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THE MULTI-PARAMETER ON-LINE MONITORING SYSTEM APPLIED FOR ROTATING MACHINERY

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ABSTRACT

The paper deals with the designed multi-parameter on-line monitoring system for rotating machinery based on LonWorks Technology. It analyzes the basic theoretical assumptions for its design with the usage of artificial intelligence elements. Moreover, it provides the description of applications of the new monitoring system to production systems of the flexoprinting machines and the small hydroelectric power plant. The effects are in the economy field, i.e. minimization of the production breakdown due to failures, and in the field of environment protection. Thus a modern maintenance characterized by minimizing the costly unscheduled downtime and unexpected breakdowns is presented.

Keywords: Monitoring, On-line, Production system, Application, Frequency, Bearing, Ventilator, Gear.

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Contribution/ Originality

The study presents the usage of the new and developing monitoring system named Oktalon characterized by on-line regime. The paper's primary contribution is presentation of the successful approach that allows preventing the undesirable breakdowns in production using the rotary motion. The descriptions of system implementations provide system's advantages and benefits.

1. INTRODUCTION

The principal tool for diagnosing the rotating machinery problems is vibration analysis [1, 2]. The important components of rotating machinery are the rolling element bearings. The bearing failure may lead to the fatal breakdown of machines or production. It is significant to be able to accurately and automatically detect and diagnosis the existence and severity of faults occurring in bearings [1, 2].

The principal questions are: when the observed process/machinery is going to fail or degrade to the point when its performance becomes unacceptable; and what is the cause of observed process/machinery degradation.

The modern maintenance is characterized by minimizing the costly unscheduled downtime and unexpected breakdowns. In last decades, the predictive intelligence tools - condition monitoring system - to monitor the degradation rather than detecting the faults are being developed. The condition monitoring systems provide the production rate increase and lower the downtime. The production machinery contains the rotating components joints that involve bearings, shafts, blade components, ventilators, seals and other parts of joints. Such assemblies transfer mechanical energy from input power device to output functional component. The high quality and effective

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mechanical energy transfer, operational reliability and long production life are main requirements of the production factories. The dynamic processes in rotating component assemblies have a critical role in correct operation without damage and failure. The vibrations, their amplitudes, velocities, accelerations, envelope accelerations, frequencies, overall values, trends etc. are main monitored parameters.

In the previous period, the research of two faculty departments and the cooperating commercial companies participated in project activities for the development of the new approach for monitoring the state of component joints caused by dynamic processes during operation. Our research goals were focused on the usage of new progressive methods/approaches, devices, and technologies. In this paper, we describe, evaluate and present the multi-parameter permanent monitoring system, its important parameters, system architecture, installation as well as applications. The monitoring system is used mainly for rolling bearings, bearing reducers and gears and for the component joints assemblies as bearing – gear – gear box, engines, generators, pumps, ventilators, compressors, turbines etc. The component joints could be monitored in various industries. Furthermore, the monitoring is suitable for machining process (more in Murčinko and Murčinková [3]) and many other systems.

2. INTELLIGENT MONITORING SYSTEMS

Lee [4] define the intelligent prognostics as a systematic approach that can continuously track health degradation and extrapolate the temporal behaviour of health indicators to predict risks of unacceptable behaviour over time as well as pinpointing exactly which components of a machine are likely to fail. The intelligent prognostic is a base of e-maintenance yielding in near-zero downtime system operation.

The designing of system and device require the knowledge of artificial intelligence and trends of multiparemetric monitoring of rotating machines in order to achieve the higher operational reliability and service life. The main goal is the innovation in form of designing the on-line intelligent monitoring system for monitoring of dynamic process. The designed system have to allow continous measuring and data analysis in automatic regime.

The designed device is the inteligent diagnostic device of new generation. The design involve integrated set of inteligent high-tech equipments, hardware and software for multiparametric monitoring of selected parameters [5]. The system allows to evaluate parameters according to specified criteria and moreover examinate dynamic and tribotechnic processes of mechanical power transmission components.

2.1. Oktalon System

The measuring system Oktalon (Fig.1) was chosen and implemented into the designed monitoring chain. Oktalon system is a modular multi-parameter measuring system for permanent monitoring of mechanical vibrations and diagnostics of roller bearings. The system is constructed on the base of neuron nets of LonWorks (local operating network) type with opened architecture. The measuring, evaluating and saving of measured values are realized in the automatic regime. The measured values are compared with a set of the alarm level values [4].

The communication and data transfer into PC and visualization software are allowed by double data line with protocol LonTalk (up to 2500m), by interface RS 232 or by modem (in the un-switched telecommunication network or mobile GSM (Global System for Mobile Communications) network). The measuring system Oktalon is made of standard “intelligent” modules of LonWorks type based on Echelon processor. Each of used components is developed for functioning in heavy industrial environment. It is characterized by high reliability and resistance to interference.

The vibration measuring was realized by system PXI (PCI eXtensions for Instrumentation - NI LabVIEW Order Analysis Toolkit, NI LabVIEW Sound, and Vibration Toolkit).

Fig-1. Oktalon system.
Source: www.tdgonline.sk

The following types of failure can be identified by measuring of vibration velocity for estimation the mechanical vibration in the low-frequency range: dynamic unbalance, un-axial shafts alignment by clutches, bent shaft, low stiffness of base or mechanical unfastening, resonance effects of supporting frames, housing, boxes, bases, etc [2].

2.2. LonWorks Systems

With thousands of application developers and millions of devices installed worldwide, the LonWorks system is the leading open solution for building and home automation, industrial, transportation, and public utility control networks. A control network is any group of devices working in a peer-to-peer fashion to monitor sensors, control actuators, communicate reliably, manage network operation, and provide complete access to network data. A LonWorks network uses the LonWorks protocol, also known as the ANSI/EIA 709.1 Control Networking Standard [6, 7].

The LonWorks system is based on the following concepts:

• control systems have many common requirements regardless of application,

• a networked control system is significantly more powerful, flexible, and scalable than a non-networked control system.

• managers can save and make more money with control networks over the long term than they can with non – networked control systems.

Fig. 2 shows characteristic LonWorks application applied to monitor the ventilators of flexoprinting machine drying section as one of Oktalon system application.

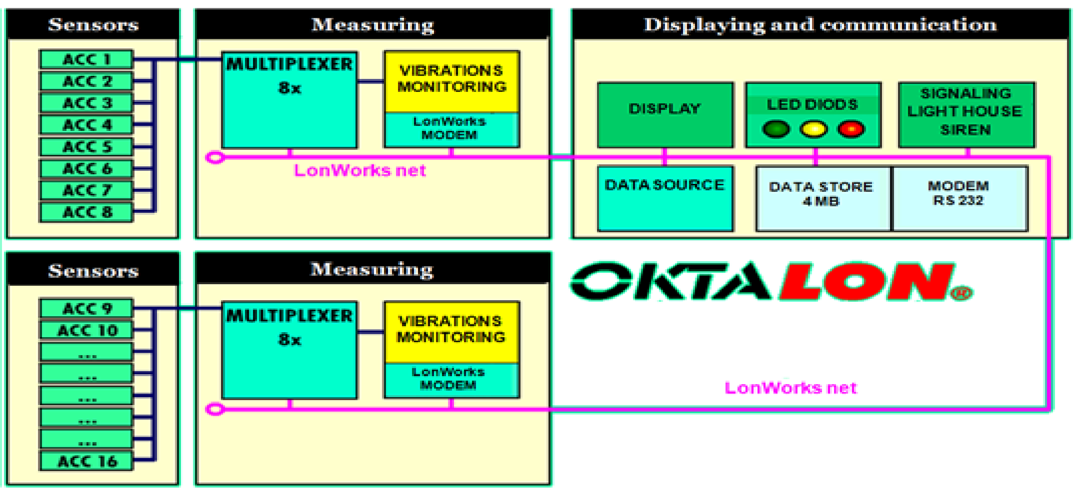

Fig-2. LonWorks application

Source: www.tdgonline.sk

In some ways, a LonWorks network resembles a computer data network referred to as a Local Area Network or LAN. Data networks consist of computers attached to various communications media, connected by routers, which communicate with one another using a common protocol such as TCP/IP. Data networks are optimized for moving large amounts of data, and the design of data network protocols assumes that occasional delays in data delivery and response are acceptable. Control networks contain similar pieces optimized for the cost, performance, size, and response requirements of control. Control networks allow networked systems to extend into a class of applications that data networking technology cannot reach. Manufacturers of control systems and devices are able to shorten their development and engineering time by designing LonWorks components into their products. The result is cost-effective development and consistency that allows devices from multiple manufacturers to be able to communicate. Fig. 3 presents some hardware of LonWorks system.

Fig-3. Hardware for LonWorks system
Source: www.loytec.com , www.infranet-partners.co.uk, www.distech-controls.com

2.3. Diagnostic Signal Transmission

In generally, the transmission of obtained diagnostic signals can be realized by various types of connections. If the cable lines are available, it is the best to use them. The transmission speed for cable lines is much higher than with wireless technology. Another advantage is the near-zero weather conditions influence. The large financial expenses are the disadvantage for use in mountainous terrain.

This disadvantage is eliminated by wireless technologies. The most frequently used network is GSM which availability is the best. Its competitors are networks based on microwave technology (WiFi and WiMAX). Their transfer rates are higher, but the need of direct visibility transmission points makes limits for use.

In industries as well as in energy and automobile industry in the world, the TETRA radio communication succeeds. Each wireless network has some advantages and disadvantages to consider when choosing the most appropriate.

For our system, the GSM network was the best to use regarding finances and mostly mountainous terrain in Slovakia. Thus the condition monitoring system can work in different modes with output on a computer or mobile phone of operator or owner allowing on-line control.

3. APPLICATIONS

Multi-parametric permanent monitoring system Oktalon is implemented in various applications characterized by rotating components with the high frequency of revolutions, i.e. ventilators of the flexoprinting machine, bevel gear, and bearings of the small hydroelectric power plant and bearings of the wind turbine.

3.1. Drying Section of Flexoprinting Machine

The application was made for 8-colour and 10-coulor flexographic printing machines consist of 8 (10) printing sections in package printing factory. The packaging foil is winded off and passes through printing positions of individual colours (yellow, green, blue, etc.). The combination of colours and images forms the final printed graphic image. The used liquid inks are dried through the evaporation of organic solvents. More in [8, 9].

The operating environment of ventilators is explosively regarding the high concentration of emissions. The air is sent to combustion section where the emissions are burned. The whole drying section is bounded by covering and the entrance to operating ventilators is impossible. To repair the ventilators in a case of failure or damage, the total downtime has to be done. The flexoprinting machine and view to dryer are in Fig. 4. Each rotating ventilator wheel of printing machine dryer is fixed directly on the output electromotor shaft. The engine speed is regulated in dependence on demand of drying air volume. The sensors in each section measure the emission concentration in air. In a case of increased concentration, the revolutions of electromotor (ventilator) are increased up to a maximum value, i.e. 5000 min^{-1}. The diameter of ventilator wheel is 500mm; the electromotor power is up to 10kW.

Fig-4. Flexoprinting machine and ventilators of drying section (right)

Source: Autors' photos

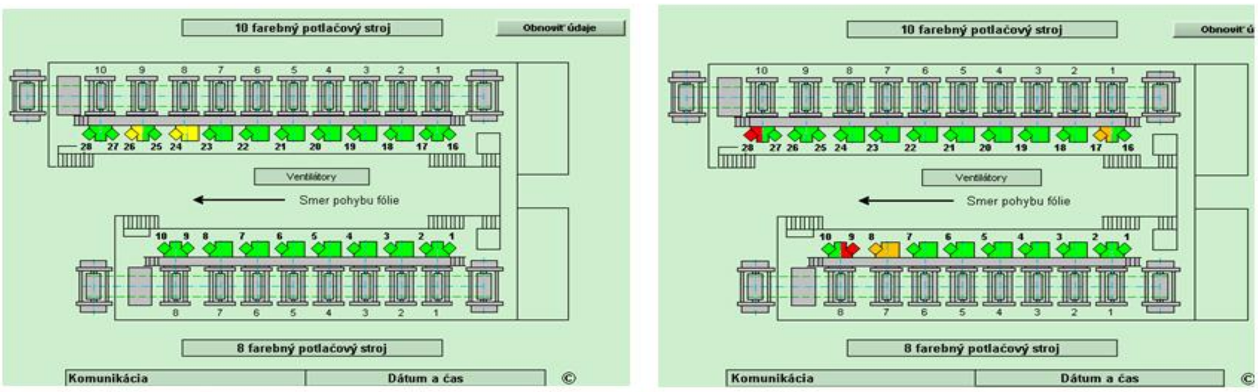

Fig-5. Scheme of measuring positions and its states

Source: Measurement protocol

Fig. 5 shows the display of Oktalon system applied to printing machine drying section. The applied system architecture is in Fig. 2. The positions labelled by green colour mean the good condition. The yellow and red colours denote Alarm1 "Warning" and Alarm 2 "Danger". The limit values of individual states are set according to standard STN ISO 108 16-3 (Slovak Technical Standard modified according to International Organization for Standardization). To present the system measuring and on-line intelligent monitoring, we provide the case of ventilator 9 situated in drying section labelled as the measuring position 26 (Fig. 5, left). The on-line Oktalon system identified the state of "Alarm" at position 26 by yellow colour. Fig. 5, right, shows different view at the display showing another ventilator vibration state.

The values of Velocity (VEL) and Envelope2 (EN2) for alarm Alarm1 and Alarm2 are 2.8 mm/s and 4.5 mm/s, respectively. The values are the same for both methods VEL as well as EN2. The following tables (Tab. 1, 2) involves evaluated values measured by diagnostics system Oktalon for ventilator 9, position 26.

The bearing geometry and shaft revolutions influence the frequencies of defects. Mostly, the bearing defect frequencies are provided by manufacturers or vibration analysis software that incorporates the database of them.

Table-1. Measured values for bearings 6308 and 6308E and rpm=4200 min^{-1}

Frequency (Hz)	**70**		**RPM =4200 min^{-1}**
	SKF 6308	SKF 6308E	
BPFO (Hz)	215.0	179.7	outer race
BPFI (Hz)	345.0	310.3	inner race
BSF (Hz)	142.7	122.0	rolling element
2*BSF (Hz)	285.5	243.9	2x rolling element
FTF (Hz)	26.9	25.7	cage

Source: Measurement protocol

Table-2. Measured values for bearings 6212 and 6212E and rpm=4200 min^{-1}

	FAG 6212	**SKF Explorer 6212E**	**SKF 6212**
Frequency (Hz)	**70**		
BPFO (Hz)	284.9	250.677	287.538
BPFI (Hz)	415.8	379.323	412.462
BSF (Hz)	181.3	164.248	189.874
FTF (Hz)	28.7	27.853	28.754

Source: Measurement protocol

The abbreviations in tables depict fundamental bearing defect frequencies:

- BPFO – Ball Pass Frequency of Outer race – frequency created when all rolling elements roll across a defect in outer race f_{or}
- BPFI – Ball Pass Frequency of Inner race – frequency created when all the rolling elements roll across defect in the inner race f_{ir}
- BSF – Ball Spin Frequency – circular frequency of each rolling element as it spins f_{re}
- FTF – Fundamental Train Frequency – frequency of cage f_c

The bearing defect frequencies depend on relative speed between outer inner race, α contact angle (°), n_g number of rolling elements, D_1 pitch diameter (mm) and d_g ball diameter (mm).

The trend graph of summing values of the dynamic signal of operating conditions in Fig. 6 provides the values in order to determine the actual state of failure in bearings of ventilator 9. The measured method has to involve the actual state of lubrication, friction, and operating temperature. In a period of 3 months, it was found that high-frequency vibrations increased. The signal values were in the Alarm1 range (yellow, Fig. 6), even shortly in the Alarm2 range – danger (red, Fig. 6).

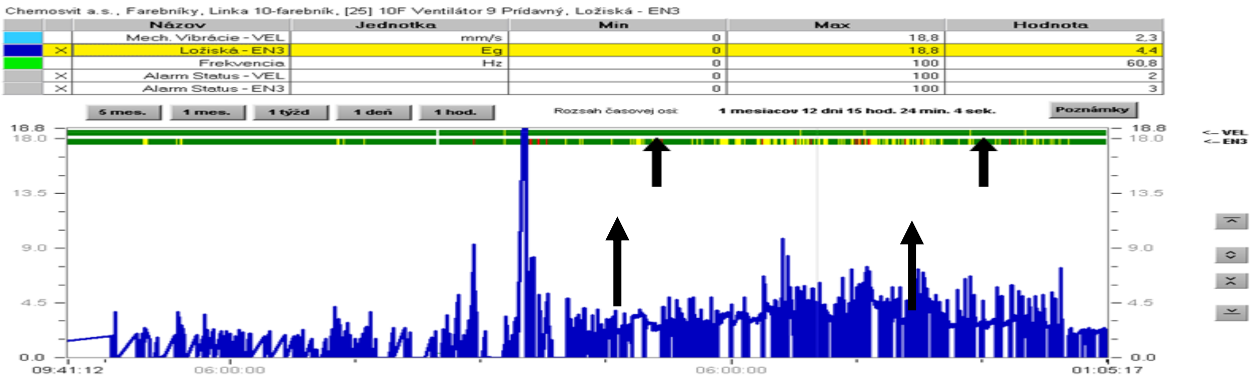

Fig-6. Trend graph before repair

Source: Measurement protocol

The repair of position 26 was made. The damaged bearing was replaced by new one. The strong improvement of operating state was measured (green colour, Fig. 7).

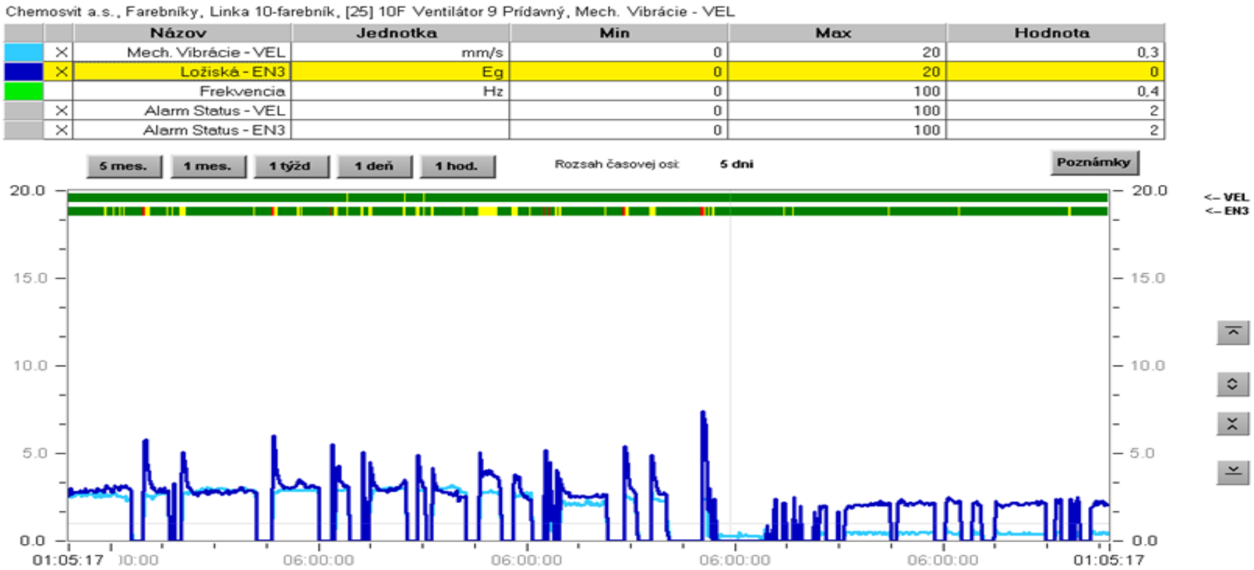

Fig-7. Trend graph after repair

Source: Measurement protocol

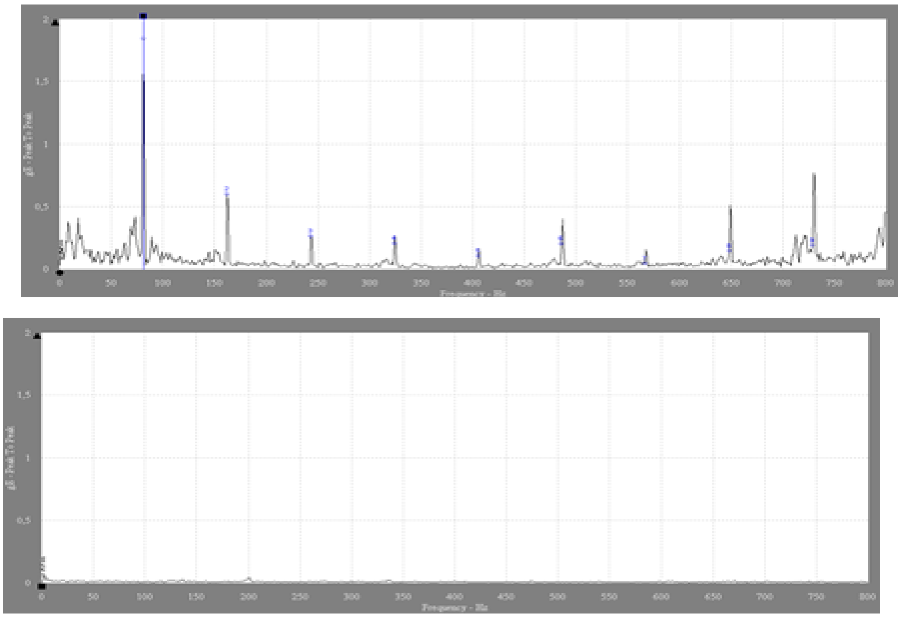

Fig-8. FFT spectrum before repair (EnvAcc=6.2gE), left, and after repair (EnvAcc=0.5gE)

Source: Measurement protocol

Fig. 8, left, shows FFT spectrum of velocity values before repair. The ball spin frequency (81.2 Hz) and multiplies are visible in Fig. 8, left. The summing value of EnvAcc is 6.2gE. This value is over the Alarm2 limit – danger. Fig. 8, right, presents values of velocity (mm/s, rms) after repair. The summing value of EnvAcc is 0.5gE. This value is under the Alarm1 limit that identifies the good operating state.

3.2. Small Hydroelectric Power Plant

Fig. 9, left, shows the worn bevel pinion. The exchange of the damaged gear may take about 6-9 months in the case of the complete gear failure and none spare gear in the storeroom. During the mentioned period involving manufacturing, supply, and gear exchange, the small hydroelectric power plant either does not operate or it operates with significantly reduced power (30-50%). At that time, there is no financial income from the power plant performance. If the sources of damage would not be removed then the failure repeats and it would lead to the end of business due to huge repeating expenses for frequent repairs. The power plant owner prevented the mentioned worst case scenario using the monitoring system and setting and arrangement of component joint (Fig. 10).

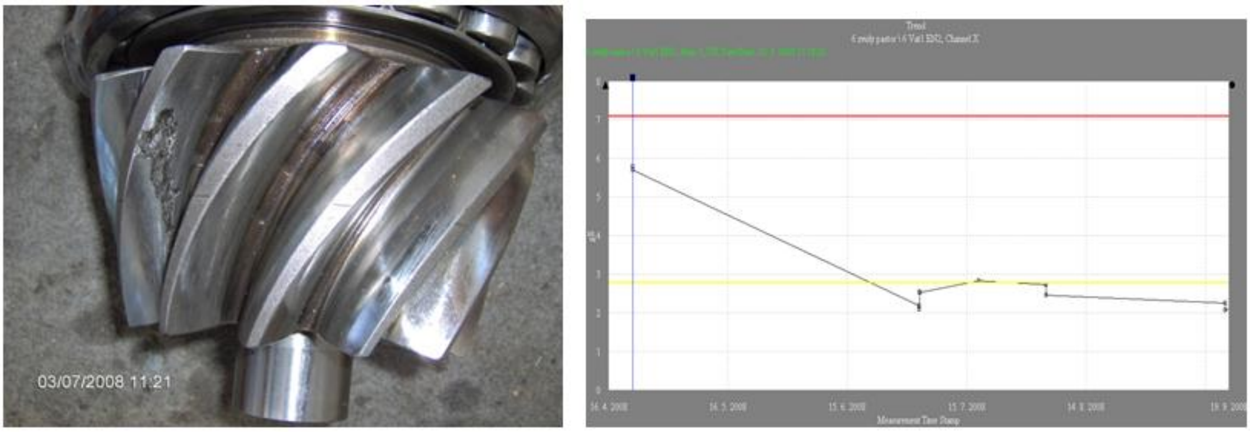

Fig-9. Damaged teeth of bevel gear and trend graph

Source: Authors' photo, measurement protocol

Till the implementation of the on-line monitoring system, the often (about every third month) repair works had to be made to exchange the bevel gear as it was described in the previous paragraph. The CAD/CAE model (Fig. 10) of frequently damaged bevel gear by pitting was made to analyze the static, kinematic and dynamic parameters and the distribution of forces and moments (Fig. 10) to find out the forces/moments ratio per one revolution and confirm the distribution of the most stressed locations of component joint. Moreover, the on-line monitoring system implementation required the setting of the individual components alignment, mainly the shafts and their angular and parallel misalignment and imbalance moment. The trend graph after arrangement and implementation of the monitoring system is shown in Fig. 9, right. The values are under red and yellow lines indicating the alarm and danger level.

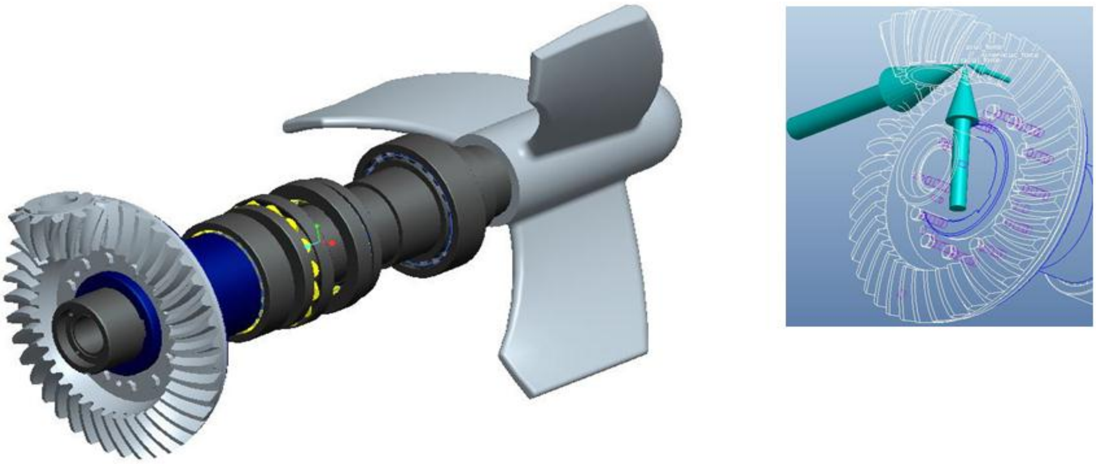

Fig-10. Component joint of small hydroelectric plant and forces in gear

Source: authors' analysis

4. CONCLUSIONS

The vibration diagnostic is requested for the well-operation systems which are considerably dynamically loaded. The vibration diagnostic can be realized by the patrolling measuring in specific time intervals or by the monitoring diagnostic system implementation. There are two approaches to condition monitoring system implementation:

- predictive maintenance with proactive control – the monitoring system elements are mounted in the production stages, i.e. when assembling the component joints, arranging into structural units and putting into service; thus prevention of early failure and damage of key machine units is made,
- monitoring system is mounted only after the occurring of damage problem and the fault has to be removed,

In a case of predictive maintenance, the costs of condition monitoring system design and installation are substantial in comparison to other maintenance approaches but in the longer operating condition, the monitoring system provides benefits surpassing the costs. This approach needs to be recommended to the companies that invest in similar projects to protect a rapid return on their investment and to ensure reliability. Moreover, the mutual consultation between a supplier of components/units of the production system and the diagnostic company is required to determine the method and the measuring points. Finally, the application and usage of monitoring system makes the competitive advantage for producer and avoids potential financial losses.

The presented facts obviously confirm that implementation of on-line control systems for operating machines in mass production with environmental effect is principal and required. The paper analyses the basic theoretical incomings for design and application of new monitoring system. The previous patrolling system was unable to detect fails and collision states on time. In a case of ventilators collision in the dryer of the flexoprinting machine, the required amount of dangerous exhalation could not flow out into combustion section. It can cause the disaster with environmental impact.

The new system of the automatic monitoring regime with the use of artificial intelligence elements, that was designed and tested, confirms the validity of purpose. The implementation of intelligence elements into on-line control eliminates human errors and furthermore it enables the quality prediction of collisions. The effects are in the field economy (minimization of the production breakdowns due to failures) and in the environment protection field.

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