**TECHNICAL TRANSACTIONS** | **CZASOPISMO TECHNICZNE**
ELECTRICAL ENGINEERING | ELEKTROTECHNIKA
2-E/2015

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# MULTI-CRITERION FAULT DIAGNOSIS OF ROLLING BEARINGS

# MULTIKRYTERIALNA DIAGNOSTYKA USZKODZEŃ ŁOŻYSK TOCZNYCH

A b s t r a c t

In this paper, the possibilities of rolling bearing diagnostics, according to the PN and ISO standards, utilising the dimensionless discriminants of vibroacoustic processes, CPB frequency analysis and envelope detection methods are presented. The test bench, the measuring system, as well as the obtained results are described in detail. The authors' own algorithm for the course of action during the process of detecting damage torolling bearings, involving the multi-criterion diagnostic utilising the afore methods is also described.

*Keywords*: *bearings damage*, *CPB frequency analysis method*, *envelope detection*, *PN ISO standards*, *discriminants of vibroacoustic processes*

S t r e s z c z e n i e

W artykule przedstawiono możliwości: diagnostyki łożysk tocznych z użyciem metod PN i ISO, wykorzystania amplitudowych dyskryminant bezwymiarowych procesów wibroakustycznych, analizy częstotliwościowej CPB i analizy obwiedni. Opisano szczegółowo stanowisko pomiarowe, na którym przeprowadzono badania, układ pomiarowy oraz uzyskane wyniki analizy. Zaprezentowano też autorski algorytm postępowania podczas wykrywania uszkodzeń łożysk tocznych obejmujący diagnostykę multikryterialną z zastosowaniem powyższych metod.

*Słowa kluczowe*: *uszkodzenie łożysk*, *metoda analizy częstotliwościowej CPB*, *detekcja obwiedni*, *normy PN ISO*, *dyskryminanty procesów wibroakustycznych*

**DOI: 10.4467/2353737XCT.15.084.3916**

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## 1. Introduction

The non-invasive diagnosis of electrical machines and devices functioning in various technological processes is a very important issue in the process of maintaining proper functioning of these elements. The purpose of the diagnostic of these objects is to detect their impermissible states and to prevent damage in order to assure longevity and trouble--free work of industrial drive systems [3, 4, 10].The bearings are very important elements of electrical machines working in drive systems. Independent statistical data, published by the American sources [5] EPRI and IEEE, state that over 40% of mechanical damage stems from damage to rolling bearings [9].

Detecting defects of rolling bearings at an early stage is a very important element of monitoring the technical condition of electrical machines [3]. Currently in the industry, the dominant methods in the diagnosis of rolling bearings involve the analysis of signals in time and frequency domains [4], and the basic quantities are mechanical vibrations and phase currents. Simultaneous occurrence of several types of damage can give identical symptoms in the analysed diagnostic signals, which as a consequence can make the proper assessment of the condition of rolling bearings difficult [10].

In this paper, the selected methods, which can be applied jointly to the diagnosis of the condition of rolling bearings in selected electrical machines, are shown and discussed. The application of several independent diagnostic methods provides an increase in the precision and the reliability of the diagnosis of the condition of rolling bearings.

In further sections, the comparative analysis and the assessment of the effectiveness of detecting faults in rolling bearings using the following methods is presented: procedures determined in the PN and ISO standards [6, 7]; utilising the dimensionless discriminants of vibroacoustic process [2, 12]; CPB (Constant Percentage Bandwidth) frequency analysis method [8, 12]; the envelope detection method [8, 12, 13].

The simultaneous application of these methods and combining them into one as a multi--criterion indicator of the bearing diagnosis will improve the reliability of the assessment of the technical condition of the diagnosed bearings in the supervised machine. One method is not always sufficient to assure the increasing reliability requirements applicable to the technical condition of rolling bearings in electrical machines.

## 2. Construction of the test bench

The test bench (Fig. 1) for testing damage to bearings was equipped with an induction motor and connected to the DC machine by the means of an elastic shaft. The analysed induction motor: Sg112M4 ($P_N$ = 4 kW, $U_N$ = 400 V, $\Delta I_N$ = 8.1 A, $n_N$ = 1445 rpm) is a typical, general purpose, low voltage, low power machine, which is used in industry. To be able to test the induction motor at various loads, the shaft of the induction motor was connected to the PZM5545DC machine ($P_N$ = 4.5 kW, $U_N$ = 230 V, $I_N$ = 19.6 A, $n_N$ = 1450 rpm, $I_w$ = 0.86 A), working as a generator. This solution allowed achieving a fluid regulation of the applied load. The torque measuring device (DataFlex 22 series) was installed on the shaft of the machine; this allowed the rotational speed and torque on the machine's shaft to be measured. Two accelerometers were installed on the bearing end shield, in the pre--determined positions, in the *OX* and *OY* axes. The signals from the accelerometers and the PA-3000 signal conditioner were connected to the DAQ NI-USB 6259 BNC data acquisition card; whereas signals from the torque measuring device were delivered directly to the data acquisition card.

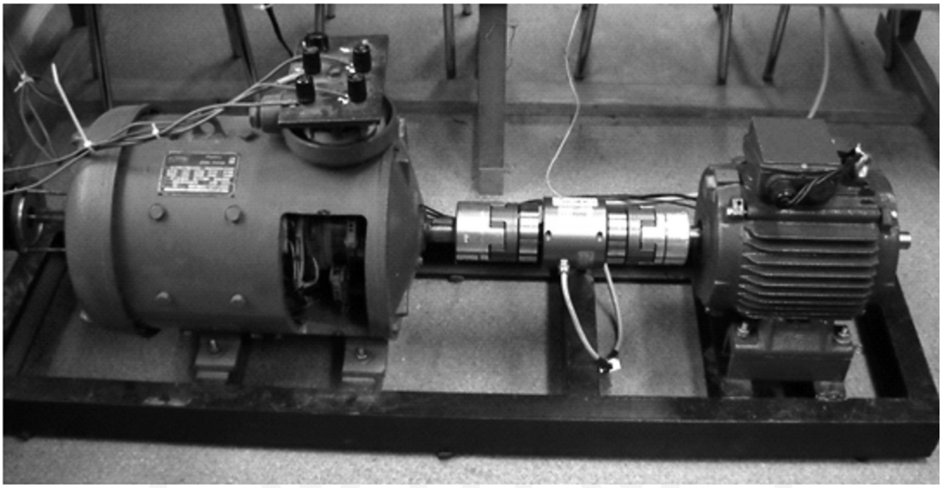

Fig. 1. Connection of the electrical machines

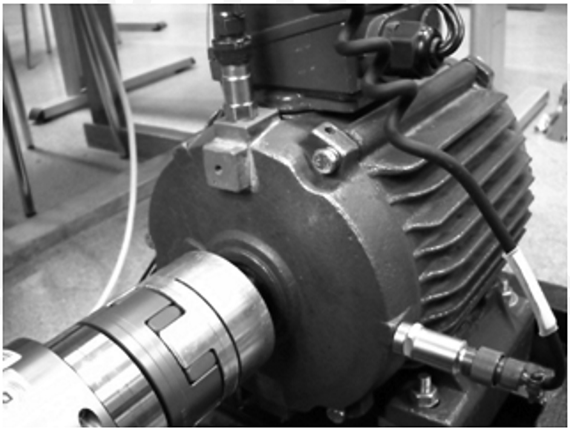

Fig. 2. Location where the vibration acceleration measurements were taken

In the analysed induction motor, the FAG 6306 2R bearings were installed, one after another. The bearings were pre-conditioned and damaged in a specific way. The types of bearings damage are presented in Table 1.

Bearings damaged differently were analysed during the normal work of the motor, at idling motor and during normal work of the machine under various, pre-determined loads.

Table 1

**Categories of analysed bearings**

| Name | Technical condition of the rolling bearing |
|---|---|
| Bearing 1 | Symmetrical (healthy) |
| Bearing 2 | One ball defect |
| Bearing 3 | Two ball defects |
| Bearing 4 | An inner bearing race defect |
| Bearing 5 | An outer bearing race defect |
| Bearing 6 | An outer bearing race defect – external incision |
| Bearing 7 | An inner and outer bearing race defect |

For each of the bearing categories, several measuring series were arranged for each of the bearings, for changes in the load current of the analysed machine between 0.5 A and 3.5 A, with 0.25 A increments. Such a measurement procedure allowed us to obtain a family of characteristics, for which it was possible to determine the damage during normal exploitation of the bearings.

## 3. Methods of diagnosing the technical condition of rolling bearings

Diagnosing the condition of rolling bearings in electric machines is usually based on utilising the information obtained from the machine during its normal work, i.e. vibroacoustic signals [5, 11, 12]. Those signals are generated during every exploitation and manufacturing process. They are a source of information regarding the dynamic processes in the machine and pertain to acoustic phenomena and vibrations. While analysing the vibrations of an electrical machine, particular attention is paid to vibrations generated by each element of the system, beginning with the rolling bearing and ending with the coupling elements. The bearing is one of the most important elements of electrical motors and correctly diagnosing their technical condition can significantly influence the prolonged exploitation of the machine.

The vibration standards recommend the measurement of the RMS value of the effective vibration velocity for frequencies from 10 to 1000 Hz in bearing nodes in *V*, *H*, *A* directions [6, 7]. This value is calculated in accordance to the dependency:

$$V_{\mathrm{RMS}} = \sqrt{\frac{1}{T}\int_{0}^{T} V(t)^2\,dt} \tag{1}$$

where:

- $V_{\mathrm{RMS}}$ – value of the effective vibration velocity for the specified frequency limits,
- $T$ – period of time, for which the $V_{\mathrm{RMS}}$ is determined, integration time,
- $V(t)$ – vibration velocity, signal of the vibration velocity.

The vibration signal measured at the measurement points indicated by the standard does not react clearly enough to the damage of the rolling bearings at the initial phase of the damage (noise phase, beginning of the vibration phase). One can only expect a reaction during the vibration phase and thermal phase.

The important factor influencing the assessment performed using this method is the rotational speed. The obtained results suggest that in the *OY* axis, the vibrations increase as the rotational speed decreases, that is when the load applied to the machine increases (Fig. 3).

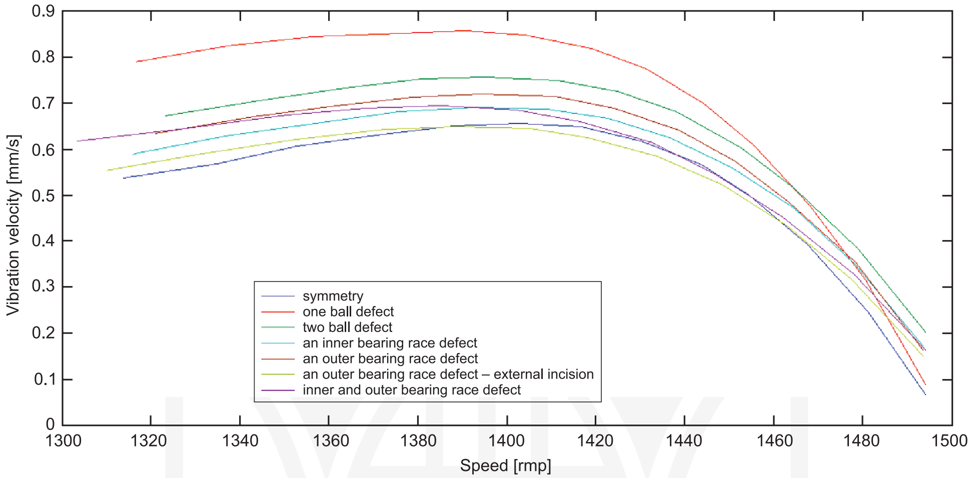


Fig. 3. Graphical representation of vibration velocity, with reference to the rotational speed for the accelerometer of the *OY* axis

The loaded machine is subjected to a larger mechanical moment, this is visible in the machine vibration velocity. The representation of the bearing defects on the graph shows planes, these can be used for assessing the technical condition of the bearings. Due to taking repeated measurements of the condition of the rolling bearings in the drive system, it is possible to accumulate the defect model database. Every machine has its own vibrations resulting from the work of the machine system or its reaction to the stimuli from the surrounding area. The prepared defect model database will be designed only for one, selected machine set. In this situation, it is impossible to develop a universal model, which would be used for determining defects in any machine. Further regular measurements will give a picture of the defects of the rolling bearings in the particular analysed machine.

Another, useful diagnostic method involves the utilisation of amplitude discriminants of dimensionless vibroacoustic processes. This method is based on measurements of vibration acceleration [11, 13], and the important factor here is the change of the peak coefficient during the electric machine exploitation time. Those measurements are made with the use of a measuring device able to determine the actual effective value and the peak value.

The method of measuring the peak coefficient only assesses the technical condition of the rolling bearing, but it does not determine the cause of the change of state. The advantage of this method is a fast and easy measurement taking process. The effectiveness of this method decreases when other sources of impulse signals are located in the vicinity of the analysed system [12].

Also, the $K(t)$ parameter, determining the rolling bearing exploitation time, expressed in the manner described below, can be used for diagnosing the technical condition of the rolling bearings [10]:

$$K(t) = \frac{a_{\mathrm{RMS}}(0) a_{\mathrm{PEAK}}(0)}{a_{\mathrm{RMS}}(t) a_{\mathrm{PEAK}}(t)} \tag{2}$$

where:

$a_{\mathrm{RMS}}(0)$, $a_{\mathrm{RMS}}(t)$ – effective values of the bearing node vibrations acceleration for the time $t = 0$ – start of the observation procedure (first start of the machine) and for time $t$ – any moment in time during the period of bearing exploitation,

$a_{\mathrm{PEAK}}(0)$, $a_{\mathrm{PEAK}}(t)$ – peak values of the bearing node vibrations acceleration for the time $t = 0$ – start of the observation procedure (first start of the machine) and for time $t$ – any moment in time during the period of bearing exploitation.

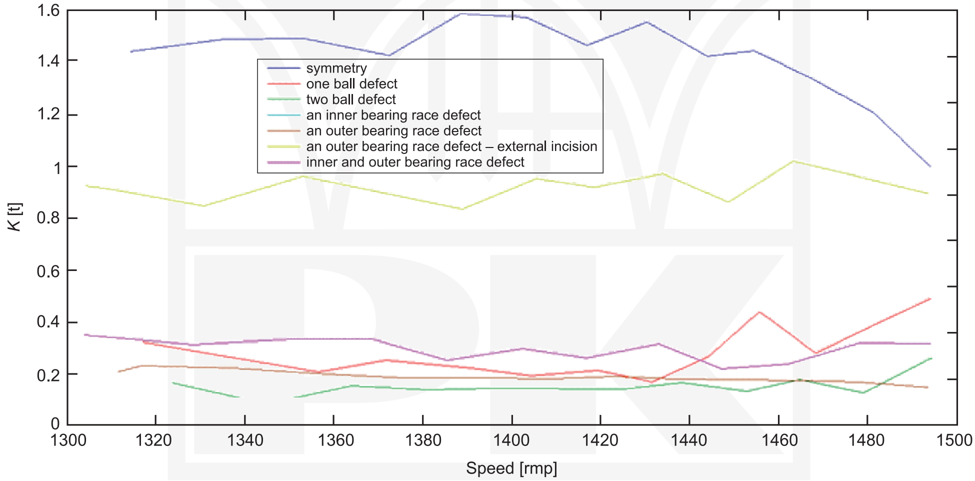


Fig. 4. Graphic representation of the *K* parameter, in relation to the rotational speed for accelerometer of the *OY* axis

This method was not designed to analyse a specific type of damage, as all values of the exploitation factor remain at comparatively the same level. We are not able to unequivocally determine the plane which corresponds with one, specific type of bearing damage. Thus, the method of measuring the shape coefficient is not suitable for a detailed analysis, but can only be used to determine that the bearings are damaged, but without indicating the specific element which has become worn during the normal exploitation process.

The CPB frequency analysis method is based on the frequency distribution of the vibration spectrum, this is used for seeking the characteristic frequencies and is responsible for the damage of the specific component of the rolling bearing [1, 8, 12].

Fundamental Train Frequency (frequency of the cage), FTF:

$$f_K = \frac{1}{2} f_r \left(1 - \frac{BD}{PD}\cos\beta\right) \tag{3}$$

Ball Defect Frequency, BDF:

$$f_{ET} = f_r \frac{PD}{BD}\left[1 - \left(\frac{BD}{PD}\cos\beta\right)^2\right] \tag{4}$$

Ball Pass Frequency of the Outer Race, BPFO:

$$f_{BZ} = f_r \frac{n_k}{2}\left(1 - \frac{BD}{PD}\cos\beta\right) \tag{5}$$

Ball Pass Frequency of the InnerRace, BPFI:

$$f_{BW} = f_r \frac{n_k}{2}\left(1 + \frac{BD}{PD}\cos\beta\right) \tag{6}$$

Table 2

**Specification of the frequency of damage for the selected loads applied to the machine [Hz]**

| **Machine status** | **Rotational speed [rotations/min$^{-1}$]** | **Outer bearing race** | **Inner bearing race** | **Ball defect** | **Fundamental train** | **Rotational frequency** |
|---|---|---|---|---|---|---|
| Idle | 1493 | 73.95 | 125.15 | 45.19 | 9.24 | 24.88 |
| Under load | 1289 | 63.84 | 108.03 | 39.01 | 7.98 | 21.48 |

Characteristic frequencies calculated for the outer bearing race, the inner bearing race, the ball, the fundamental train and for the first rotational frequency were presented in Table 2. The frequencies were determined using formulas 3–6 for catalogue sizes of the analysed, FAG 6306 rolling bearing. By analysing the aforementioned table, one can notice that the characteristic frequencies are strongly dependent on the current rotational velocity of the machine.

The CPB frequency analysis method is very difficult to interpret, but it is possible to precisely determine which components were damaged. The conducted research proved the validity of the measurement of vibration acceleration in the node of the bearing and suggest the vertical axis of measurement for the analysed machine setup.

The conducted research proved that interpretation of the defects associated with the damage of the inner and outer race is relatively easy (Fig. 5), whereas damage from defects of the rolling elements proved to be difficult to interpret (Fig. 6).

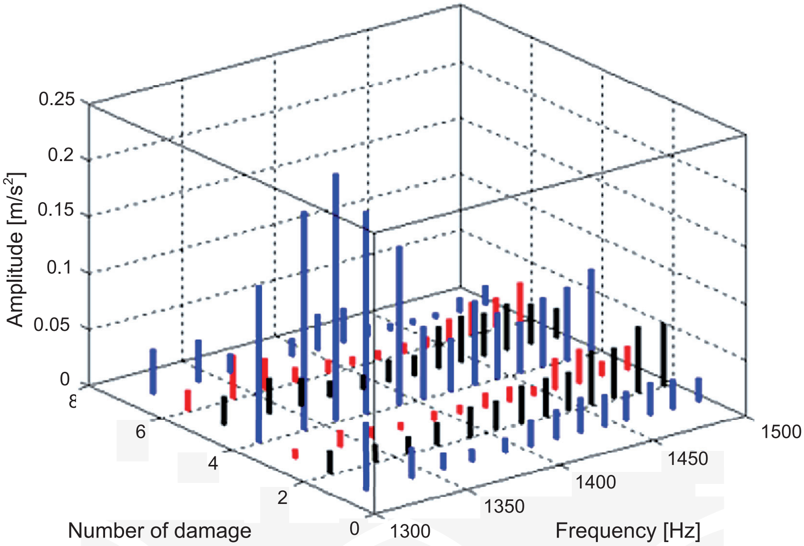


Fig. 5. Attrition, erosion of the outer ring and outer race

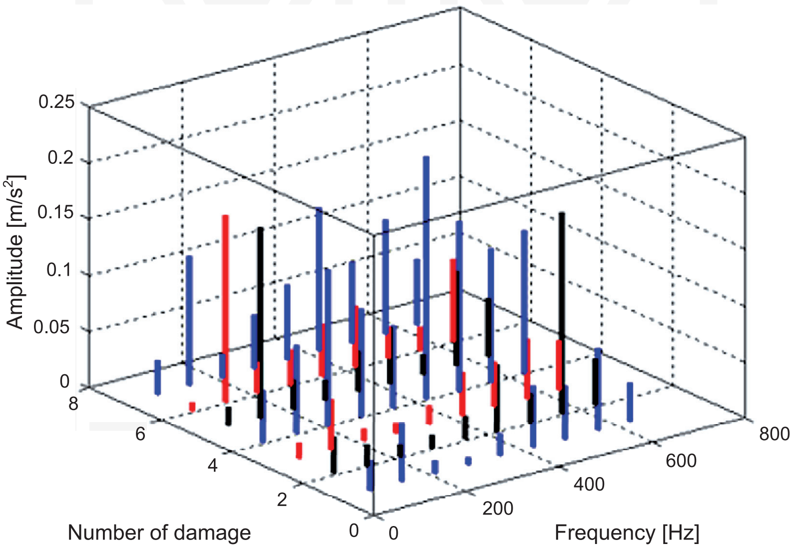


Fig. 6. Indentations and cracks on the outer ring of outer race – under full load

Another diagnostic method effective at assessing the condition of the rolling bearings is the envelope detection method. The envelope detection method is one of the most popular methods of vibroacoustic diagnosis of rolling bearings. This is the most reliable method, and in addition, it allows us to precisely determine the type and degree of damage, as well as allowing the detection of damage at an early stage [8, 12, 13].

The envelope detection method involves the specific analysis of the resonance vibrations of the machine. The vibration signal from the sensor, after filtration, utilises the sensor's own resonance, which is subjected to demodulation and next, on this basis, the signal envelope spectrum is determined. The spectrum of the vibration signal envelope contains components, characterised by vibration frequencies is consistent with the defects of the particular components of the rolling bearing [1, 12].

The envelope detection method is used for analysing slowly changing signals. During the conducted research, the defect of the outer race was most significant (Fig. 7).

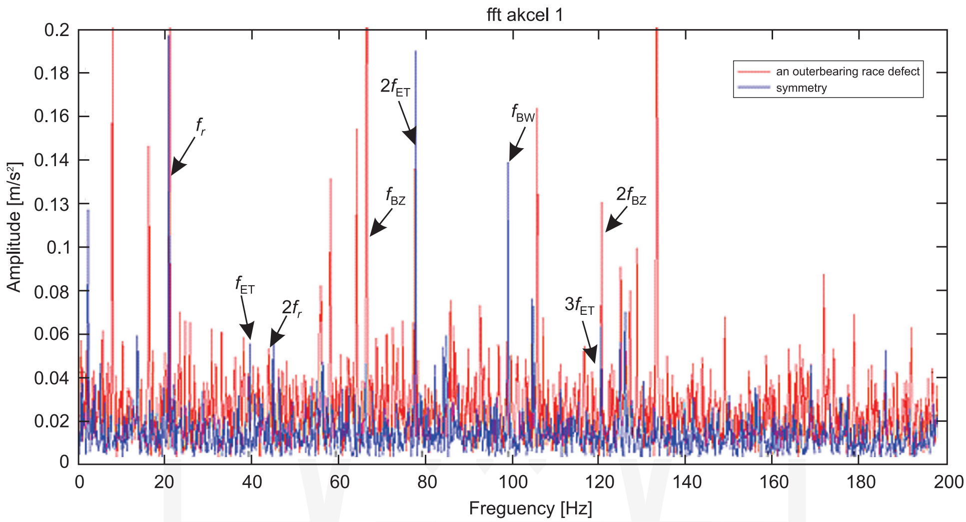


Fig. 7. Damaged outer bearing race and the symmetry state – for the *OY* axis

The modified envelope detection method can be used as an initial method of transforming the vibration signal for the CPB method. Determining the envelope from the vibration signal and subsequently completing the spectrum analysis using the FFT method allows us to improve the differentiation of the particular frequency lines. The CPB method itself is used to determine the specific defects of the analysed rolling bearing on the basis of the characteristic frequency symptoms selected from the vibration spectra.

## 4. Work algorithm for determining the defects of rolling bearings using multi-criteria diagnostics

The assessment of the technical condition of the bearing is conducted over several stages. The development of the algorithm aims at systematising the measurement process, so the person, who is involved in diagnostic measurements for the first time, would be able to knowingly complete the analysis, without analysing in detail the specific character of the particular method and to ensure that the entire process of assessing the technical condition of the bearing could be performed intuitively (Fig. 8).

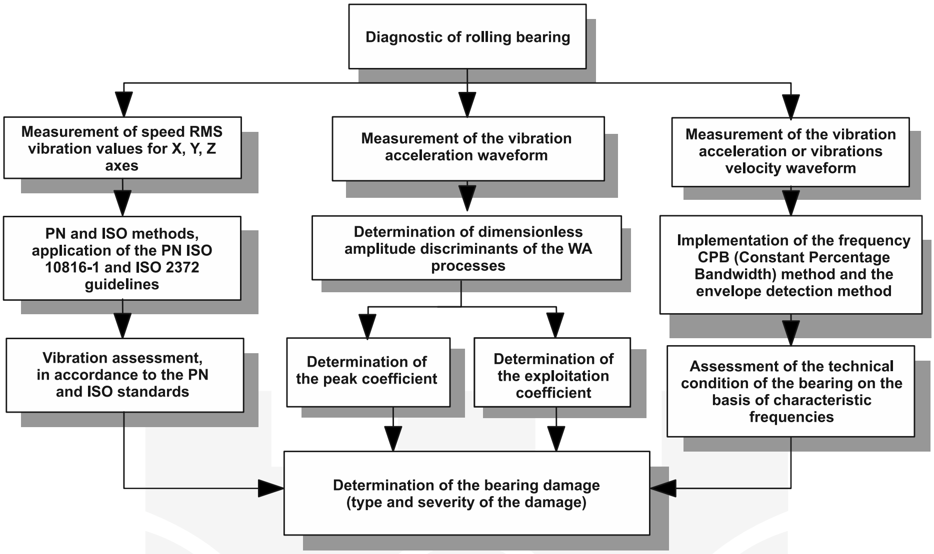


Fig. 8. Algorithm for determining the defects of rolling bearings

Using the PN and ISO methods, it is important to firstly notice that the measurements are taken along three axes (*OX*, *OY*, *OZ*), in accordance to the instructions specified in the PN-ISO 10816-1 standard [6]. The *OX* and *OY* axes are used for measuring the vibrations, whereas the *OZ* axis is used for detecting defects in the machine foundation. The standard classifies the machines with regard to their power and the method of attaching the machine to the foundation. The analysis of the obtained measurement results are done on the basis of the vibrations acceleration for the particular machine. It is clearly visible that the PN and ISO method, based on the ISO 2372 and PN-ISO 10816-1 standards, is a general method, used only for detecting the occurrence of the bearing damage, without the possibility of determining the type of the defect.

Another method is utilising the dimensionless discriminants of the vibroacoustic process. Particular attention is paid to the two following aspects – the peak coefficient and the exploitation coefficient of the rolling bearing. Long lasting work involving the systematic analysis of bearings might lead to the development of a pattern for determining the peak coefficient [9]. In addition, the analysis of the exploitation coefficient alone, which is conducted systematically, can be demonstrated by the exploitation curve for the specific type of bearing defect and can indicate the machine's utility threshold without knowledge regarding the damaged element.

The two aforementioned methods are very easy to implement in industry. They do not require extensive knowledge or the ability to interpret the measurement data. The damage of the rolling bearings can be observed only on the basis of the analysis of diagrams presented in form of trends.

The CPB frequency analysis method, used in conjunction with the envelope detection method, is one of the most advanced methods of analysing the defects of the rolling bearings.

It is suggested that it should be used at the end of the machine's exploitation process [12]. Due to this method, it is possible to differentiate the types of defects. In industry, the defects of the bearings occur during the exploitation process, but it is possible to determine cases of bearing damage during installation. On the basis of the frequency analysis of the machine, it is possible to ascertain that the defects occurred early in the exploitation process. The spectrum of the vibration signal allows us to assess the amplitudes and to derive conclusions pertaining to the damaged bearing component. The increase of the characteristic frequencies amplitudes, responsible for the selected types of defects, e.g. for the damage of the rolling element. Each type of defect is illustrated by the characteristic line in the vibrations frequency spectrum. By putting the amplitude diagrams side by side it is possible to notice that the dispersion of the characteristic frequencies changes during the exploitation time of the bearing. By observing the characteristic frequencies, it is possible to notice the first symptoms of damage at the early stage of machine exploitation. It allows a more effective utilisation of the machine, downtime planning, and preventing the defects of the entire machine assembly.

## 5. Conclusions

Vibroacoustic signals are associated with the work of each electrical machine and they reflect the most important physical phenomena occurring in the machines, e.g. the interaction between the particular components of the assembly, the imminent failure condition, mechanical stresses, and others. The course of those processes determines the correct functioning of the machine. The measurement of vibrations in the bearing nodes is a common and widely used practice used for assessing the technical condition of the machine. Diagnosis of the state of rolling bearings is mostly associated with the vibration diagnostics. The development of electronics and the increasing database of diagnostic information turn the vibroacoustic diagnostic into an effective tool for detecting defects of rolling bearings.

In this paper, the important problems of diagnosing the rolling bearings were presented. In addition, frequently occurring defects of the rolling elements were described and the selected defects were characterised and presented in a graphical form. Numerous problems associated with the diagnostics of rolling bearings and the correct determination of the particular components of the exploited system was discussed.

Neither of the diagnostic methods give unambiguous results of the assessment of the technical condition of the bearings. The analyses conducted with the use of the proposed methods can help to develop the exploitation curve of the machine and plant the assembly overhaul and change of the rolling bearings. The completion of the diagnostic process will allow for minimising the costs associated with the defects of the exploited machines.

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