



A HYBRID DIAGNOSTIC SYSTEM OF MAIN DRIVE OF INDUSTRIAL PRESS LINE

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Abstract

The idea of Industry 4.0 indicates Condition Based Maintenance (CBM) and Predictive Maintenance (PdM) as fundamental maintenance strategies in modern factories. CBM and PdM could be implemented with use of on-line continuous monitoring and diagnostic systems and also as a program of systematic examinations of asset condition done by maintenance personnel. Using data collected from hand held instruments and from on-line systems it is possible to build full image of current asset condition and predict probable faults in the future. This paper presents system of condition monitoring and diagnosing of main drive of industrial press line. The system uses diagnostic data coming from different sources like vibration, electrical and thermal measurements. Application of different types of data makes the system hybrid and allows improve diagnostic inference process. The article describes how the system is designed and implemented.

Keywords: MFMEA, CBM, press drive, diagnostics, vibration, MCSA, monitoring system

HYBRYDOWY SYSTEM DIAGNOSTYCZNY NAPĘDU GŁÓWNEGO PRZEMYSŁOWEJ LINII PRAS

Streszczenie

Idea Przemysłu 4.0 wskazuje Condition Based Maintenance (CBM) oraz Predictive Maintenance (PdM) jako podstawowe strategie służb utrzymania ruchu w nowoczesnych fabrykach. CBM i PdM mogą zostać wdrożone z wykorzystaniem ciągłego monitoringu w trybie online oraz systemów diagnostycznych, a także systematycznej kontroli stanu urządzenia przeprowadzanej przez personel utrzymania ruchu. Używając danych zgromadzonych za pomocą przyrządów ręcznych, a także systemów pracujących w trybie online możliwym jest zbudowanie kompletnego obrazu aktualnego stanu urządzenia i przewidywanie potencjalnych awarii w przyszłości. Poniższa publikacja opisuje system diagnostyczny przemysłowej linii pras. System wykorzystuje dane pochodzące z różnych źródeł: drgania, natężenie prądu elektrycznego i pomiarów temperatury. Różnorodność danych sprawia, że system staje się hybrydowy, co pozwala usprawnić wnioskowanie diagnostyczne. Artykuł opisuje proces projektowania takiego systemu oraz jego implementację.

Słowa kluczowe: MFMA, CBM, MCSA, metody diagnostyczne, napęd prasy

1. INTRODUCTION

Metal stamping is commonly used in the automotive industry. The stamping process is carried out on the press lines which could be treated as a critical industrial object due to extremely high costs of production losses caused by press line breakdown. The reasonable way of avoiding unexpected press line breakdowns is application of Condition Based Maintenance (CBM) and Predictive Maintenance (PdM). CBM and PdM are ideas known for many years. However, since the trend of Industry 4.0 is currently so popular the two aforementioned could be treated as the fundamental strategies in modern factories including stamping departments. CBM and PdM could be based on

continuous monitoring and diagnosis systems. Contemporary market offers solutions for press line condition monitoring. There are solutions offered by press lines manufacturers [12] or automation and measurement systems manufacturers [10, 13, 14]. Scientific researches indicate modern solution for stamping monitoring based on tooling integrated sensors [16] or press tonnage sensors. Interesting solution integrating different sources of information for press condition monitoring was proposed by Fraunhofer Institute for Machine Tools and Forming Technology [14]. Currently available commercial systems can be used for the purpose of press condition monitoring. One of them is SIPLUS system invented by Siemens company [17]. Data analysis is performed in accordance to ISO 10816-3

standard which is related to vibration analysis. In this system it is possible to add analog inputs module and perform measurement of any other physical quantity with use of analog output sensor. Products of ifm electronic [18] are also based on vibration measurement. The system provides motor diagnosis techniques, limited to signals coming from accelerometers. Similar solution was developed by TURCK [19]. A really interesting solution is delivered by ABB - Ability™ Smart Sensor for motors. Sensors are easily mounted to the motor housing and may provide basic data (i.e. temperature) about motor condition to the system with use of Wi-Fi system. One may see that there are many possibilities of condition monitoring systems that can be applied also for press drive system. Most of them perform either vibration or temperature analysis. Of course, advanced frequency inverters also provide possibility of current measurement. It is possible to calculate frequency spectrum of motor current, without implementation of MCSA. Despite the large availability of comprehensive diagnostic solutions supporting CBM and PdM they are rarely used due to the lack of sufficient knowledge in maintenance departments or/and high costs inadequate to application in old press lines working in many companies for years.

Due to the fact that there are many papers [2, 5, 6, 8] that provide information on capabilities and suitability of MCSA it was decided to invent own diagnostic system.

This paper presents concept of condition monitoring and diagnosing system dedicated for industrial press line based on data coming from different sources like vibration, electrical and thermal measurements what makes the system hybrid and allows improve diagnostic inference process. The paper focuses on currently implemented subsystem allowing monitoring and

diagnosing press main drive with use of electrical and vibration parameters.

2. PRESS LINE AS A COMPLEX OBJECT FOR CONDITION MONITORING

In stamping process different types of presses are used. Generally, the three main types of presses are in use: mechanically-, hydraulically- and servodriven ones. The most common are mechanical presses which are assembled into lines operating in different ways. The condition monitoring system described in the article concerns tandem press line with mechanical presses. It is characteristic for this type of press line that each station (press) has its own, individual drive system. Fig. 1 presents the diagram of tandem press line with an exit conveyor. Basically, the following subsystems can be distinguished in most of press lines:

- cushion (hydraulic or pneumatic);
- hydraulic unit (for lubrication and power hydraulic unit);
- drive system with main motor, shaft, gears, connecting rods, clutch and brake;
- counterbalance system;
- slide adjustment;
- controls system with safety subsystems;
- parts transport system;
- pneumatic system;
- front of line with de-stacking unit and centering station;
- end of line with conveyor, collecting chute or automatic racking system;
- slide system with clamping units
- moving bolsters and bed unit

The press line is a complex system where any fault could influence the whole stamping process and in some cases cause unexpected breakdown of the line.

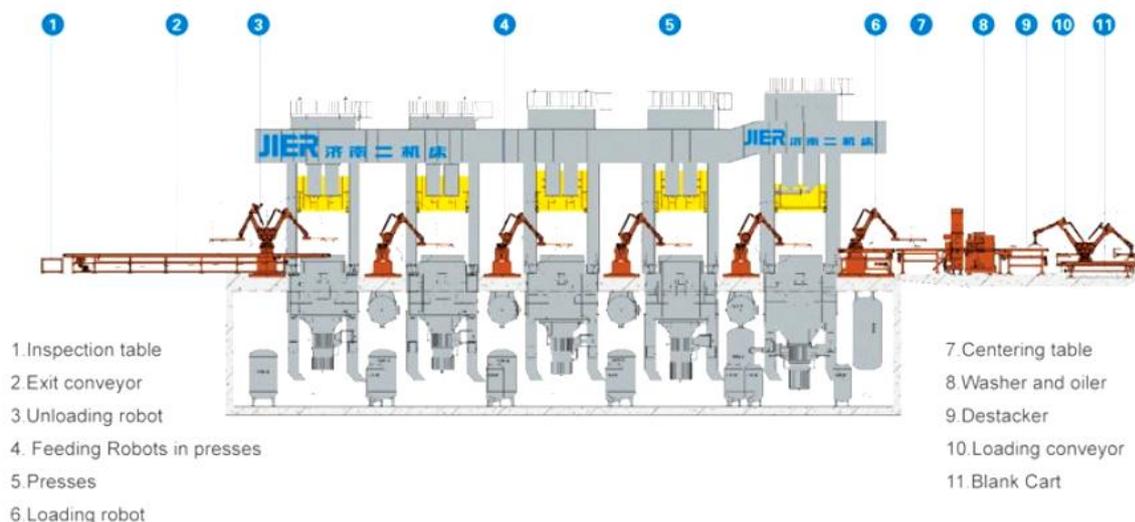


Fig. 1. Diagram of tandem press line [21]

2.1. Criticality analysis of press line

Considering press line from operational point of view it has a serial structure where breakdown of any link of the chain cause stoppage of the whole line. Due to the complexity of the press line it was necessary to point out critical elements which will be monitored and diagnosed continuously. Defining the most important parts of the press line could be based on the criticality analysis. This method allows to point out the elements that are most critical for production stability. Criticality analysis gave a good basis for further design process of condition monitoring system. There are many methods that can be implemented for that purpose, like AHP (Analytic Hierarchy Process) [17], ABC (Activity Based Costing) [18] or MFMEA (Machinery Failure Mode and Effects Analysis) [2]. During designing of condition monitoring systems of press line the authors were basing on MFMEA which allows to assign the problem to particular element of the analysed object. The method requires the following steps to be undertaken [19]:

- identification of equipment and its mode of operation;
- indication of potential failures and their root causes;
- analysis of failure effects on particular object component with use of Severity, Probability and Detectability coefficients;
- measurement of potential effects of the failure modes based on *Risk Priority Number (RPN)* as a product of Severity, Probability and Detectability coefficients.

The result of the analysis indicates components of the objects in order of their criticality. This gives the opportunity to simplify prioritization of necessary actions to reduce probability of failure. Analysis of the press line was performed on the basis of historical data derived from the maintenance reports. Table 1 presents a part of MFMEA evaluation that was performed for the stamping press. In that particular case the most critical subsystem for this machine is the main drive. In the considered case the main drive consists

of an induction motor, a set of bearings and a shaft between the motor and the flywheel.

2.2. Main drive system of press line

MFMEA evaluation indicates that main drive system is critical for reliability of the whole press line. Each station of the tandem press line is equipped with its own main drive system. In such situation it is necessary to diagnose each of them. However, the structure of condition monitoring system can be similar for all the above mentioned drives. This results from similar design of those drive systems. In fig. 2 an exemplary press main drive system and its parameters were presented. From the diagnostic point of view one may distinguish several main components of drive system: main motor, elastic coupling, bearing set of belt drive and shaft with the pulley.

4. THE HYBRID CONTINUOUS CONDITION MONITORING SYSTEM OF THE MAIN DRIVE OF THE PRESS LINE

Due to the press line complexity and criticality a general concept of monitoring and diagnosing system was proposed. Structure of the system is presented in fig. 3. The main part of the system is the data base server, whose main task is to collect, process and share data between subsystems as well as enterprise divisions. A distributed structure of subsystems responsible for each part of press line was assumed. Subsystems can be divided into automated and personnel driven ones. Condition monitoring and diagnosing subsystems of each press and transfer equipment are automated what means that they are able to diagnose and predict how asset condition will change in the future. Information about past, present and future asset condition is shared to each subsystem including maintenance department. Maintenance personnel are responsible for detailed manual inspection of the press line suspicious areas to confirm correctness of diagnosis performed by automated system as well as for planning repairs.

Table 1. Part of MFMEA – own evaluation

Item / Function	Potential Failure Mode(s)	Potential Effect(s) of Failure (downtime [h])	S e v	Potential Cause(s)/ Mechanism(s) of Failure	P r o b	Current Design Controls (detectability)	D e t	RPN	Recommended Action(s)
Drive	Bearing ball breakdown	48	8	Lost of drive alignment	5	TPM	10	400	1. Preventive temperature measurement 2. Online current analysis
Drive bearings	Race failure	48	8	Material failure	5	Vibration monitoring	10	400	Online vibrations analysis
Drive	Loss of axiality	9	8	Bearings	4	No controls	10	320	Axiality check according to TPM
Breaking plates	Wear	120	10	Spring broken	2	No controls	10	200	Overrun regular measurement
Flywheel	Loss of balance	72	8	Main bearings	2	No controls	10	160	Online vibrations control
Drive	Insulation damage	48	8	Broken short circuit protection	2	Periodic, manual connections check	10	160	Installation of predictive system
Clutching plates	Wear	120	8	Distance increase	2	No controls	10	160	Regular distance measurement
Robot	Collision with press	1	2	Unexpected press stop	4	Press stops during upward movement	10	80	1. Network analysis 2. Press stops analysis
Robot	Collision with previous robot	1	2	Robot stop due to part control fault	4	Part check in Pick depart point by vacuum check	10	80	1. Analysis of induction sensors installation
Drive	Insulation damage	9	10	Too high temperature inside the motor	1	TPM temperature measurement	7	70	1. Preventive temperature measurement 2. Online current analysis

The focus of system development was to design subsystem of condition monitoring and diagnosing of single press. General structure of such subsystem is presented in fig. 4. Subsystem of condition monitoring system consists of main drive system, hydraulic system, stamping and synchronization

system, material transfer system. Due to high criticality a condition monitoring and diagnosis system of main drive was designed and launched at first. Logical structure of the system is presented in fig. 5.

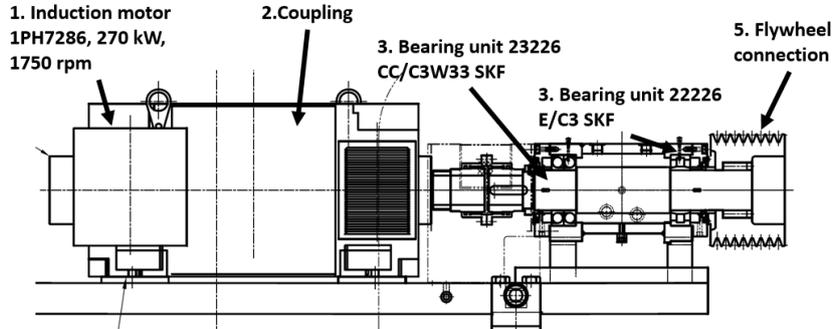


Fig. 2. General structure of the analyzed press main drive system

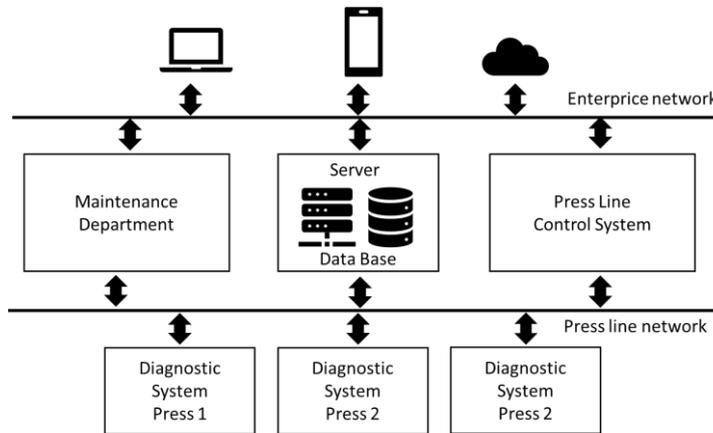


Fig. 3. General structure of press line diagnostic system

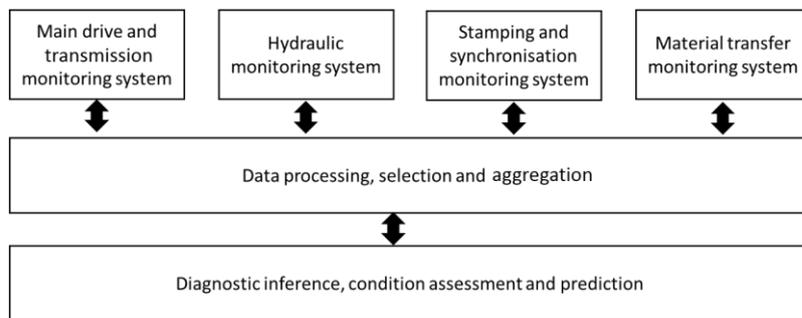


Fig. 4. General structure of single press diagnostic system

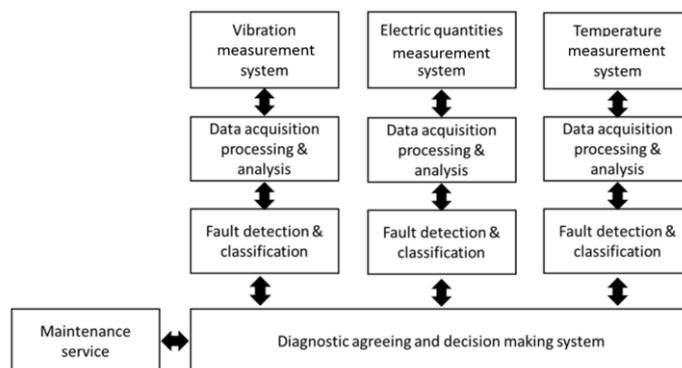


Fig. 5. Structure of condition monitoring system of press main drive

Evaluation of main drive condition is based on data acquired from simultaneous measurements of vibration, electrical current and temperature. Data from each measurement system is transferred to data acquisition, processing and analysis system where condition evaluation connected with fault detection and classification are performed independently for each type of measured data. Results of condition evaluation are agreed upon additional data from maintenance services and sending to local decision support system.

Information concerning main drive condition, warnings, alarms and suggestions about further operational decisions are transferred by DeviceNet to press control system and by Ethernet to main data base server, and is shared with another press line condition monitoring and diagnosis subsystems. The system server allows to send the email with information about the detected press faults and suggestions of further check for maintenance service.

Connection of monitoring system to existing press controller was necessary to receive information about current machine mode of operation and to send information about the current status of main dive system. On the basis of the data taken from press controller it was possible to synchronise measurements which correspond to steady state press operation cycle. Stationary

conditions of press operation occur when the slide is at Top Dead Centre. It assures repeatable measurements during comparable load conditions of the press drive.

Hardware part of monitoring system was based on modular National Instruments Compact RIO system and software part was developed using National Instruments LabView development system.

4.1. Subsystem of electrical parameters based condition monitoring

A part of monitoring systems based on electrical parameters measures the intensity of motor electric current. For measurement purposes the subsystem used (Fig. 6) consists of electric current transducers LEM HAT 400-S fixed on inverter output wires (Fig. 7) supplying electric motor. Current transducer output signals are inputs of Data Acquisition Card (DAQ) NI 9215 of Compact RIO system where they are converted to digital signals required for further Motor Currents Signature Analysis (MCSA) purposes. Signal processing and analysis were performed by dedicated software developed in LabView and embedded in local computer of Compact RIO system. An exemplary screen of the developed software for spectral analysis of current signal is presented in Fig 9.

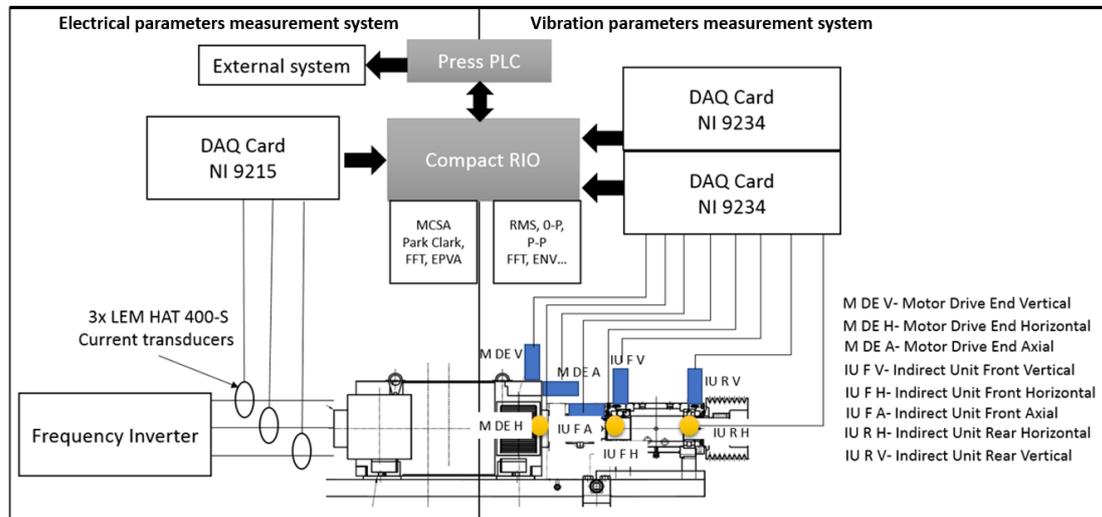


Fig. 6. Diagram of press main drive monitoring system

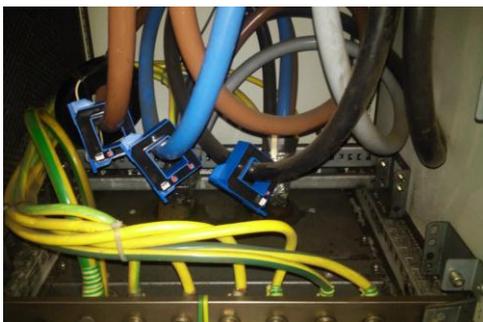


Fig. 7. LEM transducers



Fig. 8. Compact RIO module

The gathered current signals were 0.2 second long (20×10^4 samples) and were verified at stationarity at first. Before further analysis, values of signals were statistically standardized. Next, scalar features in time and frequency domain were calculated. In total, 35 point features in the time domain and 90 point features in the frequency domain, were considered [1][2][3]. Some of the features were calculated based on Fast Fourier Transform (FFT) of AC level of the current Park's vector modulus [4] known as extended Park's vector approach (EPVA) [20]. FFT spectra were estimated and analysed according to methods described in International Standard ISO 20958:2013 [5]. The standard defines specific spectral symptoms of such electric motor faults like: broken bars, rotor eccentricity and bearings defects. Additionally, total harmonic distortions, crest factor, impulse factor, form factor, rms, peak-peak, kurtosis, skewness, smoothing factor and many other current signal features were also estimated and monitored.

In fig. 9 screen with MCSA symptoms marked on the spectrum of Extended Park's Vector Approach of current intensity signal was presented. Different colours were applied to point the frequency bands where symptoms corresponding to particular faults can appear in the spectrum.

4.2. Subsystem of vibration based condition monitoring

The structure of vibration based condition monitoring subsystem (Fig. 6) includes accelerometers CTC M/AC240-1D and M/AC154-1A mounted in bearing housing of motor and belt drive (Fig. 10a) and DAQ modules (NI 9234) located in separate Ni Compact RIO chassis (Fig. 10b). Accelerometers measure vibration in radial and axial directions. Vibration signals are processed and converted to digital form and then estimated in time and frequency domain by software developed in LabView embedded in Compact RIO controller. The software contains modules for calculation of classical features like RMS, Peak and Peak to Peak amplitudes of vibration velocity and acceleration signals. Scalar features are plotted as time series for trend analysis and additionally are compared to limit values according to vibration standards ISO 10816 and VDI 3832. Additionally, velocity and acceleration signals are transformed to frequency domain with use of FFT algorithm which allows to estimate and monitor spectral features connected with typical mechanical faults like unbalance, misalignment and belt drive problems. Additional functions of software allows assessment of bearings conditions on the basis of envelope analysis of filtered acceleration signal.



Fig. 9. User interface of current analysis with use of EPVA



Fig. 10a. Accelerometer installed on motor housing



Fig. 10b. Additional chassis for accelerometers connection

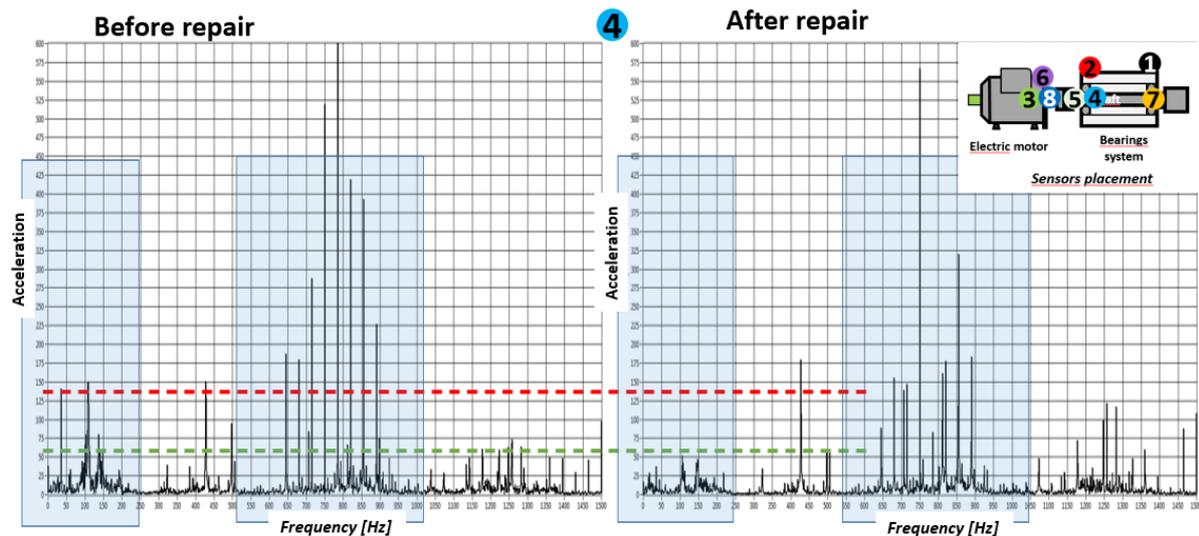


Fig. 11. FFT spectrum of vibration signal before and after replacement of elastic coupling

Different placement, radial and axial, of vibration sensors were applied. Plots of acceleration spectra taken from one of sensors before and after replacement of elastic coupling and bearings are presented in fig. 11.

5. CONCLUSIONS

This paper presents originally developed hybrid condition monitoring system of press main drive. The main parts of the system are subsystems devoted to the analysis of vibration and electric current parameters. The current based condition assessment subsystem is based on originally developed features useful for diagnosis of most induction motor faults. During the system operation it was possible to early detect and repair serious problems with main drive of the press. It helps avoid unexpected downtime and production losses. The presented system is under continuous development especially in the area of data fusion and automation of condition assessment. Results of further research will be published in subsequent scientific papers.

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