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Statistical correlation between vibration characteristics, surface temperatures and service life of rolling bearings – artificially contaminated by open pit coal mine debris particles

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Abstract

Nowadays, two most often used methods for rolling bearings condition monitoring are thermographic inspection and vibrodiagnostic.

However, analysis of the relevant literature has shown that so far there is no established correlation between rolling bearings surface temperatures and measured radial vibration intensities. These variables also strongly depend on rolling bearing's service life and it's environmental operating conditions, especially in case of open pit coal mine conveyor idler's rolling bearings; where high concentration of debris particles (such as surface dust, dirt and excavated coal) is present.

Taking into account previously listed facts; the main goal of the presented research results was to establish statistically significant correlation between listed variables: rolling bearings surface temperatures, radial vibration intensities, service life and concentration level of debris particles in bearing grease. In order to achieve this goal, specific experimental methodology was developed and implemented. Obtained results were then processed using standardized statistical software and appropriate correlation was generated and later verified in praxis.

At this moment, developed experimental methodology is applied only to open pit coal mine conveyor idler's rolling bearings, but its principles are universal, so with minor modifications it could be used for prediction of any of listed variables for different kinds of rolling bearings, operating in different environments.

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1. Introduction

Environmental contamination can significantly affect rolling bearings service life, especially in case of conveyor idlers rolling bearings, because of very high concentration of solid contaminant particles in their working environment (open pit coal mines). The study of conveyor systems has shown that no matter how efficient the sealing devices are, the environment conditions could be so hostile that they eventually become seriously damaged. This allows the debris particles to enter the rolling bearings inner space.

Nowadays, in order to prevent premature bearing failure, there are several monitoring techniques in use such as oil analysis, wear debris analysis, vibration analysis and thermographic inspection (Bakic et al. (2007)). However, the vibration analysis and the thermographic inspection are most frequently used because they provide complex information about the state of rolling bearing's component parts (Manjunath and Girish (2013)). According to Tomovic et al. (2010) the cause for vibration inducement in rolling bearings can be classified into several groups, but negative environmental impact (vibration due to the environmental effects) is among most important causes.

Vibration acceleration (usually expressed as the RMS value) is the most logical choice for consideration because it is most dominant vibration characteristic on high frequency ranges typical for rolling element bearings.

Beside vibration analysis, progress in science nowadays allows very precise recording of temperature distribution on wide spectrum of objects surfaces using thermal imaging digital cameras. Rolling bearings are not exception. It could be even claimed that thermographic inspection rapidly becomes standardized methodology for rolling bearings condition monitoring. However, except for monitoring purposes, mentioned methodology could be used for scientific researches in unexplored areas of bearings thermal behavior.

Despite numerous performed experiments and analysis there are still no mathematical models for contaminated bearings vibrations prediction based on measured surface temperatures and concentration level of contaminant particles present in bearings grease. Solving this problem was the main goal of research presented in this paper: to establish a statistically significant correlation between listed variables.

Nomenclature

q	mass of contaminant particles in bearing's grease [g]
T	highest measured bearing's surface temperature [°C]
t	bearing's service time [h]
V	bearing's radial vibration acceleration, expressed as RMS [m/s ²]

1.1. Theoretical and experimental background

There are several possible mechanisms of rolling bearings wear due to contamination (Nikas G. K. (2010)). When hard particles go into the interference, surface damage by mechanisms such as denting is inevitable (Lazovic et al. (2009)). Dents represent stress concentration sites, which increase the possibilities for the occurrence of spalling, accelerating the failure process (Singotiaa and Jainb (2013)). In terms of contaminant particle sizes, Maru et al. (2007) state that the critical size of the contaminant particles is in the order of the lubrication film thickness. However, other authors claim that when particles larger than the oil film thickness enter the contact zone, they cause stress peaks and permanent indentations in the raceway as they are over rolled. These stress peaks lead to a reduced life of the rolling bearing due to fatigue.

Mary et al. (2005&2007) presented works with a goal to study how contamination in the lubricant can affect vibrations, taking into account the effect of the contaminant particle size and its concentration level in the lubricant. In their experiments the oil of 6205 ball bearings (bore diameter: 25 mm) was contaminated by standard quartz particles, with the average sizes of 37 μm , 59 μm and 111 μm . Also, three oil contamination levels were used, with nominal concentrations from 0,04 g/l up to 0,7 g/l. The results have shown that it's possible to identify the presence of contamination from some specific frequency bands of the bearing vibration signal. Retesting of the rolling bearings with clean oil also revealed that some frequency bands are excited due to wear in the contacting elements.

Koulocheris et al. (2013) performed experiments with three types of ball bearings (1207, 2207 and YSA – bore diameter: 35 mm) whose grease was contaminated by hard corundum particles (alumina, Al_2O_3 , hardness 2000HV) with sizes of 62–73 μm and 105–177 μm , where a quantity of 0,75 cm^3 of particles were premixed with 50 g of clean SKF LGMT3 grease. The results have shown that wear is progressing faster when smaller particles are used. Similar experiment was performed by Lazovic et al. (2009) with standardized diamond dust as contamination material. Gained results were very similar and the influence of contamination on ball bearings internal radial clearance was also determined. Mahajan and Utpat (2012) investigate the trends in the amounts of vibration affected by contamination in the bearing grease and by the bearing wear itself. Experimental tests were performed on 6206-2RS deep-groove ball bearings (bore diameter: 30 mm) and the Dolomite powder in three concentration levels (5%, 15% and 25% of contaminant in 5 g of grease) and three different particle sizes (53 μm , 75 μm and 106 μm). Their method of vibration analysis was effective in trends characterization in vibration due to solid contaminant in lubrication.

Despite overall accessibility of wide range of different models of thermal imaging cameras, analysis of the available literature have shown that so far thermographic inspection was not used in researches dealing with the rolling bearings contaminated by solid particles. However, other methodologies for temperature measurement (such as thermocouple probes) were actively used – as in research performed by Kahlman and Hutchings (1999). They have tested hybrid rolling bearings, artificially contaminated by two types of contaminant particles: titania (TiO_2 ; anatase), a relatively soft oxide with a small particle size (4 μm , mainly <1 μm); and silica (SiO_2 ; α -quartz), a harder material with a larger particle size (75–103 μm). Seo et al. (2011) used thermographic inspection to observe rolling bearings surface temperature change in different lubricating conditions (normal condition, lubricating oil loss condition and spalling) with variable rotational speeds of 1000 rpm, 2000 rpm and 3000 rpm. As a test samples, they have used 6004, 6204 and 6304 radial ball bearings.

Inspired by described researches, authors of this paper have designed and implemented appropriate contaminated ball bearings experimental testing, which includes thermographic inspection as well as vibration analysis (described in details in following chapters).

2. Experimental setup

In case of coal transportation, where transported material is lignite (density: 1,3 t/m^3) and weight of 1 m of rubber belt is approximately 33 kg, radial load acting on the garland's middle conveyor idler equals 3,875 kN. If radial load due to conveyor idlers rotational parts mass is added (0,165 kN, obtained by standard 3D modelling software), it is calculated that radial load acting on each of the two conveyor idlers bearings in described conditions equals $\sim 2,0$ kN. However, during the experimental research in this paper, experimental load applied on tested rolling bearings was $\sim 4,6$ kN in order to accelerate the bearings contact surface damage (it's important to mention that under this load bearing rings permitted angular deflection was not exceed – CEMA book).

The most common conveyor idlers used on open pit coal mines of the Republic of Serbia and Western Balkan region are those with outer diameters of 159 mm (Fig. 1) so their rolling bearings are chosen to be experimentally tested.

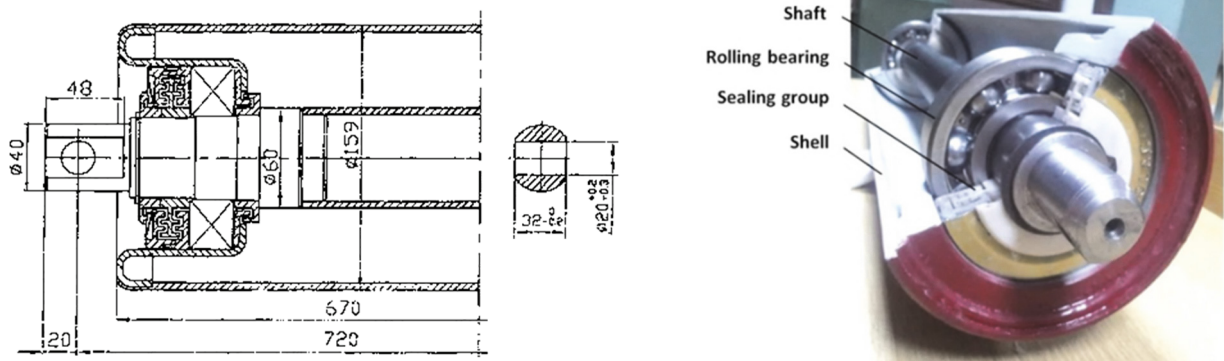


Fig. 1. Technical drawing of conveyor idler commonly used in the Republic of Serbia and Western Balkan region.

Similar to the experimental radial load, in order to accelerate the damage of the tested conveyor idler bearings, applied experimental rotational speed (~1140 RPM) was roughly two times larger than operational, which leads to the conclusion that acceleration of the performed experiments was ~22,7x. This means that 1 h of bearings work in described experimental conditions corresponds to 22,7 hrs. of its real working conditions – without contamination particles present.

The average amount of grease per 6310-2Z/C3 bearing (9,3 g) is experimentally determined by weight measuring and averaging of the results from 70 tested samples. Also, as the standardized grease for pre-contamination, the SKF LGWA 2 grease was chosen because it is commonly used for high loads and extreme pressures like those in conveyor idler bearings. It is considered that mass of grease in the rolling bearings does not decrease during the exploitation, and environmental contamination particles are uniformly distributed in it. Despite the fact that chemical structure and origin of the contamination particles causing the failure of the rolling bearings from conveyor idlers on open pit coal mines were experimentally determined they have to be normalized to be used as an artificial contaminant regarding their size so it's adopted that their size couldn't be larger than 120 µm, which is achieved by sieving with appropriate mechanical screens.

Regarding to the performed thermal imaging inspection, it's very important to mention that all thermal resistances in heat transfer between inner and outer bearings raceways and its rings surfaces are neglected (because of the fact that the sample bearings were made from good heat conductor – steel).

2.1. Test samples

The 6310-2Z/C3 rolling bearings were selected for testing because they are commonly used in conveyor idlers with outer diameters of 159 mm. Among 70 samples, 6 were chosen for further testing because their internal radial clearance was the same – 30 µm. That was important because, after a while the wear due to contamination increases the bearings internal radial clearance, thus affecting the overall level of bearings vibrations.

Selected bearings were then regreased with pre-contaminated SKF LGWA 2 grease, prepared for thermographic inspection by painting of their inner and outer rings with black paint (emissivity ε=0,93), and finally exposed to the previously determined experimental radial load and rotational speed.

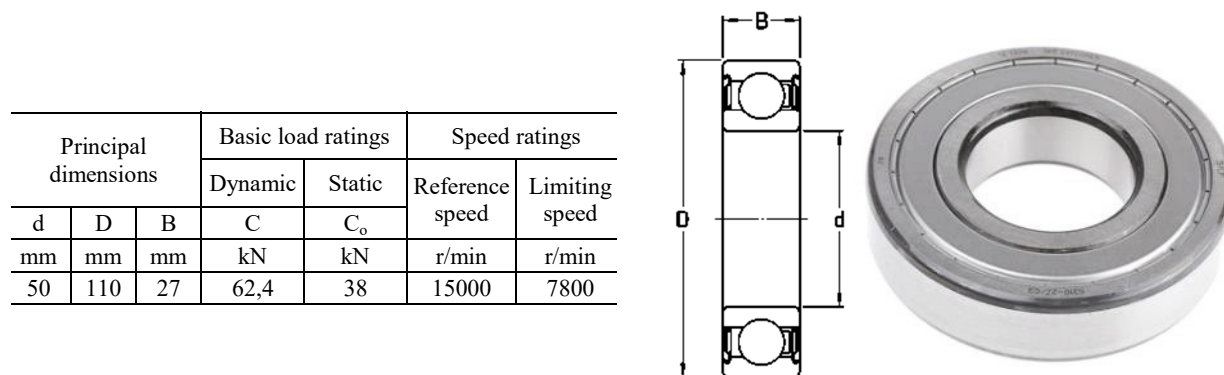


Fig. 2. Designation and overall look of 6310-2Z/C3 rolling bearings.

2.2. Experimental contamination particles

First step in preparation of the contamination particles relevant for planned experiments was to analyze structure and size of particles present on open pit coal mines: surface dust, excavation dirt and coal dust (Fig. 3).

After that, fifteen failed conveyor idlers were taken from the open pit coal mine conveyor and disassembled. Contamination particles from their bearings were then extracted, analyzed and compared with the previous results, pointing out that typical cause of conveyor idler bearings failure was the excavation dirt (not the surface dust, as expected), and mostly consisted of different kinds of quartz, hematite and magnetite. When origin of conveyor idlers

contamination particles was successfully determined, sample for artificial bearing contamination was prepared by sieving excavation dirt with appropriate mechanical screen (mesh size less than 120 μm).

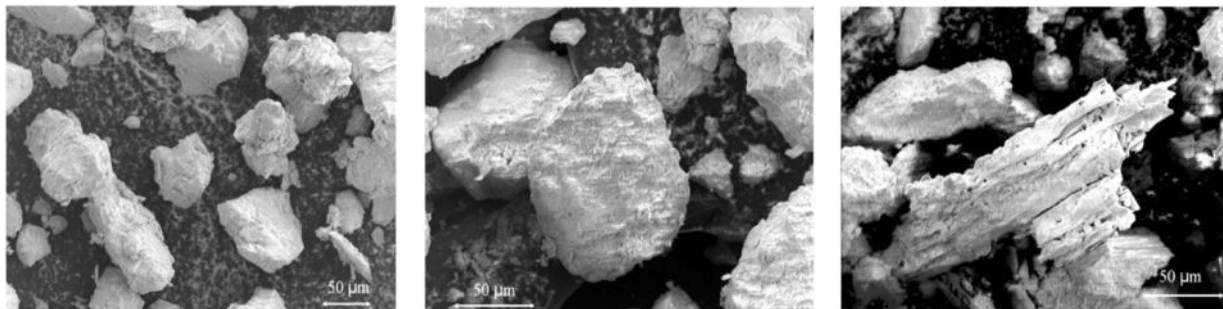


Fig. 3. SEM images of the particles from open pit coal mine a) surface dust b) excavation dirt c) coal dust.

2.3. Pre-contaminated grease characteristics

Because of its high endurance and temperature resistance, as well as widespread usage, the SKF LGWA 2 grease was chosen for pre-contamination. Basic characteristics of mentioned grease are presented in Table 1.

Table 1 Basic characteristics of SKF LGWA 2 grease.

DESIGNATION	SKF LGWA 2	
DIN 51825 code	KP2N-30	
NLGI consistency class	2	
Soap type	Lithium complex	
Base oil type	Mineral	
Operating temperature range	-30 to +140 °C	(-20 to +285 °F)
Dropping point DIN ISO 2176		
Base oil viscosity		
40 °C, mm ² /s	185	
100 °C, mmVs	15	

In total, three samples of pre-contaminated grease were prepared:

- Clean grease (in packages of 9,3 g);
- Grease with 10,75% of contaminant particles (in packages of 9,3 g of clean grease + 1 g of contaminant particles);
- Grease with 21,5% of contaminant particles (in packages of 9,3 g of clean grease + 2 g of contaminant particles).

During the sample preparation, METRON (Germany) scales with precision of 0,001 g were used. However, estimated uncertainty of measurement was much higher – approximately 0,1 g.

2.4. Testing equipment

For applying of the predetermined bearings radial load and rotational speed the custom made test frame, developed at the University of Belgrade – Faculty of Mechanical Engineering, was used (Fig. 4a).

Bearings vibrations level measurements were performed by standard vibration measuring instrument (Fig. 4b) – SKF Microlog Analyzer GX with appropriate accelerometers (vibration sensors).

Rolling bearings rings surface temperature distributions were recorded using advanced digital thermal camera IRC57 InfraCAM SD, manufactured by FLIR Co. (USA), with temperature measurement range of 10-350°C, and $\pm 2\%$ accuracy.

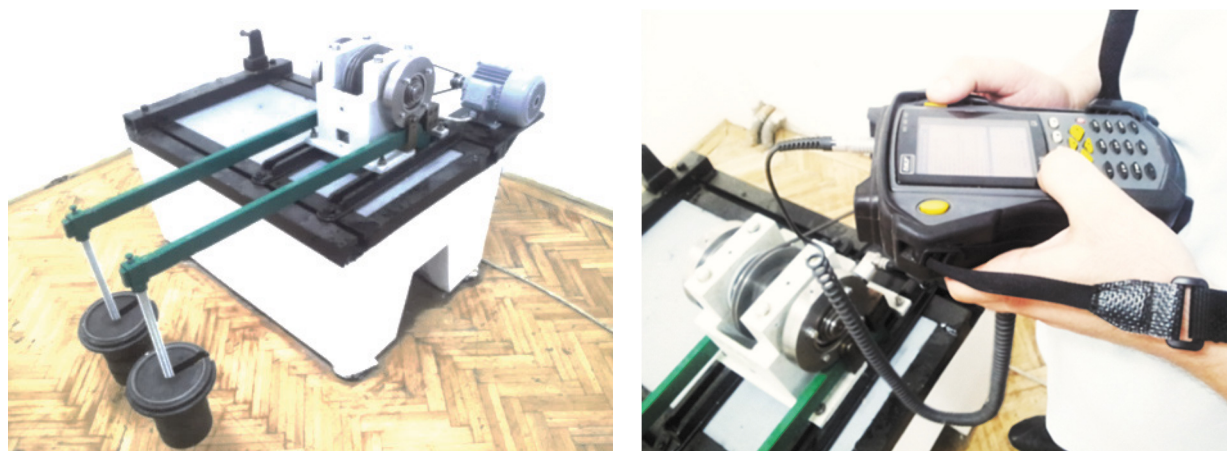


Fig. 4. a) Test frame developed at the University of Belgrade - Faculty of Mechanical Engineering; b) Vibration measurement instrument SKF Microlog Analyzer GX.

It's adopted that for further analysis only the highest measured bearings temperatures are relevant, because they are located closest to the bearings rings contacts with rolling elements. Those temperatures are obtained by thermal images analysis (in total, 378 thermal images), performed in publicly available licence free software FLIR QuickReport Version 1.2 SP2, as in example presented in Fig. 5.

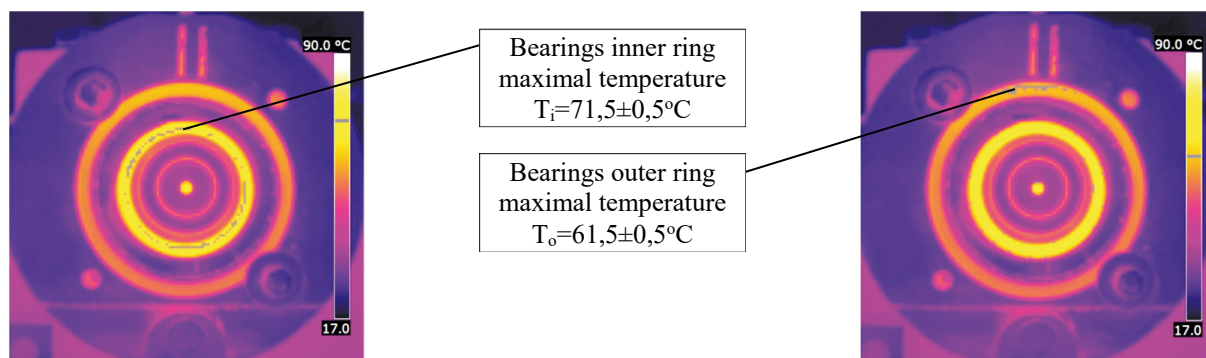


Fig. 5. Maximal temperatures of sample bearings inner and outer ring.

2.5. Testing procedure

- First bearing sample was greased by 9,3 g of clean grease;
- Second bearing sample was greased by 9,3 g of grease and contaminated by 1 g of contamination particles;
- Third bearing sample was greased by 9,3 g of grease and contaminated by 2 g of contamination particles;
- Samples were mounted on the test frame and exposed to radial load of 4,6 kN and rotational speed of 1140 RPM;
- Every 30 minutes sample's radial vibration acceleration (RMS values) and surface temperatures were recorded;
- After 10 hrs. of testing experiment was finished and sample bearings were dismantled from the test frame;

3. Results and discussion

Graphical presentation of measured bearings surface temperatures and vibration accelerations change in time is shown on Fig. 6.

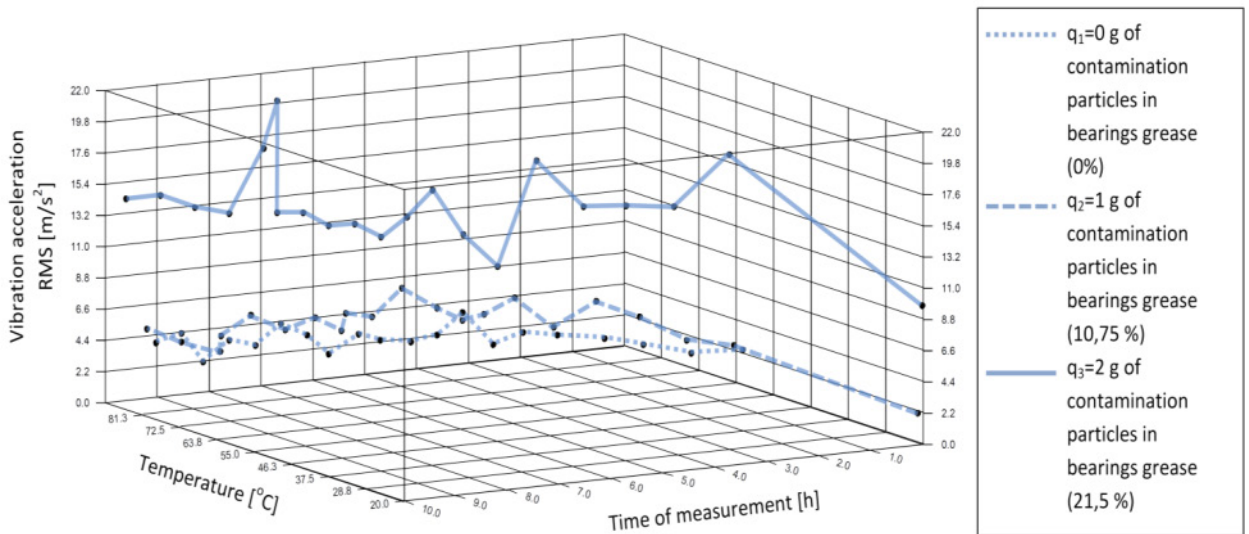


Fig. 6. Measured bearings highest surface temperatures and vibration accelerations (RMS) change in time.

Using software for statistical analysis and data interpolation, over 200 different interpolation models were implemented on measured experimental values, and the most relevant regarding to its statistical significance was:

$$V = \exp(a \cdot q + b \cdot T + c \cdot t + d) \quad (1)$$

Coefficient of multiple determination (R^2) for presented mathematical model equals 0,818 and its adjusted coefficient of multiple determination (Ra^2): 0,809 – which are the highest gained values for all implemented interpolation models. Gained R^2 and Ra^2 values are relatively high ($>0,5$), which leads to the conclusion that model represents measured values with rather reasonable accuracy.

Coefficients a, b, c and d for mathematical model (1) and confidence interval of 95% are shown in Table 3.

Table 2. Coefficients of generated model for 95% Confidence intervals.

Variable	Value	95% (+/-)
a	0.7807516	0.1219969
b	-0,0020409	0,0055364
c	0,04028505	0,024156
d	0.9362069	0.4099336

Analysis of the results presented at Fig. 6., have shown that there is a peak of bearings vibration at the beginning of their work, which is in accordance with theory that contamination particles larger than the bearings grease film thickness are at first mechanically crushed, directly inducing initial vibration level increment. Later, when contamination particles are smaller in size, bearings radial vibrations levels slowly grow until they reach the certain value when their intensity again rises in time. That moment could be conditionally taken as the beginning of bearings failure.

It's also interesting to notice that vibration levels of uncontaminated bearings and bearings contaminated by 1 g of contaminant particles were very close, and vibration levels of bearing contaminated by 2 g of contaminant particles were 3-5 times higher. This indicates that there is a critical value of contamination particles concentration level (somewhere between 10,75% and 21,5%) and when this value is reached, bearings vibration levels rapidly increase in time.

Bearings highest surface temperatures are also affected by contamination but not as much as bearings vibration levels – highest difference in measured surface temperatures of bearings contaminated by 0, 1 and 2 g of contamination particles is below 7°C (8% of maximal measured temperature).

4. Conclusions

Taking into account total number of tested bearing samples it could not be fully claimed that developed mathematical model is perfect – however, at the moment it is unique, so it could be successfully used as a basis for further researches.

During the presented research, it was noticed that there is a critical value of contamination particles concentration level (somewhere between 10,75% and 21,5%) directly causing rapid increment of bearings vibration intensities. However, this is not the case with bearings highest surface temperatures – they seem much less affected by contamination particles concentration than by bearing's mounting conditions.

Finally, developed testing methodology could be used for qualitative assessment of different types of rolling bearings, indirectly increasing the overall quality of matching conveyor idlers and other rotating machines.

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