Research of the influence of the 2D and 3D surface roughness parameters of bearing raceways on the vibration level

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Abstract. The level of generated vibrations is one of the most important exploitation parameters of rolling bearings. The vibration analysis allows for the evaluation of the technical condition of new and operating bearing assemblies. There are numerous factors affecting the level of generated vibrations. The condition of topography of active surfaces of rolling bearings is one of them. The state of the surface texture may be described with the use of 2D and 3D roughness parameters. Since there are no unanimous guidelines, the paper's authors decided to analyse whether, when evaluating topography of the active surface of rolling bearings it is beneficial to measure 3D roughness parameters, or whether the evaluation of 2D roughness parameters fully suffices. Fifth pieces of type 6304 ball bearings were examined. The measurement of selected 2D and 3D roughness parameters of the bearings races was performed using a contact method on a Form Talysurf PGI 1230 device made by Taylor Hobson. The measurement of vibrations generated by the bearings was performed with an Anderometer, a device developed by the employees of the Kielce University of Technology. Statistical analysis based on the correlation calculation was used to evaluate the impact of 2D and 3D roughness parameters of active surfaces of rolling bearings on the level of generated vibrations.

1. Introduction
Rolling bearings are a fundamental group of mechanical elements. Most mechanisms that rotate use rolling bearings. They are applied in almost all devices and mechanisms, from white goods, elements of machine tools, through elements of jet engines [1-3]. The functioning of entire mechanisms sometimes depends on the correct operation of ball bearings. Consequently, the technical condition of rolling bearings must be examined thoroughly to predict their wear and to schedule their replacement, if needed. In production processes, an unforeseen malfunction of bearings may result in the stoppage of an entire production line, thus generating high costs.

The level of generated vibrations is considered to be the rolling bearings' basic exploitation parameter. The vibration analysis proves to be a powerful diagnostic tool that allows to determine which component of a bearing generates the dominating level of vibrations, in consequence allowing the level of wear to be evaluated. The measurement of the level of vibrations is commonly used due to its non-destructive character. Prior to leaving the factory, each bearing is subject to vibration analysis to determine whether it can be released for use. We can also measure the vibrations of entire bearing assemblies, so that monitoring the technical condition of working bearings is possible [4]. The vibration analysis has been taken up as a subject of many scientific projects [5-7].
One of the main reason affecting the level of generated vibrations is the condition of the geometrical structure of the rolling bearings' active surfaces, such as the inner and outer race. Size reduction and constant improvements in the performance of devices and mechanism require that bearings support higher and higher loads, have lower and lower frictional resistance and are increasingly quieter, while maintaining long life cycle. Therefore, bearings manufacturers and scientists never stop researching ways to optimize the geometry of active surfaces of bearings in order to obtain products that satisfy the requirements of the modern technology. Consequently, the requirements relating to the modern measurement technology and methods of analyzing signals also grow [8, 9].

According to ISO 25178-6:2011 [10,11] the surface geometric structure can be examined using line-profiling method (2D roughness) and areal-topography method (3D roughness). 2D roughness parameters are commonly used in industrial and laboratory environments for the purpose of evaluating the condition of the surface texture of various products. Such parameters are measured easily and quickly, with portable measuring devices, on-site, in industrial conditions [12]. Still, the condition of the surface should be examined more thoroughly in certain cases. At such times, 3D roughness measurement and analysis of parameters are recommended [13]. Specialized, costly measuring devices is needed to conduct such measurements. It may take several hours to measure the 3D roughness of a single surface. Hence, this type of measurement is not fit for quick control of the manufactured elements of rolling bearings. Moreover, advanced knowledge and rich experience are required to interpret the results of such measurements, meaning that highly qualified personnel must be employed [14]. Additionally, in case of elements produced in additive technologies, the measurement of 3D roughness parameters is either difficult or downright impossible [15].

Currently, the most popular 2D roughness parameter, namely the arithmetical mean roughness value $Ra$, is used in the bearing industry to evaluate the surface quality of the raceways and the balls. Despite its big popularity, the parameter does not allow for the evaluation of the unevenness of the surface [11]. Still, there are no standards that recommend the use of other roughness parameters. The development of modern measurement techniques allows for the analysis of multiple roughness parameters, both in 2D and 3D aspect, which are related to the examined product's operating properties. This is especially important in the case of new series of bearings, where the production process may be unstable. As there are no standards or clear guidelines specifying the type of roughness parameters that should be examined by the bearings manufacturers, the paper's authors decided to analyze whether it is necessary to apply the time-consuming and costly analysis of roughness parameters of rolling bearings' surfaces in 3D, or the 2D analysis is sufficient.

2. Experimental examinations
The examinations presented in this paper were conducted in the laboratories of the Kielce University of Technology, namely in the Laboratory of Computer Measurements of Geometric Quantities and the Laboratory of Rolling-Elements Bearings. Fifty pieces of type 6304 ball bearings were examined.

2.1. Examined bearings
In order to eliminate the impact of the factory-used lubricant on the level of generated vibrations, a decision was made to use type 6304 open rolling bearings for measurements. Still, to ensure an oil film is present, a few drops of machine oil were added before the measurement of vibrations. This type of bearings is commonly used in the machinery building industry. Figure 1 presents an image of the examined bearing.
2.2. Vibration analysis

The first step of the examination procedure was to measure the vibration velocity generated by the bearings. An Anderometer measuring stand, developed at the Kielce University of Technology within the framework of a project financed from the resources of the National Centre for Research and Development of Poland, was used for this purpose. The photography of the device along with one of the examined bearings is shown in figure 2.

The examined bearings are fixed to a measuring mandrel and a pneumatic clamp ensures a constant pressure force of 65N. To eliminate the impact of external vibrations, the spindle is lubricated with an oil mist. Through a belt transmission gear, the motor rotates the spindle at 1800 min. This speed is consistent with the standard on the measurement of vibrations. The spindle's rotational speed may be freely adjusted and controlled via the digital display. A piezoelectric sensor for measuring the vibration velocity was used in the device. In comparison to the vibrations acceleration sensors commonly used in such devices, the applied sensor operating in the velocity function has a number of advantages [6, 16]. The obtained vibration signal is divided into three basic frequency bands: low (LB) from 50 to 300 Hz, medium (MB) from 300 to 1800 Hz and high (HB) from 1800 to 10 000 Hz. The level of generated vibrations is expressed with a unit called Anderon [6, 16].
2.3. Measurement and analysis of surface topography parameters

The measurements of roughness parameters of the raceway of type 6304 rolling bearings were taken with the Form Talysurf PGI 1230 measuring system. This is a professional device for precise evaluation of topography of the examined surface in 2D and 3D. Due to its high measurement accuracy the system is especially recommended to manufacturers of high precision rolling bearings [17]. Four basic 2D roughness parameters (Ra, Rt, Rsk, Rku) were used for the purpose of the examination, along with the relevant roughness parameters analyzed in 3D (Sa, St, Ssk, Sku). The 3D surface measurements were performed by scanning the consecutive cross-sections of the measured surface with a measuring probe. The scanning surface was 1.35 x 1.35 mm. The table 1 shows information related to conditions of measurement.

| Table 1. Measurement conditions |
|-------------------------------|
| Sampling interval | ΔX=0.05µm, ΔY=10µm |
| Number of repetitions | 125 |
| Cut-off value | 0.25 mm |
| Kind of filter | Gaussian filter (ISO 11562) |
| Form removal method | third-order polynomial |

3. Research results

The research results were presented in tables and as diagrams showing the dependence of the level of vibrations from the selected 2D and 3D roughness parameters. Table 2 shows the overall results of measurements, where \( \bar{x} \) is mean value, \( x_{\text{max}} \) is a maximum value, \( x_{\text{min}} \) is a minimum values, \( s \) is a standard deviation, \( R \) is a range (difference between \( x_{\text{max}} \) and \( x_{\text{min}} \)). The results in the first main column apply to the measured level of the generated vibrations expressed in Anderon units [6]. The results of measurement of vibrations were presented for three frequency bands: low (LB), medium (MB) and high (HB). The second column presents 2D roughness parameters and the third column presents 3D roughness parameters.

| Table 2. Research results |
|---------------------------|
| Vibration level, Anderon | Roughness 2D | Roughness 3D |
| LB | MB | HB | Ra, µm | Rt, µm | Rku | Rsk | Sa, µm | St, µm | Sku | Ssk |
|---|---|---|---|---|---|---|---|---|---|---|---|
| \( \bar{x} \) | 8.70 | 8.92 | 8.42 | 0.03 | 0.56 | 10.15 | -1.57 | 0.03 | 1.25 | 31.10 | -2.56 |
| \( x_{\text{max}} \) | 14.48 | 14.79 | 13.93 | 0.05 | 0.95 | 18.00 | -0.29 | 0.04 | 2.81 | 76.90 | -0.38 |
| \( x_{\text{min}} \) | 4.52 | 5.12 | 3.33 | 0.02 | 0.34 | 4.62 | -2.85 | 0.02 | 0.69 | 5.89 | -7.51 |
| \( s \) | 2.343 | 2.750 | 2.313 | 0.006 | 0.136 | 3.014 | 0.612 | 0.006 | 0.481 | 35.764 | 1.487 |
| \( R \) | 9.96 | 9.67 | 10.60 | 0.03 | 0.61 | 13.38 | 2.56 | 0.02 | 2.12 | 71.01 | 7.13 |

The selected results were presented on diagrams for the purpose of a broader analysis and to determine the dependences between the 2D and 3D roughness parameters and the amplitudes of the generated vibrations. Therefore, the parameters Ra and Sa are widely used in laboratory and industrial application the Figure 3 presents the relationship between the level of generated vibrations and the Ra parameter of the race's roughness profile while Figure 5 shows impact of Sa parameter on the vibration level.
Figure 3. Diagrams of the relationship between the level of generated vibrations and the arithmetical mean roughness value (Ra) of the race's roughness profile, where: a) LB - low frequency bandwidth, b) MB - medium frequency bandwidth, c) HB - high frequency bandwidth.

The analysis of results presented on diagrams in figure 3 allows for the drawing of a conclusion that the Ra roughness parameter ranging from 0.02÷0.05 µm was obtained for the races of the examined bearings. The standard deviation was s=0.006 µm. This indicates low variability of the Ra parameter for the series of the examined bearings. Examining the impact of the arithmetical mean roughness value on the level of generated vibrations, a conclusion can be made that an increase in the Ra parameter causes a slight drop of the level of generated vibrations in the low and medium frequency band (see figure 3a and 3b). However, as the Ra parameter increases, the level of generated vibrations registered in the high frequency band shows an increasing tendency (figure 3c).

Additionally Figure 4 shows example of surface roughness profile characterized by various values of the Ra parameters.

Figure 4. Example of surface roughness profile.
Analyzing the stereometry of the surface of the bearings' races it may be concluded that the range of the obtained Sa parameters was 0.02÷0.05 µm. In the case of analysis of the 3D roughness parameter i.e. Sa it may be concluded that the same value and the mean square error were calculated for the Ra parameter (see table 2). In this case, too, an increase in the roughness parameter Sa causes a slight drop of the vibrations measured in low (LB) and medium (MB) ranges of frequency. An increasing tendency, however, was noted for the high frequency band.

When comparing the values of the measured roughness parameters Ra with their counterparts in the aspect of 3D measurements, namely the Sa parameters, a conclusion can be made that the results overlap to a large extent. In relation to this, when analyzing the Ra and Sa parameters, there is no need to measure the 3D roughness parameters because the 2D parameter yields similar results.

Another group of the analyzed parameters were the total height of the roughness profile Rt and the total height surface roughness St. The variability range of the parameter determining the total roughness height was within range Rtc<0.34µm; 0.95µm>. Analyzing research results it may be concluded that an increasing the roughness parameter Rt causes an increase in the level of generated vibrations across all analyzed frequency bands. However, the largest impact was registered for the mean frequency band - MB.

As per the European standard [18], the equivalent of the Rt parameter in 3D is the total height surface roughness St. Consequently, this parameter was also used to analyze the impact of the parameters of the roughness of the bearing raceway on the level of generated vibrations.

When analyzing the measured values of the St parameter that determines the height surface roughness, a conclusion can be made that, similarly to the Rt parameter, an increasing value of the St parameter causes an increase in the level of the generated vibrations in the low frequency band LB and the medium range of frequencies. However, a slight drop of the amplitude of the generated vibrations can be observed as the St parameter rises.

While comparing parameters which specify the height of the profile of roughness of the examined races of rolling bearings, namely Rt parameters measured in 2D and St parameters measured in 3D, one can conclude that the results show a higher divergence than in the case of Ra and Sa parameters. A mean square error of s=0.136 µm was obtained for Rt parameters, and of s=0.481 µm for St parameters. This proves that the dispersion of the determined parameters is significantly broader. Moreover, this dispersion was broader for the St parameter which determines the total height of surface roughness.

Functional parameters were analyzed in order to describe in detail the nature of surface texture of examined bearings. The first group comprised parameters describing the flattening of roughness peaks (kurtosis) i.e. Rku and Sku. These parameters are especially important when evaluating the tribological properties of rolling bearings, because they can be related to friction coefficient [19].

Analyzing research results a conclusion can be made that the values of the Rku parameters show a high divergence. This is confirmed by the value of the determined standard deviation of s=3.014 at an average value of $\bar{x} = 10.15$ (see table 2). The value of kurtosis of Rku>3 was obtained for all
measured races, proving the presence of sharp peaks and grooves in the roughness profile. This is confirmed by the exemplary roughness profiles that were shown in Figure 4.

Similarly to Rku parameters, Sku parameters show a high divergence. The variability range of the distribution concentration ratio of the height of surface topography was within the range Sku = 15–175.

The summary of analysis of the impact of Rku and Sku roughness parameters on the level of generated vibrations fails to yield unanimous conclusions. The examined parameters determining the character of roughness peaks exhibited very high divergence. The standard deviations achieved high values both for the parameters derived from the 2D profile, i.e. Rku, and for the 3D parameters, i.e. Sku.

The Rsk parameter is an important parameter determining the skewness of the roughness profile. This parameter can be related to friction coefficient. Consequently, it is advisable to use such a parameter to evaluate the topography of the surface of rolling bearings in terms of friction and wear. The equivalent of the Rsk parameter in 3D is Ssk (skewness).

A conclusion can be drawn from the analysis of results table 2 that negative values of Rsk parameters were obtained for all examined bearing races. This means that material is concentrated in the vicinity of peaks of the roughness profile, which indicates surfaces whose shape is similar to plateaus. The negative value of the asymmetry factor of the roughness profile also indicates the presence of "deep valleys" in the surface of the examined element. Such a nature of surface allows for the better retention of a lubricant, indicating good bearing surface. The analysis measuring results leads to a conclusion that as the value of the Rsk parameter increases, the value of generated vibrations recorded in the low and medium frequency range remains at a constant level. However, when considering the high range of vibration frequency, a slight drop in the amplitude of the generated vibrations was observed, along with an increase in skewness of the roughness profile.

The parameters describing the profile skewness are difficult to link to the values of vibrations generated by the examined bearings, because despite the changes of the values of the analyzed parameters, the values of the generated vibrations would remain at a constant level. Still, the Rsk parameter may serve to evaluate the shape of the peaks of the roughness profile, which is of crucial importance when evaluating the tribological properties of the surface of bearings. Therefore, it seems justified to analyze the values of parameter Rsk when evaluating the frictional moment of rolling bearings.

The equivalent of the Rsk parameter for the purpose of analysis of surface topography is the Ssk parameter. This parameter may be used to evaluate the friction and wear of the active surface of rolling bearings. Similarly as for the Rsk parameter, the values of topography skewness (Ssk) of rolling bearings are negative. The Ssk parameter is interpreted similarly to the Rsk parameter, meaning that negative values indicate a surface with plateau-shaped roughness peaks.

However, in the case of the equivalent of the parameter in 3D we observe a relationship between the values of Ssk parameters and the values of generated vibrations. An increase in the value of the Ssk parameter causes a decrease in the value of generated vibrations across all analyzed frequency ranges. The impact is most evident for the medium frequency band.

A conclusion can be drawn on the basis of the analysis of parameters of skewness of profiles and roughness topography that determining the 3D parameter, namely Ssk, seems justifiable. This parameter allows for the description of the nature of the peaks of unevenness with higher complexity, thus making it easier to evaluate tribological properties.

Pearson correlation coefficients (see table 3) were calculated in order to quantitatively evaluate the relationship between the determined 2D and 3D roughness parameters and the level of vibrations generated by the rolling bearings. Additionally, the correlation between the 2D roughness parameters and their equivalents analyzed in 3D aspect was examined. The results were presented in Table 4.
Table 3. Matrix of Pearson correlation coefficients between respective roughness parameters and the level of generated vibrations

|     | Ra   | Sa   | Rt   | St   | Rku  | Sku  | Rsk  | Ssk  |
|-----|------|------|------|------|------|------|------|------|
| LB  | 0.233| 0.205| 0.275| 0.087| 0.133| 0.133| -0.116| -0.188|
| MB  | -0.218| -0.214| -0.065| 0.061| 0.015| 0.102| 0.192| -0.016|
| HB  | 0.112| 0.123| 0.021| -0.066| -0.154| -0.018| 0.075| 0.041|

The analysis of the calculated values of Pearson linear correlation coefficients presented in Table 3 permit a conclusion that weak or low correlations could be observed between the 2D and 3D roughness parameters and the level of measured vibrations of rolling bearings. Considering the Ra and Sa parameters, higher correlation between the measured 2D parameters can be seen than between the 3D parameters. The high frequency band is an exception. This confirms the previous finding that there is no need to conduct time-consuming measurements and analysis of the Sa parameter when analyzing the raceways of rolling bearings. Similar results were obtained for parameters specifying the total height of the roughness profile Rt and St. Higher correlative dependence was obtained for the Rt parameter than for the St parameter. When considering the Rku and Sku parameters describing the skewness of the roughness profile, it can be observed that Pearson correlation coefficients assumed the same value for the low range of vibration frequency (LB). However, a higher correlation for the parameter Sku was obtained for the medium range of vibration frequency (MB). The analysis of the high range of vibration frequency (HB) shows higher correlative dependence for the 2D parameter, Rku. The interpretation of results for parameters describing the skewness of the roughness profile, namely Rsk and Ssk, is inconclusive. In the case of low band of vibration frequency, higher correlation was achieved for Ssk parameters. However, higher correlation is shown by 2D parameters, namely Rsk, for vibrations analyzed in the medium and high frequency range.

Table 4. Matrix of Pearson correlation coefficients between individual 2D and 3D roughness parameters.

|     | Ra   | Rt   | Rku  | Rsk  |
|-----|------|------|------|------|
| Sa  | 0.96 | 0.50 | 0.27 | -0.04|

Considering the results of calculations presented in table 4, a conclusion may be drawn that the highest correlation exists between the group of amplitude parameters, namely Ra and Sa parameters. A very certain correlative relationship was achieved in this case. A significant correlative relationship was observed among parameters specifying the total height of the roughness profile, i.e. Rt and St. Worse results were obtained for Rku and Sku parameters, where low correlation was found. The correlative relationship between 2D and 3D parameters was almost insignificant for parameters determining the profile's skewness (Rsk and Ssk).

It should be noted that the discrepancies between parameters Rt, Rku, Rsk and their 3D extension may result from the number of measurement points. It is known, that the number of measurement points used areal-topography method is greater than in line-profiling method.

4. Summary

The dynamic development of the bearing industry results in the growth of qualitative requirements of the manufactured products with the simultaneous reduction of production costs. To satisfy the requirements of the modern market the manufacturers must improve their measurement procedures, apart from constantly increasing the efficiency of production. This is of special importance in the case of analysis of the topography of active surfaces of bearings, because its quality affects the operating properties of bearing assemblies. There is no one universal parameter that can sufficiently characterize
the condition of the surface texture of the elements of rolling bearings. Currently, the surface roughness can be analyzed with line-profiling method (2D roughness) or areal-topography method (3D roughness). The selection of a suitable measurement method and the selection of roughness parameters that allow for the sufficient evaluation of the condition of the surface layer of rolling bearings is not fully unequivocal. It is recommended to select such roughness parameters that can be correlated with other operating parameters of rolling bearings, e.g. the level of generated vibrations. There are no generally available standards and guidelines determining the type of roughness parameters to analyze.

Thanks to the development of measurement systems which allow for the comprehensive analysis of the surface topography, 3D roughness measurements are gaining popularity. However, measuring a single surface using contact methods may take up to several hours. Consequently, the paper presents examinations whose purpose is to specify which 2D and 3D roughness parameters can be related to the level of generated vibrations.

Based on the research results presented in this paper, a conclusion can be made that the time-consuming analysis of surface topography of the raceways of rolling bearings is not always justified. Considering the amplitude roughness parameters, namely Ra and Sa, most commonly used in industrial conditions, it can be observed that it is the 2D roughness parameters (Ra) that exhibit higher correlation with the level of vibrations generated by the bearing. Similar results were obtained for the Rt and St parameter. Consequently, 2D profile analysis is sufficient for such parameters. However, when considering the results of examinations obtained for parameters describing in detail the surface texture, such as Rsk, Ssk, Rku and Sku, it is recommended to analyze the roughness parameters determined on the basis of 3D surfaces.

Summing up the results of the examination a conclusion may be drawn that the analysis of 2D roughness parameters, namely Ra and Rt, is sufficient for the more stabilized production processes. However, when beginning the production of new types of bearings or when modifying the processing parameters, it is recommended to analyze the 3D roughness parameters which describe the nature of surface topography in finer details.

The examinations presented in this paper are of initial research. The direction of further examinations will consist in expanding them with further 2D and 3D roughness parameters. Additionally, other types of rolling bearings will be examined. Research results indicate low and weak correlation between roughness parameters and vibration level. Therefore, the impact of the other factors (roundness and waviness deviation, internal clearance or lubrication types) on the vibration level should be investigated.

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