Strojniški vestnik - Journal of Mechanical Engineering 68(2022)9, 552-559

DOI:10.5545/sv-jme.2022.184
Original Scientific Paper
Received for review: 2022-05-04
Received revised form: 2022-07-05
Accepted for publication: 2022-08-17

Industrial Experimental Research as a Contribution to the Development of an Experimental Model of Rolling Bearing Vibrations

Mateusz Wrzochal[1,*] – Stanisław Adamczak[1] – Grzegorz Piotrowicz[2] – Sylwester Wnuk[2]
[1] Kielce University of Technology, Poland
[2] Fabryka Lozysk Tocznych-Krasnik S.A., Poland

The influence of rolling bearing contamination on the level of generated vibrations is ignored in many cases. The influence is clearly visible in the theoretical and experimental works on the mathematical modelling of rolling bearing vibration. The authors of the most recent works in this field use substantial simplifications, often ignoring the presence of solid particles between the rolling bearing mating surfaces. However, bearing in mind the continuous improvement of the rolling bearings production processes, a series of exploratory tests in industrial conditions should be carried out, taking into account the factors affecting the bearing vibrations that are crucial in terms of quality control of the manufactured bearings. The analysis presented in this paper show that the cleanliness of the bearings is a critical factor that determines whether the rolling bearings meet quality requirements.

Keywords: rolling bearings, vibrations, bearings cleanliness, quality control

Highlights

- *Bearing contamination is an important factor in deciding whether a manufactured bearing is positively evaluated during final vibration inspection.*
- *Ignoring the cleanliness condition in the mathematical models of bearings or experimental tests is not justifiable.*
- *Bearing manufacturers focused on the development of precision bearings should, in addition to investing in the manufacturing process, develop the process of ensuring technical purity in parallel.*
- *It is necessary to conduct detailed research on the analysis of the influence of the degree of rolling bearing contamination on its vibration and to study the degree of detectability of this type of incompatibility by applied instruments and measurement methods in the bearing industry.*

0 INTRODUCTION

Various mathematical models of rolling bearing vibrations can be found in the available publications. These models are oriented toward various applications important from the point of view of the model the authors present. The theoretical studies [1] carried out thus far on the mathematical models of rolling bearings enabled us to observe that the models are constructed with far-reaching simplifications and refer only to a few factors affecting the bearing level of vibrations [2] and [3]. There is no mathematical model that includes the vast majority of real factors, and the contamination of bearings and grease is one of the most commonly ignored factors in vibration analysis [4]. In addition, most analytical models focus on a bearing with an obvious defect that may appear only as a result of a prolonged operation or inappropriate conditions of operation [5] and [6]. Therefore, the models proposed in the latest literature on the subject are not universal and cannot be applied in industrial practice [7] and [8]. The analysis of the recently published studies shows that even if contamination is included in the experimental studies, they are mainly focused on grease contamination as a result of bearing operational use [9] and [10]. Therefore, the possible contamination in the process of production and its impact on the result of quality control is definitely a separate problem [11]. The construction of a model aimed at typical industrial applications is important because there are no reference bearings (which define the correct value of the vibration level of a bearing with specific characteristics), and even more so because there are no exact reference systems with which we could compare the results obtained on individual industrial systems for vibration measurement that differ (e.g., in design) [12] and [13]. Therefore, efforts should be made to create an experimental model for brand-new bearings. To create such a model, a series of tests should be performed, including all factors influencing the vibration level, with the use of multicriteria statistics. The desired model should consider not only the imperfections affecting discrete vibrations (deviations in shape, size and position, excessive waviness, micro waviness and roughness) but also and above all the presence of solid particles in the bearing, which is an inherent result of the production process [14] and [15].

*Corr. Author's Address: Kielce University of Technology, al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland, mwrzochal@tu.kielce.pl

The basic parameters determining the quality of rolling bearings include durability (operating time in given conditions), rotation accuracy (the amount of the momentary deviation of the bearing from the operating position), rolling friction moment (mainly determining the efficiency of the device the bearing is installed in, which affects its energy efficiency), noise level (important from the everyday operation), as well as the level of vibrations (which affects the behaviour of the entire structure) [16] and [17]. The mutual proportionality of the vibration level and other indicators defining the bearing quality allows, in a simplified form, to make the bearing quality dependent on the vibration level itself (slight vibrations:high quality; significant vibrations:low quality) [18] to [20]. This quality criterion means that every bearing (without exception) is subjected to vibration control in bearing production plants. Other parameters are checked randomly or at the customer's request [21]. It can also be noted that among the applied diagnostic methods, the measurement of vibrations gives the best results and is used much more often than, for example, acoustic- or temperature-based quality control [22]. Therefore, the importance studying the vibrations of rolling bearings is justified.

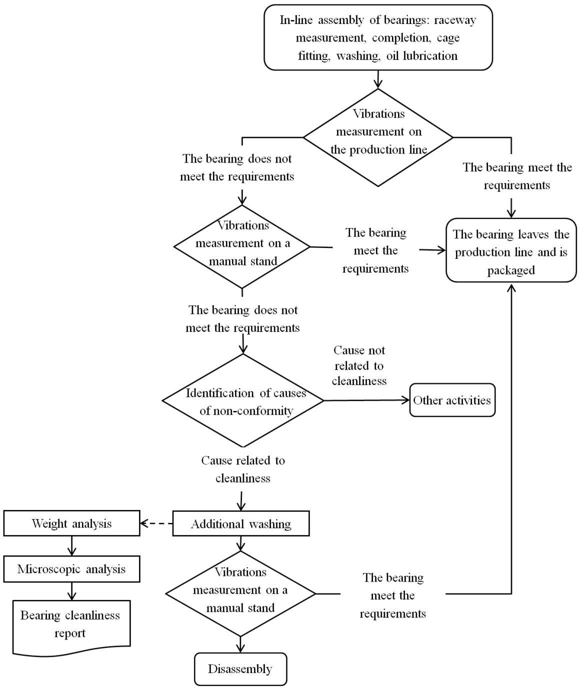


Fig. 1. *Identification and evaluation of rolling bearing contamination in the quality control process*

The study investigated the relevance of the initial bearing cleanliness in the quality control process. In order to understand the position of cleanliness control in the overall bearing acceptance inspection, a flow chart was prepared, as shown in Fig. 1.

1 VIBRATION MEASUREMENT ON THE PRODUCTION LINE

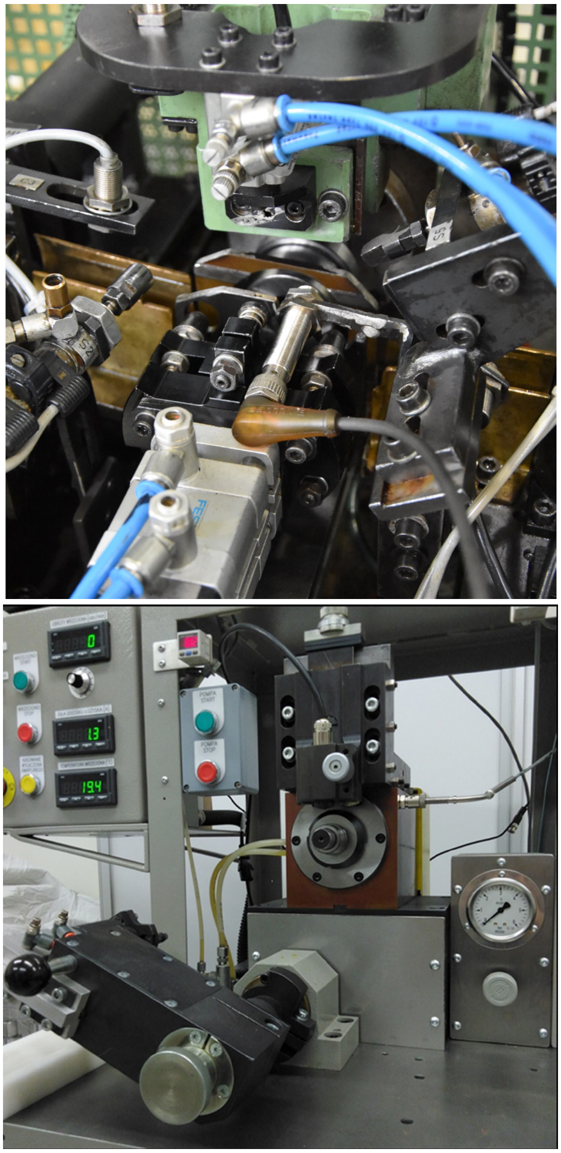
Two types of measuring devices are used to measure the level of vibrations generated by bearings in industrial conditions: automatic and semi-automatic measuring devices. Shown in Fig. 2a, automatic measuring devices are generally used in automatic assembly lines, while semi-automatic devices are used to control small series of dismantlable bearings (Fig. 2b).

The main components of such devices are a measuring unit with a vibration sensor, a measuring spindle (hydrodynamic, hydrostatic or pneumatic) and its drive, a pressure unit of the tested bearing, a bearing feeding system to the measuring stand (manual or automatic), a supporting structure with shock absorbers, and a control system.

The tested rolling bearing is mounted on a shaft rotating in the spindle (the spindle has a universal socket for shafts adapted to different types of bearings). The correct vibration measurement requires an axial load of the tested bearing. The load is introduced by pressing the outer ring with a force depending on the type of bearing. Usually, the clamps are adjustable, replaceable or, within certain limits, are universal to match the size of the tested bearing. Radial vibrations of the running and loaded bearing are recorded by an electrodynamic vibration velocity sensor with a direct contact with the stationary outer ring. The sensor is mounted in a holder and can be moved along two axes.

In the variant for measuring vibrations on a production line shown in Fig. 2b, the bearings move in turn through a trough where they are placed on the measuring shaft by a pneumatic pressure. In the case of the manual device shown in Fig. 2b, the operator places the bearing on the shaft by applying the pusher.

The above-mentioned measuring devices allow to measure the level of vibrations in three frequency bands: Low (50 Hz to 300 Hz), Medium (300 Hz to 1800 Hz) and High (1800 Hz to 10 000 Hz). The frequency bands listed above are related to the constant spindle rotational speed of 1800 min^{-1} at which all tests are carried out. This rotational speed is the reference speed and is determined by the standards for industrial measurement of bearing vibration levels (i.e., ISO 15242-1:2015 [23], ISO 15242-2:2015 [24], ISO 15242-3:2015 [25]). During the measurement, the effective value of the vibration velocity (RMS) and the maximum value (peak) are determined for each frequency band. The vibration level is expressed in different units, depending on the client's requirements: dB, μm/s, μm/s², A (anderon) or % (the conventional unit of one of the clients).



a) b)

Fig. 2. *Industrial vibration measurement devices; a) in an automatic production cycle directly on the production line, and b) in a semi-automatic/manual production process*

In the automatic cycle, the bearing is measured twice, and the measurement is taken on both sides of the bearing; in the semi-automatic/manual cycle, the bearing is measured four times, with two measurements on each side of the bearing, every 90° in relation to the axis of measurement of the bearing. During semi-automatic/manual measurement, the bearing is additionally checked for sounds it emits. The bearing should emit a "hum" appropriate for a given bearing. Audible disturbances such as rattling, whistling, or crackling caused by contamination, damage to the race of the inner ring, outer ring, or rolling elements are unacceptable. If the device is not equipped with a vibration spectrum analyser, oscilloscopes are additionally used for measurements. The image of the vibration amplitude observed on the oscilloscope should be uniform and should not show peaks and irregularities of waves higher than one half of the baseband width for standard bearings and one third of the baseband width for bearings with a reduced level of vibrations (i.e., electric bearings (C66)). These bearings (C66) are 100 % vibration controlled, while for standard bearings, the measurement frequency is 3 % for each assembly lot but not less than 10 pieces.

The RMS value is displayed on the screen of the device in numerical form and additionally visualized in the form of bar graphs. For the bearing being measured, the RMS and "peak" limits for each band are entered before starting the measurements. The comparison of the four values obtained with the values set as the limit is decisive for the recognition of the bearing as meeting the quality requirements. Fig. 3 shows two different measurement results. Fig. 3a indicates the good quality of the tested rolling bearing: the vibration level does not exceed the assumed limits, and all bars are green). Fig. 3b shows the result of insufficient quality of the tested rolling bearing: the assumed limits are exceeded in the medium and high range (the second and third bars turn red).

The vibration level generated by the bearings is measured on open and empty bearings (without grease and seals). Such bearings are protected only with a thin film of oil. If the exposed bearing meets the quality requirements regarding the vibration level, then the closed (i.e., lubricated and sealed) bearing will meet such conditions all the more (the grease dampens vibrations in the bearing). The customer may wish to measure the vibration level in a closed bearing. In this case, the drive of the measuring device must be more powerful, and the contact pressure must be greater. The increase of these parameters (higher power of the drive and higher bearing pressure force) may accelerate the wear of the measuring device. This risk increases with the diameter and the weight of the tested bearing.

The result of the vibration level test proves its technical perfection. By making this measurement, we obtain information about potential defects of individual bearing components (outer ring, inner ring, rolling elements, cage) and possibly about impurities

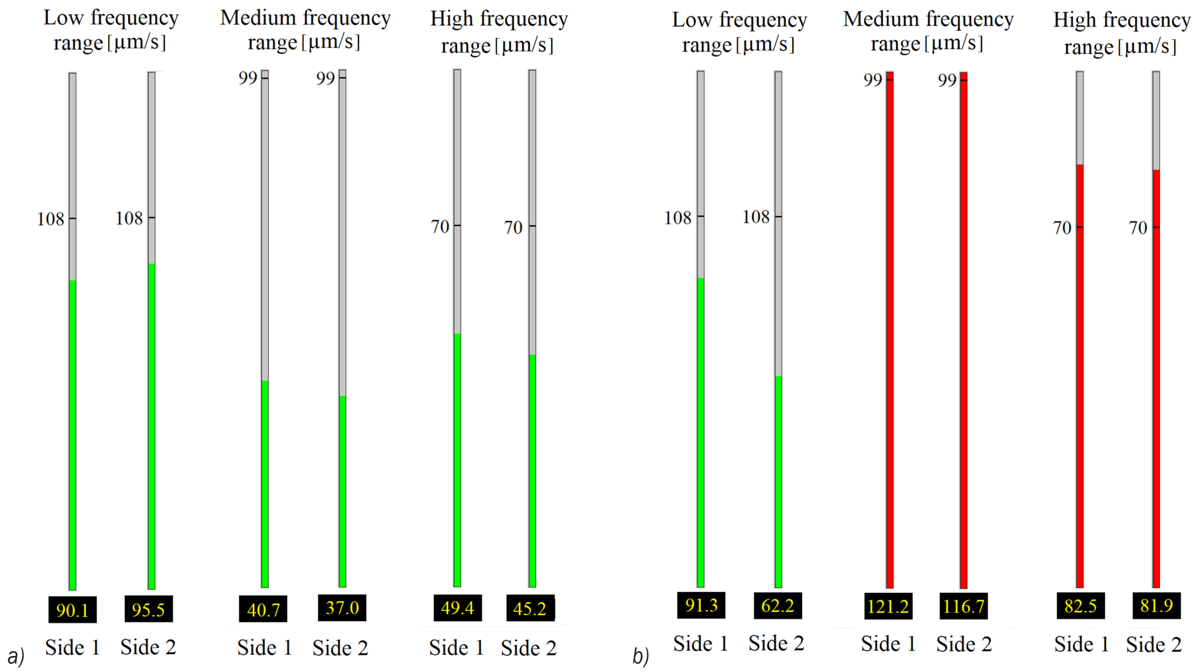


Fig. 3. *a) Bar graph that shows the vibration level measurement of a bearing in good technical condition, and b) bar graph that shows the vibration level measurement of a bearing that does not meet the assumed quality control limits*

in the bearing. The results of the vibration level measurement are subject to continuous analysis and, depending on the result, the quality controllers react in accordance with the procedures in place. Whether the defective bearings with exceeded vibration levels are isolated cases or there is an error in the process of production should be investigated.

Dirty bearings are rewashed. Bearings with exceeded vibration levels that do not show signs of significant damage, are reclassified as lower-class bearings and still offered for sale. Bearings with exceeded vibration levels that show symptoms of significant damage are dismantled. Bearing components to be dismantled: inner rings, outer rings, and rolling elements are subject to microscopic inspection. The results of this inspection have an impact on the next steps. If the problem is isolated, the production procedures should be analysed, but if more pieces are affected, the root cause of the problem should be identified and resolved. Defective bearing components are subject to regeneration if possible, and if not, they are scrapped. The detected deficiencies have an impact on the improvement of the technological process. Each improvement in the technological process upgrades the parameters of the manufactured bearing. All the improvements automatically influence the process of design and production of new, more and more accurate devices for measuring the vibration level.

2 MAIN CAUSES OF NON-CONFORMITIES FOUND BY THE QUALITY CONTROL

Contamination of the lubricating layer with solid particles is an important parameter affecting the durability of rolling bearings. The degree of life reduction caused by solid particles in the lubricating layer depends on the type, size, hardness, and quantity of particles, as well as the thickness of the lubricant layer (viscosity) and the size of the bearing. Durability tests, however, are destructive and time-consuming tests.

The level of vibration generated by a rolling bearing is a critical parameter and is inversely proportional to service life. Bearing vibration tests are much less time-consuming and do not damage the bearing. However, both in theoretical models of bearing vibrations and in experimental tests, the cleanliness of the bearing interior is largely ignored. This is due to the fact that, firstly, the contamination is very difficult to simulate mathematically, and, secondly, the experimental studies are focused on high-amplitude components in the low and medium frequency range initiated by damage or surface geometry.

To discover the most important causes of rejects, a six-month observation of the production process of rolling bearings of ten different types was performed. A total of 46,811 bearings were tested. Products that were rejected from the production process during the quality control involving the measurement of vibrations were thoroughly analysed. The causes of the defects of a given product were grouped into four categories:

- Defects in the rolling element related to an incorrect shape of one or more rolling elements, a significant surface defect, or an unsuitable size.
- Defects of the inner or outer ring related to the inadequate geometric structure of their surfaces or shape errors, less often to a local defect.
- Contamination was understood as residues left in the process of production. In most cases, after thorough washing, the bearing met the quality requirements.
- Other defects not related to the rolling element rings and contamination (i.e., cage defect or exceeding the limit of one of the three frequency bands) not related to any of the potential causes. The test results are presented in Table 1.

Table 1. *Percentage of specific causes of rejects of rolling bearings from the production line*

Type	Reject rate [%]			
	Ball defect	Outer/ inner ring defect	Contamination	Other
6016Z	53	16	31	0
63007-2RS	41	18	35	6
6311Z	64	21	12	3
6313P63	80	8	12	0
6317-2RS	52	18	20	9
6208Z	60	5	13	21
6211Z	84	16	0	0
6217-2RS	40	24	20	16
6219Z	66	21	12	2
6405	35	36	28	1

The data presented in Table 1 show that the main cause of the rejection due to the level of vibration was a ball defect. This is a special situation because this type of defect is a critical defect that, if occurs, disqualifies the bearing even though it does not exceed the limits on any of the analysed frequency bands. The reason for this situation was that the observation coincided with the delivery of defective balls deliveries from one of the suppliers. Therefore, further evaluation of the bearing vibration level was focused mainly on the detection of defective balls. After the defect was discovered, a complaint procedure was initiated in order to find the root cause, and the collected materials served as evidence confirming the scale of the problem. In addition to the defects of the balls in the observed production process, the contamination of the bearings was also a significant problem that significantly affected the level of vibration and made it difficult to assess the bearing, to capture single defects on the rings or the aforementioned defects on the balls. Therefore, when conducting research aimed at analyzing the vibrations of rolling bearings in the industrial environment, it is impossible to ignore the contamination, which constitutes a significant cause of all discrepancies. It is very important, especially for high-precision bearings designed for high-speed applications for which the evaluation of the vibration level is an important parameter determining the quality of the bearings.

3 TESTING CLEANLINESS OF BEARINGS IN INDUSTRIAL CONDITIONS

As shown by the presented long-term tests on several types of bearings, contamination is a significant cause of discrepancies discovered during quality control in bearing production plants. Bearings that are suspected of not meeting the cleanliness conditions set for them are re-washed in accordance with the procedure in place. Bearing samples, both contaminated and clean, are sent to the laboratory. There, the degree of pollution and its structure is determined. The test is performed using weight analysis and microscopic analysis.

The weight analysis consists of washing the bearing parts in extraction naphtha using ultrasound. The liquid after washing and rinsing the bearing parts is filtered through a previously soaked (in extraction naphtha), dried, and weighed nylon membrane with a mesh side of 0.8 µm. The filtrate with the bearing residue is dried and then weighed to the nearest 0.1 mg. The difference in weight of the filter after and before filtration represents the weight of the contaminations. The resulting contaminant mass is compared to the requirements.

Table 2. *The result of the weight analysis of the contaminants found in the bearings*

Bearing number	Bearing type, quantity	Mass of contaminants [mg/kg]		Contaminants above 300 μm Quantity (max. Dimension)	
		Requirements	Result	Requirements	Result
1.	6208Z	max 5 mg/kg	6.6	max 300 μm	0
2.	6208Z		4.8		1 (420)
3.	6208Z		3.7		0

After weight analysis, the filters are examined using a microscope. Microscopic analysis involves the computerized counting of particle sizes divided into five ranges: 25 µm to 50 µm, 50 µm to 100 µm, 100 µm to 150 µm, 150 µm to 200 µm, and 200 µm to 300 µm. Contaminants below 25 µm are disregarded, while those above 300 µm are not acceptable. The counting of contaminants on the surface of the dried nylon membrane is carried out at a zoom of ×100. The test allows a specific cleanliness class to be assigned according to the standards described in ISO 16232:2018 **[26]**.

Examples of the results of the weight analysis are given in Table 2. Table 3 presents an example of the result of the microscopic analysis of the tested bearings contaminants, while Fig. 4 shows the filters and the captured foreign bodies.

Table 3. *The result of the microscopic analysis of the contaminants found in the bearings*

Size ranges of contaminants [µm]		Amount of metallic contaminants [pcs]						class
		25-50	50-100	100-150	150-200	200-300	>300 (max. dimension)	
Bearing 6208Z no.	1	217	78	15	4	4	0	8
	2	93	30	13	4	1	1 (420)	ofc
	3	62	30	11	4	0	0	7

ofc - out of class

In order to ensure the appropriate cleanliness class of the bearings, modern devices with extensive filtration systems are increasingly designed for washing individual bearing elements, as well as assembled bearings. Thus, thanks to accurate systems used for measuring the level of vibration generated by bearings, we are able to determine the cause of the increased vibration level. We can also determine the reason for the problem and which stages of the technological process of bearing production can be improved.

4 CONCLUSIONS

Contamination of the lubricating layer with solid particles is a critical problem that reduces the life of rolling bearings. The degree of reduction in service life caused by solid particles in the lubricant layer depends on the type, size, hardness, and quantity of the particles, the thickness of the lubricant layer (viscosity) and the size of the bearing **[27]** and **[28]**. However, durability tests are destructive tests and are very time-consuming.

The level of vibration generated by a rolling bearing is a critical parameter that is inversely proportional to service life. Bearing vibration tests, however, are significantly less time-consuming and do not damage the bearing. However, both in theoretical models of bearing vibration and in experimental studies, bearing cleanliness is largely neglected. This is due to the fact that, firstly, the contamination is very difficult to simulate mathematically, and, secondly, the experimental studies are generally focused on high-amplitude components in the low and medium frequency range due to the damage or the geometric structure of the surface.

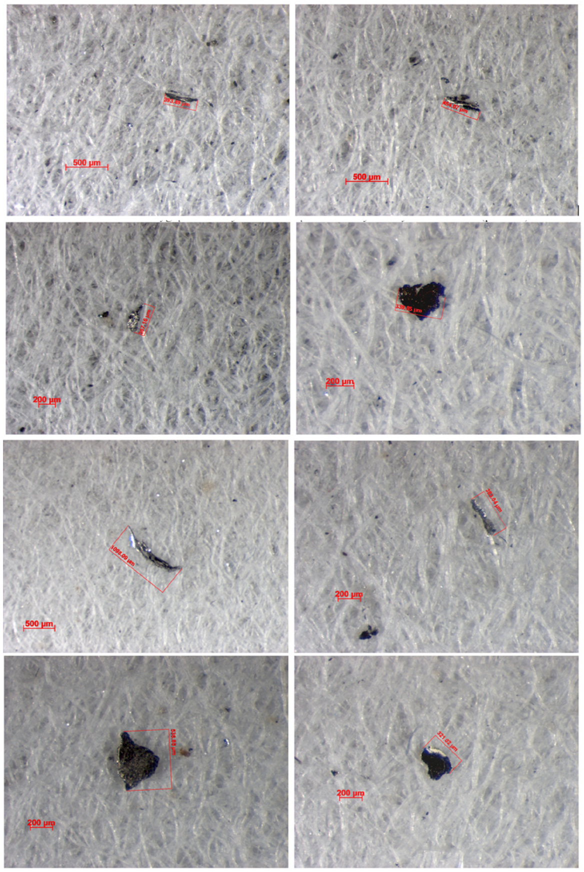


Fig. 4. *Examples of microscopic photos of the filters showing contamination of the rolling bearings*

The most important conclusion from the descriptions given in the paper is that the contamination in bearings is a very important factor that determines the positive assessment of the manufactured bearing during the final control of the vibration level. Therefore, ignoring this factor in mathematical models or experimental research is unjustified, especially since the industry trends in downsizing and striving for ever-higher operating performance make rolling bearings operate in increasingly difficult conditions with greater precision of rotation, high operating speed, minimizing noise, vibrations, and heat.

Therefore, bearing companies focused on the development of precision bearings, in addition to investing in the production process, should simultaneously develop the process of ensuring technical cleanliness. Providing and maintaining perfect cleanliness in the production process is a real challenge.

In companies producing parts for the automotive industry, the technical cleanliness of components in accordance with the requirements of ISO 16232 and VDA19 is one of the most important issues.

Due to the requirements, not only the production process and the washing process affect the final level of technical cleanliness of the components that are delivered to the final assembly. Of key importance will also be the level of cleanliness of the rooms in which the bearing production and assembly operations are performed, as well as the packaging and measures to prevent re-contamination.

In the future, the authors of this paper plan to conduct detailed research on the analysis of the impact of the degree of contamination of the rolling bearing on its vibrations and to test the degree of detection of this type of non-compliance by the instruments and measurement methods used in the bearing industry; as a result of the planned tests, it will be possible to predict the importance of bearing cleanliness to limit the level of vibrations. In turn, the planned research will be part of the preliminary research for broader studies related to an attempt to develop a model based on multi-criteria statistics that could be used to forecast vibrations of a newly manufactured bearing in the industrial environment. A model built on the basis of real data collected in a rolling bearings production plant will undoubtedly have great practical significance.

8 REFERENCES

[1] Wrzochal, M., Adamczak, S. (2020). The problems of mathematical modelling of rolling bearing vibrations. *Bulletin of the Polish Academy of Sciences: Technical Sciences*, vol. 68, no. 6, p. 1363-1372, **DOI:10.24425/bpasts.2020.135398**.

[2] Shi, P., Su, X., Han, D. (2016). Nonlinear dynamic model and vibration response of faulty outer and inner race rolling element bearings. *Journal of Vibroengineering*, vol. 18, no. 6, p. 3654-3667, **DOI:10.21595/jve.2016.16944**.

[3] Deák, K., Mankovits, T., Kocsis, I. (2017). Optimal wavelet selection for the size estimation of manufacturing defects of tapered roller bearings with vibration measurement using Shannon entropy criteria. *Strojniški vestnik - Journal of Mechanical Engineering*, vol. 63, no. 1, p. 3-14, **DOI:10.5545/sv-jme.2016.3989**.

[4] Liu, J., Shao, Y. (2015). Vibration modelling of nonuniform surface waviness in a lubricated roller bearing. *Journal of Vibration and Control*, vol. 23, no.7, p. 1115-1132, **DOI:10.1177/107754631 5589675**.

[5] Do, V.T., Nguyen, L.C. (2016). Adaptive empirical mode decomposition for bearing fault detection. *Strojniški vestnik - Journal of Mechanical Engineering*, vol. 62, no. 5, p. 281-290, **DOI:10.5545/sv-jme.2015.3079**.

[6] Kong, F., Huang, W., Jiang, Y., Wang, W., Zhao, X. (2019). Research on effect of damping variation on vibration response of defective bearings. *Advances in Mechanical Engineering*, vol. 11, no. 3, p. 1-12, **DOI:10.1177/1687814 019827733**.

[7] Soni, A., Pateriya, A., Dewada, S. (2018). Study the effects of solid and liquid contamination in ball bearing through vibration analysis. *International Research Journal of Engineering and Technology*, vol. 5, no. 5, p. 4397-4401.

[8] Jamaludin, N., Mba, D., Bannister, R.H. (2001). Condition monitoring of slow-speed rolling element bearings using stress waves. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, vol. 215, no. 4, p. 245-271, **DOI:10.1177/095440890121500401**.

[9] Malla, C., Panigrahi, I. (2019). Review of condition monitoring of rolling element bearing using vibration analysis and other techniques. *Journal of Vibration Engineering & Technologies*, vol. 7, p. 407-414, **DOI:10.1007/s42417-019-00119-y**.

[10] Dadouche, A., Conlon M.J. (2016). Operational performance of textured journal bearings lubricated with a contaminated fluid. *Tribology International*, vol. 93, p. 377-389, **DOI:10.1016/j.triboint.2015.09.022**.

[11] Maru, M.M., Castillo, R.S., Padovese, L.R. (2007). Study of solid contamination in ball bearings through vibration and wear analyses. *Tribology International*, vol. 40, no. 3, p. 433-440, **DOI:10.1016/j.triboint.2006.04.007**.

[12] Shah, D.S., Patel V.N. (2014) A review of dynamic modeling and fault identifications methods for rolling element bearing. *Procedia Technology*, vol. 14, p. 447-456, **DOI:10.1016/j.protcy.2014.08.057**.

[13] Boškoski, P., Petrovčič, J., Musizza, B., Juričić, Đ. (2010). Detection of lubrication starved bearings in electrical motors by means of vibration analysis. *Tribology International*, vol. 43, no. 9, p. 1683-1692, **DOI:10.1016/j.triboint.2010.03.018**.

[14] Xiong, Q., Zhang, W., Xu Y., Peng, Y., Deng, P. (2018). Alpha-stable distribution and multifractal detrended fluctuation analysis-based fault diagnosis method application for axle box bearings. *Shock and Vibration*, vol. 2018, art. ID 1737219, **DOI:10.1155/2018/1737219**.

[15] Ouadine, A., Mjahed, M., Ayad H., El Kari, A. (2018). Aircraft air compressor bearing diagnosis using discriminant analysis and cooperative genetic algorithm and neural network approaches. *Applied Sciences*, vol. 8, no. 11, art. ID 2243, **DOI:10.3390/app8112243**.

[16] Kahaei, M.H., Torbatian, M., Poshtan, J. (2007). Bearing-fault detection using the meyer-wavelet-packets algorithm. *Strojniški vestnik - Journal of Mechanical Engineering*, vol. 53, no. 3, p. 186-192.

[17] Li, J., Li, M., Zhang, J., Jiang, G. (2019). Frequency-shift multiscale noise tuning stochastic resonance method for fault diagnosis of generator bearing in wind turbine. *Measurement*, vol. 133, p. 421-432, **DOI:10.1016/j.measurement.2018.10.054**.

[18] Adams, M.L. (2018). *Bearings: Bearings Basic Concepts and Design Applications*. 1st ed., CRC Press, Boca Raton, p. 92-123, p. 212-231, **DOI:10.1201/b22177**.

[19] Harris, T.A., Kotzalas, M.N. (2006). *Rolling Bearing Analysis Essential Concepts of Bearing Technology*, 5th ed., CRC Press, Boca Raton, p. 329-348, **DOI:10.1201/9781420006582**.

[20] Taylor, J.I. (2003). *The Vibration Analysis Handbook*, 2nd ed. VCI, p. 167-221.

[21] Pan, H., He, X., Tang, S., Meng, F. (2018). An improved bearing fault diagnosis method using one-dimensional CNN and LSTM. *Strojniški vestnik - Journal of Mechanical Engineering*, vol. 64, no. 7-8, p. 443-452, **DOI:10.5545/sv-jme.2018.5249**.

[22] Delgado-Arredondo, P.A., Moríñigo-Sotelo, D., Osornio-Rios, R.A., Avina-Cervantes, G.J., Rostro-Gonzales, H., Romero-Troncoso R.J. (2017). Methodology for fault detection in induction motors via sound and vibration signals. *Mechanical Systems and Signal Processing*, vol. 83, p. 568-589, **DOI:10.1016/j.ymssp.2016.06.032**.

[23] ISO 15242-1:2015. *Rolling bearings - Measuring methods for vibration - Part 1: Fundamentals*. International Organization for Standardization, Geneve.

[24] ISO 15242-2:2015. *Rolling bearings - Measuring methods for vibration - Part 2: Radial ball bearings with cylindrical bore and outside surface*, International Organization for Standardization, Geneve.

[25] ISO 15242-3:2006. *Rolling bearings - Measuring methods for vibration - Part 3: Radial spherical and tapered roller bearings with cylindrical bore and outside surface*. International Organization for Standardization, Geneve.

[26] ISO 16232:2018. *Road vehicles - Cleanliness of components and systems*. International Organization for Standardization, Geneve.

[27] Espejel, G. M., Gabelli A., Ioannides S. (2010). Lubrication and Contamination effects on bearing life. *Evolution*, vol. 2, p. 25-30, *from https://evolution.skf.com/wp-content/uploads/2013/02/EN_lubrication0.pdf*, accessed on 2022-07-28.

[28] Espejel, G. M., Gabelli A., Ioannides S. (2010). Lubrication and Contamination effects on bearing life, part 2. *Evolution*, vol. 3, p. 25-31, from *https://evolution.skf.com/wp-content/uploads/2014/10/EN_lubrication_part_2.pdf*, accessed on 2022-07-28.