING VIBRACIJA

Cilj istraživanja prikazanog u radu je razvoj optimalne mikrokonfiguracije za monitoring vibracija pumpnih agregata zasnovanom na Mikročipovom mikrokontroleru (MC). Mikrokontrolerski 10-bitni hardver unapređen je 12-bitnim A/D konvertorom. Softver za akviziciju i analizu podataka optimizovan je za testiranje turbo pumpi, čiji je broj obrtaja rotora do 2000o/min. Ovo softversko ograničenje odnosi se na automatski režim rada, ako se testiranje izvodi manuelno, jedino ograničenje potiče od ograničenje akcelerometra. Autori su izveli veliki broj merenja na širokom spektru turboagregata u cilju utvrđivanja stanja radne ispravnosti pumpi.

Ključne reči: mikrokonfiguracija, monitoring vibracija, mikrokontroleri