UTILIZATION OF COMPONENTS OF SIGNALS FROM HIGH FREQUENCY RANGE IN CONDITION MONITORING OF BEARINGS

Adam GAŁĘZIA

The Institute of Automotive Engineering, Warsaw University of Technology
84, Narbutta St., 02-524 Warsaw, Poland
e-mail: agalezia@simr.pw.edu.pl

Summary

The paper describes the utilization of high frequency range of vibro-acoustic signals in condition monitoring of bearings. High frequency components of signals, generated by a bearing working under operational conditions, contain low energy disturbances which might carry information related to the technical condition of the bearing. These high frequency signal components are most probably related to friction effects and the effects related to the behaviour of structure in mesoscale. The emergence of cracks leads to the changes in the friction of mating elements in bearings and has an influence on the structure in mesoscale. This in turn causes changes in high frequency range of the signal. Based on the monitoring of high frequency structure of signals, it is possible to draw conclusions about the changes in the technical condition of a bearing. The paper describes the application of measures, typical for acoustic emission, to acoustic signals recorded from bearings working on a laboratory stand. The measurements were performed with the uses of an ultrasonic microphone.

Keywords: acoustic emission parameters, ultrasonic, spectral moments, condition monitoring.

WYKORZYSTANIE SKŁADOWYCH SYGNAŁU Z WYSOKIEGO PASMA CZĘSTOTLIWOSCI W DIAGNOSTYCE ŁOŻYSK

Streszczenie

Publikacja przedstawia wykorzystanie wysokoczęstotliwościowych sygnałów wibroakustycznych w diagnostyce technicznej łożysk. Wysokoczęstotliwościowe składowe sygnałów, emitowanych przez pracujące łożysko, zawierają niskoenergetyczne zaburzenia, które mogą nieść informację związane ze stanem technicznym łożyska. Te wysokoczęstotliwościowe składowe sygnałów są najprawdopodobniej związane ze zjawiskami tarcia i zjawiskami zachowania struktury w mezoskali. Powstanie uszkodzenia prowadzi do zmian w tarciu współpracujących powierzchni łożyska i ma wpływ na zachowanie struktury w mezoskali. W wyniku tego następują zmiany w wysokoczęstotliwościowym paśmie sygnału. Wykorzystując monitoring wysokoczęstotliwościowej struktury sygnału, możliwe jest wnioskowanie o zmianach stanu technicznego łożyska. Publikacja przedstawia wykorzystanie miar, typowych dla emisji akustycznej, w analizie sygnałów akustycznych pracujących łożysk na stanowisku badawczym. Pomiary zostały przeprowadzone z wykorzystaniem mikrofonów ultradźwiękowych.

Słowa kluczowe: parametry emisji akustycznej, ultradźwięki, momenty widmowe, diagnostyka techniczna.

1. INTRODUCTION

The condition monitoring of bearings allows, on the one hand, to reduce the probability of a catastrophic failure of a machine and costs related to it and, on the other hand, to increase the reliability and extended working time of a machine. Economic and ecological factors exert an increased pressure on the development of new, more reliable techniques which would allow to determine the technical state of a machine, predict changes in its technical state, and to estimate the remaining useful life of a machine. The correct and reliable assessment of the technical state is an important issue in condition monitoring and it allows to define future operating strategies in order to minimise the operating costs and the hazard of failure. The change in the technical state of equipment is usually related to the changes in kinematics of an object, its degradation, and changes in cooperation of kinematic pairs.

Common bearing diagnostic techniques are based on vibro-acoustic signals that range from few to 10,000 Hz. The frequency analysis of recorded signals is the basic method of signal analysis. An early detection of the time of the origination of a defect allows to control its build-up and to plan repairs and optimal operation conditions.

Present research in the filed of condition monitoring of bearings is often related to the development and application of technologies used in other domains of technical diagnostics, signal processing and analysis techniques, as well as building of diagnostic models and systems.

The development and application of techniques related to acoustic emission [1, 2, 3] and stress-wave technology [4] is of increased interest to scientist and maintenance engineers. These technologies base on the detection of transient elastic waves generated by a rapid release of a strain of energy caused by a deformation or damage within or on the surface of a material [5]. The transient elastic waves can be also generated by the interaction of two surfaces in relative motion e.g. the interaction of the surface of a rolling element and the race of a bearing. The acoustic emission detects events from a very high range of frequencies such as 100,000-1,000,000 Hz.

Signal processing and analysis techniques such as higher order spectral analysis, Teager-Kaiser energy operator, cepstrum analysis, time-frequency analysis are widely used to obtain diagnostically useful information, based on which it is possible to determine the technical state and to make decisions regarding further operation of machine [6, 7].

Based on diagnostic knowledge and information obtained from signals, it is possible to build a model of degradation process or to establish a decision-support system. Such solutions can be based on neural networks or expert's knowledge [8].

The paper presents results and conclusions from a preliminary research, made by the author, which aimed at retrieving useful diagnostic information in the high frequency bands of an acoustic signal. As a result, it was possible to identify the band of signal, in which the highest differences were observed for different technical stages. Different signal analysis techniques were used to identify signal parameters, some of which will be used in further research to build the hidden Markov model for bearing degradation process.

2. TEST STAND AND MEASUREMENT SETUP

The test stand presented below (Figure 1) was used to record signals during the experiment.

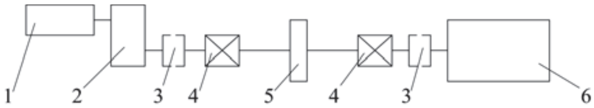

Fig. 1. Sketch of the test stand (description in text)

The test stand consisted of: 1. driving motor, 2. gearbox, 3. coupling, 4. bearings in housings, 5. unbalance disk, 6. electric dynamometer, (numbers according to sketch).

The driving motor (1), via the gearbox (2) and the coupling (3), set in motion the shaft with the unbalance disk (5) placed on it. The shaft was supported on bearings in housings (4). The energy from the shaft was dissipated by an electric dynamometer (6). Two self-aligning ball bearings (SKF 1205 EKTN9) were mounted in bearing housings. The unbalance disk allowed to introduce different unbalance states by screwing in grub screws. The bearing placed closer to the gearbox was subject to artificially introduced damage, that is described in the next section. The applied gearbox was a one-stage gearbox, with reduction ratio i=2.84. The nominal input power of the gearbox was 0.37 kW, the power of the applied driving motor was 0.25 kW. The technical condition of the gearbox during the measurements was good. The gearbox was after the grind-in of co-acting parts and its working time was short. Working conditions of the gearbox can be described as under its nominal load. Vibrations of the gearbox were low and did not affected diagnostic results.

Measurements of the acoustic signals from the bearings were made using NI PXI computer with NI PXI-4462 measurement card. The signals generated by the bearings were recorded with the use of VIS-311 vibration sensors and G.R.A.S. 40BE ultrasonic microphones. These one-direction vibration sensors, with the frequency range of 0.5-10,000 Hz, were used to measure vertical vibrations carried out by the bearing's housing. The ultrasonic microphones with the frequency range from 10 Hz up to 100,000 Hz were mounted on stands close to the shaft opening in the bearing housing. Their aim was to record the acoustic signals generated by the working bearing. The sampling frequency of the measurement card was set to 200,000 Hz, which, according to Nyquist–Shannon sampling theory, allowed to record the signals components up to 100,000 Hz.

3. MEASUREMENTS

During the experiment, measurements were carried out for three types of unbalance and three simulated stages of bearing degradation. All together, there were 9 measurement sessions: one for each combination of unbalance and degradation stage. The unbalance was obtained by installing a number of grub screws in the disk. In a set of measurements, the unbalance disc was rotating without screws, with one and with six screws. The degradation stage was changed by artificially introduced cracks. There were three stages of degradation considered: 1. bearing without an artificial defect, 2. bearing with a "small" defect introduced in the inner race, approximately: 1 mm in diameter and 0.5 mm deep, 3. bearing with a "big" defect introduced in the inner race, approximately: 4 mm long, 1 mm wide, and 1 mm deep.

During the experiment, the speed of the shaft was constant and equal to 986 rpm. Each measurement session consisted of ten one-second measurements. The measurements in a given session were held at 1-second intervals. In this way a set of data was recorded which allowed for averaging the results.

4. MEASUREMENT RESULTS

4.1. Preliminary analysis

The review of the measurement results started with the analysis of a signal spectrum. The signals' spectra, watched in linear scale in full range of frequencies, did not reveal any particular phenomena. Except for peaks in the frequency band up to 10,000 Hz, it seemed that the rest of the spectrum contains only components related to noise. However, the comparison of spectra presented in logarithmic scale of values, revealed an interesting phenomenon, which was an incentive for further research (Figure 2).

Figure 2 presents comparison between spectra of signals recorded for the analysed bearings with different stages of unbalance, but without an artificial defect. The first plot presents the signal from the bearing with no screws in the unbalance disk, the second - with one unbalance screw, the third one - with six screws. An interesting phenomenon could be observed in the frequency band ranging from 40,000 Hz to 60,000 Hz. It was possible to notice that in this frequency band, an observable change of spectrum occurred in relation to the change of the degree of unbalance. It was noted that a local increase of spectrums magnitude, as compared to the full spectrum, was shifting and changing its distribution in reaction to the increase of the stage of unbalance. An important observation is that all signals from a given measurement session look similar and observed effect is repetitive.

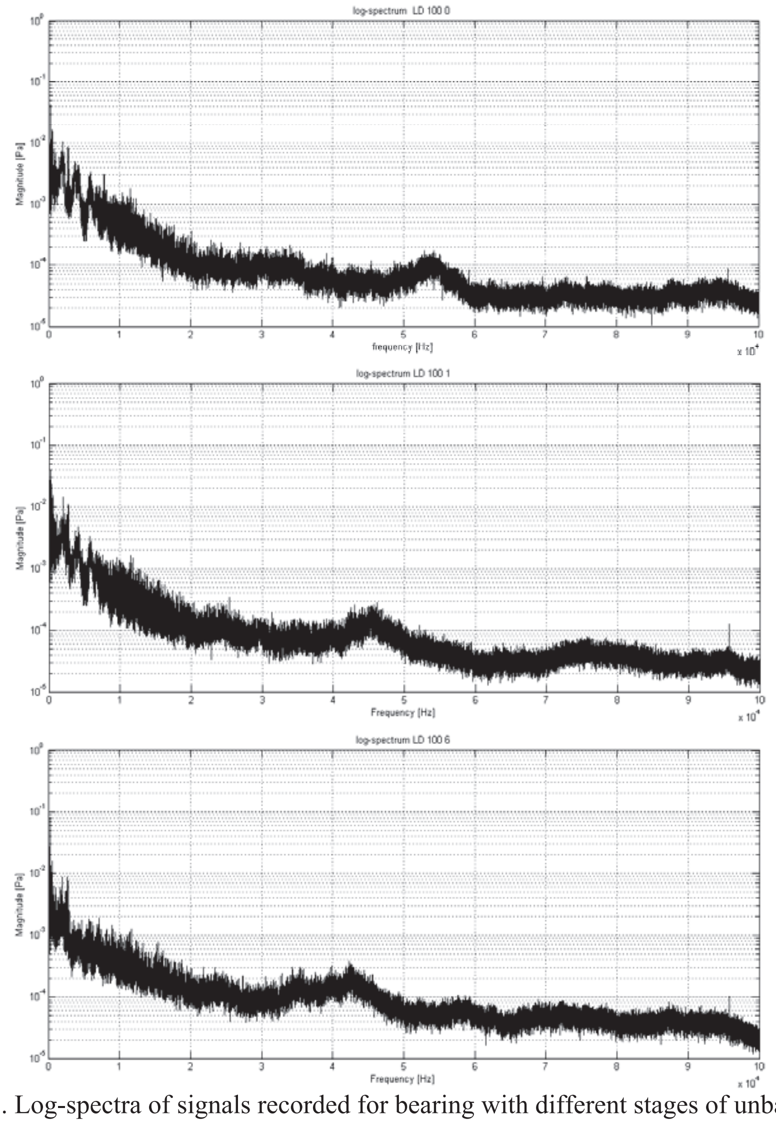

Fig. 2. Log-spectra of signals recorded for bearing with different stages of unbalance

Also comparisons of other log-spectra calculated from different measurement sessions reveal changes in the high frequency band from 40,000 to 60,000 Hz. It must be pointed out that changes in the band mentioned above were different in shape, range or distribution for individual comparative measurements – the different stages of degradation and unbalance. Each time it was possible to conclude that some kind of change had taken place in the technical state of the bearing. Following the observation, spectral moments were calculated. This was done in order to extract information which could describe the changes, observed in the spectrum, with the use of specific parameters.

4.2 Spectral moments

Spectral moments are the measures describing parameters of spectrum's shape such as centre of gravity, standard deviation, skewness and kurtosis [9]. Spectral moment of order **m** is:

$$M(m) = \sum_{f_i=f_d}^{f_i=f_g} \left|G(f_i)\right| \left[f_i\right]^m \qquad (1)$$

where: $G(f_i)$ - signal's spectrum f_i,

f_i - centre frequency of analysed band,

f_d, f_g - lower and upper frequencies of band.

Most commonly, normalised spectral moments are used:

$$M_u(m) = \frac{M(m)}{M(0)} \qquad (2)$$

Calculation of the first four normalised spectral moments was performed for frequency bands of the width of 10,000 Hz, from 0 up to 100,000 Hz. All spectral moments for all measurements in a given measurement session were concentrated around the mean value. Performed calculations and analysis of the spectral moments for all measurement sessions reveal no significant differences in values of averaged spectral moments in frequency bands of interest. Also the distribution of values did not reveal any particular trend. The main reason for this might be a very low magnitude of the signal components in a given frequency band, compared to the width of the band. Therefore, the spectral moments defined by (1) and (2), tuned out to be improper measures for detecting and inferring on changes of the technical state of the tested object (unbalance and defect).

Due to the fact that the spectral moments did not provide expected reliable information, the attention was directed to the analysis of the time signal and measures characteristic for the acoustic emission.

4.3. Acoustic emission measures

Acoustic emission (AE) is a decaying elastic wave that results from a vehement release of energy concentrated in material by propagating micro defect (increase of micro gaps, movement of dislocations) in material [10]. In non-destructive testing (NDT) of materials, acoustic emission is a passive listening technique, which is very sensitive and can detect defects such as the movement of a few atoms. Usually during tests, these waves can be separated into two types of behaviour: (1) burst emission, which is a discrete packet of waves associated with a single event or a small number of events and (2) a continuous emission, which tends to be a cluster of many small interlinked events. The basic measures used in acoustic emission are: the number of events, the number of counts, energy of the event, duration of the event. Figure 3 presents a sketch of AE event and its basic measures. [10].

In case of signals emitted by a working bearing, no typical acoustic emission events were expected. However, it was expected to find a continuous train of transient waves. Figure 4 presents, as an example, part of signal, filtered from 40,000 up to 60,000 Hz, recorded for a bearing under working conditions.

For further analysis of the signals, recorded for all measurement sessions, a uniform discrimination level was chosen, which allowed to compare parameters of signals from different measurements. For a detailed analysis of signals, the following parameters were calculated: the number of events in a measurement, energy of the event, duration of the event, time between events, maximum height of the event, height to width ratio of the event, skewness of the event, kurtosis of the event. The analysis of parameters was carried out in order to determine, which of these parameters can be used to identify the technical states of an analysed machine.

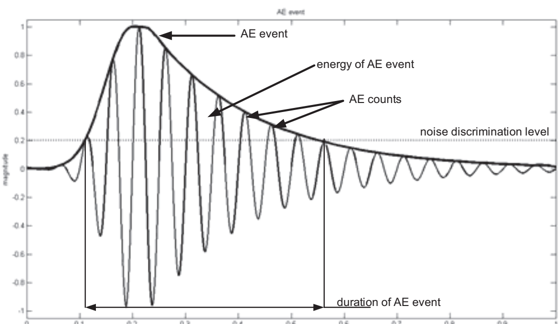

Fig. 3. AE event and its basic measures.

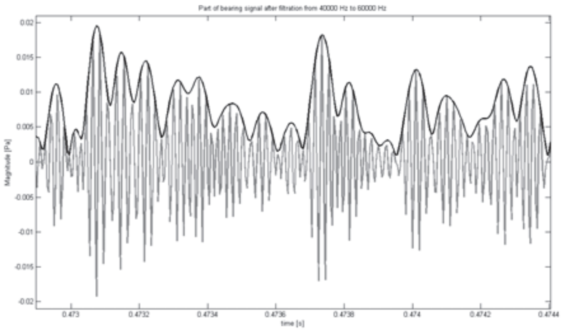

Fig. 4. Part of bearing signal after filtration from 40,000 Hz to 60,000 Hz with its envelope

As a result of calculations and analysis it was noted that only the number of events and the energy of the event seemed to be diagnostically useful. Their analysis is presented in detail in the further part of this paper. Neither the duration of the event nor its kurtosis revealed such a trend in the distribution of values which could be unequivocally connected with changes in the technical state of the tested object.

The number of events during the measurement was the first parameter to be analysed. Figure 5 presents the distributions of the numbers of events for each measurement for each combination of the degree of unbalance and degradation. The value of the analysed parameter is indicated on the horizontal axis. The vertical axis represents the bearing's technical state. The bearing is described by a combination of two characters separated by an underscore. First letter informs about the degree of degradation were "G", "SC", "C" respectively mean: bearing without an artificial failure, bearing with a "small" failure introduced in the inner race (approximately: 1 mm in diameter and 0.5 mm in depth), bearing with a "big" failure introduced in inner race (approximately: 4 mm long, 1 mm wide, 1 mm deep). The number standing next to the letter U informs about the stage of unbalance: 0 – without grub screw, 1 – with one grub screw, 6 – with six grub screws (Table 1).

Each circle on Figure 5 represents the number of events for one measurement. This presentation allows to observe how numbers of events differ in measurement sessions and in which regions they overlap. For the bearing without an artificial failure, the change of unbalance had the highest influence on the number of events during the measurement. For a bearing with an introduced defect, the change of unbalance did not have an equally strong impact. However, in these cases, the changes are still observable and what is more, the distribution of values of the analysed parameter is more concentrated.

Table 1. Indicators of technical state used in article

Technical state indicator	Failure	Unbalance
G_U0	no	no
G_U1	no	one unbalance screw
G_U6	no	six unbalance screws
SC_U0	"small" defect	no
SC_U1	"small" defect	one unbalance screw
SC_U6	"small" defect	six unbalance screws
C_U0	"big" defect	no
C_U1	"big" defect	one unbalance screw
C_U6	"big" defect	six unbalance screws

Energy of the event was another analysed parameter. Although the energy was calculated for every event, during each of ten measurements performed during the measurement session, the mean value of energy from each measurement was used for further calculations. Figure 6 presents the distribution of mean values for different technical stages of bearings.

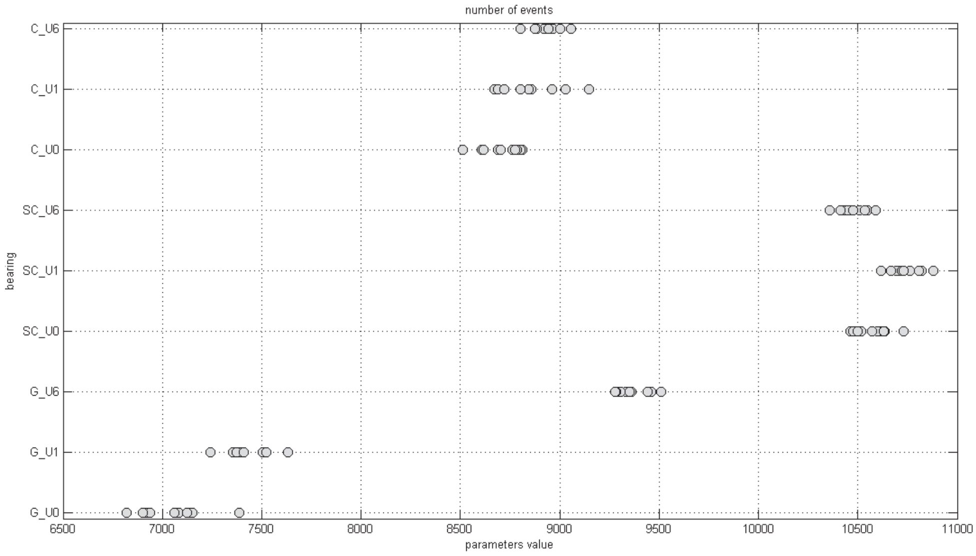

Fig. 5. Distribution of numbers of events for each measurement for each combination of the degree of unbalance and degradation

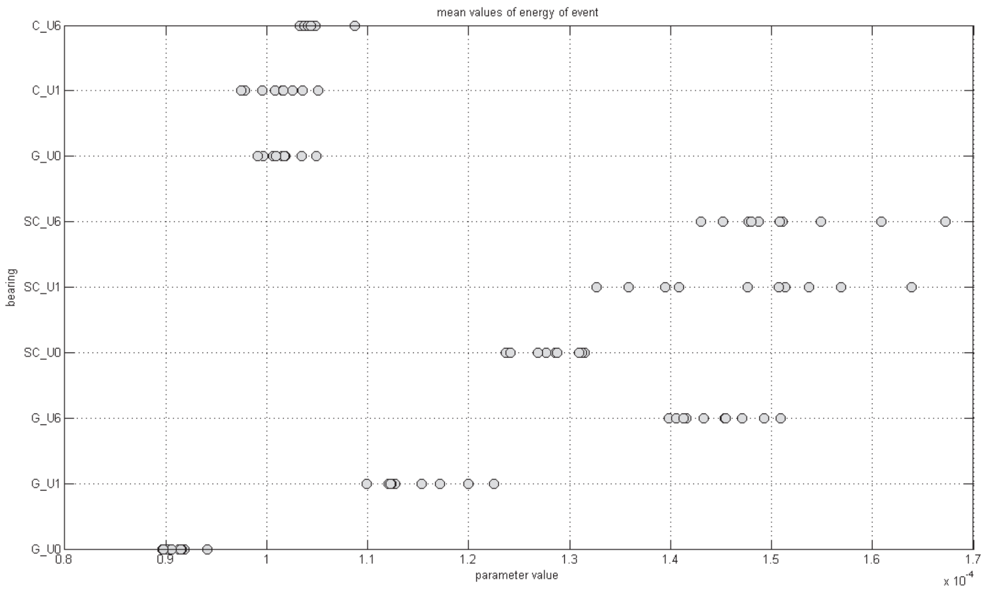

Fig. 6. Distribution of mean values of event energy for different technical stages of bearings

For the bearing without an introduced failure and with introduced small crack (small degree of degradation) it is possible to observe that the higher the degree of unbalance, the higher are the values of energy and the higher is their dispersion. A closer analysis of the dispersion of values reveals interesting trends. Figure 7 and 8 present comparisons of dispersion of values of energy of events for bearings without and with an artificial fault. For measurements made for the bearing without failure, the change of the degree of unbalance causes a shift and change in the distribution of values of energy of the event. Such effect is not so clearly observable in the case of the bearing with a small introduced failure. For the bearing with highest degree of degradation, this effect is not observable at all.

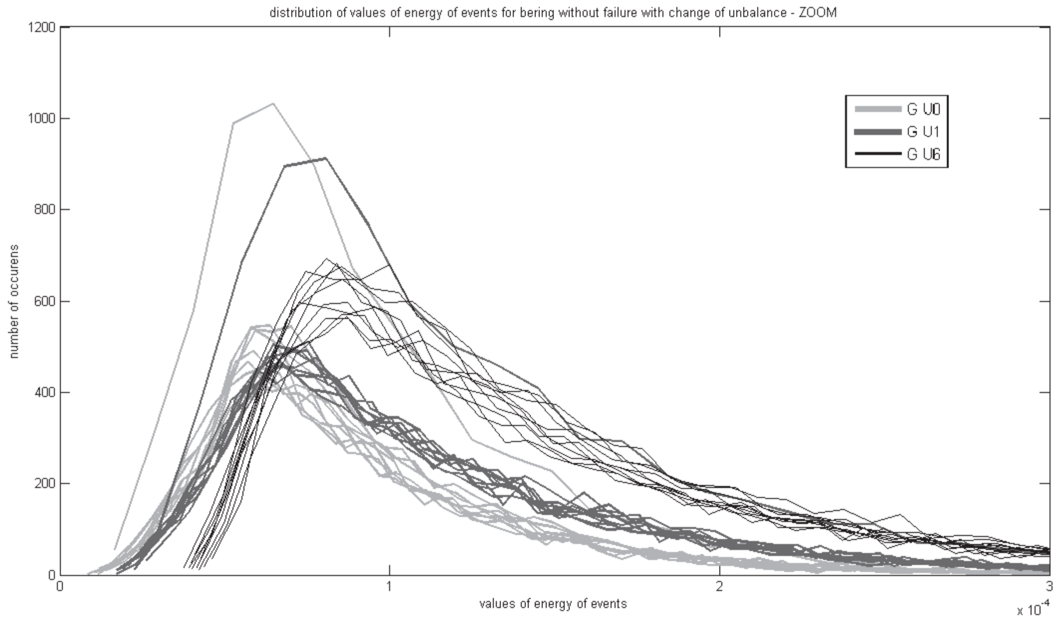

Fig. 7. Comparison of dispersion of values of energy of events for bearings without introduced crack

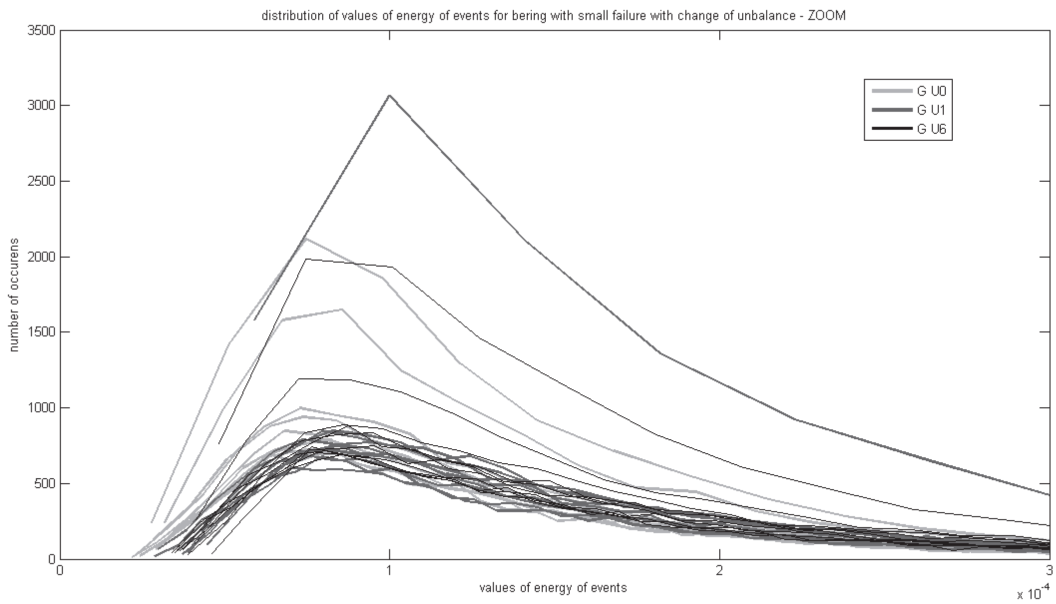

Fig. 8. Comparison of dispersion of values of energy of events for bearings with introduced "small" crack

Figure 9 presents comparison of the distribution of values of energy of an event calculated for each measurement session. For measurement sessions performed for the bearing without introduced failure (G_U0, G_U1, G_U6), the increase of unbalance caused the widening of the distribution with simultaneous shift of its maximum value. No such behaviour was observed for the results of other measurement sessions – sessions form bearing with "small" defect (SC_U0, SC_U1, SC_U6) and "big" defect (C_U0, C_U1, C_U6). Changes in the energy of the events occurring for measurement sessions for the bearings with defect had no strict trend. This is most probably related to the fact that the bearing's failure causes strong impulses during the passing of roller elements through the damaged area. These strong impulses demonstrate themselves in the low band of frequencies and can be observed there.

For a signal from the bearing in which no defect was introduced, changes of unbalance have stronger observable influence on high bands of signals, which can be related to the friction effects and effects related to the behaviour of structure in mesoscale.

Other parameters such as the height of the event (its maximum value) reveal correlation with the energy of the event and therefore, they were not analysed in detail. Neither the number of events during measurement nor the mean energy of events or any other parameter demonstrated unique changes that would be sufficient to indicate changes in the technical state of the tested object.

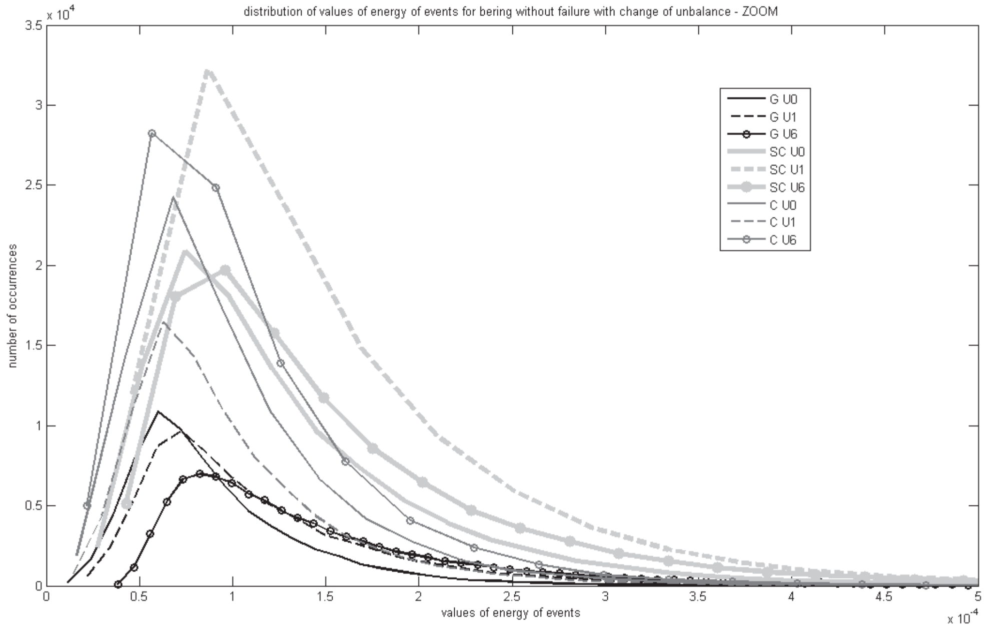

Fig. 9. Comparison of distribution of values of energy of event calculated for measurement sessions

To enhance the probability of correct determination of technical state of the bearing, distributions of values of pairs of parameters were analysed. This was made to verify whether it is possible to find such a pairs of parameters, observation of which would allow to classify the technical state of a bearing.

The analysis of distributions of values of pairs of parameters were made on two-dimensional parameter-plane with the axes reflecting the values of analysed parameters. From all possible combinations of parameters pairs, figure 10 and 11 presents the ones that best represented different technical states. For the clarity of the presentation, the technical state is reflected by numbers from 1 to 9 (Table 2). The location of a number is determined by the values of the analysed parameters.

It can be seen that both pairs of parameters have similar distribution and allow to use a simple technique to distribute the space of the technical state. For bearing without introduced failure, a strong diversification is observed with the change of unbalance. These states are well separated and can be determined based on the analysed parameters. For bearings with both stages of defect there is no such a good separation of data based on measurements for different stages of unbalance. During the analysis of different pairs of parameters, no such combination was found which would allow for easy separation of stages of unbalance of bearing with failures. In order to reach such a separation, it would be necessary to use other parameters and also other frequency bands.

Table 2. Number indicator of technical state for figures 10 and 11

Numerical indicator	Technical state indicator	Failure	Unbalance
1	G_U0	no	no
2	G_U1	no	one unbalance screw
3	G_U6	no	six unbalance screws
4	SC_U0	"small" defect	no
5	SC_U1	"small" defect	one unbalance screw
6	SC_U6	"small" defect	six unbalance screws
7	C_U0	"big" defect	no
8	C_U1	"big" defect	one unbalance screw
9	C_U6	"big" defect	six unbalance screws

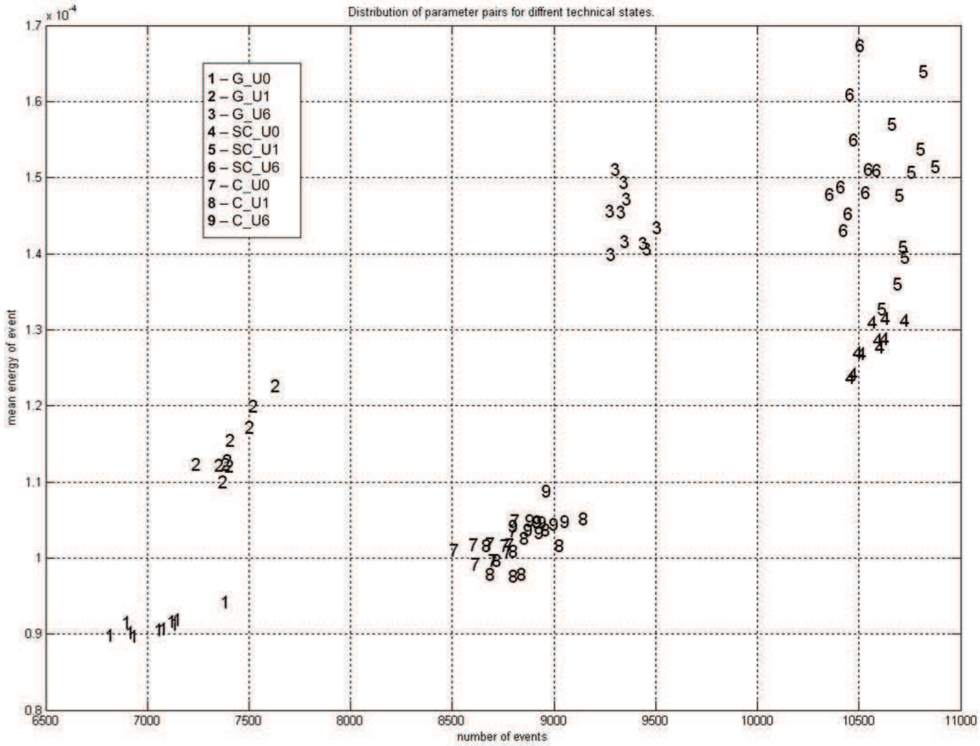

Fig. 10. Distribution of mean energy of event and number of events pairs on parameter plane

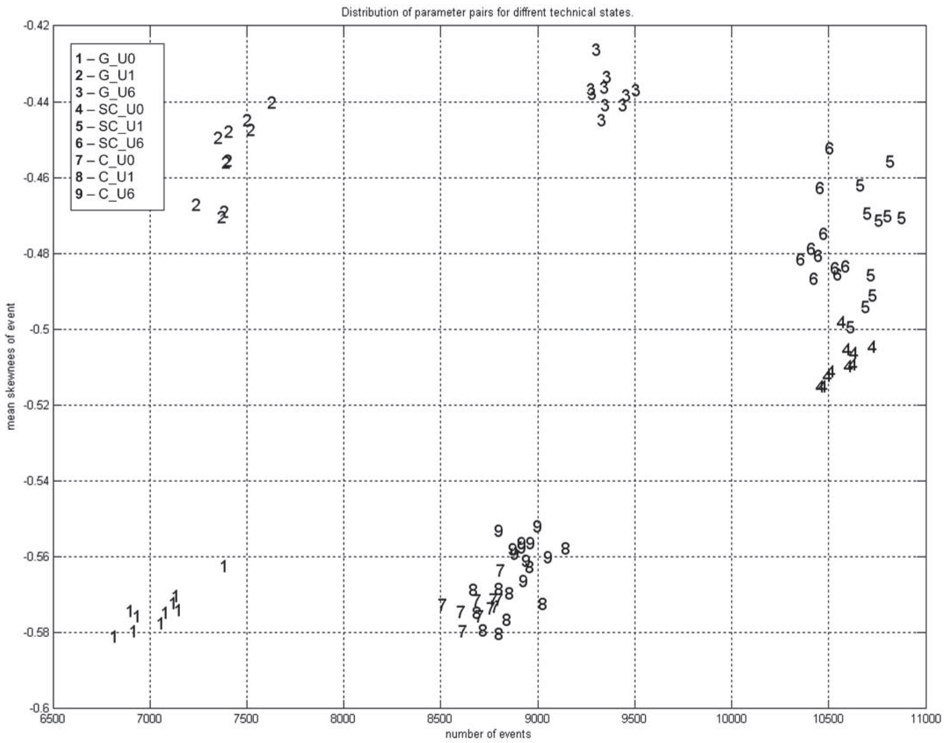

Fig. 11. Distribution of mean skewness of event and number of events pairs on parameter plane

To perform the separation process, subspaces must be defined for each separable state. The separation process can be performed as an iteration process. The depth of this process can be related to the number of accessible parameters and the degree of problem complexity. In the analysed case, a two-iteration separation can be used. In the first iteration, the parameter plane, which gives the best separation of data for degradation degree is used. After determination of the degree of degradation, depending on the need, different parameters, from different frequency bands, are used for analysis of the degree of unbalance. Markov models or neural networks can be then used as a tool for determination of the degradation scenario [11]. In case of big number of analysed parameters combinations it is possible to use neural classifiers such as SVM or NBV [12, 13] to increase quality of classification of technical state.

5. CONCLUSIONS

The performed analysis proves that high frequency components of signals recorded for working bearings can be used to determine its technical state. It was demonstrated that based on acoustic emission parameters calculated for the acoustic time signal, it is possible to conclude about changes in the technical state of a bearing. The separation performed on parameter plane allows to determine the state of unbalance. Further research will be carried out for higher number of different technical stages and types of degradation.

Additionally work related to implementation of the hidden Markov models, as tools to determine the degradation stage and degradation scenario, will be preformed in the future.

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M.Sc. **Adam GAŁĘZIA** is worker of Integrated Laboratory of Automotive Mechatronics Systems, Warsaw University of Technology. His scientific interests are related with condition monitoring of machines and vehicles, structure analysis.