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APPLICATION OF SMART MOBILE PHONES IN VIBRATION MONITORING

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Abstract. *The purpose of the research presented in this paper is the development of the smart mobile phone application for vibration monitoring of pumping aggregate, based on Microchip's microcontroller (MC). Hardware used is based on Bluetooth connection between smart sensor and smart mobile phone. Software for acquisition and data analysis is optimized for imbedded application in smart sensors. Smart acceleration sensor in conjunction with Bluetooth connection to smart mobile phone creates one touch mobile vibration monitoring system. The authors have performed numerous measurements on a wide range of aggregates for establishing the operating functionality of the newly created system. The possibility of system application I rail vehicle vibration monitoring is also analyzed.*

Key Words: *Smart Phone, Vibration Monitoring, Smart Sensors, Bluetooth Connection*

1. INTRODUCTION

Vibration monitoring is one among many methods of technical diagnostics for continuous monitoring of the technical state of a device by observing the level of mechanical oscillation in a real time. The mechanical oscillation is the device manifestation during its operation. Certain parts become vibration exciters, others, depending on excitation, react specifically. Therefore, the vibration monitoring is one of the most important methods used in technical diagnostics for identifying a technical state. With the use of vibration diagnostics we are able to detect an incipient failure, locate its place and predict the length of time during which a device is going to work before the failure occurs or a preventive action is performed [1, 3, 4, 5, 7].

According to the ISO 10816 standard, all machines are sorted into four classes and for each of them references are given for allowed level of vibrations, points for measuring

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vibrations, way of measuring and selection of measuring parameters. It is possible to carry out further fusion of certain machine classes, regarding the possibility of causing prospective dynamic problems, into two general groups:

GROUP 1 (G1)

Class I machines according to ISO 10816-1, small machines, typically electric motors up to 15 kW.

Class II machines according to ISO 10816-1, medium machines, electro motors with power from 15 kW to 75 kW without special foundation, rotational machines with special foundation and power up to 300 kW.

The primary characteristic of this machine group is embedment of rolling bearings. The most common causes of dynamic problems with this group of machines are: imbalance, defects at rolling bearings, misalignment and support errors. Less frequent are errors of electrical origin, damages at gears, errors caused by the effects of aerodynamic and hydraulic force, defects in belt transmitters, defects caused by pulsation and between rotor and stator [2, 3, 4, 6, 9, 10].

GROUP 2 (G2)

Class III machines according to ISO 10816-1, large machines on rigid foundations

Class IV machines according to ISO 10816-1, large machines on soft foundations

The machines of this group may have sleeve or rolling element bearing. The most common causes of dynamic problems with this group of machines are: imbalance, misalignment, malfunctions on roller and sleeve bearings, support errors and resonance phenomenon.

Less frequent are errors of electrical origin, errors caused by the effects of aerodynamic and hydraulic force, contacts (friction) between rotor and stator, and anisotropy of rotor [1, 8]. Based on our experimental research (a long-term one with over a thousand turbo aggregates examined) and using other sources from the referential literature [2, 5, 6, 7], frequency spectra components are statistically analyzed regarding causal dynamic problems in real exploitation conditions for these two groups of machines, as shown in the following tables. They contain data obtained in a scientific research project of turbo pumps exploitation optimization, conducted at the City of Niš waterworks system "Naissus":

Table 1 Possibility of certain defect appearance at machines (G1)

Damage type	
Misalignment	17.5%
Errors at roller and sleeve bearings	27.5%
Support errors	7.5%
Imbalance	40.0%
Other defects	7.5%

Table 2 Possibility of certain defect appearance at machines (G2)

Damage type	
Misalignment	15%
Errors at roller bearings	15%
Support errors	15%
Imbalance	25%
Other defects	15 %

2. VIBRATION CHARACTERISTICS

Vibrations occur as a result of rotating or straight-line moving bodies. The course of vibrations is mainly under the influence of technical states of single machine components such as shafts, gear boxes, crank mechanisms, cam mechanisms, antifriction bearings, as well as by imbalances of rotating parts, backlash in friction bearings, wear, material fatigue, occurring cracks, corrosion and other parameters affecting a smooth machine run. The vibration itself is then defined as a dynamic phenomenon when particles or solid bodies move around a zero equilibrium position. They are given by a combination of six movements, namely by a shift in orthogonal coordinate system x, y, z and rotation about these axes. Vibrations can be described by amplitude and a phase at a certain period of time. Depending on the time variations of values, the vibrations are of a periodical, non-periodical or random character. As for periodical vibrations, a time course of vibration measured values repeats. A harmonic vibration which has a sinusoidal waveform is based on these vibrations. For harmonic vibrations we need to set only one determining value and the other ones can be calculated.

The basic way of describing oscillations is to determine their displacement x, velocity v, acceleration a, maximum amplitude X_{max}, a root of mean square X_{RMS}, and an absolute value X_{ave} (Fig. 1).

The measurement of displacement x is convenient for low-frequency events such as measuring backlashes, etc. which might be calculated the following way:

$$x = X_{max} \sin \omega t \tag{1}$$

$$\omega = 2\pi f \tag{2}$$

where X_{max} - maximum amplitude (maximum displacement), ω - angular frequency, f - frequency (oscillation), t - time.

Velocity can be expressed as the characteristics of motion which informs us about the way of changing the position of a body (particle) in time. Velocity is a vector physical value because it defines both the change magnitude and its direction. Velocity might be determined as the time derivation of trajectory (displacement) using the equation given below:

$$v = \frac{dx}{dt} = X_{max} \omega \cos \omega t \tag{3}$$

Acceleration can be expressed as the characteristic of motion which shows the way the velocity of a body (particle) changes in time. The acceleration is a vector physical value since it gives both the change magnitude and its direction. It is possible to calculate momentary acceleration and average acceleration. The acceleration might be also determined as the time derivation of velocity using the formula below [11].

$$a = \frac{dv}{dt} = -X_{max} \omega^2 \sin \omega t = X_{max} \omega^2 \sin\left(\omega t + \pi\right) \tag{4}$$

If the acceleration has the orientation opposite of motion, it is called deceleration and has a negative sign.

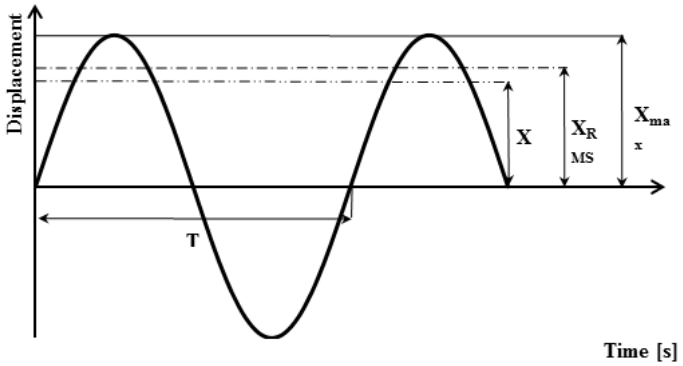

Fig. 1 Harmonic oscillation with the illustration of maximum amplitude $X_{\max}$, a root of mean square X_{RMS}, and an absolute value X_{ave}

Mean absolute value X_{ave} can be expressed as follows:

$$x_{ave} = \frac{1}{T}\int_0^T |x| dt \quad (5)$$

where T – a period expressed by the formula.

The root of mean square can be calculated by the equation below [12, 13]:

$$x_{RMS} = \sqrt{\frac{1}{T}\int_0^T x^2 dt} = \frac{1}{\sqrt{2}} X_{\max} \quad (6)$$

In order to interpret the measured values correctly, it is advisable to transform the oscillation time course into a frequency domain, i.e. vibrations are to be replaced by a sequence of its oscillation components. It can be said that the time signal contains the information about when a certain event occurred, but the frequency spectrum contains the information about how often the same event occurs in an observed signal. The procedure during which complex signals are subdivided into their frequency components is called a frequency analysis which applies either selective band-pass filters or more often a Fast Fourier transformation (FFT). Along with the FFT also a wavelet, cosine or Walsh-Hadamard transform can be used for expressing a signal by orthogonal basis functions. In the paper we have applied a Fast Fourier transformation; therefore, we introduce the formula expressing its transformation which is as follows [12]:

$$F(f) = \int_{-\infty}^{\infty} x(t) e^{-j2\pi ft} dt \quad (7)$$

where f – frequency, j – imaginary unit, $x(t)$ – continuous signal.

3. REALIZED EMBEDDED SYSTEM

Although measuring systems used for diagnostics and vibration measurement already exist at the market, the system that has been described in this paper has certain advantages. First, this system enables the user to measure and monitor vibration from a distance, more precisely, the user does not have to be near the place where the measuring is taking place. This is important, primarily, at potentially dangerous sites, big industrial systems, where some unpredictable malfunctioning may occur. It is also important in a situation when the measuring has to be made in the environment that can be harmful for human health, that is, the environment containing some poisonous substances, or the like. Another advantage of this system is the fact that monitoring can be done by widely available devices, such as laptop computers and smart phones, via the embedded Bluetooth connection. All diagnostic measurements and calculations (DFFT transformations) are done within the embedded microcontroller, so the diagnostic accuracy is not dependent on the performance or the state of the operative system (software) of the user's device.

The system that has been realized contains three major units: the sensor with the signal acquisition circuit, the microcontroller with the proper software and the Bluetooth module (Fig. 2). The vibration sensor used is of the analogue type, and in order to achieve the satisfactory measuring accuracy, the external 12 bit A/D converter has been used. The microcontroller is attached to the A/D converter by the SPI connection, and to the Bluetooth module by the RS232 port [14, 15].

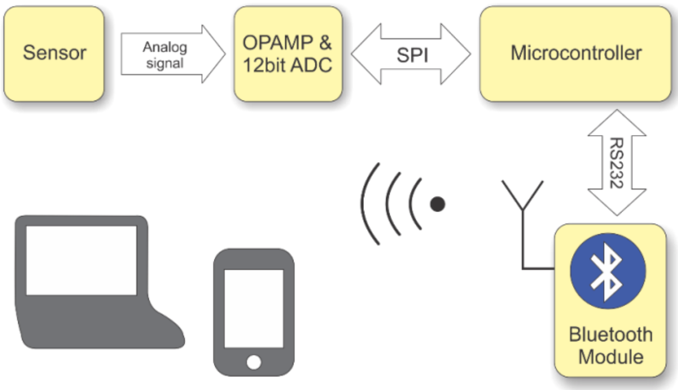

Fig. 2 Block diagram of the realized embedded system

Vibration sensors are used for measuring physical values (displacement, velocity and acceleration) and their transformation into an electric signal which is later worked with. There is a great variety of different vibration sensors which are used for achieving results as accurate as possible. We have the sensors of acceleration, velocity and displacement. The principle of the vibration sensor function is the motion of seismic matter of mass m towards an object of mass M whose vibrations are measured.

For the calculation the formula below is used:

$$ma_h + bv + ky = ma_0 \quad (8)$$

where y - displacement, v - velocity, a_h - acceleration of seismic matters motion, a_o - object acceleration, m - seismic matters mass, k - spring stiffness, b - damping coefficient [2].

For the system realized the accelerometer ADXL 311 by Analog Devices Company is used [1, 13, 14]. It is a dual-axis sensor realized in the iMEMS technology with the analogue voltage output. The sensor can measure dynamic and static acceleration ranging ±2 g, which is sufficient for the realized application (Fig. 3).

Capacitors C_1 and C_2 together with the inner resistance of the sensor make a low pass filter and define the maximum frequency detected by the sensor:

$$F_{-3dB} = \frac{1}{2\pi \cdot 32k\Omega \cdot C} = \frac{5\mu F}{C} \tag{9}$$

Therefore, with the standard defined valued for C_1 and C_2 of 4.7 nF, maximum frequency is slightly higher than 1 kHz.

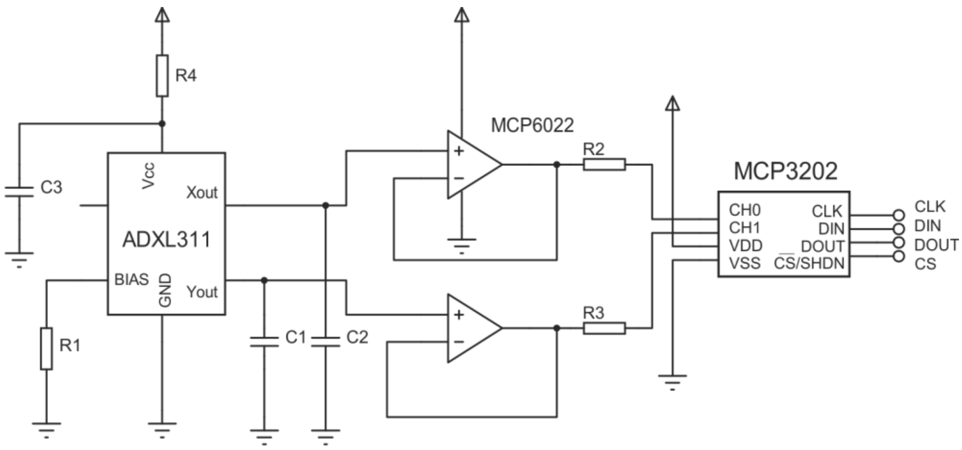

Fig. 3 Detailed scheme of the part of the system with the sensor

The operational amplifier MCP6022 12 has been used in the configuration unity gain and it presents an impedance buffer. A/D converter MCP3202 13 has two channels with 12 bit resolution and it communicates with the microcontroller via SPI connection. The software enables the switching of the measuring channels and reading of the measured voltage values.

The chosen microcontroller is the PIC18F45K22 14, by Microchip Company. It has been chosen for its stability with the interior oscillator at even 64 MHz with the 3.3 V voltage as well as for its containing sufficient software and operational memory necessary for the complicated calculation of the DFFT analysis, Fig. 4. All measuring and DFFT analysis are done inside the microcontroller, so that the final results are independent of the device and the software that user applies.

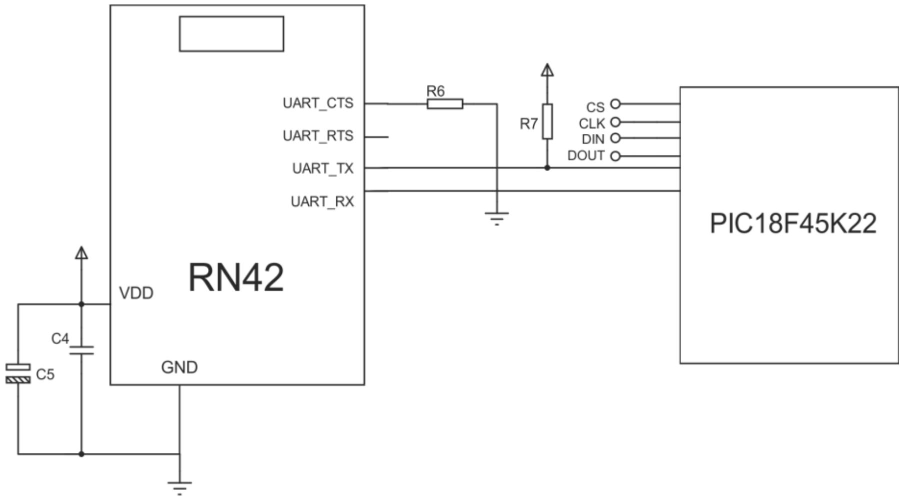

Fig. 4 The scheme of connecting the Bluetooth module and the microcontroller

In order to connect the system to the laptop computer or the Smartphone and in order to read out the measured results the Bluetooth connection is used, via the RN41 module by Microchip. This module has the embedded ceramic chip antenna, which makes the dimensions of the system even smaller. It is connected to the microcontroller by the standard RS232 connection.

4. Application of Wi-Fi System in Industry

4.1. Vibration monitoring of water pumps

Horizontal pumps play a significant role in water transportation which also defines the importance of providing for flawless work. Electro motors of horizontal pumps are extremely burdened regarding their continuous exploitation in terms of maintaining permanent operation. An adequate choice of measuring point at the pump aggregate of the horizontal pump can indicate the operational condition of electromotor bearings and rotor, the pumping aggregate bearings and coupling, as well as complete aggregate construction.

Following measuring points are chosen (Fig. 5):

- First measuring point is chosen for diagnosing the operational condition of the first bearing at electromotor.
- Second measuring point is intended to diagnose the driving electromotor second bearing condition.
- Third measuring point is determined in such a manner that it is possible to diagnose both the condition of pump first bearing and of the elastic coupling.
- Fourth measuring place is defined to diagnose the pump second bearing condition.

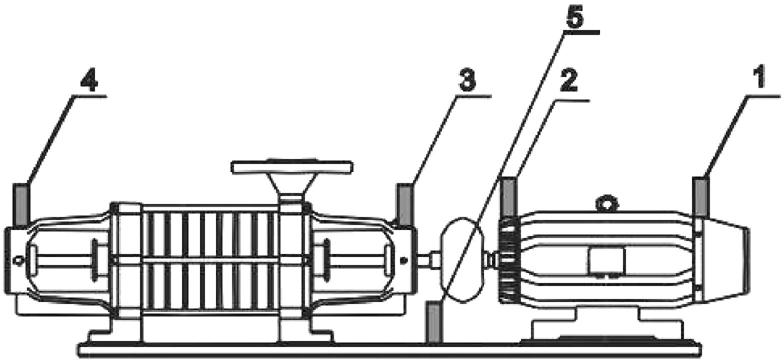

Fig. 5 Measuring point at horizontal pump aggregate CVNR 5-3, No.1

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

Measuring point 1, Fig. 6. a), horizontal and vertical acceleration not passing 1 m/s² can be observed, indicating the proper electromotor (EM) bearing operating condition. Also there is no vibration in frequency range 700-900Hz which indicates that the motor fan is installed correctly.

Measuring point 2, Fig. 6. 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. 6. c), based on the acceleration, the correct bearing operation can be determined as well as an incorrect coupling operating condition based on the analyses of previous diagrams.

Measuring point 4, Fig. 6. d), a satisfactory operating condition of the second bearing of pump can be determined.

Diagram presented in Fig. 6 (a, b) points to the following facts: for electromotor it is possible to determine bearing malfunction as well as other mechanical defects such as an incorrect coupling operating condition. Diagram presented on a Figure 6 (c, d) presents pump bearing malfunction but also a high frequency range is appearing as result of the hydro-dynamic processes in a pump.

In order to understand the results previously presented, it is necessary to emphasize that the above presented frequency amplitude diagrams are the result of several years of work aimed at determining operating condition for most 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.

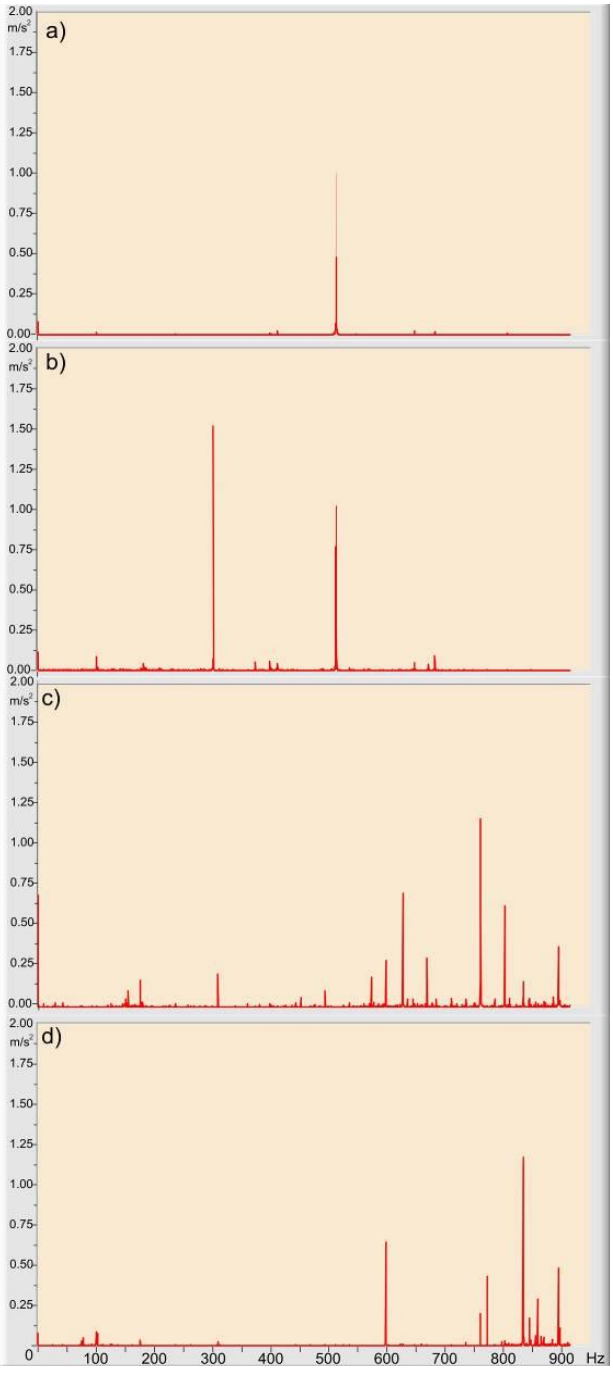

Fig. 6 FFT diagrams for horizontal pump aggregate CVNR 5-3, No.1 at measuring points (MP), a) MP 1, b) MP 2, c) MP 3, d) MP 4.

4.2. Vibration monitoring of railway vehicles

Complex conditions of exploitation of railway vehicles as well as the conditionality of the high level of safety and security require a high reliability operation of all vehicle components. To ensure a failure-free rail vehicles operation it is necessary to carry out diagnostics of working correctness based on the given parameters. The complexity of identifying the parameters on the basis of which the vehicle diagnosis is done is worked out in detail in the UIC regulations. Value of dynamic characteristics and their measurement technique, recording and analysis are given in UIC 518 standard. Wi-Fi system for vibration monitoring is easy to customize according to regulations of standard UIC 518.

The granting of the exploitation permit for a railway vehicle, regarding its dynamic behavior, should be based on an experimental examination (rather than on simulations). It is important to comply with the provisions of the UIC 518 concerning the conditions under which testing is performed as follows: track geometry, the characteristics of the vehicle and driving conditions and characteristics of the zone for testing (on the right tracks, in large radius curves, small radius curves, state vehicles (empty, loaded ...)). Thus the application of Wi-Fi system for vibration monitoring can be useful since system is compact and mobile.

Vibrations of mobile mechanical systems such as railway vehicles are more complex and more difficult to determine. Thus, vibrations are consequences of a large number of relative and absolute motions of elements of rail vehicles and therefore the Wi-Fi system can be used for conducting complex condition monitoring.

5. Conclusions

Examination of the 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 obtained results the safety level for pump and the whole plant is evaluated. To this we should add that, in most cases, it is necessary to determine the cause of non-stationary occurrences. Operating ranges that should be avoided are determined in many cases. 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 the mechanical and electrical sources, partially or completely, lowering the vibrations level in that way.

However, hydraulic vibrations are hard or almost impossible to avoid. 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 are not taken into consideration in this paper – given are the experimental results obtained by newly 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.

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