STUDIES ON FLEXIBLE JOURNAL BEARINGS FOR IMPROVED TRIBOLOGICAL AND STABILITY BEHAVIOURS

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by

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in fulfillment of the requirements of the degree of Doctor of Philosophy
to the

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Dedicated to

*My parents, my wife **Munmun**, and my daughters **Ananya** & **Ayesha***

Certificate

This is to certify that the thesis entitled "**Studies on Flexible Journal Bearings for Improved Tribological and Stability Behaviours**" being submitted by **Mr. Pranabesh Ganai** 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 work carried out by him under our supervisions. This thesis is in conformity with the rules and regulations of the Indian Institute of Technology Delhi, New Delhi. We further certify that the thesis has attained a standard required to IIT Delhi for the award of the degree of Doctor of Philosophy to Mr. Ganai. As per our awareness, the research results reported in the thesis have not been submitted in part or full to any other institute or university for the award of any other degree or diploma.

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Abstract

Vertical rotor-bearing systems exist in many machines and mechanical systems such as vertical centrifugal oil filters (COF), vertical condensate pumps (VCP), vertical sinking machines, helicopter rotors etc. It is worth noting here that oil-lubricated journal bearings are employed in COF and VCP to support and guide the vertical rotors energy efficiently. Since vertical rotors are get balanced before making them operational in the real applications, hence, the journal bearings supporting these rotors are subjected to extremely light radial loads may be due to minor installation and other field issues. It is worth mentioning here that a centrifugal oil filter processes different oils (having different viscosities) and uses the oil being filtered for lubrication in the supporting journal bearings of vertical rotor. But as per the concept of design of a rigid bore oil journal bearing, the clearance is kept constant for a set of operating parameters including a lubricating oil. Thus, need arises to perform the study on a vertically installed centrifugal oil filter (COF) for addressing the concerns of instability arising due to the light load by accommodating the different viscous oils for lubrication by varying the clearance in the journal bearing.

To address the concerns mentioned above, mainly flexible (bump) bore journal bearings have been considered herein with the objectives of exploring numerically and experimentally the frictional and dynamic characteristics of the system. Explorations have also been made with multi-axial slotted floating bush bearings and employing textured journal surface.

Numerical investigations have been performed considering the textured, micro-grooved and micro-rectangular pocketed top foil surfaces for understanding and improving the lubrication

and dynamic performance behaviors of the rotor bearing system employing air as a lubricant. Moreover, pocketed top foil has also been used for analyzing the performance behaviors of oil lubricated bump foil journal bearing. With air lubrication cases, the micro-rectangular pocketed top foil yielded better dynamic performances as compared to the textured, grooved and conventional cases. It also yielded a significant reduction in friction coefficient varying in the range of 8 -11% as compared to conventional case. Inspired from these results, pockets have been employed on the top foil of oil lubricated bump foil bearing. The six-pocketed top foil yielded the best performances followed by four, eight, and ten pocketed cases. With micro-pocketed top foil, the coefficient of friction reduced in the range of 7-18% in comparison to the conventional foil case. Furthermore, pocketed foil provided improved stability of the rotor-bearing system in oil lubricated cases.

Experimental studies on lightly loaded vertical rotor (rotor of centrifugal oil filter) have been conducted employing three pairs of bearings and journals namely: (a) conventional foil bearing with plain shaft (b) conventional foil bearing with textured shaft, and (c) multi-axial slotted floating bush with plain shaft. For conducting the experiments on rotor of centrifugal oil filter, a specialized test rig was designed and got fabricated. Different viscosity grade oils namely: SAE 10W30, SAE 15W40, SAE 20W40 and SAE 20W50, were employed in performing the experiments. The frictional characteristics and stability of rotor-bearing system improved significantly with pair of conventional top foil and textured journal surface. However, the pair of multi-axial slotted floating bush and plain shaft surface also provided encouraging results. Moreover, at the elevated operating speed of vertical rotor, seizure between conventional top foil and plain journal surface has taken place. The pairs namely: textured shaft vs. conventional top foil and multi-axial slotted floating bush vs. conventional journal surface, exhibited improved performance behaviors irrespective of viscosity of oil i.e., grades of oils.

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सार

वर्टिकल रोटर-बेयरिंग सिस्टम कई मशीनों और मैकेनिकल सिस्टम जैसे वर्टिकल सेंट्रीफ्यूगल ऑयल फिल्टर (COF), वर्टिकल कंडेनसेट पंप (VCP), वर्टिकल सिंकिंग मशीन, हेलिकॉप्टर रोटर आदि में मौजूद हैं। यहां यह ध्यान देने योग्य है कि ऑयल-लुब्रिकेटेड जर्नल बियरिंग्स कार्यरत हैं सीओएफ और वीसीपी में ऊर्ध्वाधर रोटर्स ऊर्जा को कुशलतापूर्वक समर्थन और मार्गदर्शन करने के लिए। चूंकि ऊर्ध्वाधर रोटार वास्तविक अनुप्रयोगों में संचालन करने से पहले संतुलित हो जाते हैं, इसलिए, इन रोटारों का समर्थन करने वाले जर्नल बेयरिंग बेहद हल्के रेडियल भार के अधीन होते हैं जो मामूली स्थापना और अन्य क्षेत्र के मुद्दों के कारण हो सकते हैं। यहां यह उल्लेखनीय है कि एक केन्द्रापसारक तेल फिल्टर विभिन्न तेलों (अलग-अलग चिपचिपाहट वाले) को संसाधित करता है और ऊर्ध्वाधर रोटर के सहायक जर्नल बियरिंग्स में स्नेहन के लिए फ़िल्टर किए जा रहे तेल का उपयोग करता है। लेकिन एक कठोर बोर ऑयल जर्नल बेयरिंग के डिजाइन की अवधारणा के अनुसार, चिकनाई वाले तेल सहित ऑपरेटिंग मापदंडों के एक सेट के लिए निकासी को स्थिर रखा जाता है। इस प्रकार, जर्नल बेयरिंग में क्लीयरेंस को अलग-अलग करके स्नेहन के लिए विभिन्न चिपचिपा तेलों को समायोजित करके हल्के भार के कारण उत्पन्न अस्थिरता की चिंताओं को दूर करने के लिए लंबवत स्थापित केन्द्रापसारक तेल फ़िल्टर (सीओएफ) पर अध्ययन करने की आवश्यकता उत्पन्न होती है।

ऊपर उल्लिखित चिंताओं को दूर करने के लिए, मुख्य रूप से लचीले (टक्कर) बोर जर्नल बियरिंग्स को संख्यात्मक और प्रयोगात्मक रूप से सिस्टम की घर्षण और गतिशील विशेषताओं की खोज के उद्देश्यों के साथ यहां माना गया है। बहु-अक्षीय स्लॉटेड फ्लोटिंग बुश बेयरिंग और टेक्सचर्ड जर्नल सतह को नियोजित करने के साथ अन्वेषण भी किए गए हैं।

लुब्रिकेंट के रूप में हवा को नियोजित करने वाले रोटर बेयरिंग सिस्टम के स्नेहन और गतिशील प्रदर्शन व्यवहार को समझने और सुधारने के लिए बनावट, सूक्ष्म-ग्रूव्ड और माइक्रो-आयताकार पॉकेटेड टॉप फ़ॉइल सतहों पर विचार करते हुए संख्यात्मक जाँच की गई है। इसके अलावा, पॉकेटेड टॉप फ़ॉइल का उपयोग ऑयल लुब्रिकेटेड बम्प फ़ॉइल जर्नल बेयरिंग के प्रदर्शन व्यवहार का विश्लेषण करने के लिए भी किया गया है। एयर ल्यूब्रिकेशन केस के साथ, माइक्रो-रेक्टेंगुलर पॉकेटेड टॉप फ़ॉइल ने टेक्सचर्ड, ग्रूव्ड और पारंपरिक मामलों की तुलना में बेहतर गतिशील प्रदर्शन दिया। इसने पारंपरिक मामले की तुलना में 8 -11% की सीमा में भिन्न घर्षण गुणांक में उल्लेखनीय कमी की। इन परिणामों से प्रेरित होकर, ऑइल लुब्रिकेटेड बम्प फ़ॉइल बेयरिंग के शीर्ष फ़ॉइल पर पॉकेट्स लगाए गए हैं। छह-पॉकेट वाले शीर्ष फ़ॉइल ने चार, आठ और दस पॉकेट वाले मामलों के बाद सर्वश्रेष्ठ प्रदर्शन किया। माइक्रो-पॉकेट टॉप फ़ॉइल के साथ, पारंपरिक फ़ॉइल केस की तुलना में घर्षण का गुणांक 7-18% की सीमा में कम हो गया। इसके अलावा, पॉकेटेड फ़ॉइल ने तेल चिकनाई वाले मामलों में रोटर-असर प्रणाली की बेहतर स्थिरता प्रदान की।

हल्के लोडेड वर्टिकल रोटर (सेंट्रीफ्यूगल ऑयल फिल्टर का रोटर) पर प्रायोगिक अध्ययन तीन जोड़ी बियरिंग्स और जर्नल्स को नियोजित करते हुए आयोजित किया गया है: (ए) प्लेन शाफ्ट के साथ पारंपरिक फ़ॉइल बेयरिंग (बी) टेक्सचर्ड शाफ्ट के साथ पारंपरिक फ़ॉइल बेयरिंग, और (सी) मल्टी सादे शाफ्ट के साथ अक्षीय स्लॉटेड फ्लोटिंग बुश। केन्द्रापसारक तेल फिल्टर के रोटर पर प्रयोग करने के लिए, एक विशेष परीक्षण रिग डिजाइन किया गया था और इसे तैयार किया गया था। विभिन्न चिपचिपाहट ग्रेड तेल अर्थात्: SAE 10W30, SAE 15W40, SAE 20W40 और SAE 20W50, प्रयोग करने में कार्यरत थे। रोटर-बेयरिंग सिस्टम की घर्षण विशेषताओं और स्थिरता में पारंपरिक शीर्ष पन्नी और बनावट जर्नल सतह की जोड़ी के साथ काफी सुधार हुआ है। हालांकि, बहु-अक्षीय स्लॉटेड फ्लोटिंग बुश और सादे शाफ्ट सतह की जोड़ी ने भी उत्साहजनक

परिणाम प्रदान किए। इसके अलावा, ऊर्ध्वाधर रोटर की उच्च परिचालन गति पर, पारंपरिक शीर्ष पन्नी और सादे जर्नल सतह के बीच जब्ती हुई है। जोड़े नामत: बनावट वाले शाफ्ट बनाम पारंपरिक शीर्ष पन्नी और बहु-अक्षीय स्लॉटेड फ्लोटिंग बुश बनाम पारंपरिक जर्नल सतह, तेल की चिपचिपाहट यानी तेलों के ग्रेड के बावजूद बेहतर प्रदर्शन व्यवहार प्रदर्शित करते हैं।

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Nomenclature

a	Texture width, m
b	length of transverse groove, m
C_r	radial clearance, m
c_{ij}	damping coefficients, N-s/m
C_{ij}	dimensionless damping ($c_{ij}C_r\omega / p_a R^2$)
D	bearing diameter, m
e	eccentricity, m
E	modulus of elasticity, Pa
F	applied load, N
F_x	bearing force in horizontal direction, N
F_y	bearing force in vertical direction, N
h	film thickness, m
$\bar{h}$	dimensionless film thickness (h/C_r)
h_s	texture depth, m
$\bar{h}_s$	dimensionless film thickness associated with texture
k_{ij}	direct stiffness coefficients, N/m
K_{ij}	dimensionless stiffness ($k_{ij}C_r / p_a R^2$)
l	bump radius, m
l_p	rectangular pocket length span along circumferential direction, m
L	bearing length, m
m	half mass of shaft, kg
$\bar{m}$	dimensionless parameter ($mC_r\omega^2 / F$)
M_{cr}	stability parameter (critical mass)
N	journal speed, rpm

N_θ	number of nodes along circumferential direction
N_Z	number of nodes along axial direction
p	pressure, Pa
$\bar{p}$	dimensionless pressure (p / p_a)
p_a	ambient pressure, Pa
$\bar{Q}_{in}$	dimensionless in-flow rate in circumferential direction
$\bar{Q}_{lk}$	dimensionless side leakage rate
$\bar{Q}_s$	dimensionless side leakage $(Q_s / C_r UL)$
R	bearing radius, m
s	bump pitch, m
t_b	bump foil thickness, m
T	friction force, N
$\bar{T}$	Dimensionless force $(T / \eta_0 \omega LR)$
U	journal peripheral speed, m/s
$\bar{u}$	dimensionless journal peripheral speed ($u / \omega C_r$)
u	θ -velocity component, m/s
w	Z-velocity component, m/s
W	load carrying capacity, N
$\bar{W}$	dimensionless load ($W / p_a RL$)
$\bar{W}_x$	dimensionless load component in horizontal direction
$\bar{W}_y$	dimensionless load component in vertical direction
X , Y	Coordinates, m
$\bar{X}$, $\bar{Y}$	dimensionless coordinates (X/C_r , Y/C_r)
X_h , Y_h	dimensionless amplitude of response
ΔX , ΔY	displacement perturbation in x and y directions, respectively
$\Delta \dot{X}$, $\Delta \dot{Y}$	velocity perturbations in x and y directions, respectively
$\Delta \ddot{X}$, $\Delta \ddot{Y}$	instantaneous acceleration of journal center

$\Delta\bar{\dot{X}}$, $\Delta\bar{\dot{Y}}$	$(\Delta\dot{X}/C_r\omega, \Delta\dot{Y}/C_r\omega)$
$\Delta\bar{\ddot{X}}$, $\Delta\bar{\ddot{Y}}$	$(\Delta\ddot{X}/C_r\omega^2, \Delta\ddot{Y}/C_r\omega^2)$
Z	coordinate in axial direction along the length of bearing, m
$\bar{z}$	dimensionless coordinate, Z/L
ρ	lubricant density, kg/m^3
ϕ	attitude angle, degree
ϕ_c	cavity fraction
θ	coordinate in circumferential direction
ε	eccentricity ratio
η	viscosity of lubricant, Pa-s
μ	coefficient of friction
ω	angular velocity of the journal, rad/s
ν	whirl frequency, rad/s
υ	Poisson's ratio of bump foil
σ	composite roughness of shaft and top foil surface
κ_s	dimensionless generalized/ equivalent stiffness
α	dimensionless compliance $\left(\frac{2p_a s}{EC_r}\left(\frac{l}{t_b}\right)^2\left(1-\upsilon^2\right)\right)$
λ_c	whirl frequency ratio (ν/ω)
Λ	bearing number or compressibility number $\left(\frac{6\eta UR}{p_a C_r^2}\right)$