Stanisław ADAMCZAK*, Łukasz GORYCKI*,
Włodzimierz MAKIEŁA*

THE ANALYSIS OF THE IMPACT OF THE DESIGN PARAMETERS ON THE FRICTION TORQUE IN BALL BEARINGS

ANALIZA WPŁYWU WYBRANYCH PARAMETRÓW KONSTRUKCYJNYCH ŁOŻYSK TOCZNYCH NA ICH MOMENT OPOROWY

Key words:

ball bearings, frictional moment, coefficient of friction, curvature ratio

Słowa kluczowe:

łożyska toczne, moment oporowy, współczynnik tarcia, współczynnik opasania

Abstract

One of the many factors influencing the frictional moment in the bearings are construction parameters. These parameters include curvature ratio (the ratio of the radius of the track to the diameter of the ball) and the accuracy of the track shape. Although these factors influence the frictional moment, they are not included in the model used to determine the theoretical frictional moment. In this article, an analysis was carried out to determine the quantitative impact of the curvature ratio at the frictional moment in ball bearings. In order to

* Kielce University of Technology, Department of Manufacturing, Engineering and Metrology, al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland, tel. 41 34-24-434, e-mails: adamczak@tu.kielce.pl; lgorycki@tu.kielce.pl; wmakiela@tu.kielce.pl.

determine the quantitative effects of this parameter, a linear regression analysis was carried out on five groups of bearings and under five measuring parameters (the rotational speed, the radial and axial load and curvature ratio of the inner and outer ring).

INTRODUCTION

Bearings are elements of machines that constrain relative motion to only the desired motion and passing loads, ensuring the lowest possible energy losses due to friction. Ball bearings, due to their construction, are capable achieving high speed and multidirectional load, and they are used in the largest number of applications. For the bearing users, the most important quality parameter is durability, which is the parameter that determines how long the bearing will work without the need for replacement.

Due to the importance of the durability as a parameter closely related to the devices reliability (in which the bearings are mounted), manufacturers are obliged to provide their users with specific technical catalogues containing the required parameters, which are the basis for calculating the optimal selection of bearings that will work in specific conditions.

Bearing life depends on many factors. External factors are the operating conditions, which include rotational speed, load, temperature, and contamination of the environment **[L. 1]**, as well as the correct mounting of the bearing. To internal factors, we include bearing design, manufacturing accuracy of rotating elements, the play, the type of lubricant, and the presence of contaminants. These factors affect such basic performance parameters like load capacity, the maximum speed, generated vibration levels, and the frictional moment (which determines the energy losses, translating into the amount of heat generated during work). Operating parameters determine at what level the bearing temperature will stabilize, and this has an important impact on the life of the lubricant and, in consequence, on the bearing itself. Therefore, the ability to determine the exact frictional moment determines the life forecast of rolling bearings under certain conditions.

Existing dependencies used to determine the theoretical moment of resistance do not account for all the factors that affect this moment. These factors include the type of cage, curvature ratio, and the manufacturing accuracy of the track **[L. 2, 3]**. The curvature ratio is defined as the ratio of the raceway radius to the ball diameter. This article contains analysis on the curvature ratio impact on the ball bearing frictional moment.

The study group contained five samples of 6203 bearings with different curvature ratios (each sample contained 10 elements). An important factor in the selection of the bearings was the fact that the bearing of individual samples came from the same production batch. This allowed us to assume that the impact of the production process on the curvature ratio was minimized. Each of the samples was made at different time, which did not guarantee maintaining the same level of other parameters of the precision (macro- and micro waviness, roundness, track deviation profile, etc.).

FRICTION TORQUE CHARACTERISTIC

The friction torque as a utility parameter allows the determination of how well and how long the bearing will work in given conditions. The larger the frictional moment, the greater the energy loss in a working bearing; therefore, the wear of the bearing occurs faster. This is described by the following formula (1) **[L. 4]**:

$$NR = 1.05 \cdot 10^{-4} \cdot M \cdot n \tag{1}$$

where: NR – power loss [W]; M – total frictional moment of the bearing [N mm]; n – rotational speed [r / min].

In order to predict the durability of a bearing, operating under certain conditions, each bearing should by examined before use. This would entail additional financial costs and the loss of time. We can also analyse the theoretical frictional moment, but currently used models give inaccurate results and do not account for all of the factors that affect the frictional moment. Research conducted in the Department of Mechanical Technology and Metrology at Kielce University of Technology focused on the determination of the relationship between frictional moment and factors such as rotational speed, axial load, radial load, and curvature ratio (the ratio of the radius of the track to the diameter of the ball). Currently used equations used to determine the theoretical value of the frictional moment (2) and (3) ignore the value of the curvature ratio. As it is shown in **[L. 2]**, the curvature ratio has an influence on the frictional moment in roller bearings. The study assumed a theoretical value of the curvature ratio, because this value is given by the manufacturer, and, for this value, the frictional moment will be determine. To determine the real value of the curvature ratio, the bearings should be dismantled, measured, and then, in order to perform additional measurements of the frictional moment, the bearing has to be reassemble. These actions could cause damage to the bearing elements, for example, the deformation of the outer ring, which would prevent any further research on these bearing.

Where the exploitation takes place under standard conditions and when good lubrication is applied, the following equation can be applied in order to determine the frictional moment **[L. 5]**:

$$M = \frac{P\mu d}{2} \tag{2}$$

where: P – equivalent dynamic bearing load, μ – constant bearings coefficient of friction which depends on the bearing type, and d – bearing bore diameter.

Another approach to determine the theoretical frictional moment was presented by SKF **[L. 4]**. The company uses a mathematical equation that takes into account a larger range of friction sources that can occur in a bearing.

$$M = M_{rr} + M_{st} + M_{seal} + M_{drag} \tag{3}$$

where: M_{rr} – rolling frictional moment, M_{st} – sliding frictional moment, M_{seal} – seals frictional moment, M_{drag} – frictional moment resulting from the lubrication system, the resistance movement in the oil environment, and kneading lubricant splashes.

MATHEMATICAL MODEL USED TO DETERMINE THE FRICTION TORQUE

From previous studies **[L. 2**, **3]**, in addition to the parameters, such as rotational speed, axial load, radial load, and the type and quantity of lubricant, the frictional moment is also affected by the curvature ratio and the cage type. These studies did not indicate the quantitative effect on the frictional moment, but only confirmed that this parameter and the cage type have a clear impact on the frictional moment in the bearings.

At the current stage of research, there is no basis to develop a theoretical model for determining the frictional moment, taking into account various factors. Therefore, it was decided to develop an experimental model using linear regression. As a first approximation, it is assumed that the frictional moment is based on four structural parameters: rotational speed, axial load, radial load, and a linear curvature ratio.

The general model for linear regression is as follows:

$$y_i = x_1 \alpha_{i1} + \ldots + x_p \alpha_{ip} + \varepsilon_i \tag{4}$$

In this model, y_i is the observed response of the i-th experiment; α_{ij}, $i = 1, \ldots, n$; $j = 1, \ldots, p$; explanatory variables are also called j-th regression coefficients α_j, in i-th experiment; $x_1, \ldots, x_p$ are unknown parameters; while the quantities ε_i re random variables representing errors in the relationship –

"measurement error," the ε may be "natural" fluctuations associated with the feature of the examined object or can represent measurement error response *y* **[L. 6]**.

A linear regression model equations based on the correlation between frictional moment and five construction parameters is as follows:

$$y_i = x_1 p_i + x_2 o_i + x_3 v_i + x_4 w_{pz\,i} + x_5 w_{pw\,i} + \varepsilon_i \qquad (5)$$

where: y_i – the result of the i-th frictional moment measurement [N mm], v_i – rotational speed [r / min], o_i – axial load [N], p_i – radial load [N], $w_{pz\,i}$/ $w_{pw\,i}$ – theoretical curvature ratio of the outer / inner bearing ring, x_i – unknown parameters, and ε_i – measurement error.

To determine the mathematical model, we should carry out a comprehensive study, taking into account the whole range of the regressor variations, and then, using the formula mdl = fitlm (A, Y) in the MatLab program, determine the linear regression equation.

DESCRIPTION OF THE MEASURING DEVICE

To perform necessary measurements of the frictional moment, we used torque-meter STPM. This device is designed and manufactured at Kielce University of Technology. The torque-meter STPM has the ability to perform measurements at preset values of speed, and axial and radial loads. Most of the equipment used to frictional moment cannot perform these measurements under radial load. This capability allows us to carry out research in conditions similar to those in which the bearings are used.

The software of the torque-meter allows for real time measurement analysis and to changes the parameters in real time. Thanks to the software, we have the ability to program the course of the entire measurement. This allows us to carry out further measurements in reproducible conditions. The software also allows starting the implementation of the measurement after reaching predetermined conditions, for example, an appropriate temperature of the bearing. This is especially important in cases of measurements frictional moment in open or closed bearings with a lubricant. Due to the strong relationship between the lubricant resistance and its viscosity, the measurements of the bearing have to be performed in the same temperature. For bearings used for this test, the temperature was 40°C.

MEASUREMENT RESULTS AND ANALYSIS

Measurement conditions

In this research, 50 bearings (6203) were used, as mentioned before, there were open and with lubricant. The bearings were divided into five groups according to their theoretical values of the curvature ratio. The main reason for choosing these bearings was the fact that each individual group came from the same production batch. The selection of the five groups were made to meet the requirements of the model used to determine the linear regression, namely, the number of measurements must be the same as the number of input parameters (square matrix). The measurements were carried out for the speed limit of 6203 bearings (amounting to 10 000 r/min) and for the maximum value of the axial and radial load of the torque-meter STPM (400 N and 200 N). Under these conditions, there are opportunities to achieve the greatest frictional moment, and the differences between the results of each group should be the most visible.

Summary of the results

The measurement results are shown in **Table 1**. In **Table 1**, we see the average values of the frictional moment, axial load, radial load, and speed obtained from each group. It should be emphasized that the parameters that influence the frictional moment change slightly, and yet the results of the frictional moment are quite different. In fact, significantly different values in these groups are the values of the curvature ratios.

Table 1. Measurement results
Tabela 1. Wyniki pomiarów

Measurement number [i]	frictional moment y_i [N·mm]	radial load p_i [N]	axial load o_i [N]	Rotation speed v_i [obr/min]	curvature ratio $w_{pz\,i}$	curvature ratio $w_{pw\,i}$
1	14.56	384.64	200.01	9935. 41	0.532	0.516
2	16.44	384.28	200.00	9933.37	0.521	0.515
3	17.31	382.73	200.02	9934.05	0.531	0.506
4	17.63	381.99	199.99	9933.45	0.531	0.510
5	20.95	381.68	200.01	9945.86	0.515	0.515

Therefore, in the first phase of research, it was decided to designate the dependency of the frictional moment from 2 factors, namely, external and internal curvature ratios. Determination of the full model will be possible after taking into account a wider range of variation of other factors.

In addition, analysing the results (**Table 1**), it may appear that there are no relations between them. It must be taken into account that there are a large number of factors that influences operating parameters (frictional moment or vibration). We cannot expect a very clear and unequivocal result based on the evaluation of only a few factors. When taking this into account, it can be assumed that further analysis will give clearer results.

Calculations

Therefore, the scope of the study take into account the variation of the curvature ratio (inner and outer track), and a simplified linear model was used to determine the association between the frictional moment and the curvature ratio. Dependence is determined by the least square method.

The results obtained in the given measurement conditions took the following form:

$$y = -\,343.1w_{pz} - 340.1\mathrm{w}_{\mathrm{pw}} + 372.2 \quad (6)$$

From the given model, the frictional moment decreases with increasing the curvature ratio of both the track and the proportion of each is at the same level.

Thanks to the formula mdl = fitlm(A, Y), a linear model showing the dependency between the frictional moment and five preset factors was obtained.

After entering the results into the equation (5), it adopted the following form:

$$y = -1.1037\, p - 6.039 \cdot o + 0.18036\, v - 138.88 \cdot w_{pz} - 138.99 \cdot w_{pw} + 0 \quad (7)$$

The values of the measurement results show that the higher the rotational speed, the greater the frictional moment, and it confirms that the growth of any of the curvature ratio will decrease the frictional moment. These relationships are consistent with generally accepted assumptions. In the case of the axial and radial load, we see that the increase in the value of these parameters will decrease frictional moment, which is inconsistent with the theoretical analysis. This clearly confirms that the relationship (7) is not too reliable. In order to determine a more precise form of the equation (7), a higher volatility of other factors affecting the frictional moment should be taking into account in subsequent measurements.

Models (6) and (7) unequivocally confirm that the curvature ratio has a significant impact on the frictional moment.

SUMMARY

Analysis of dependence (6) clearly shows that the curvature ratio of the outer and inner ring have a significant impact on the frictional moment, i.e. the higher curvature ratio, the smaller is the frictional moment. In addition, analysis of the results contained in **Table 1** showed that, in order to create a more accurate mathematical model to determine the theoretical frictional moment, we must take into account additional factors. One of these factors is the play in the bearings. The smaller the play, the greater the work angle of the in the rolling element in the bearing; thus, the greater the actual force acting in the bearing. Continuation of the research must take into account a larger number of study groups of bearings, thereby enhancing the credibility of the results. In addition, an estimate of the error of approximation will be performed.

Further research aimed at creating a mathematical model to determine the theoretical fractional moment must include the following:

– Correction of the acting forces on the bearing, basing on the bearing play; and
– Performing additional measurements under different conditions (different speed, different axial and radial load) and taking into account the full range of variation of these parameters.

REFERENCES

1. Wpływ smarowania i zanieczyszczenia na trwałości łożyska, część 1. Evolution nr 2/2010.
2. Gorycki Ł., Domagalski R., Zmarzły P., Pomiary momentów oporowych łożysk tocznych w aspekcie dokładności kształtowo-wymiarowej elementów współpracujących. Mechanik nr 3/2015, s. 187–193.
3. Gorycki Ł., Analysis of the Impact of the Cage Type on the Frictional Moment Ball Bearings. Journal of Mechanics Engineering and Automation, Vol. 8, No. 8 (2015): pp. 450÷453.
4. SKF katalog łożysk tocznych.
5. Krzemiński-Freda H., Łożyska toczne. Państwowe Wydawnictwo Naukowe. Warszawa 1985.
6. Muciek A., Wyznaczanie modeli matematycznych z danych eksperymentalnych. Oficyna Wydawnicza Politechniki Wrocławskiej. Wrocław 2012.
7. Jankowski R., Lubowiecka I., Witkowski W., Matlab – podstawy programowania. Politechnika Gdańska, Wydział Inżynierii Lądowej. Gdańsk 2001.

Streszczenie

Wśród wielu czynników, które mają wpływ na moment oporowy w łożyskach są parametry konstrukcyjne. Do tych parametrów zaliczamy: współczynnik opasania (stosunek promienia bieżni do średnicy kulki) oraz do-

kładność wykonania bieżni. Chociaż są to czynniki mające wpływ na moment oporowy, nie są one uwzględniane we wzorach stosowanych do wyznaczenia teoretycznego momentu oporowego. W niniejszym artykule przeprowadzono analizę mającą na celu wyznaczenie ilościowego wpływu współczynnika opasania na moment oporowy w łożyskach tocznych. W celu ustalenia ilościowego wpływu tego parametru przeprowadzono analizę regresji liniowej na pięciu grupach łożysk, przy pięciu zadanych parametrach pomiarowych (prędkości obrotowej, obciążeniu promieniowym i osiowym oraz współczynniku opasania wewnętrznego i zewnętrznego pierścienia).