

# **PERFORMANCE STUDIES OF NEW MICRO-POCKETED AND BIONIC TEXTURED FIXED AND TILTING PAD THRUST BEARINGS USING FEM APPROACH**

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# **Performance Studies of New Micro-Pocketed and Bionic Textured Fixed and Tilting Pad Thrust Bearings using FEM Approach**

by

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Submitted

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

to the



**Indian Institute of Technology Delhi**  
**June 2022**

**Dedicated to**

*My parents and brother*

# Certificate

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This is to certify that the thesis entitled “**Performance Studies of New Micro-Pocketed and Bionic Textured Fixed and Tilting Pad Thrust Bearings using FEM Approach**” being submitted by **Mr. Jeewan Chandra Atwal** 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 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 Mr. Atwal has pursued the prescribed course of research at Indian Institute of Technology Delhi.



Dr. R. K. Pandey

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(Jeewan Chandra Atwal)

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# Abstract

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Fluid film thrust pad bearings are employed to sustain and guide the axial/thrust loads in hydraulic and steam turbines, large size air compressors, medium to large size impeller pumps, and high-power rated helical gearboxes. Such bearings possess inherent high damping capacity; however, at the same time consume significant amount of shaft power in overcoming the friction of lubricated film. But due to growing awareness for energy conservation and need of performance improvement of bearings at elevated operating conditions, great attempts are being made globally by the research community to address the concerns i.e., minimizing the power loss without sacrificing the load-carrying capacity and having desirable minimum film thickness. It is worth noting that since recent past, micro/nano geometries containing surface textures and pockets have emerged as potential technology to reduce the frictional power loss and enhance the operational life of pads at elevated operating conditions. In light of encouraging results achieved in presence of surface textures, there is a scope of study by conceiving and developing new surface textures/pockets for exploring the performance improvements of hydrodynamically lubricated fixed and tilting pad thrust bearings.

The main objective of study presented in this thesis is to investigate the performance parameters of fixed and tilting pad thrust bearings employing new conceived bionic texture design inspired from the micro-structures of the fish scales. However, the additional objective reported in the thesis involves the exploration of role of micro-pockets (including new pocket) on the performance behaviours of water lubricated fixed pad thrust bearing operating at the elevated speeds. Moreover, a chapter has been added in the thesis having new design charts involving two different micro-pockets on pads and empirical relations for finding the performance parameters of tilting thrust pad bearings. The governing lubrication equation incorporating mass-conserving issue has been discretized using the finite element method (FEM) and the solution of the non-linear algebraic equations has been found employing the Newton-Schur method. The mathematical model employed in the thesis has been validated with numerical and experimental results available in the published literature for developing the confidence in the numerical results presented in the thesis.

The performance behaviours of sector-shaped fixed thrust pad bearings incorporating new pad surface designs namely, (1) Labeo rohita fish scale textured pad, (2) Micro-rectangular

pocketed pad, and (3) Micro-rectangular pocketed pad with fish scale texture towards exit side, have been presented. The effects of texture parameters such as pocket/texture depth, extend of pocket and fish texture spread in the circumferential and radial directions, the number of scale texture waves in circumferential and radial directions, have been investigated for improving the performance of the bearings. On the basis of the investigations reported in this thesis, it has been found that the fixed pad surface having micro-rectangular pocketed pad with fish scale texture towards exit side, yields substantial increase (10-45%) in minimum film thickness and reduction (5-18%) in friction coefficient as compared to conventional pad design. Investigations were also carried out for determining the performance of fixed pad bearings employing a new conceived texture (i.e., trapezoidal pocket followed by scale texture) on pads' surface. It has been concluded that minimum film thickness has increased up to 48%, and the friction coefficient reduced up to 24% in comparison to conventional plain pad case. Moreover, the new textured pad has more metal surface area over the pad as compared to the conventional rectangular pocketed pad, which is beneficial in terms of reduction in load per unit area during the stopping/starting and mixed lubrication regimes.

To explore the effect of pocket/texture on a water lubricated thrust pad bearing operating in the turbulent flow regime, the performance parameters (minimum film thickness, friction coefficient, and bearing dynamic coefficients) of the bearings have been analysed. The performance behaviours achieved with a new pocketed pad bearing have been compared with the findings of the plain pad (without any pocket), and rectangular (conventional) pocketed bearing. With a new pocket, the minimum film thickness has increased in the range of 11–38% and friction coefficient has decreased up to 2% as compared to the conventional rectangular pocketed pad. The difference between bearing dynamic coefficients of new and conventional pocket has been found to be negligible.

Performance parameters of the sector shaped tilting pad thrust bearings employing the new micro-structural geometries (i.e., trapezoidal-textured, and trapezoidal-pocketed pads) on pad surfaces have been investigated. The pad equilibrium in the analysis is established using the Newton-Raphson and Braydon methods. The influence of attributes of microstructures such as depth, circumferential and radial positioning extents have been explored on the performance behaviours. In comparison to the rectangular-pocketed pad, the trapezoidal-textured and trapezoidal-pocketed pads have produced enhancement in the minimum film thickness varying in the range of 10-28.5% and 18-37%, respectively. The reduction in the power loss has also

been found up to 3% and 5.5% with trapezoidal-textured and trapezoidal-pocketed pads, respectively. However, the percentage decrease in maximum temperature is observed up to 5% and 10% with trapezoidal-textured and trapezoidal-pocketed pads, respectively.

Finally at the end, the thesis presents, new design charts and associated empirical relations for design of hydrodynamically lubricated rectangular-pocketed & trapezoidal-pocketed tilting pad thrust bearings. Numerical examples have been provided to demonstrate the use of the charts. The empirical relations are useful for developing the computer programs for speedy design of pad thrust bearings.

## सार

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हाइड्रोलिक और स्टीम टर्बाइन, बड़े आकार के एयर कंप्रेसर्स, मध्यम से बड़े आकार के इम्पेलर पंप और हाई-पावर रेटेड हेलिकल गियरबॉक्स में अक्षीय / थ्रस्ट लोड को बनाए रखने और मार्गदर्शन करने के लिए फ्लुइड फिल्म थ्रस्ट पैड बियरिंग्स को नियोजित किया जाता है। इस तरह के बियरिंगों में निहित उच्च भिगोना क्षमता होती है; हालांकि, एक ही समय में चिकनाई वाली फिल्म के घर्षण पर काबू पाने में महत्वपूर्ण मात्रा में शाफ्ट शक्ति का उपभोग करते हैं। लेकिन ऊर्जा संरक्षण के लिए बढ़ती जागरूकता और उन्नत परिचालन स्थितियों में बियरिंग्स के प्रदर्शन में सुधार की आवश्यकता के कारण, अनुसंधान समुदाय द्वारा चिंताओं को दूर करने के लिए विश्व स्तर पर महान प्रयास किए जा रहे हैं, अर्थात् भार-वहन क्षमता का त्याग किए बिना बिजली की हानि को कम करना और वांछनीय होना न्यूनतम फिल्म मोटाई। यह ध्यान देने योग्य है कि हाल के दिनों से, सतह बनावट और जेब वाले सूक्ष्म / नैनो ज्यामिति घर्षण बिजली के नुकसान को कम करने और उन्नत परिचालन स्थितियों में पैड के परिचालन जीवन को बढ़ाने के लिए संभावित तकनीक के रूप में उभरे हैं। सतही बनावट की उपस्थिति में प्राप्त उत्साहजनक परिणामों के आलोक में, हाइड्रोडायनामिक रूप से लुब्रिकेटेड फिक्स्ड और टिल्टिंग पैड थ्रस्ट बियरिंग्स के प्रदर्शन में सुधार की खोज के लिए नई सतह बनावट / जेब की कल्पना और विकास करके अध्ययन की गुंजाइश है।

इस थीसिस में प्रस्तुत अध्ययन का मुख्य उद्देश्य मछली के तराजू की सूक्ष्म संरचनाओं से प्रेरित नई कल्पित बायोनिक् बनावट डिजाइन को नियोजित करने वाले फिक्स्ड और टिल्टिंग पैड थ्रस्ट बियरिंग्स के प्रदर्शन मापदंडों की जांच करना है। हालांकि, थीसिस में बताए गए अतिरिक्त उद्देश्य में उच्च गति पर चलने वाले पानी के स्नेहक फिक्स्ड पैड थ्रस्ट बियरिंग के प्रदर्शन व्यवहार पर माइक्रो-पॉकेट (नई पॉकेट सहित) की भूमिका की खोज शामिल है। इसके अलावा, थीसिस में एक अध्याय जोड़ा गया है जिसमें पैड पर दो अलग-अलग माइक्रो-पॉकेट शामिल हैं और थ्रस्ट पैड बियरिंग के प्रदर्शन मापदंडों को खोजने के लिए अनुभवजन्य संबंध शामिल हैं। बड़े पैमाने पर संरक्षण के मुद्दे को शामिल करने वाले शासी स्नेहन समीकरण को परिमित तत्व विधि (FEM) का उपयोग करके विवेकित किया गया है और गैर-रेखीय बीजीय समीकरणों का समाधान न्यूटन-शूर विधि को नियोजित करते हुए पाया गया है। थीसिस में प्रयुक्त गणितीय मॉडल को थीसिस में प्रस्तुत संख्यात्मक परिणामों में विश्वास विकसित करने के लिए प्रकाशित साहित्य में उपलब्ध संख्यात्मक और प्रयोगात्मक परिणामों के साथ मान्य किया गया है।

नए पैड सतह डिजाइनों को शामिल करते हुए सेक्टर के आकार के फिक्स्ड थ्रस्ट पैड बेयरिंग का प्रदर्शन व्यवहार, (1) लैबियो रोहिता फिश स्केल टेक्सचर्ड पैड, (2) माइक्रो-रेक्टेंगुलर पॉकेटेड पैड, और (3) फिश स्केल टेक्सचर के साथ माइक्रो-रेक्टेंगुलर पॉकेटेड पैड निकास की ओर, प्रस्तुत किया गया है। बेयरिंग के प्रदर्शन में सुधार के लिए पॉकेट/टेक्सचर की गहराई, पॉकेट का विस्तार और परिधि और रेडियल दिशाओं में फैली मछली की बनावट, परिधि और रेडियल दिशाओं में स्केल टेक्सचर तरंगों की संख्या जैसे बनावट मापदंडों के प्रभावों की जांच की गई है। इस थीसिस में रिपोर्ट की गई जांच के आधार पर, यह पाया गया है कि फिक्स्ड पैड की सतह में सूक्ष्म-आयताकार पॉकेट वाले पैड होते हैं, जिसमें बाहर निकलने की ओर मछली पैमाने की बनावट होती है, पारंपरिक पैड डिजाइन की तुलना में न्यूनतम फिल्म मोटाई में पर्याप्त वृद्धि (10-45%) होती है घर्षण गुणांक में (5-18%) की कमी पाई गई। पैड की सतह पर एक नई कल्पित बनावट (यानी, ट्रेपेज़ॉइडल पॉकेट के बाद स्केल टेक्सचर) को नियोजित करने वाले फिक्स्ड पैड बेयरिंग के प्रदर्शन को निर्धारित करने के लिए भी जांच की गई। यह निष्कर्ष निकाला गया है कि पारंपरिक सादे पैड मामले की तुलना में न्यूनतम फिल्म मोटाई 48% तक बढ़ गई है, और घर्षण गुणांक 24% तक कम हो गया है। इसके अलावा, नए बनावट वाले पैड में पारंपरिक आयताकार पॉकेटेड पैड की तुलना में पैड के ऊपर अधिक धातु की सतह का क्षेत्र होता है, जो स्टॉपिंग / स्टार्टिंग और मिश्रित स्नेहन व्यवस्थाओं के दौरान प्रति यूनिट क्षेत्र में लोड में कमी के मामले में फायदेमंद होता है।

अशांत प्रवाह व्यवस्था में काम कर रहे पानी के लुब्रिकेटेड थ्रस्ट पैड बेयरिंग पर पॉकेट / टेक्सचर के प्रभाव का पता लगाने के लिए, बेयरिंग के प्रदर्शन मापदंडों (न्यूनतम फिल्म मोटाई, घर्षण गुणांक और असर गतिशील गुणांक) का विश्लेषण किया गया है। एक नए पॉकेटेड पैड बेयरिंग के साथ प्राप्त किए गए प्रदर्शन व्यवहार की तुलना प्लेन पैड (बिना किसी पॉकेट के), और आयताकार (पारंपरिक) पॉकेटेड बेयरिंग के निष्कर्षों से की गई है। एक नई पॉकेट के साथ, फिल्म की न्यूनतम मोटाई 11-38% की सीमा में बढ़ गई है और पारंपरिक आयताकार पॉक पैड की तुलना में घर्षण गुणांक 2% तक कम हो गया है। नई और पारंपरिक जेब के गतिशील गुणांक असर के बीच अंतर नगण्य पाया गया है।

पैड सतहों पर नए माइक्रो-स्ट्रक्चरल जियोमेट्री (यानी, ट्रेपेज़ॉइडल-टेक्सचर्ड, और ट्रेपेज़ॉइडल-पॉकेटेड पैड) को नियोजित करने वाले सेक्टर के आकार के टिल्टिंग पैड थ्रस्ट बेयरिंग्स के प्रदर्शन मापदंडों की जांच की गई है। न्यूटन-रैफसन और ब्रेयडन विधियों का उपयोग करके विश्लेषण में पैड संतुलन स्थापित किया गया है। प्रदर्शन व्यवहारों पर गहराई, परिधि और रेडियल स्थिति विस्तार जैसे

सूक्ष्म संरचनाओं की विशेषताओं के प्रभाव का पता लगाया गया है। आयताकार-पॉकेट वाले पैड की तुलना में, ट्रेपोज़ाइडल-बनावट और ट्रेपोज़ाइडल-पॉकेट वाले पैड ने न्यूनतम फिल्म मोटाई में क्रमशः 10-28.5% और 18-37% की सीमा में वृद्धि की है। ट्रेपेज़ॉइडल-टेक्सचर्ड और ट्रेपोज़ाइडल-पॉकेट वाले पैड के साथ क्रमशः 3% और 5.5% तक ऊर्जा के नुकसान में कमी पाई गई है। हालांकि, अधिकतम तापमान में प्रतिशत की कमी क्रमशः ट्रेपेज़ॉइडल-बनावट और ट्रेपोज़ाइडल-पॉकेट पैड के साथ 5% और 10% तक देखी गई है।

अंत में, थीसिस प्रस्तुत करता है, नए डिजाइन चार्ट और हाइड्रोडायनामिक रूप से लुब्रिकेटेड आयताकार-पॉकेट और ट्रेपोज़ॉइडल-पॉकेट टिल्टिंग पैड थ्रस्ट बियरिंग्स के डिजाइन के लिए संबंधित अनुभवजन्य संबंध। चार्ट के उपयोग को प्रदर्शित करने के लिए संख्यात्मक उदाहरण प्रदान किए गए हैं। पैड थ्रस्ट बियरिंग्स के त्वरित डिजाइन के लिए कंप्यूटर प्रोग्राम विकसित करने के लिए अनुभवजन्य संबंध उपयोगी हैं।

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# Nomenclature

|                  |                                                                                                                      |
|------------------|----------------------------------------------------------------------------------------------------------------------|
| $a$              | width of a fish texture in the Fig. 4.3(b), m                                                                        |
| $A_e$            | area of the $e^{\text{th}}$ element                                                                                  |
| $b$              | spacing between two adjacent fish textures in the Fig. 4.3(b), m                                                     |
| $b_{np}, b_{cp}$ | width of new pocket and conventional pocket respectively (in the radial direction), m                                |
| $b_r$            | radial width of pocket, m                                                                                            |
| $B$              | bearing width in radial direction, m                                                                                 |
| $B_q, B_t$       | radial length of trapezoidal-pocketed & trapezoidal-textured pads, respectively, m                                   |
| $C_p$            | fluid heat capacity, J/kg-K                                                                                          |
| $C_{np}, C_{cp}$ | dimensionless circumferential extents of the new pocketed and rectangular (conventional) pocketed pads, respectively |
| $E_p$            | power loss, W                                                                                                        |
| $F$              | fluid friction, N                                                                                                    |
| $h$              | film thickness, m                                                                                                    |
| $h_d$            | depth of texture, m                                                                                                  |
| $h_{df}$         | fish scale texture depth, m                                                                                          |
| $h_{dp}, h_{cp}$ | pocket depth, m                                                                                                      |
| $h_{np}$         | depth of new pocket, m                                                                                               |
| $h_1$            | inlet film thickness, m                                                                                              |
| $h_2$            | minimum film thickness, m                                                                                            |
| $k$              | index used in fish textured pad equations                                                                            |
| $k_r$            | convergence ratio $[(h_1 / h_2) - 1]$                                                                                |
| $L$              | length of bearing, m                                                                                                 |
| $L_p$            | width of taper land, m                                                                                               |

|               |                                                              |
|---------------|--------------------------------------------------------------|
| $L_{ui}$      | untextured length at inlet, m                                |
| $M$           | moment of a fluid force about the pivot axis, N-m            |
| $n$           | index used for updating viscosity                            |
| $n_n$         | number of nodes in an element                                |
| $n_r$         | component of unit normal vector in radial direction          |
| $n_t$         | total number of nodes in computational domain                |
| $n_\theta$    | component of unit normal vector in circumferential direction |
| $N$           | shape function                                               |
| $N_e$         | number of elements                                           |
| $N_g$         | number of grooves                                            |
| $N_r$         | number of elements in radial direction                       |
| $N_\theta$    | number of elements in circumferential direction              |
| $p$           | gauge pressure, N/m <sup>2</sup>                             |
| $r$           | radial coordinate, m                                         |
| $r_{initial}$ | starting point of texture defined by $(0.5 * B - b_r)$       |
| $R_1$         | bearing inner radius, m                                      |
| $R_2$         | bearing outer radius, m                                      |
| $Re$          | local Reynolds number $(\rho \omega r h / \eta_0)$           |
| $Re_g$        | global Reynolds number $(\rho \omega s_h R_2 / \eta_0)$      |
| $s_h$         | shoulder height $(h_1 - h_2)$ , m                            |
| $T$           | temperature, K                                               |
| $T_{max}$     | maximum oil temperature, °C                                  |
| $U$           | speed of runner defined at mean radius of bearing, m/s       |
| $W_{ext}$     | external applied load on bearing, N                          |
| $W, W_{int}$  | load carrying capacity, N                                    |

|                              |                                                                                                   |
|------------------------------|---------------------------------------------------------------------------------------------------|
| $x_p$                        | Pivot circumferential position from inlet, m                                                      |
| $z$                          | axial coordinate, m                                                                               |
| $Z_n$                        | number of pads                                                                                    |
| $\theta$                     | circumferential coordinate, degree                                                                |
| $\theta_a$                   | half-wave extents in $\theta$ direction for new textured pad, degree                              |
| $\theta_c$                   | circumferential half wave extents of fish texture, degree                                         |
| $\theta_f$                   | circumferential extents of texture, degree                                                        |
| $\theta_0$                   | pad angle, degree                                                                                 |
| $\theta_p$                   | circumferential extents of pocket in case of pocket with fish texture pad, degree                 |
| $\theta_{np}$                | extents of the pocketed pad in the circumferential direction in case of new textured pad          |
| $\theta_{pp}$                | pivot circumferential position from inlet of a pad, degree                                        |
| $\theta_{tc}$                | circumferential extent of trapezoidal portion of trapezoidal-textured pad, degree                 |
| $\theta_{tp}, \theta_{tt}$   | circumferential extents of trapezoidal-pocketed & trapezoidal-textured pads, respectively, degree |
| $\theta_{pce}, \theta_{tce}$ | circumferential extents of the pocketed pad and new textured pad respectively, degree             |
| $\eta$                       | lubricant dynamic viscosity, N-s/m <sup>2</sup>                                                   |
| $\eta_0$                     | lubricant dynamic viscosity at inlet temperature, N-s/m <sup>2</sup>                              |
| $\mu$ or $f$                 | coefficient of friction                                                                           |
| $\rho$                       | lubricant density, kg/m <sup>3</sup>                                                              |
| $\rho_0$                     | lubricant density in full film region, kg/m <sup>3</sup>                                          |
| $\rho_T$                     | texture density                                                                                   |
| $\Omega$                     | rotational speed, s <sup>-1</sup>                                                                 |
| $\alpha$                     | inclination angle of an edge in the Fig. 6.3(b), degree                                           |

|          |                                                                                |
|----------|--------------------------------------------------------------------------------|
| $\beta$  | inclination angle of an edge of trapezoid for trapezoidal-pocketed pad, degree |
| $\phi$   | cavity fraction                                                                |
| $\gamma$ | temperature viscosity coefficient, K <sup>-1</sup>                             |

## Dimensionless parameters

|                |                                  |
|----------------|----------------------------------|
| $\bar{C}$      | $Ch_2^3 / \mu R_2^4$             |
| $\bar{h}$      | $h / h_2$                        |
| $\bar{h}_T$    | $(h + h_d) / h_2$                |
| $\bar{p}$      | $ph_2^2 / (\eta_0 \Omega R_1^2)$ |
| $\bar{r}$      | $r / R_1$                        |
| $\bar{s}$      | $h_d / h_2$                      |
| $\bar{S}$      | $Sh_2^3 / \mu \omega R_2^4$      |
| $\bar{z}$      | $z / h$                          |
| $\bar{\theta}$ | $\theta$                         |
| $\bar{\eta}$   | $\eta / \eta_0$                  |

\*\*\*\*\*