

DEVELOPMENT AND TRIBODYNAMIC STUDIES OF NEW MICRO-GROOVED AND TEXTURED RADIAL BALL BEARINGS

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Development and Tribodynamic Studies of New Micro-grooved and Textured Radial Ball Bearings

by

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Submitted

in fulfilment of the requirements for the degree of Doctor of Philosophy
to the



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Dedicated to

My parents and wife

Certificate

This is to certify that the thesis entitled “Development and Tribodynamic Studies of New Micro-Grooved and Textured Radial Ball Bearings” being submitted by **Mr. Bansidhar Gouda** to the **Indian Institute of Technology Delhi**, New Delhi, India for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him under our guidance and supervision and as per our awareness the results contained in this thesis have not been submitted in part or in full to any other university or institute for award of any degree or diploma.

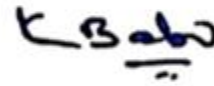
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Abstract

Rolling bearings are widely employed in mechanical systems/assemblies to support and guide the rotating/oscillating rotors energy efficiently. Among the family of rolling bearings, about 80% bearings employed in machines, mechanical systems, and appliances have been found to be ball bearings due to their involved low friction, low noise, and simplicity in lubrication with grease. Among the ball bearings, radial ball bearings are largely used due to their efficient functioning even in presence of combined loadings (with axial and radial loads). It is also found that approximately 90% of the rolling bearings are grease lubricated because of their better leak resistance, seal ability from dust and dirt, and reasonably good tribological behaviours at the economical cost. Inadequate lubrication has been reported as one of the major reasons of bearing failures, accounting around 43% of the total bearing failures. Thus, improving lubrication in rolling bearings by enhancing lubricants' availability/retainability in the vicinity of the contacts of races and rolling elements is a vital task for achieving better tribo-dynamic performances and life of rolling bearings. Moreover, large amount of the lubricant, particularly grease is normally pushed aside from its track by the rolling elements during their motions (rolling/ sliding) or thrown away due to the centrifugal action. This forces the bearings to operate in the starved lubricating condition. Moreover, the displaced greases hardly return back to the balls' tracks on their own due to their high yield strength as compared to oils. Hence, exploring the techniques for enhancing effective lubrication by improving the retainability of greases at (and in the vicinity of) the contacts between balls and races to improve the overall performance behaviours of ball bearings is a vital research task.

Hence, it is planned to develop new micro-grooved and textured radial ball bearings keeping in core about how to improve the effective lubrication for reducing the frictional torque, vibrations and fatigue life by enhancing lubricant retainability. Thus, in this work it is proposed; (a) To develop a radial ball bearing by introducing a micro-groove on the outer race for enhancing the lubricant retainability/availability and consequently improving the tribo-dynamic performances (increase in lubricating film thickness, decrease in frictional torque, and reduction in vibrations) and fatigue life, (b) Compare tribo-dynamic

performances of micro-grooved and conventional radial ball bearings employing three different grades of lithium soap-based greases (NLGI grade 000, 2 and 3) to understand the effectiveness of the grease grades in lubrication, and (c) Explore the tribological and vibrational effect of micro-textures present in the vicinity of contacts formed between the race and balls in radial ball bearings and also to understand the effect of micro-textures on the extended/fatigue life of ball bearings.

The experiments have been carried out employing an indigenously designed test rig. It is found that in radial ball bearings possessing micro-groove on stationary outer race, has yielded reduction in frictional torque by 15-30%, decrease in overall vibrations (RMS velocity) in the range of 14-41%, and about 11% reduction in the capacitance (i.e., up to 11% increase in the film thickness) as compared to conventional bearings at various operating parameters. Also, the experiments carried out to check the life of the micro-grooved bearings, indicate improvement in fatigue/extended life in micro-grooved bearings i.e., longer life as compared to the corresponding conventional cases. Furthermore, the effect of different grades of greases (NLGI 000, 2 and 3) have also been explored on the micro-grooved bearings at different operating parameters. In micro-grooved bearings about 11-19 % reductions in capacitance (i.e., improvement in film formation), 14-26% lower frictional torque, 10-24 % reduction in temperature rise and 9-23 % lower vibration level have been observed as compared to the conventional bearings. Moreover, the reduction in vibration level in micro-grooved bearings using higher grease grades (2 and 3) is better as compared to that using 000 grade grease, but the reduction in frictional torque with low grease grade (000) is higher due to less viscous heating loss.

At the last, the thesis reports effect of circumferentially created micro-dimples in vicinity of the contact region on the inner race of a deep groove ball bearing to enhance the availability of grease at the ball and race interfaces. The experimental results show significant improvement in film thickness formation in terms of capacitance (i.e., 10-17% reduction in capacitance) and also, 4.8-24.5 %, 10-28 % and 14-23% reduction in overall RMS vibration level, frictional torque and bulk temperature rise respectively. Moreover, significant enhancement in bearing life also has been achieved in presence of micro-dimples as compared to the conventional cases.

सार

रोलिंग बेयरिंग्स को यांत्रिक प्रणालियों / सम्मिलित नायक / कंपन रोटर्स को ऊर्जा संयोजन करने वाले अस्पष्ट चक्रधारियों के समर्थन और मार्गदर्शन के लिए व्यापक रूप से प्रयोग किया जाता है। रोलिंग बेयरिंग्स के परिवार में, मशीन, यांत्रिक प्रणालियों और उपकरणों में प्रयोग किए जाने वाले लगभग 80% बेयरिंग्स ग्रीस के साथ इन्वोल्व्ड कम घर्षण, कम ध्वनि और सरलता के कारण गोलाकार बेयरिंग्स होते हैं। गोलाकार बेयरिंग्स के बीच, रेडियल बॉल बेयरिंग्स विशेष रूप से व्यापक लोडिंग (अक्षगुल्मी और रेडियल लोड के साथ) के उपस्थिति में अपने कुशल कार्य के कारण अधिकतर प्रयोग किए जाते हैं। इससे भी पाया गया है कि लगभग 90% रोलिंग बेयरिंग्स ग्रीस से स्नेहन के कारण उपयुक्त लगते हैं क्योंकि उनकी बेहतर रिसाव प्रतिरोध, धूल और कीचड़ से सील अभियंत्रण और आर्थिक लागत में अच्छे त्रिबोलॉजिकल व्यवहारों के कारण। बेयरिंग फेलियर के मुख्य कारणों में से एक के रूप में अपर्याप्त स्नेहन की वजह से रिपोर्ट किया गया है, जिससे बेयरिंग की कुल फेलियर के लगभग 43% हिसाब से है। इसलिए, बेयरिंग की जीवनकाल और उनके उपसंपर्क स्थानों के आसपास स्नेहकों की उपलब्धता / धारकता को बढ़ाकर रोलिंग बेयरिंग्स के बेहतर ट्राइबो-डायनामिक प्रदर्शन और जीवन को प्राप्त करने के लिए एक महत्वपूर्ण कार्य है। इसके अलावा, खासकर ग्रीस जैसे अधिक रॉटेटिंग आक्रिया के दौरान आम तौर पर बेयरिंग्स को अपने ट्रैक से हटाने वाले रोलिंग तत्वों द्वारा बढ़ी मात्रा में तथा सेंट्रिफ्यूगल क्रिया के कारण वे बहार किया जाता है। इससे बेयरिंग तारयी अवस्था में चलने के लिए मजबूर किया जाता है। इसके अलावा, विस्थापित ग्रीस स्नेहन तत्व अपने आप ही बॉल्स के ट्रैक्स पर वापस नहीं लौटते हैं क्योंकि उनकी तुलना में उनके उच्च यील्ड स्ट्रेंथ के कारण तेलों के प्रति अधिक हैं। इसलिए, गेंदों और रेश के बीच संपर्क स्थानों के पास (और उनके आस-पास) ग्रीस की धारकता को बढ़ाने के तकनीकों का अन्वेषण करना, गेंद बेयरिंग्स के समग्र प्रदर्शन व्यवहारों को बेहतर बनाने के लिए एक महत्वपूर्ण शोध कार्य है।

इसलिए, यह योजना बनाई गई है कि ग्रीस संभावना / उपलब्धता को बढ़ाने के लिए नए माइक्रो-ग्रूव और टेक्सचर वाले रेडियल बॉल बेयरिंग्स विकसित किए जाएं, जिससे घर्षण टॉर्क, विव्रति और थकावट जीवन को कम करने के लिए स्नेहक धारकता को बढ़ाने के बारे में विचार किया जा सकता है। इसलिए, इस काम में प्रस्तावित किया गया है; (अ) स्नेहक धारकता / उपलब्धता को बढ़ाने के लिए बाह्य रेश पर माइक्रो-ग्रूव लगाने से एक रेडियल बॉल बेयरिंग विकसित करना, और इसके परिणामस्वरूप ट्राइबो-डायनामिक प्रदर्शनों को सुधारना (स्नेहन फिल्म मोटाई में वृद्धि, घर्षण टॉर्क में कमी और विव्रति में कमी) और थकावट जीवन, (बी) तीन अलग-अलग ग्रेड के लिथियम सोप-आधारित ग्रीस (एनएलजीआई ग्रेड 000, 2 और 3) का उपयोग करके माइक्रो-ग्रूव और पारंपरिक रेडियल बॉल बेयरिंग्स के ट्राइबो-डायनामिक प्रदर्शनों की तुलना करने के लिए

विचार किया जाए, और (सी) रेडियल बॉल बेयरिंग्स में रेस और बॉल्स के संपर्क स्थानों के आसपास मौजूद माइक्रो-टेक्सचर के ट्राइबोलॉजिकल और वाइब्रेशनल प्रभाव का अन्वेषण करना और गेंद बेयरिंग्स के विस्तृत / थकावट जीवन पर माइक्रो-टेक्सचर के प्रभाव को समझना।

प्रयोग भारतीय-स्वदेशी डिज़ाइन के परीक्षण यंत्र का उपयोग करके किए गए हैं। रेडियल बॉल बेयरिंग्स में गहरे ग्रूव वाले स्थायी बाहरी रेस वाले बेयरिंग्स में पाया गया है कि इनमें घर्षण टॉर्क में 15-30% की कमी, समग्र विभ्रमों (आरएमएस वेलोसिटी) के क्षेत्र में 14-41% के बीच में घटाव और कपैसिटेंस में लगभग 11% का कमी (यानी फिल्म मोटाई में 11% वृद्धि) पाया गया है, जो पारंपरिक बेयरिंग्स की तुलना में। साथ ही, माइक्रो-ग्रीड बेयरिंग्स के जीवन की जांच के लिए प्रयोग किए गए प्रयोगों से पाया गया है कि इनमें थकावट / विस्तृत जीवन में सुधार हुआ है, अर्थात् उससे अधिक जीवन आया जाता है पारंपरिक मामलों की तुलना में। इसके अलावा, विभिन्न ग्रेड ग्रीस (एनएलजी 000, 2 और 3) के प्रभाव को भी माइक्रो-ग्रीड बेयरिंग्स पर अलग-अलग चलने के पैरामीटरों पर अन्वेषण किया गया है। माइक्रो-ग्रीड बेयरिंग्स में लगभग 11-19% की कपैसिटेंस में कटौती (यानी फिल्म गठन में सुधार), 14-26% कम घर्षण टॉर्क, 10-24% कम तापमान बढ़ना और 9-23% कम विभ्रम स्तर देखे गए हैं पारंपरिक बेयरिंग्स की तुलना में। इसके अतिरिक्त, उच्च ग्रीस ग्रेड (2 और 3) का उपयोग करके माइक्रो-ग्रीड बेयरिंग्स में विभ्रम स्तर कम होता है, जो 000 ग्रेड ग्रीस का उपयोग करके बेहतर होता है, लेकिन कम ग्रीस ग्रेड (000) के साथ घर्षण टॉर्क में कमी अधिक होती है क्योंकि वह कम घिसाई हेटिंग हानि के कारण।

आखिरी में, थीसिस रिपोर्ट में संपर्क क्षेत्र के पास परिसर में वृत्ताकार रूप से उत्पन्न माइक्रो-डिंपल्स के प्रभाव की रिपोर्ट किया गया है, जो गहरे ग्रूव वाले बॉल बेयरिंग के आंतरिक रेस पर होते हैं, ताकि बॉल और रेस संबंध जागरुकता को बढ़ाने के लिए ग्रीस की उपलब्धता में सुधार हो सके। प्रयोगात्मक परिणाम दिखाते हैं कि कैपेसिटेंस (यानी कैपेसिटेंस में 10-17% की कटौती) में उल्लेखनीय सुधार हुआ है और इसके अलावा, समग्र आरएमएस विभ्रम स्तर में 4.8-24.5%, घर्षण टॉर्क में 10-28% और बल्क तापमान बढ़ने में 14-23% तक की कमी देखी गई है। इसके अतिरिक्त, माइक्रो-डिंपल्स की मौजूदगी में बेयरिंग की जीवन में भी महत्वपूर्ण सुधार हुआ है पारंपरिक मामलों की तुलना में।

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Nomenclature

a	semi major axis of the elliptical area of contact, m
A	area of the parallel plate capacitor
b	semi minor axis of the elliptical area of contact, m
B_w	bearing width, m
d	ball diameter, m
d_i	inner race diameter, m
d_o	outer race diameter, m
C	overall capacitance
C_{Hertz}	capacitance at the Hertzian contact area
C_{tc}	total capacitance
C_0	basic static load rating
C_{out}	capacitance outside the Hertzian contact area
D	pitch circle diameter of the bearing in mm
E	modulus of elasticity for ball and race material, N / m^2
f	frequency of capacitance measurement set up
F	force experienced by load cell
F_a	axial load
F_s	static equivalent load
f_l	factor which depends on the bearing design and relative bearing load
Fr	radial load, N
h	distance between the plates in parallel plate capacitor; oil film thickness
L	distance between the load cell load line and bearing axis

N	speed (rpm)
n	natural number
P	contact surface pressure between the ball and raceway surfaces,
p_H	Hertzian pressure at the contact
P_{ref}	reference pressure for measurement of sound pressure level; 20^{-6} Pa
Q	applied load, N
R	resistance of the resistor used in capacitance measurement set up
r_{ir}	inner race groove radius, m
r_{or}	outer race groove radius, m
T_F	total frictional torque
T_{F0}	load independent component of frictional torque
T_{F1}	load dependent component of frictional torque
W	radial load, N
Z	number of balls
δ	elastic deflection at contact, m
η_0	absolute viscosity, Pa-s
ν	viscosity of the oil or base oil of grease (mm^2/s)
ε_0	absolute dielectric permittivity of vacuum
ε_r	relative dielectric permittivity of lubricant
Λ	oil film parameter
σ	composite roughness of the mating surfaces

Subscripts

<i>cont</i>	contact
h_c	central film thickness
<i>Hertz</i>	Hertzian
<i>i</i>	inner
<i>o</i>	outer
<i>in</i>	inner race
<i>out</i>	outside contact region
<i>t</i>	total
