


Evaluation of dynamic properties of rolling bearings containing contact seals

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ABSTRACT

Most machine components contain rotating parts and, for this reason, rolling bearings are an integral part of mechanical equipment. Bearing subassemblies often have to carry considerable loads and rotate at high speeds. All this takes place with a small contact area between the bearing contact elements. Such difficult operating conditions result in frequent bearing failures. Failure of rolling bearings in machinery depends on many factors, such as overloading (especially when operating under variable loads and in high intensity machinery), inadequate lubrication, assembly errors, contamination, material fatigue. Loss of bearing life can perhaps be detected by monitoring dynamic parameters, such as vibration or frictional moment. This article pointed out that the relationship between frictional moment and vibration level is not always obvious, and the use of bearings with contact seals requires additional analysis. The research presented here can contribute to a better understanding of the parameters frictional moment and vibration level. This can provide valuable insights into the development of low-friction bearings that are also dynamically stable (with low vibration levels), which is important in precision applications, such as aviation or the medical industry.

Keywords: vibration, bearings, dynamic properties, frictional moment.

INTRODUCTION

A very important consideration that affects the failure rate of rolling bearings is manufacturing precision. The high manufacturing precision of rolling bearings can be related to three aspects that affect the final quality of rolling bearings [1,2].

One of these aspects is the imposed dimensional and shape tolerances. High-quality bearings should have very tight dimensional-form tolerances. Narrow dimensional-form tolerances, in turn, mean that the individual components of the bearing, such as the inner ring, outer ring and rolling elements can be fitted together more precisely at the assembly stage [3].

The second aspect involves the technologies used to produce high-quality bearings involving-advanced machining processes, such as forming, turning, grinding, polishing and heat treatment.

The selection of appropriate machine tools, machining fixtures and machining parameters should ensure not only dimensional accuracy and the required geometric structure of the mating surfaces, but also appropriate mechanical properties, such as hardness and wear resistance [4,5].

The third aspect concerns the procedures and measurement systems used in quality control. These should be aligned as closely as possible to the imposed tolerances and technologies used at each stage of production, allowing potential production defects to be identified and eliminated [6,7]. The ever-increasing demands of customers for manufactured rolling bearings mean that production defects are increasingly discrete and difficult to detect. Therefore, the procedures used in the quality control of the bearing industry should be more sensitive than diagnostic methods, which are mainly designed to detect in-service damage [8,9].

The aim of this article was an attempt to understand the correlation between frictional moment and the vibration level of a rolling bearing. This topic is crucial for improving the efficiency, reliability and durability of mechanical systems. These two dynamic parameters of rolling bearings discussed here provide complementary information on the operating condition of the bearing, and their analysis can lead to more precise diagnosis and design optimization [10,11]. In addition, identifying their interdependence enables the development of more effective diagnostic algorithms and monitoring systems that can predict failure before it occurs. Optimization for frictional moment and vibration can lead to energy savings (less energy loss) and longer bearing life [12,13].

In the literature, the frictional moment and the level of generated vibrations are widely analyzed, but most often in the context of bearings without contact seals. In such cases, the relationship between vibration level and friction torque is relatively well understood – an increase in one parameter usually correlates with an increase in the other, resulting from worsening friction conditions, increased irregularity of the rolling element motion, and surface defects. Much less is known about this relationship for bearings with contact seals, which are widely used in industry for protection against contamination and lubricant loss. These seals introduce additional sliding friction, which affects the frictional moment, but their effect on vibration has not yet been clearly described.

A new feature to the paper was evaluation of the relationship between the frictional moment and the vibration values generated by open and sealed bearings. This allows concluding that contact seals act as vibration dampers, stabilizing the motion of the rolling elements.

METHODS

The quality evaluation process for a bearing is complex and strongly dependent on the requirements of the recipient. Some procedures are always performed, others only on the special order of the recipient, some procedures are subject to the whole population of manufactured bearings, others only to a specific statistical sample [14,15]. Some procedures are destructive, others not. Inspection systems for measuring vibrations and frictional moment are some of the most important pieces of measuring equipment found

in bearing factories, and the measurement results obtained provide a great amount of information about a newly manufactured bearing [16].

Bearing quality criteria based on vibration measurement

Measurement of vibrations is the most essential part of rolling bearing quality control. Two types of measuring instruments are used to measure the level of vibration generated by bearings under industrial conditions: automatic and semi-automatic. Automatic measuring instruments are used in automatic assembly lines [16]. If a bearing meets the criteria of the set limits, it is directed to leave the production facility. Semi-automatic devices are used to control the rejects of an automatic line or for research and development. The main components of such instruments are the measuring unit with a vibration sensor, the measuring spindle (hydrodynamic, hydrostatic or pneumatic) and its drive, the pressing unit for the tested bearing, the bearing feeding system to the measuring stand (manual or automatic), the support structure with shock absorbers and the control system [17]. An example of the appearance of such a test rig is shown in Figure 1.

The central component of the device shown in Figure 1 is a hydrodynamic spindle. One end of this spindle is designed to transmit power via a belt, whilst the other end features a tapered socket for interchangeable shafts. The shafts are adapted to the standard dimensions of the inner ring bores of the bearings. Once the appropriate shaft has been fitted, the rolling bearing under test can be mounted on it. In front of the spindle is a swing-out thrust arm which allows small axial loads to be applied and immobilises the outer ring, enabling vibration measurement. Above the bearing there is a mount for an electrodynamic vibration sensor. The sensor makes contact with the bearing and enables the recording of the vibration velocity signal. The electronics and software of the test rig enable signal filtering and processing, dividing it, amongst other things, into frequency bands.

The above-mentioned measuring equipment allows vibration levels to be measured 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 refer to the fixed spindle speed of 1.800 min^{-1} at which all tests are carried out. In special cases, the rotational speed may be different and equal 900 rpm or

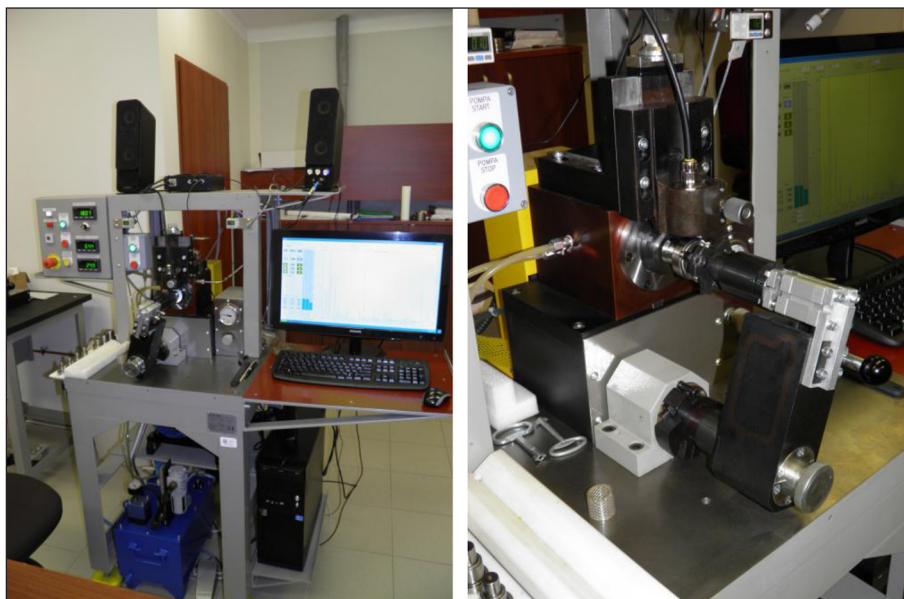


Figure 1. Semi-automatic device for measuring rolling bearing vibrations [17,18]

3600 rpm. It should then be borne in mind that the frequency bands will also change. This rotational speed is the reference speed and is defined by the standards for industrial measurement of bearing vibration levels.

During the measurement, the effective value of the vibration velocity (RMS) for each frequency band is determined. The vibration level is expressed in different units, depending on the customer's requirements, but the most common is $\mu\text{m/s}$. The bearings with exceeded vibration levels that show signs of significant damage are dismantled. The bearing components to be disassembled are subjected to a microscopic inspection. The results of this inspection influence the next steps. If the problem is random, production procedures should be analyzed, but if more than one component is affected, the cause of the problem should be identified and resolved. The detected deficiencies have a positive impact on the technological process. Every improvement in the technological process increases the performance of the manufactured bearing.

Bearing quality criteria based on the measurement of the frictional moment

The frictional moment is a parameter that determines the energy efficiency of a rolling bearing. This parameter contains a lot of information about the bearing, be it in terms of its design, the quality of the mating parts, its cleanliness or certain properties of the lubricant [19,20]. Given the widespread use of bearings in the automotive,

machinery or white goods industries, the need arises to reduce friction in rolling bearings, a key measure in the quest to improve performance, reduce energy consumption and protect the environment [21]. The work in this direction focuses on isolating the factors that increase frictional resistance in a bearing and seeking to minimise their impact. The ability to measure precisely the frictional moments present in rolling bearings, as well as knowledge of the dependence of their values on bearing operating conditions, including factors such as rotation and load, allows machine and equipment designers to optimize the selection of bearings in specific design nodes, while also enabling them to be optimized for wear [22,23]. The measurement of bearing frictional moment is not a destructive test; however, it is quite time-consuming and difficult to automate in order to be verified for each bearing tested. The ability to measure precisely the frictional moment present in rolling bearings, as well as to determine the dependence of its value on the operating conditions of the bearings, including factors such as rotation and load, allows machine and equipment designers to optimize the selection of bearings in specific design nodes, and bearing manufacturers to assess their quality as well as choose the right directions for design improvement. Figure 2 shows a laboratory device for precise measurement of frictional moment. On the main plate, on the front side of the spindle, there is a longitudinal load table with which an actuator attached to the underside of the main plate cooperates. A sensor

for measuring the axial force is connected to the table. On the left side of the spindle, on the main plate, there is a table fixed to which the measuring force gauges can be combined. The drive unit, owing to two separate motors, ensures operation of the spindle both at very low speeds (1 [rpm]) and very high speeds up to 26,000 [rpm]. The outer ring of the bearing under test is placed in a thin-walled plastic housing, the flange of which blocks the bearing from falling out at the other end. The bearing is then slide-fitted to the journal and fixed behind the face of the inner ring with a screw that is screwed into the journal via a washer. A cover is screwed into the housing. A linkage for the axial load force is fixed in the center of the cover.

In Figure 3 it can be seen that for the bearings without seals, the frictional moment and the vibration level of the rolling bearing are positively correlated with each other. In these two cases, the Pearson correlation coefficient is about 0.8. This shows that the correlation is quite high. Both parameters are related to the operating condition of the bearing and the friction conditions between the rolling elements and the raceways. Generally speaking, in durability tests, an increase in both one and the other parameter indicates a deterioration of the bearing condition. It can therefore be assumed that the quality of a bearing is inversely proportional to both the level of frictional moment and the level of vibration.

The tie rod fastening system is located on the bearing housing formation. A force gauge is mounted in the measuring table and connected to the measuring housing by a rod. The frictional resistance in the bearing tries to cause the outer ring to rotate together with the housing, which pulls the tendon with a force proportional to the thrust moment. The test rig also allows non-contact temperature measurement during the test.

The sensor directly registers the temperature of the thin-walled housing, which approximates the temperature of the bearing under test. The test bench shown measures the frictional moment at a frequency of 0.02 seconds. This makes it possible to track its discrete changes over time. In addition to the frictional moment, the system records signals of spindle speed, axial load force and bearing housing temperature.

RESULTS

General correlation between frictional moment and rolling bearing vibrations

To illustrate the general correlation between frictional moment and rolling bearing vibration, these two parameters were measured for 11 rolling bearings from different manufacturers. All bearings were of type 6204 and each had a nitrile seal on both sides, usually designated 2RS by the manufacturers. Vibration and frictional moment were recorded for the same test parameters, i.e. the rotational speed of the inner ring was 1800 rpm and the axial load was 130 N. The correlation was tested in three variants: brand new bearings, brand new bearings but with the nitrile seals removed and brand new bearings with the lubricant removed (after the washing procedure). Correlation graphs can be found in Figure 3. Linear interpolation was used to illustrate the overall trend. Such a small sample size results in the fact that it is difficult to assess unambiguously whether the relationship is linear. Besides, it can vary depending on the type and type of bearing, operating conditions such as load, speed or lubrication. The positive and high correlation seen in Figures 3b and 3c can be easily explained. A high

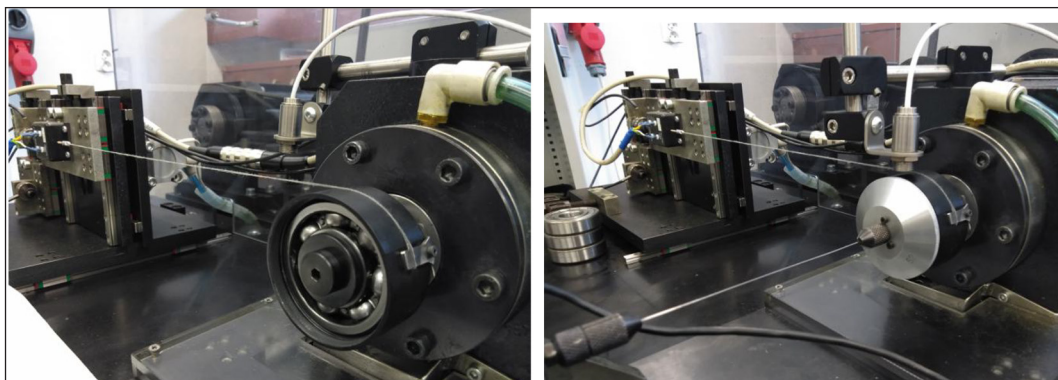


Figure 2. Semi-automatic rolling bearing frictional moment measuring device

frictional moment often leads to higher vibrations, as increased internal friction generates forces of instability and unevenness of rolling element movement. In turn, higher vibrations can cause additional dynamic friction (contact oscillations), which can increase the frictional moment. Insufficient lubrication or lubrication degradation can increase both the frictional moment and vibration levels. This is due to increased friction between the rolling elements and the raceways, which generates uneven motion and increased thrust forces. Excessive lubricant (or too high its viscosity) also increases not only the frictional moment, but also the vibration. The balls rolling on the raceway have to overcome resistance in the form of too much or too viscous a portion of lubricant, which can cause additional oscillations. However, it should be noted at this point that this is not a rule and that the right amount of lubricant with the right viscosity can in turn reduce vibrations.

The correlation observed in the two cases may also be due to the fact that imperfections such as deformations of the rolling elements or even excessive waviness and surface roughness cause local increases in frictional force, which increases the frictional moment and at the same time generates vibrations with characteristic frequencies. In principle, the greater the imperfections and

defects of the mating surfaces, the more these two parameters will increase simultaneously. With a higher load, the contact between the rolling elements and the raceways increases, which raises the frictional moment. At the same time, a higher load can lead to greater deformation and unevenness of movement, resulting in an increase in vibration.

However, the relationship is different when the bearing contains a contact seal. The graph in Figure 3a shows that the correlation is much weaker and, in addition, negative. However, the too small number of data is not able to give a true representation of the correlation. For this reason, it was decided to extend the study and focus on assessing the relationship between vibration level and frictional moment level for a larger and more diverse number of bearings containing a nitrile seal.

Evaluation of the correlation between frictional moment and vibration of bearings with contact seals

In order to further assess the correlation between frictional moment and vibration in rolling bearings containing contact seals, 30 new bearings from several different manufacturers were purchased. Different manufacturers use

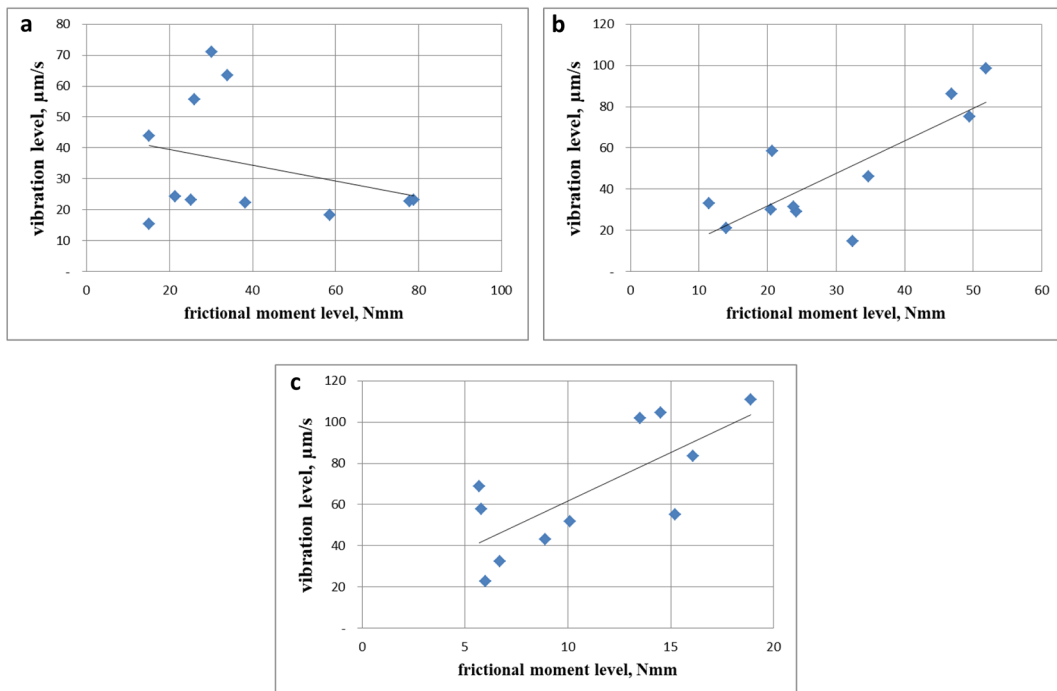


Figure 3. Dependence between the rms value of the vibration velocity in the 300–1800 Hz band and the frictional moment of rolling element bearings type 6204 (rotational speed 1800 rpm, axial load 130 N): (a) bearings with RS-type nitrile seals, (b) bearings with seals removed, (c) bearings without lubricant

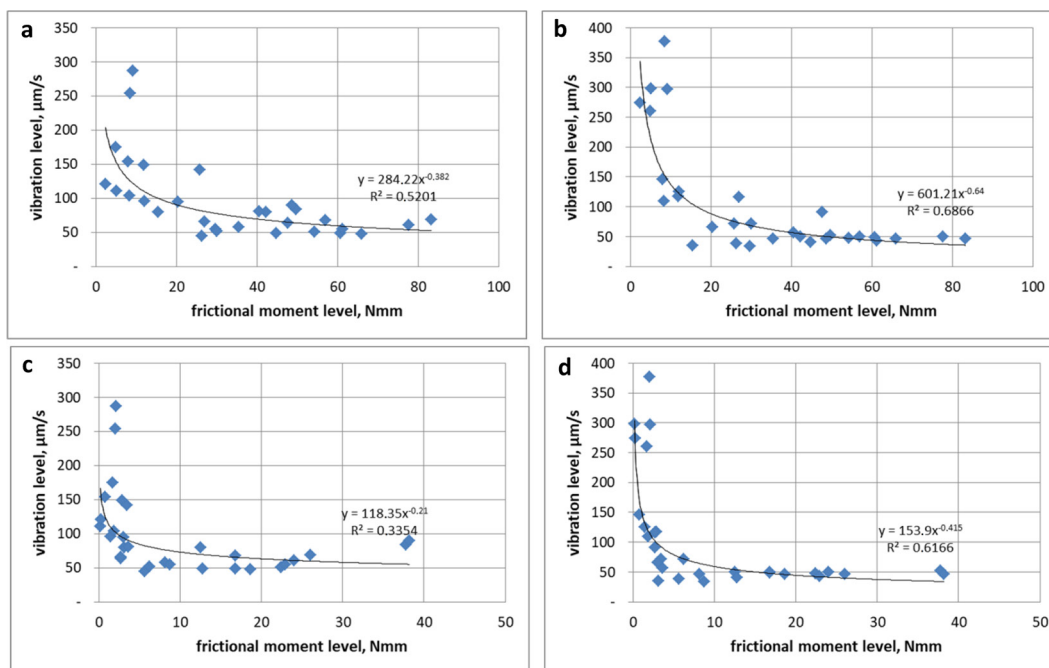


Figure 4. Correlation of vibration and friction torque measurement results of bearings containing contact seals: (a) vibration RMS in the low-frequency range with frictional moment at 1800 rpm, (b) vibration RMS in the mid- and high-frequency ranges with frictional moment at 1800 rpm, (c) vibration RMS in the low-frequency range with frictional moment at 50 rpm (d) vibration RMS in the mid- and high-frequency ranges with frictional moment at 1800 rpm

different technologies for the shape and material of the seal, as well as the geometry and surface of the inner ring to which the seal adheres. As a result of these differences, bearings from different manufacturers generate varying levels of frictional moment. In addition, the imprecision of the bearings means that, even within a single manufacturer, there is considerable variation in the results of the frictional moment level measurement.

Vibration and frictional moment levels were measured for each of the 30 bearings tested. The vibration level test was performed in accordance with parameters according to the standards designed for the bearing industry (ISO 15242) and is regarded as an objective vibration level for the bearing in question. According to the standards, vibration measurement is three results: the RMS value of the vibration velocity in three separate frequency bands 50–300 Hz, 300–1800 Hz and 1800–10000 Hz, at a rotational speed of 1800 rpm and an axial load of 135 N. Due to the very high correlation between the results in the medium and high bands, it was decided to combine the medium and high bands into a single medium-high band (M&H) in order to reduce the number of data presented. Frictional moment

measurements were taken for various combinations of test parameters - axial load and speed - to check whether the general trend in the correlation between vibration and frictional moment could be reproduced. Frictional moment was tested at an axial load of 135 N and two different speeds of 50 rpm and 1800 rpm. The correlation diagrams are shown in the graphs in Figure 4.

When measuring the bearings with contact seals, the solution is different to that of bearings without such seals. It turns out that, regardless of the test parameters at which the frictional moment was tested and the frequency band analyzed, the seals stabilize the mechanical system by damping irregular movements of the rolling elements. The contact seals act as an additional damping element that reduces the vibration amplitude, although the thrust moment is higher. This phenomenon is due to the controlled nature of the friction introduced by the seals and their ability to absorb vibration energy. As a result, contact seals improve the stability of bearing operation, although at the cost of higher energy losses. The resulting functions are of a power-law nature, which is the best-fit prediction. The power function was adopted on the basis of the evaluation of parameter R2, the

highest results of which were obtained precisely for the power function.

The relationship between vibration level and frictional moment was modeled using a power regression of the form:

$$y = ax^b \tag{1}$$

where: a is prefactor of a function and b is exponent of a function. The parameters were estimated using the least squares method. The analysis was performed in EXCEL. The obtained regression coefficients are summarized in Table 1.

The negative values of exponent b indicate a decreasing nonlinear relationship between the analyzed variables. Additionally, Table 1 presents the results of the Spearman rank correlation coefficient. Spearman’s rank correlation coefficient was used to assess the monotonic relationship between variables due to the nonlinear nature of the analyzed dependence.

Research into the correlation between frictional moment and vibration level is fundamental to understanding bearing dynamics, diagnosing bearing condition and optimizing bearing design. Conclusions from such research lead to better design, more efficient operation and increased reliability of mechanical systems, with benefits in both economic and technological terms.

In conventional rolling bearings, an increase in frictional moment usually correlates with higher vibrations, as higher friction generates greater instability forces in the system. Imperfections of the mating surfaces of rolling bearings that increase vibration also raise frictional moment.

In bearings with contact seals, especially those made of materials such as nitrile, a reversal of the correlation between thrust moment and vibration level can be observed. Contact seals generate additional sliding friction, which increases the frictional moment, but at the same

time can act as vibration dampers, reducing vibration levels.

The contact seals adhere to the inner ring, which generates additional sliding friction. This friction is constant and independent of the unevenness of movement of the rolling elements, but adds to the total frictional moment of the bearing. It turns out that contact seals can act as a damper, as their elastic structure absorbs part of the vibration energy transmitted from the raceways and rolling elements. The additional sliding friction introduces an energy loss, which reduces the amplitude of vibrations generated by the non-uniformity of motion characterizing the bearing. As a result, even if the frictional moment is high, the vibration level can be reduced compared to the bearings without seals. When seals generate stable and predictable friction, they can reduce resonance effects or irregularities in motion that would lead to increased vibration.

In all four cases, the exponent b takes on negative values (ranging from approximately -0.21 to -0.64), which means that an increase in the coefficient of friction leads to a decrease in the vibration amplitude. This confirms the existence of a non-linear damping effect, in which friction has a stabilizing effect on the dynamic system. The strongest effect is observed in case (b), where $b = -0.64$, indicating very intense vibration damping as the friction force increases at 1800 rpm and in the higher frequency band. In contrast, in case (c), where $b = -0.21$, this relationship is significantly weaker, suggesting lower damping effectiveness in the lower frequency band at low rotational speed (50 rpm). The parameter a , on the other hand, indicates the baseline vibration level. It reaches its highest value in case (b) $a = 601.21$, which means that the system generates the highest initial vibrations, but at the same time these are reduced most rapidly due to the strong damping effect.

Table 1. Regression parameters of the model $y = ax^b$ and Spearman’s rank correlation coefficients for the analyzed cases

Correlation	Prefactor	Exponent b	Spearman’s Rho ρ
Vibration RMS in the low-frequency range with torque at 1800 rpm	284.22	-0.38	0.71
Vibration RMS in the mid- and high-frequency range with torque at 1800 rpm	601.21	-0.64	0.67
Vibration RMS in the low-frequency range with torque at 50 rpm	118.35	-0.21	0.63
Vibration RMS in the mid- and high-frequency range with torque at 50 rpm	153.90	-0.42	0.76

CONCLUSIONS

This work on assessing the correlation between vibration levels and frictional moment in bearings with contact seals provide a number of benefits in the context of design, operation and diagnostics and include:

- friction surface geometries that minimize sliding friction while maintaining vibration damping capability;
- the material properties (e.g. hardness, elasticity) that best balance additional energy losses (frictional moment) and vibration damping performance;
- dependency analysis to detect sealing malfunction problems, such as excessive wear or material degradation, which can alter vibration and friction characteristics.

A sliding contact geometry was developed that offers a compromise between frictional moment and vibration damping capability depending on application requirements. Developing a new indicator used in the manufacturing process that based on the relationship between vibration levels and frictional moment – e.g. excessive frictional moment at low vibration levels may indicate a problem in the seal geometry or materials.

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