

STUDIES WITH MICRO-TEXTURED SECTOR SHAPE PAD THRUST BEARINGS

SHIPRA AGGARWAL



**DEPARTMENT OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
NEW DELHI – 110016, INDIA**

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Studies with Micro-textured Sector Shape Pad Thrust Bearings

by

Shipra Aggarwal

Department of Mechanical Engineering

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Certificate

This is to certify that the thesis entitled “**Studies with Micro-textured Sector Shape Pad Thrust Bearings**” being submitted by **Ms. Shipra Aggarwal** to the **Indian Institute of Technology Delhi**, New Delhi, India for the award of the degree of **Doctor of Philosophy** is a record bonafide research work carried out by her under my guidance and supervision and as per my 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.

I also certify that Ms. Shipra Aggarwal has pursued the prescribed course of research at Indian Institute of Technology, Delhi

Dr. R. K. Pandey

(Supervisor)

Professor

Department of Mechanical Engineering
Indian Institute of Technology Delhi,
New Delhi -110016, India

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Abstract

Hydrodynamic pad thrust bearings are widely employed in high-speed rotating machines, such as pumps, compressors, turbines, turbo-generators etc. for supporting the axial load/thrust because of their low frictional features, good load carrying capacity and high damping characteristics. Due to progress at the technological fronts, hydrodynamic pad bearings are expected to work at higher load carrying capacity having compact size. Moreover, environmental and economic concerns demand that the hydrodynamic pad bearings should operate with minimum power loss. Thus, a number of design modifications have been proposed over the years in order to enhance the load carrying capacity and decrease the power consumption in the hydrodynamic pad thrust bearings. There are indications that surface textures/profiles can improve the performance behaviours of hydrodynamic pad bearings significantly. Therefore, the performance study of hydrodynamic pad thrust bearings conceiving new patterns of textures and profiles is a vital task. Hence, it is necessary to conduct the thermohydrodynamic lubrication analyses of thrust pad bearings incorporating the effects of different surface textures/profiles/roughness.

The primary objective of this thesis is to study the performance behaviours of hydrodynamic fixed pad thrust bearing considering the new type of textures (micro/macro grooves and micro/macro pockets) on the surface of pads incorporating the thermal effects in the lubrication analysis. It involves exploring the effects of features of the textures i.e. cross sectional shape, length, width, number, and depth of grooves/pockets, on the performance behaviours in order to identify the best shapes and sizes of attributes of the textures. However, the additional objectives of this thesis are to conduct investigation for enhancing the performance behaviours of taper flat-land pad thrust bearing incorporating the textures/profiles at different locations and lastly to increase the minimum film thickness employing the textures for minimizing the chances of electrical arcing through the lubricating film.

For meeting the objectives of the thesis, the coupled solution of governing equations (Reynolds equation, energy equation, film thickness relation, and

rheological relations) is achieved by discretizing the partial differential equations using finite difference method and solving the linearized algebraic equations using Gauss-Siedel iterative method. Based on the simulated results reported in this thesis, it is found that the presence of the proposed textures at the conformal contacts is highly beneficial in terms of improving the performance behaviours if the mating surfaces have low inclinations. The texture involving the square cross-sectional shape of micro/macro grooves has yielded substantial increase (up to 97%) in the load carrying capacity and significant reduction (up to 51%) in the friction coefficient in comparison to the conventional plain pad for the adopted operating conditions.

The synergistic effects of profile (catenoidal, cubic, cycloidal, plane taper, quadratic, quartic) and pockets (elliptical, rectangular, trapezoidal, and triangular) present on the taper portion and texture on the flat portion over the performance parameters of taper flat-land pad are investigated. It is found that the rectangular pocket provides lower friction coefficient in comparison to other pockets considered. Moreover, the minimum film thickness obtained with quartic profiled pad is higher in comparison to other profiles. It is understood that due to the electrical arcing in pad bearing, the performance behaviours of it deteriorates. However in presence of texture (which comprises of grooves placing towards the entry region of pad), the minimum film thickness enhances for the same operating parameter. This indicates that with textured pad the chances of electrical arcing can be reduced since enhanced film thickness means better insulation.

सार

हाइड्रोडायनामिक पैड थ्रस्ट बियरिंग्स व्यापक रूप से उच्च गति घूर्णन मशीनों, जैसे पंप्स, कंप्रेसर्स, टर्बाइन, टर्बो-जनरेटर आदि में कम से कम घर्षण सुविधाओं, अच्छा लोड ले जाने की क्षमता और उच्च डैपिंग विशेषताओं के कारण अक्षीय भार / थ्रस्ट के समर्थन में कार्यरत हैं। तकनीकी मोर्चे पर प्रगति के कारण, हाइड्रोडायनामिक पैड बियरिंग्स, जो कि कॉम्पैक्ट साइज की होती हैं, की उच्च भार वाली क्षमता पर काम करने की संभावना है। इसके अलावा, पर्यावरणीय और आर्थिक चिंताएं यह मांग करती हैं कि हाइड्रोडायनामिक पैड बियरिंग्स को न्यूनतम विद्युत नुकसान के साथ काम करना चाहिए। इस प्रकार, लोड कैरिंग क्षमता को बढ़ाने के लिए और हाइड्रोडायनामिक पैड थ्रस्ट बियरिंग्स में बिजली की खपत में कमी के लिए वर्षों से कई डिजाइन संशोधनों का प्रस्ताव किया गया है। संकेत हैं कि सरफेस टेक्सचर्स / प्रोफाइल हाइड्रोडायनामिक पैड बियरिंग्स के प्रदर्शन में काफी सुधार कर सकते हैं। इसलिए, हाइड्रोडायनामिक पैड थ्रस्ट बियरिंगों का प्रदर्शन अध्ययन टेक्सचर्स और प्रोफाइल के नए पैटर्न की अवधारणा एक महत्वपूर्ण कार्य है। इसलिए, थर्मोहाइड्रोडायनेमिक लुब्रिकेशन का संचालन करने के लिए विभिन्न सरफेस टेक्सचर्स / प्रोफाइल / रफनेस के प्रभावों को शामिल करने वाले थ्रस्ट पैड बियरिंग का विश्लेषण करना आवश्यक है।

इस थीसिस का प्राथमिक उद्देश्य लुब्रिकेशन विश्लेषण में थर्मल प्रभाव को शामिल करने वाले पैड की सतह पर नए प्रकार के टेक्सचर्स (माइक्रो / मैक्रो ग्रूव्स और माइक्रो / मैक्रो पॉकेट्स) को देखते हुए हाइड्रोडायनामिक फिक्स्ड पैड थ्रस्ट बियरिंग के प्रदर्शन के व्यवहार का अध्ययन करना है। इसमें टेक्सचर्स की विशेषताओं के प्रभाव की खोज करना शामिल है, अर्थात् संरचनाओं के सर्वोत्तम आकृतियों और आकारों की पहचान करने के लिए प्रदर्शन के व्यवहारों पर क्रॉस अनुभागीय आकार, लम्बाई, चौड़ाई, संख्या और ग्रूव्स / पॉकेट्स की गहराई। हालांकि, इस थीसिस के अतिरिक्त उद्देश्य टेपर फ्लैट-लैंड पैड थ्रस्ट बियरिंग के प्रदर्शन के व्यवहार को बढ़ाने के लिए विभिन्न स्थानों पर टेक्सचर्स / प्रोफाइल को शामिल करने और अंतिम रूप से इलेक्ट्रोस्टैटिक डिस्चार्ज की संभावना को कम करने के लिए टेक्सचर्स को नियोजित न्यूनतम फिल्म थिकनेस बढ़ाने के लिए जांच करना है।

थीसिस के उद्देश्यों को पूरा करने के लिए, गवर्निंग समीकरणों (रेनॉल्ड्स समीकरण, ऊर्जा समीकरण, फिल्म थिकनेस संबंध, और रहिओलॉजिकल रिश्तों) के युग्मित समाधान को अंजाम विभेदक समीकरणों को अलग-अलग अंतर पद्धति का उपयोग करके अलग करना और गॉस-सिडल इटरेटिव विधि से रैखिक बीजगणित समीकरणों का समाधान करना। इस थीसिस में रिपोर्ट किए गए सिमुलेटेड परिणामों के आधार पर, यह पाया जाता है कि संगत सम्पत्तियों के कम झुकाव के कारण प्रदर्शन में सुधार के मामले में प्रस्तावित टेक्सचर्स की उपस्थिति बेहद फायदेमंद होती है। माइक्रो / मैक्रो ग्रास के वर्ग क्रॉस-अनुभागीय आकृति को शामिल करने वाला टेक्सचर्स परंपरागत सादा पैड के मुकाबले उन्ही ऑपरेटिंग पैरामीटर्स के लिए भारोत्तोलन क्षमता में महत्वपूर्ण वृद्धि (97% तक) और घर्षण गुणांक में महत्वपूर्ण कमी (51% तक) प्राप्त हुई है।

टेपर फ्लैट लैंड पैड के प्रदर्शन मापदंडों पर फ्लैट हिस्से पर सटे हुए भाग और बनावट पर मौजूद प्रोफाइल (कैटेनोडियल, क्यूबिक, साइक्लॉइड, प्लेन टेपर, द्विघात, कार्टिक) और पॉकेट्स (अण्डाकार, आयताकार, ट्रेपोजिडियल और त्रिकोणीय) के सहयोगी प्रभाव भूमि पैड की जांच की जाती है। यह पाया जाता है कि आयताकार पॉकेट अन्य पॉकेट की तुलना में कम घर्षण गुणांक प्रदान करता है। इसके अलावा, कार्टिक प्रोफाइल से प्राप्त न्यूनतम फिल्म थिकनेस अन्य प्रोफाइल की तुलना में अधिक है। यह समझा जाता है कि पैड असर में विद्युत आरीकरण के कारण, इसके प्रदर्शन के व्यवहार बिगड़ते हैं। हालांकि टेक्सचर्स की उपस्थिति में (जिसमें पैड के प्रवेश क्षेत्र की ओर स्थित ग्रास शामिल हैं), उन्ही ऑपरेटिंग पैरामीटर्स के लिए न्यूनतम फिल्म थिकनेस बढ़ जाती है। यह इंगित करता है कि टेक्सचर्ड पैड के साथ इलेक्ट्रिक आर्किंग की संभावना को कम किया जा सकता है क्योंकि बढ़ी फिल्म थिकनेस का मतलब बेहतर इन्सुलेशन है।

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Nomenclature

B	Radial width of pad (m)
B_p	Width of pocket (m)
C_p	Specific heat of lubricant (J/kg-K)
d_d	Depth of dimple (m)
\bar{d}_d	Normalized depth of dimple
d_g	Depth of groove (m)
\bar{d}_g	Normalized depth of groove
d_p	Depth of pocket (m)
\bar{d}_p	Normalized depth of pocket
F	Friction force (N)
\bar{F}	Normalized friction force ($Fh_2 / (\eta_0 \Omega R_m^3)$)
g	Switch function
h	Lubricant film thickness (m)
\bar{h}	Normalized lubricant film thickness (h/h_2)
h_1	Film thickness at entry edge (m)
h_2	Film thickness at exit edge (m)
h_c	Convective heat transfer coefficient (W/m ² K)
\bar{h}_g	Normalized film thickness for grooved surface
\bar{h}_p	Normalized film thickness for pocketed surface
h_{pr}	Lubricant film thickness for profiled pad (m)
\bar{h}_{pr}	Normalized film thickness for profiled surface

\bar{h}_d	Normalized film thickness for textured surface with dimples
\bar{h}_{g-p}	Normalized film thickness for grooved-pocketed surface
\bar{h}_{p-pr-d}	Normalized film thickness for pocketed-profiled-textured surface
i,j,k	Node counts in three directions
i_g	Land length at entry (m)
k_l	Thermal conductivity of lubricant (W/mK)
k_p	Thermal conductivity of pad (W/mK)
K_{oil}	Hot oil carry over factor
L	Circumferential length of pad at mean radius (m)
l_g	Length of the groove (m)
L_p	Length of pocket (m)
N	Runner speed (rpm)
N_a, N_r, N_θ	Number of nodes in three directions
N_g	Number of grooves
p	Pressure (Pa)
P_c	Cavitation pressure (Pa)
\bar{p}	Normalised pressure ($ph_2^2 / (\eta_0 \Omega R_m^2)$)
r, θ, z	Cylindrical coordinate in the film
r_p, θ_p, z_p	Cylindrical coordinate in the pad
\bar{r}	Normalized radial coordinate (r/R_m)
R_1	Inner radius of pad (m)
R_2	Outer radius of pad (m)
R_m	Mean radius (m)
\bar{R}_1	Normalized inner radius of pad (R_1/R_m)

\bar{R}_2	Normalized outer radius of pad (R_2/R_m)
R_f	Roughness factor
R_q	Root mean square value of surface roughness (μm)
s_h	Shoulder height of pad (μm)
s_g	Spacing between two grooves (m)
t	Taper portion (%)
t_p	Thickness of pad (m)
T	Temperature of the lubricant (K)
\bar{T}	Normalized temperature of the lubricant (T/T_0)
T_a	Ambient temperature (K)
T_{ex}	Temperature of the oil at exit (K)
T_0	Supply temperature of the lubricant at inlet (K)
T_R	Runner temperature (K)
T_{in}	Temperature of the lubricant at inlet (K)
T_p	Temperature in pad (K)
\bar{T}_p	Normalized temperature for pad (T_p/T_a)
U	Sliding velocity of runner (m/s)
u_r	Lubricant velocity in radial direction (m/s)
\bar{u}_r	Normalized lubricant velocity ($u_r/R_m\Omega$)
v_θ	Lubricant velocity in circumferential direction (m/s)
\bar{v}_θ	Normalized velocity ($v_\theta/R_m\Omega$)
w_z	Lubricant velocity in axial direction (m/s)
\bar{w}_z	Normalized lubricant velocity ($w_z/R_m\Omega$)
W	Load carrying capacity (N)

\bar{W}	Normalized load carrying capacity ($Wh_2^2/(\eta_0\Omega R_m^4)$)
W_{ext}	External applied load (N)
w_g	Width of groove (m)
w_p	Width of pocket (m)
z	Axial coordinate for fluid film region (m)
z_p	Axial coordinate in pad along pad thickness (m)

Greek symbols

β	Bulk modulus of the lubricant, Pa
η	Viscosity of lubricant, Pa-s
η_0	Viscosity of lubricant at inlet temperature, Pa-s
$\bar{\eta}$	Normalised viscosity of lubricant (η/η_0)
γ	Temperature viscosity coefficient, K^{-1}
μ	Coefficient of friction
Ω	Rotational speed, rad/s
ϕ	Fractional film content
ρ	Density of lubricant, kg/m^3
ρ_c	Density of lubricant within cavitated region, kg/m^3
ψ_1, ψ_2, ψ_3	Film thickness functions
σ^2	Variance of the height distribution
θ	Circumferential coordinate, rad
$\bar{\theta}$	Normalized circumferential coordinate