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Vpliv vrste mazanja in sestave momenta trenja na skupno trenje v kroglični ležajih

The Influence of the Lubrication Type and the Structure of Friction Torque on Total Friction in Ball Bearings

MITJAN KALIN - JOŽE VIŽINTIN

Trenje v kotalnih ležajih se pojavlja iz več vzrokov, eden ključnih je vrsta mazanja, ki jo popisuje koeficient trenja med površinama kotalnih delov in tečin. Poleg zagotavljanja ustreznega mazanja je, za dosego kakovostnega delovanja in dolge dobe trajanja kotalnih ležajev, pomembno tudi poznavanje vzrokov in sestave trenja, kar omogoča optimiranje delovanja kotalnih ležajev.

V prispevku je prikazan vpliv vrste mazanja oziroma koeficienta trenja na skupni moment trenja ter na nekatere deleže v skupnem momentu trenja v kroglični ležajih. Za določitev velikosti in sestave trenja smo uporabili meritve na preizkuševališču kotalnih ležajev ter dve računski metodi, ki temeljita na povsem različnih osnovah: računalniško simuliranje na podlagi matematičnega modela in izkustveno enačbo.

Ključne besede: ležaji kroglični, vrste mazanja, moment trenja, modeli matematični

Friction in rolling bearings arises from several sources, but one of the most influential is the type of lubrication, described by the coefficient of friction between the rolling elements and raceways. Another crucial factor influencing the rolling bearings performance and life is sliding friction, which depends on the relative motions of the contacting bodies within the loaded areas. Knowing the sources and the structure of the total friction torque allows to optimise the conditions for bearing operation.

In this paper, a description is given of the influence of the type of lubrication and coefficient of friction on the ball bearing friction torque and some of its portions. Results of measurements on the rolling bearing test rig and two different computational methods, i.e. mathematical model and empirical equation, were used to determine the values and the structure of friction torque in the ball bearings.

Keywords: ball bearings, type of lubrication, torque, mathematical models

0 UVOD

Moment trenja v kotalnih ležajih je posledica več dejavnikov [1], [2], ki se kažejo prek kotalnega in drsnega trenja, elastične histereze deformiranega materiala, vrtinčenja maziva itn. Eden ključnih parametrov je gotovo vrsta mazanja [3], ki jo popisuje koeficient trenja med površinama kotalnih delov in tečin. Posledice prevelikega momenta trenja v kotalnih ležajih se najprej poznajo pri izgubah moči s povišano delovno temperaturo, posredno pa s kakovostjo delovanja ležajev in sosednjih delov ter dobo trajanja [4]. Vzroki za prevelik moment trenja običajno izvirajo iz poškodb samih ležajev (npr. jamičenje), tako da so te vzrok za lokalne preboje mazalnega filma, ali pa iz neustreznega mazalnega filma, katerega vzroki so lahko v mazivu, temperaturah, silah, hitrostih itn..

0 INTRODUCTION

Rolling bearings friction torque is the result of several factors [1], [2], reflected through rolling and sliding friction, elastic hysteresis in rolling, viscous drag of the lubricant, etc. One of the most influential parameters is the type of lubrication [3], in the first approximation described by the coefficient of friction between the rolling elements and the raceways. Friction in the rolling bearings represents an energy loss and causes increase in operating temperature and retardation of motion, thus influencing the performance and life of the bearings and associated elements [4]. The reasons for high friction torque could arise from the bearing damages (pitting, for example) which result in the local break-downs of the lubricating film or from the poor lubrication conditions influenced by inappropriate types of lubricant, temperatures, forces or speeds.

Moment trenja je torej lahko ključen kazalnik, stanja in kakovosti delovanja ležajev, hkrati pa tudi vseh preostalih parametrov, ki nanj vplivajo. Sem sodijo kakovost maziv z vsemi svojimi lastnostmi, količina potrebnega maziva, ustrezna delovna temperatura, kakovost samih ležajev, tolerance, zračnost, tip ležaja, obremenitve, hitrosti itn. Seveda to ne pomeni, da bi moral biti moment trenja diagnostični parameter, saj se vzroki, ki privedejo do povečanega momenta trenja, pokažejo z zvišano temperaturo in vibracijami, ki jih je laže meriti kakor sam moment. Vendar je s poznavanjem vzrokov in sestave momenta trenja mogoče ležaje bolj premišljeno uporabljati, tako z vidika konstruiranja kakor tudi vzdrževanja strojev in naprav.

V prispevku je prikazan vpliv vrste mazanja oziroma koeficienta trenja na skupni moment trenja ter na nekatere deleže v skupnem momentu trenja v kroglični ležajih. Za določitev velikosti in sestave trenja smo uporabili meritve na preizkuševališču za kotalne ležaje [5] do [7] ter dve računski metodi, ki temeljita na povsem različnih osnovah: računalniško simuliranje [7], [8] po matematičnem modelu [9] in izkustveno enačbo [1].

1 TRENJE V KOTALNIH LEŽAJIH

Trenje v kotalnih ležajih lahko razdelimo na trenje zaradi kotaljenja, drsenja ter upora maziva.

V praksi se lahko celotno trenje v kotalnih ležajih, ki je torej vsota omenjenih vrst trenja, izmeri kot upor proti gibanju kotalnega ležaja. Ta upor pomeni celotni moment trenja. Z namenom, da se torne razmere v kotalnih ležajih popišejo z brezdimenzijskim faktorjem, ki ni odvisen od vrste samih ležajev, definiramo koeficient trenja:

$$\mu = \frac{M}{F\,d/2} \qquad (1),$$

pri tem so: M - izmerjeni celotni moment trenja, F - zunanja sila na ležaj in d - notranji premer ležaja.

Kotalno in drsno trenje se pojavlja v kotalnih ležajih deloma zaradi elastične histereze materiala in deloma zaradi zdrsov med kotalnimi deli in tečinami v obremenjenem območju ležaja. Pogosto ta del trenja poimenujemo kar kotalno trenje. Ker pa prav zaradi tega pogosto pozabljamo, da je vzrok za del tega trenja razlika relativnih hitrosti kroglic in tečin, torej zdrs, v prispevku dosledno omenjamo kotalno in drsno trenje. Matematični popis kotalnega in drsnega trenja je zaradi medsebojnih odvisnosti zunanjih sil, porazdelitve obremenitev znotraj ležaja, hitrosti kotalnih elementov ter porazdelitev obremenitev po posameznem dotiku med kotalnim elementom in tečino zelo zapleten. Pri krogličnih ležajih je model še posebej zapleten, saj se giblje kroglica v ležaju okoli vseh svojih osi in ne le v smeri vrtenja obročev. Različna primera črt drsenja v dotiku med kroglico in tečino prikazuje slika 1.

Friction torque could therefore act as an indicator for the quality of the bearing operation and, indirectly, for all parameters which influence its performance. These parameters are lubricant with all its properties: the amount of the lubricant, appropriate operating temperature, loads and speeds, the quality of the rolling bearing itself, tolerances and clearance of the bearing, and many others. Of course, it is not suggested here that the friction torque should be used as a parameter for monitoring bearing condition, since the reasons affecting the friction are easier detected through temperature and vibration measurements. Nevertheless, a better understanding of the rolling bearing friction sources and the structure of the torque could lead to more effective use of the bearings. This is addressed to the field of design and maintenance.

This paper is focused on the influence of the type of lubrication and coefficient of friction on the friction torque and some of its portions in ball bearings. The rolling bearings test machine [5] to [7] and two different computational methods, i.e. computer simulation [7], [8] based on the mathematical model [9] and empirical equation [1], were used to determine the values and the structure of friction torque.

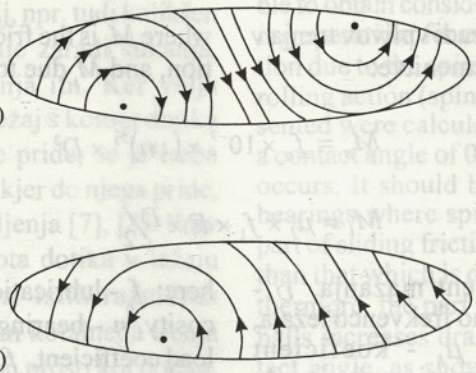
1 ROLLING BEARING FRICTION

The friction in rolling bearings consists of rolling, sliding and lubricant reistance.

In operation, the total friction of a bearing, - i.e. - the sum of rolling, sliding and lubricant friction, is measured as the resistance the bearing exerts against its movement. This resistance represents a torque and is generally referred to as the frictional torque. The difference of frictional behaviour between various rolling bearing types can be recognized by defining the coefficient of friction:

where M - is the frictional torque, F - applied load, and d - inner diameter of the bearing.

Rolling and sliding friction occurs in a loaded part of a rolling bearing partially due to elastic hysteresis and partially due to sliding resistance on the contacts between rolling elements and raceways. This kind of friction is usually called rolling friction. In our paper we strictly call it "rolling and sliding" friction because it is often it is forgotten that a very important part of that friction arises from the slip between rolling elements and raceways. A mathematical model of the rolling and sliding friction is very complex due to relations between applied loads, distribution of the loads in the bearing, internal speeds, and distribution of the load on a contact between the raceways and rolling elements, especially for the ball bearings. Fig.1 shows lines of two different sliding conditions occurring on the contact between the ball and raceway.



Sl. 1. *Črte drsenja v dotiku kroglice in tečine ležaja*
a) pri velikih obremenitvah in majhnih vrtilnih frekvencah, b) pri majhnih obremenitvah in velikih vrtilnih frekvencah

Fig. 1. *Sliding lines in the contact of ball and raceway*
a) at high loads and low speeds, b) at low loads and high speeds

V analitičnem izračunu momenta drsnega in kotalnega trenja (pogl. 3.2), ki temelji na matematičnem modelu [9], je torej upoštevano trenje zaradi zdrsov kroglic v tečinah ležaja. Pomanjkljivost omenjenega matematičnega modela je v tem, da zajema le del celotnega trenja v krogličnem ležaju in je treba koeficient trenja, ki znatno vpliva na rezultate, predpostaviti.

Poleg že omenjenega drsnega in kotalnega trenja je vir trenja v kotalnih ležajih še drsno gibanje, ki se pojavlja med kletko in kroglicami ter v valjčnih ležajih med valjčki in vodilnim robom obroča, oziroma med valjčki in vodilnim robom kletke. Tega dela trenja v našem analitičnem modelu nismo zajeli, kakor tudi ne trenja zaradi viskoznosti maziva.

Trenje zaradi viskoznosti maziva je sestavljeno iz deleža, ki nastaja zaradi notranjega trenja v mazivu med obremenjenimi površinami ter zaradi vrtinčenja maziva. Velikost tega dela trenja v skupnem trenju kotalnega ležaja je odvisna predvsem od viskoznosti in količine maziva, vrtilnih hitrosti, pa tudi konstrukcijskih značilnosti ležajev in okolice. Prav ta del celotnega trenja v kotalnih ležajih je matematično najteže popisati in za zdaj še ne obstaja model, ki bi to zmogel.

Zaradi problemov pri matematičnem popisu trenja, zaradi viskoznosti maziva, dela drsnega trenja ter elastične histereze materiala, se za približen izračun momenta trenja v kotalnih ležajih uporabljajo izkustvene enačbe. Problem izkustvenih enačb je predvsem v velikem številu koeficientov, katerih vrednosti določamo zgolj približno glede na opisane lastnosti delovnih razmer in samih ležajev. Pri tem ni mogoče razpoznavanje poglavitnih vplivnih parametrov, saj so določeni eksperimentalno. Prav v tem je prednost matematičnih modelov in simuliranj, ki omogočajo vpogled v glavne procese delovanja. V poglavju 3.3 so predstavljeni rezulati na podlagi izkustvene enačbe (2):

Analytical calculation of the rolling and sliding friction moments, based on the mathematical model [9], which is presented in section 3.2, take into account friction due to slip action between the balls and raceways. Although it is a very accurate model, has also some imperfections; first, it cannot predict all the friction moments in ball bearings and second, the friction coefficient must be supposed, which greatly influences the results.

There is also a second part of the sliding friction in rolling bearings, which occurs at the guiding surfaces of the rolling elements in the cage, at the guiding surfaces of the cage and - in roller bearings - at the roller faces and the raceway lips. This part of the sliding friction and lubricant friction was not included in our analytical calculations.

The lubricant friction in a rolling bearing is composed of the internal friction of the lubricant between the working surfaces and the churning of the lubricant at higher speeds. The total lubricant friction depends mainly on the viscosity and amount of the lubricant, speed of the bearing and design. This part of the total friction torque is the most difficult to predict, and there is no successful mathematical model yet.

Due to the problems in the mathematical modeling of the friction generated in rolling bearings, empirical equations are often used. Problems related to these equations arise from many coefficients which must be selected on the basis of description of the operating conditions. Such a method gives only approximate results and, in the contrast to mathematical models, does not allow for detailed analysis of the influencing factors. In section 3.3 results from the calculations of friction torque using the empirical equation (2) are presented:

$$M = M_o + M_l \quad (2),$$

kjer M_o pomeni moment trenja zaradi vplivov trenja v mazivu in M_l zaradi vplivov obremenitve:

where M_o is the frictional torque due to lubricant friction, and M_l due to effects of load:

$$M_o = f_o \times 10^{-7} \times (\upsilon n)^{2/3} \times D^3 \quad (3),$$

$$M_l = \mu_l \times f_1 \times F \times D/2 \quad (4),$$

pri tem pomenijo: f_o - koeficient mazanja, υ - kinematično viskoznost, n - vrtilno frekvenco ležaja, D - srednji premer ležaja, μ_l - koeficient obremenitve, f_1 - koeficient smeri zunanje sile in F - zunanjo silo.

here: f_o - lubrication coefficient, υ - kinematic viscosity, n - bearing speed, D - pitch diameter, μ_l - load coefficient, f_1 - coefficient of load direction and F - applied load.

2 MERITVE MOMENTA TRENJA NA PREIZKUŠEVALIŠČU CTD-ML1

Podrobni postopki in rezultati meritev na preizkuševališču kotalnih ležajev CTD-ML1 so predstavljeni drugje [5] do [7], na tem mestu pa je podan zgolj rezultat meritve skupnega momenta trenja pri razmerah, ki so predstavljene v preglednici 1.

Skupni izmerjeni moment trenja: 1,238 Nm

Preglednica 1: *Razmere pri meritvah*
Table 1: *Experimental conditions*

kroglični ležaj s prostim kotom dotika 0° - ball bearing, free contact angle 0°	6312
radialna sila - radial force	20 kN
vrtilna frekvenca - inner raceway speed	3000 rpm

2 MEASUREMENTS OF FRICTION TORQUE ON THE ROLLING BEARINGS TEST MACHINE CTD-ML1

Detailed test and operating procedures with the results are presented elsewhere [5] to [7].

Here, we introduce only the result of the friction torque measurements under the conditions described in Table 1.

Measured total friction torque of a single ball bearing: 1.238 Nm

3 RAČUNSKI METODI DOLOČITVE MOMENTA TRENJA

3.1 Parametri izračunov

Parametri za izračun na podlagi matematičnega modela in izkustvene enačbe temeljijo na okoliščinah in meritvah, ki smo jih izvedli na preizkuševališču CTD-ML1, tako da je mogoča primerjava vseh treh metod določevanja momenta trenja v krogličnih ležajih. Upoštevane so razmere iz preglednice 1 ter na preizkuševališču izmerjeni koeficient trenja, ki je pri omenjenih razmerah znašal 0,002.

3.2 Analitični izračun na podlagi matematičnega modela

Že v uvodu je bilo omenjeno, da je virov trenja v kotalnih ležajih več. Matematični model [9] in njegovo računalniško simuliranje [7], [8] omogočata izračun samo deleža, ki ga v skupnem momentu trenja prispevata drsno in kotalno trenje. To je torej delež, ki ga odločilno določa koeficient trenja med površinama kroglice in tečin ter je neposredno odvisen od vrste oziroma tipa mazanja. Za dane razmere smo izračunali, da znaša moment drsnega in kotalnega trenja: 0,029 Nm.

3 COMPUTATIONAL METHODS FOR DETERMINING THE FRICTION TORQUE

3.1 Computational parameters

Parameters for both computational methods are based on the test conditions applied on the rolling bearings test machine CTD-ML1 and some of the results obtained from those tests, so that comparison of all three methods is possible. The parameters from Table 1 and actually-measured coefficients of friction $\mu = 0.002$ at selected conditions were used.

3.2 Analytical calculation based on the mathematical model

As already mentioned, there are many sources of rolling bearings friction. The mathematical model [9] and analytical calculation [7], [8] basically considers only a portion of the total friction torque, i.e. the part resulting from the rolling and sliding friction. This part of the total friction is mostly influenced by the coefficient of friction between the surfaces in contact and it is directly related to the type of lubrication. For selected test conditions it was calculated: torque due to rolling and sliding friction: 0.029 Nm.

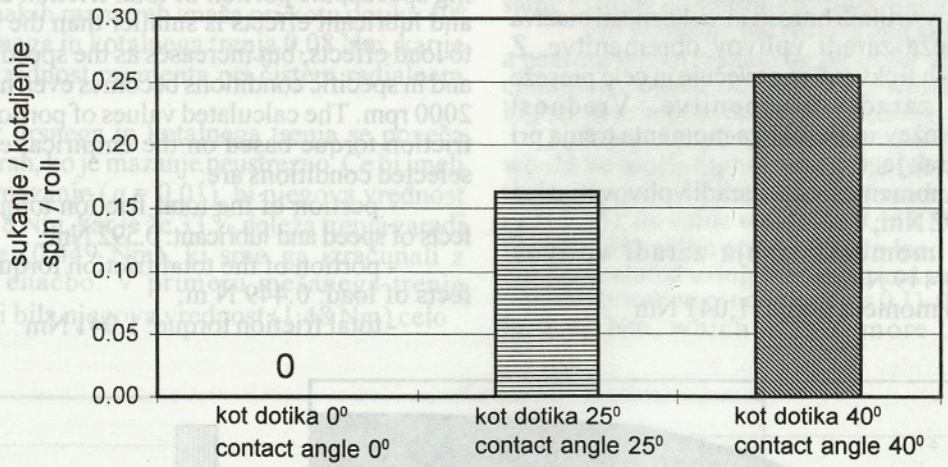
Z računalniškim simuliranjem je mogoče pridobiti še vrsto drugih informacij, npr. tudi kolikšen delež tega trenja prispeva drsenje zaradi sukanja, koliko drsenje v smeri kotaljenja itn. Ker velja predstavljen rezultat za radialni ležaj s kotom dotika 0^0, kjer do sukanja teoretično ne pride, se je treba zavedati, da je prispevek sukanja, kjer do njega pride, bistveno večji od prispevka kotaljenja [7], [8]. Prav delež sukanja se z večanjem kota dotika v ležaju močno povečuje (sl. 2). Če pri istih razmerah izračunamo še moment drsnega in kotalnega trenja za enake ležaje, ki imajo le različen prosti kot dotika, ugotovimo, da se ta delež v momentu trenja poveča skoraj 3-krat, če povečamo prosti kot dotika od 0^0 na 40^0 (preglednica 2).

On the basis of computer simulation it is possible to obtain considerable information about ball bearing operation, for example the portion of sliding friction due to the spinning motion of the ball and due to rolling action (spin to roll ratio), etc. The results presented were calculated for a radial ball bearing with a contact angle of 0^0, where theoretically no spinning occurs. It should be noted that for angular contact bearings where spinning of the balls is present, the part of sliding friction due to spinning is much greater than that which is due to rolling motion [7], [8]. Furthermore, the part of friction due to spinning of the balls increases drastically with increase of the contact angle, as shown in figure 2. In calculating the friction torque due to sliding and rolling motion for the same ball bearing, in which only the contact angle is different, it can be seen that this portion of the total friction torque increases by a factor of 3 when the contact angle changes from 0^0 to 40^0 (Table 2).

Preglednica 2: *Vrednost momenta drsnega in kotalnega trenja v odvisnosti od kota dotika* ($N = 3000\ \text{min}^{-1}$, $F = 20$ kN, $\mu = 0{,}002$)

Table 2: *Rolling and sliding friction torque as a function of contact angle* ($N = 3000$ rpm, $F = 20$ kN, $\mu = 0{,}002$)

moment drsnega in kotalnega trenja pri prostem kotu dotika 0^0 rolling and sliding friction torque, contact angle 0^0	0,029 N m
moment drsnega in kotalnega trenja pri prostem kotu dotika 25^0 rolling and sliding friction torque, contact angle 25^0	0,064 N m
moment drsnega in kotalnega trenja pri protem kotu dotika 40^0 rolling and sliding friction torque, contact angle 40^0	0,080 N m

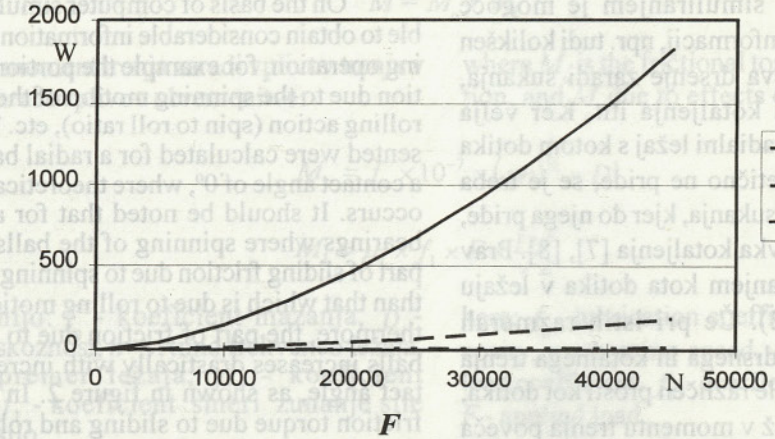


Sl. 2. *Razmerje sukanje/kotaljenje v dotiku na notranjem obroču* ($N = 3000\ \text{min}^{-1}$, $F = 20$ kN)

Fig. 2. *Spin to roll ratio - inner raceway contact* ($N = 3000$ rpm, $F = 20$ kN)

Na sliki 3 je prikazana moč izgub v krogličnem ležaju v odvisnosti od zunanje radialne sile za tri izbrane koeficiente trenja, ki približno popisujejo tri najbolj značilne vrste mazanja: EHD ($\mu = 0{,}001$), mejno ($\mu = 0{,}01$) ter mešano ($\mu = 0{,}1$). Očitno je, da je moč izgub, ki je premo sorazmerno odvisna od momenta trenja, odločilno odvisna od vrste mazanja in s tem koeficienta trenja.

Figure 3 shows the power loss in the ball bearing as a function of load for three values of coefficient of friction, in the first approximation representing three most typical types of lubrication, i.e. EHD ($\mu = 0.001$), boundary ($\mu = 0.01$), and mixed ($\mu = 0.1$) lubrication. Clearly, the power loss, which is linearly proportional to the friction torque, depends vitally/strongly on the coefficient of friction and type of lubrication.



Sl. 3. *Moč izgub zaradi kotalnega in drsnega trenja* ($N = 3000$ min^{-1}, prosti kot dotika 0^0)

Fig. 3. *Power loss due to rolling and sliding friction* ($N = 3000$ rpm, free contact angle 0^0)

3.3 Izračun na podlagi izkustvene enačbe

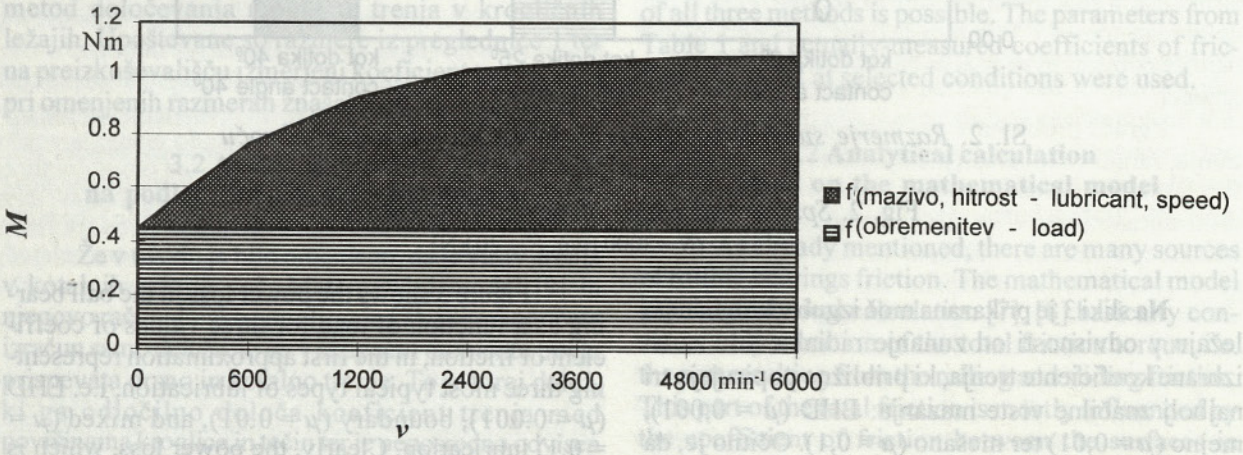
Z izkustveno enačbo (2) lahko ločeno določimo delež v skupnem momentu trenja, ki ga prispevajo vplivi hitrosti in maziva (3), ter delež, ki ga prispeva obremenitev (4). Na sliki 4 je prikazana porazdelitev obeh deležev za podano obremenitev, vendar ob spreminjajoči se vrtilni frekvenci. Razberemo lahko, da se delež trenja zaradi obremenitve z večanjem vrtilnih frekvenc ne spreminja. Prav tako lahko vidimo, da je pri majhnih vrtilnih frekvencah ležaja delež trenja zaradi vplivov vrtilnih hitrosti in viskoznosti maziva manjši od deleža zaradi vplivov obremenitve. Z večanjem vrtilnih frekvenc se povečuje in celo preseže delež trenja zaradi obremenitve. Vrednost posameznih deležev in skupnega momenta trenja pri izbranih razmerah je:

- delež momenta trenja zaradi vplivov maziva in hitrosti: 0,592 Nm;
- delež momenta trenja zaradi vplivov obremenitve: 0,449 Nm;
- skupni moment trenja: 1,041 Nm

3.3 Calculation based on the empirical equation

Using the empirical equation (2), one can separately calculate the portion of the total friction torque due to effects of speed and lubricant (3) and the effect of load (4). Figure 4 shows the distribution of both portions for selected load and coefficient of friction with increasing bearing speed. It can be seen that the part of friction influenced by the load remains constant with increasing speed. At low bearing speeds, the portion of total friction due to speed and lubricant effects is smaller than the portion due to load effects, but increases as the speed intensifies, and in specific conditions becomes even higher above 2000 rpm. The calculated values of portions and total friction torque based on the empirical equation for selected conditions are:

- portion of the total friction torque due to effects of speed and lubricant: 0.592 Nm;
- portion of the total friction torque due to effects of load: 0.449 N m;
- total friction torque: 1.041 Nm



Sl. 4. *Momenti trenja zaradi vplivov obremenitev ter zaradi vplivov maziva in hitrosti, izračunani z izkustveno enačbo* ($F = 20$ kN)

Fig. 4. *Friction torque due to load effect and due to speed and lubricant effects, calculated by empirical equation* ($F = 20$ kN)

4 ANALIZA REZULTATOV

Na sliki 5 je predstavljena primerjava rezultatov, dobljenih z vsemi tremi uporabljenimi metodami. Za primerjavo so podani tudi rezultati na podlagi matematičnega modela za izmerjeni koeficient trenja pri različnih kotih dotika ter pri kotu dotika 0^0 za različne vrste mazanja in s tem koeficiente trenja.

Po matematičnem modelu smo izračunali momente drsnega in kotalnega trenja za razmere, ki smo jih izmerili na preizkuševališču. Na izračunani moment drsnega in kotalnega trenja najbolj vplivajo obremenitve in koeficient trenja, neodvisen pa je od vrtilne frekvence, kar se ujema tudi s teorijo na podlagi izkustvene enačbe. Momenti drsnega in kotalnega trenja so torej sestavni del tistega deleža trenja, ki ga k celotnemu momentu trenja prispeva vpliv obremenitve. V našem primeru je vrednost momenta drsnega in kotalnega trenja 0,029 Nm in pomeni le 2,4% celotnega izmerjenega momenta trenja (1,238 Nm). Z izkustveno enačbo (2), ki upošteva vse vrste trenja, pa smo izračunali skupni moment 1,041 Nm, kar je 84% celotnega izmerjenega momenta. Vidimo, da je primerljivost rezultatov izkustvene enačbe in meritev dobra, medtem ko da analitični model precej manjše vrednosti, saj ne upošteva vseh virov trenja.

Seveda je treba poudariti, da smo upoštevali obremenitveni primer čistega radialnega ležaja, kjer so momenti zaradi kotalnega in drsnega trenja pri neki obremenitvi precej manjši od momentov v ležajih s poševnim dotikom pri isti obremenitvi (preglednica 2).

Ob enakih razmerah znaša pri kotu dotika 40^0 moment drsnega in kotalnega trenja 0,08 Nm, kar je 2,7-kratna vrednost momenta pri čistem radialnem ležaju.

Delež drsnega in kotalnega trenja se poveča tudi v razmerah, ko je mazanje neustrezno. Če bi imeli npr. mejno mazanje ($\mu = 0{,}01$), bi njegova vrednost znašala 0,148 Nm, kar je že 33 % deleža trenja zaradi obremenitve (0,449 Nm), ki smo ga izračunali z izkustveno enačbo. V primeru mešanega trenja ($\mu = 0{,}1$), bi bila njegova vrednost (1,48 Nm) celo

4 DISCUSSION

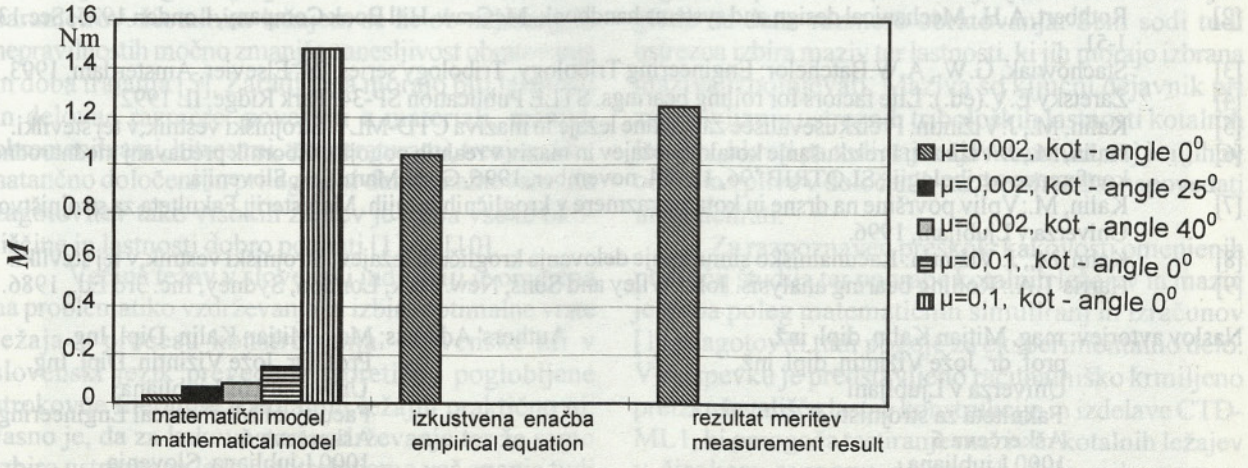
The results obtained by all three methods used for the selected conditions are presented in Figure 5. For the sake of comparison, the presentation offers the results of numerical calculations based on the mathematical model for the actually-measured coefficient of friction at different contact angles and at contact angle of 0^0 for different types of lubrication.

On the basis of the mathematical model, the sliding and rolling friction torque was calculated, using the parameters measured in the tests. Loads and the coefficient of friction appear to be the most influential factors of this portion of the total friction torque. The sliding and rolling friction torque does not depend on bearing speed, which also agrees with calculations using the empirical equation. Rolling and sliding friction torque are therefore the part of bearing friction which is mostly influenced by the loads. In our case, the value of this portion was 0.029 Nm which is only 2,4 % of the total measured friction torque (1.238 Nm). From the emiprical equation (2), which ttake in account all friction sources, we have calculated that the friction torque was 1.041 Nm, i.e. 84 % of the total measured torque. It can be seen that the results from the measurements and from calculations by the empirical equation (2) agree well. On the other hand, mathematical model gives much lower values, since it does not include all the friction sources in ball bearings.

It must be noted, that our calculations were made for pure radial bearing, where no spinning occurs and that in angulat contact bearings the portion of sliding and rolling friction in the total torque at the same loading conditions is much greater, table 2.

For instance, the rolling and sliding torque of a bearing with a contact angle of 40^0 under the same conditions would be 0.08 Nm, which is 2.7 times higher than in pure radial ball bearing.

Also, this portion of the total friction torque would be much higher when the lubrication conditions are poor. In the case of boundary lubrication ($\mu = 0.01$), its value would be 0.148 Nm, which represents 33% of the portion due to load effects (0.449 Nm) calculated using the empirical equation. In the mixed lubrication conditions ($\mu = 0.1$), the value would be 1.48 Nm, which is even more than the total



Sl. 5. *Primerjava rezultatov*
Fig. 5. *Comparison of results*

večja od skupnega momenta trenja, izračunanega z izkustveno enačbo, pa tudi izmerjenega momenta trenja na preizkuševališču. K temu bi bilo treba dodati še vse druge prispevke k skupnemu momentu trenja, tako da bi se njegova vrednost bistveno povečala. Pomen drsnega in kotalnega trenja bi bil v primeru valjčnih, stožčastih ali sodčastih ležajev še precej večji, saj so v teh primerih dotikalne površine bistveno večje kakor pri krogličnih ležajih. To pomeni, da je mazanje v takih primerih še bolj odločujoče in je lahko le najmanjše poslabšanje razmer že kritično.

Sklenemo lahko, da sta v primeru dobrega mazanja, ko so razmere zelo blizu razmeram EHD mazanja ter so vrednosti momentov sukanja majhne, vrednost in pomen drsnega ter kotalnega trenja minimalna. S slabšanjem razmer mazanja in večanjem kota dotika ležaja, to se navezuje tudi na slabše razmere mazanja, pa se njegov pomen zelo poveča. Analiza je torej pokazala, kako pomembne so razmere pri mazanju in s tem vpliv tribologije pri zagotavljanju ustreznih delovnih razmer krogličnih ležajev.

5 SKLEP

Pri kakovostnem mazanju, ko je delež drsnega in kotalnega trenja v krogličnih ležajih najmanjši, prevladujeta predvsem vpliva obremenitve in vrtilnih frekvenc. Ko pa so razmere mazanja slabe, postane drsenje v dotikih izjemno pomemben ali celo odločujoč dejavnik delovanja krogličnih ležajev.

Velikost momenta trenja v krogličnih ležajih, ki se ob poslabšanju vplivov mazanja znatno poveča, lahko kritično vpliva na delovanje in dobo trajanja krogličnih ležajev.

Z večanjem kota dotika krogličnih ležajev se zaradi večjega vpliva sukanja kroglic povečuje tudi moment trenja.

friction torque calculated using the empirical equation or actually measured total torque in the tests. This value should be increased by the values of the other sources, so that the total torque would be actually much higher. Rolling and sliding friction is even more important in roller bearings, where the contact areas between the moving parts are much greater. This means that the lubrication conditions are crucial for optimal operating performances of rolling bearings, and that even small changes could drastically affect the bearing operation and life.

From these results it can be concluded that when the lubrication conditions in ball bearings are as good as EHD lubrication, or very close to them and the portion of the torque due to the spinning of the balls is small, the influence of rolling and sliding friction is reduced to the minimum. But, when the lubrication conditions become worse, and when the contact angle is increased (also influencing the lubricating film, due to higher shear stress) its influence increases significantly. Therefore, our analysis confirmed the critical influence of tribology in attaining the appropriate operating conditions for rolling bearings.

5 CONCLUSION

In the case of good lubrication conditions when the portion of rolling and sliding friction in the total friction torque is small, load and speed are the most influential parameters in ball bearings. On the other hand, when the lubrication is poor, sliding motion between the surfaces in the ball bearings become a more important or even critical factor.

The friction torque in ball bearings with poor lubrication could result in rapidly increasing friction, thus greatly affecting its performance and working life.

With the increasing contact angle of the ball bearings, the total friction torque also increases, due to the spinning motion of the balls.

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