

TRIBOLOGICAL AND VIBRATIONAL STUDIES OF TEXTURED SPUR GEARS

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TRIBOLOGICAL AND VIBRATIONAL STUDIES OF TEXTURED SPUR GEARS

By

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Certificate

This is to certify that the thesis entitled “**Tribological and Vibrational Studies of Textured Spur Gears**” being submitted by **Ms. Niharika Gupta** (2015ITZ8141) to the **Indian Institute of Technology Delhi**, New Delhi, India, for the award of the degree of **Doctor of Philosophy** is a bonafide record of original research work carried out by her under our supervisions in conformity with rules and regulations of the institute.

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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Dedicated to my

Husband

*who have always been my source of inspiration, guidance and encouragement, and my
gratitude for whom can never be put into words*

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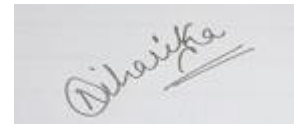
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A rectangular box containing a handwritten signature in cursive script, which appears to read 'Niharika'.

(Niharika Gupta)

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Abstract

Gearsets play vital role in the transmission systems of industrial machines and vehicles (buses, trucks, earth moving machinery, loco-engines, cars, marine engines etc.). Therefore, there is increasing demand for hard and efficient working gearsets possessing very high gear transmission density and long life for use in several mechanical systems. In this situation, the improvement in the tribological performance at the gear teeth interfaces is needed for preventing the surface failures and controlling the vibration. Elastohydrodynamic, mixed or boundary lubrication regimes occur between the contact of the mating teeth surfaces of gearsets due to its high non-conformity. This increases friction at the teeth contacts. Thus, the existence of effective lubricating film at the gear teeth interfaces is necessary to avoid the gearsets operation under mixed/boundary lubrication regime or starved lubrication at elevated loads and slow speeds. It is worth noting here that since recent past, the tribological performance in gearsets operating in boundary lubrication regime is being improved by employing nano-lubricants, extreme pressure additives and increase in teeth surface hardness and surface finish. It is widely reported by the researchers that the improvement in tribological behaviour at gear teeth interfaces leads to reduced dynamic problems and increased life/reliability of gear transmission systems.

After the emergence of surface textures as technology, the researchers are exploring to improve the tribological and vibration behaviours of conformal and non-conformal contacts using different surface textures. These studies have shown significant reductions in the friction and vibration. However, careful selection of various texture parameters such as texture density, depth, dimensions, and texturing methods are extremely important to achieve the significant

improvement in tribodynamic performance of tribological elements. Therefore, the objective of this research work is to explore the tribodynamic behaviours of textured teathed gearsets experimentally and numerically for enhancing the performance parameters in comparison to conventional teathed gearsets operating at the same parameters under fully flooded/starved lubricating conditions.

The tribological and vibrational behaviors of conventional and textured spur gearsets have been experimentally explored under fully flooded and starved lubricating conditions at different operating parameters. Three different textures on gears' teeth profiles were created by placing the dimples of vertically oriented ellipsoid, horizontally oriented ellipsoid and hemisphere in the zigzag patterns using nanosecond pulsed fiber laser. Tribological parameters (contact resistance, temperature rise and surface topography) and vibration (in time and frequency domains) were obtained, compared, and analysed. The results revealed significant reduction in vibration amplitudes, increase in contact resistance, decrease in temperature rise and less damage of mating surfaces in the presence of textures. Moreover, the texture involving vertically oriented ellipsoidal dimples has yielded the best results. Further, to explore the critical role of texture on the tribodynamics of gearsets, accelerated testing has been done. Experimental investigation of the tribodynamic behaviour of spur gearsets has been done by employing conventional and textured teeth (presence of variable size micro-cylindrical dimples increasing from PCD to tip/root) from comparison perspective. The micro-cylindrical dimples of non-uniform diameters were fabricated using chemical etching on the gears' teeth surface. The vibration results obtained employing conventional and textured gearsets have been compared and analysed in time and frequency domains. Moreover, the surface topography and temperature rise have been measured. Based on the experimental results, it is found that in the presence of texture on gear teeth, the vibration amplitudes, oil film temperature rise and teeth surface damage have substantially reduced.

Furthermore, the synergistic effects of surface texture and Molybdenum disulphide (MoS_2) blended grease have also been explored on the tribodynamic performance of spur gearsets. It was decided to use the texture involving the best performing vertically oriented ellipsoidal dimples, which was explored and established for oil lubricated textured gearsets. The experiments were performed at different applied torques and a pitch line velocity of 4 m/s keeping in mind the practical application of the results. Contact resistance, vibrations, temperature rise and surface topographies have been measured and analysed. Substantial increase in contact resistance and reduction in vibration amplitudes at gear mesh frequency were found in the presence of texture. Reduction in interfacial temperature rise and less damage to teeth surface were also observed.

Numerical investigation on performance behaviour of elastohydrodynamically lubricated concentrated line/teeth contacts of gearset incorporating surface texture have also been done. In the numerical analysis, the Reynolds and elasticity equations have been solved simultaneously and discretized using finite difference method considering cavitation effect. The performance parameters (film thickness, coefficient of friction, side leakage and dynamic coefficients) have been numerically investigated and analysed for varying input data. The results show that the textured line contact having ellipsoidal dimples yields substantial increase in minimum film thickness and reduction in friction coefficient as compared to the conventional contact. The side leakage has also decreased in the presence of surface texture. Overall, the textured contact has shown much better static performance among all the cases. It has also shown better dynamic coefficients in comparison to conventional contacts.

सार

गियरसेट औद्योगिक मशीनों और वाहनों (बसों, ट्रकों, धरती पर चलने वाली मशीनरी, लोको-इंजन, कार, समुद्री इंजन आदि) के संचरण प्रणालियों में महत्वपूर्ण भूमिका निभाते हैं। इसलिए कई यांत्रिक प्रणालियों में उपयोग के लिए बहुत अधिक गियर ट्रांसमिशन घनत्व और लंबे जीवन वाले कठोर और कुशल काम करने वाले गियरसेट की मांग बढ़ रही है। इस स्थिति में, सतह की विफलताओं को रोकने और कंपन को नियंत्रित करने के लिए गियर दांत इंटरफेस में जनजातीय प्रदर्शन में सुधार की आवश्यकता है। इलास्टोहाइड्रोडायनामिक, मिश्रित या सीमा स्नेहन व्यवस्था इसकी उच्च गैर-अनुरूपता के कारण गियरसेट के संभोग दांतों की सतहों के संपर्क के बीच होती है। इससे दांतों के संपर्कों में घर्षण बढ़ता है। इस प्रकार, उच्च भार और धीमी गति पर भूखे स्नेहन के अस्तित्व में भी मिश्रित/सीमा स्नेहन व्यवस्था के तहत गियरसेट के संचालन से बचने के लिए गियर दांत इंटरफेस पर प्रभावी स्नेहन फिल्म का अस्तित्व आवश्यक है। यहां यह ध्यान देने योग्य है कि हाल के दिनों से, नैनो-लुब्रिकेंट्स, अत्यधिक दबाव एडिटिव्स को नियोजित करके और दांतों की सतह की कठोरता और सतह की फिनिश में वृद्धि करके सीमा स्नेहन शासन में संचालित गियरसेट में जनजातीय प्रदर्शन में सुधार किया जा रहा है। शोधकर्ताओं द्वारा यह व्यापक रूप से बताया गया है कि गियर दांत इंटरफेस में जनजातीय व्यवहार में सुधार से गतिशील समस्याएं कम हो जाती हैं और गियर ट्रांसमिशन सिस्टम के जीवन/विश्वसनीयता में वृद्धि होती है।

प्रौद्योगिकी के रूप में सतह बनावट के उद्भव के बाद, शोधकर्ता विभिन्न सतह बनावट का उपयोग करके अनुरूप और गैर-अनुरूप संपर्कों के जनजातीय और कंपन व्यवहार में सुधार करने के लिए खोज रहे हैं। इन अध्ययनों ने घर्षण और कंपन में महत्वपूर्ण कमी दिखाई है। हालांकि, विभिन्न बनावट मापदंडों जैसे कि बनावट घनत्व, गहराई, आयाम और बनावट विधियों का सावधानीपूर्वक चयन आदिवासी तत्वों

के ट्राइबोडायनामिक प्रदर्शन में महत्वपूर्ण सुधार प्राप्त करने के लिए अत्यंत महत्वपूर्ण है। इसलिए, इस शोध कार्य का उद्देश्य पारंपरिक दांतेदार गियर जोड़े की तुलना में प्रदर्शन मापदंडों को बढ़ाने के लिए प्रयोगात्मक और संख्यात्मक रूप से बनावट वाले के ट्राइबोडायनामिक व्यवहार का पता लगाना है। पूरी तरह से बाढ़/भूखे स्नेहन स्थितियों के तहत समान पैरामीटर।

पारंपरिक और बनावट वाले स्पर गियर पेयर के ट्राइबोलॉजिकल और वाइब्रेशनल व्यवहारों को विभिन्न ऑपरेटिंग मापदंडों पर पूरी तरह से बाढ़ और भूखे स्नेहक परिस्थितियों में प्रयोगात्मक रूप से खोजा गया है। गियर के दांतों के प्रोफाइल पर तीन अलग-अलग बनावट नैनोसेकंड स्पंदित फाइबर लेजर का उपयोग करके ज़िगज़ैग पैटर्न में लंबवत उन्मुख दीर्घवृत्त, क्षैतिज रूप से उन्मुख दीर्घवृत्त और गोलार्ध के डिम्पल को रखकर बनाए गए थे। जनजातीय पैरामीटर (संपर्क प्रतिरोध, तापमान वृद्धि और सतह स्थलाकृति) और कंपन (समय और आवृत्ति डोमेन में) प्राप्त, तुलना और विश्लेषण किया गया था। परिणामों से कंपन आयामों में उल्लेखनीय कमी, संपर्क प्रतिरोध में वृद्धि, तापमान वृद्धि में कमी और बनावट की उपस्थिति में संभोग सतहों की कम क्षति का पता चला। इसके अलावा, लंबवत उन्मुख दीर्घवृत्तीय डिम्पल से युक्त बनावट ने सर्वोत्तम परिणाम प्राप्त किए हैं। इसके अलावा, गियरसेट के ट्राइबोडायनामिक्स पर बनावट की महत्वपूर्ण भूमिका का पता लगाने के लिए त्वरित परीक्षण किया गया है। तुलनात्मक दृष्टिकोण से पारंपरिक और बनावट वाले दांतों (पीसीडी से टिप/रूट तक बढ़ते हुए चर आकार के सूक्ष्म-बेलनाकार डिम्पल की उपस्थिति) को नियोजित करके स्पर गियरसेट के ट्राइबोडायनामिक व्यवहार की प्रायोगिक जांच की गई है। गैर-समान व्यास के सूक्ष्म-बेलनाकार डिम्पल गियर्स के दांतों की सतह पर रासायनिक नक्काशी का उपयोग करके गढ़े गए थे। पारंपरिक और बनावट वाले गियरसेट का उपयोग करके प्राप्त कंपन परिणामों की समय और आवृत्ति डोमेन में तुलना और विश्लेषण किया गया है। इसके अलावा, सतह स्थलाकृति और तापमान वृद्धि को मापा गया है। प्रयोगात्मक परिणामों के आधार पर, यह पाया गया है कि गियर दांतों पर बनावट की उपस्थिति में, कंपन आयाम, तेल फिल्म तापमान वृद्धि और दांतों की सतह की क्षति में काफी कमी आई है।

इसके अलावा, सतह बनावट और मोलिब्डेनम डाइसल्फाइड (MoS_2) मिश्रित ग्रीस के सहक्रियात्मक प्रभावों को भी स्पर गियरसेट के ट्राइबोडायनामिक प्रदर्शन पर खोजा गया है। सबसे अच्छा प्रदर्शन करने वाले लंबवत उन्मुख दीर्घवृत्तीय डिम्पल को शामिल करते हुए बनावट का उपयोग करने का निर्णय लिया गया था, जिसे तेल लुब्रिकेटेड बनावट वाले गियरसेट के लिए खोजा और स्थापित किया गया था। प्रयोगों को विभिन्न लागू टोक्रों और परिणामों के व्यावहारिक अनुप्रयोग को ध्यान में रखते हुए 4 मीटर/सेकेंड की पिच लाइन वेग पर किया गया था। संपर्क प्रतिरोध, कंपन, तापमान वृद्धि और सतह स्थलाकृतियों को मापा और विश्लेषण किया गया है। बनावट की उपस्थिति में संपर्क प्रतिरोध में पर्याप्त वृद्धि और गियर मेश आवृत्ति पर कंपन आयामों में कमी पाई गई। इंटरफेशियल तापमान वृद्धि में कमी और दांतों की सतह को कम नुकसान भी देखा गया।

सतह बनावट (एलिप्सोइडल डिम्पल) को शामिल करते हुए गियरसेट के इलास्टोहाइड्रोडायनामिक रूप से लुब्रिकेटेड केंद्रित लाइन/दांत संपर्कों के प्रदर्शन व्यवहार पर संख्यात्मक जांच भी की गई है। संख्यात्मक विश्लेषण में, रेनॉल्ड्स और लोच समीकरणों को एक साथ हल किया गया है और गुहिकायन प्रभाव पर विचार करते हुए परिमित अंतर विधि का उपयोग करके विवेक किया गया है। प्रदर्शन मापदंडों (फिल्म की मोटाई, घर्षण का गुणांक, साइड लीकेज और डायनेमिक गुणांक) को अलग-अलग इनपुट डेटा के लिए संख्यात्मक रूप से जांच और विश्लेषण किया गया है। परिणाम बताते हैं कि दीर्घवृत्ताकार डिम्पल वाले बनावट वाले लाइन संपर्क से पारंपरिक संपर्क की तुलना में न्यूनतम फिल्म मोटाई और घर्षण गुणांक में कमी में पर्याप्त वृद्धि होती है। सतह बनावट की उपस्थिति में साइड रिसाव भी कम हो गया है। कुल मिलाकर, बनावट वाले संपर्क ने सभी मामलों में बेहतर स्थिर प्रदर्शन दिखाया है। इसने पारंपरिक संपर्कों की तुलना में बेहतर गतिशील गुणांक भी दिखाया है।

Table of Contents

Certificate	i
Acknowledgements	iii
Abstract	v
List of Contents	xi
List of Figures	xvi
List of Tables	xxiv
Nomenclature	xxv

Chapter 1	Introduction	1-9
1.1	Background	1
1.2	Surface modification in tribological machine elements	5
1.3	Scope of study	7
1.4	Organisation of thesis	8
Chapter 2	Literature Review	10-22
2.1	Techniques for improving tribodynamic performance of oil lubricated gearsets	10
2.1.1	Effects of surface modifications of gear teeth surfaces	10
2.1.2	Influence of tooth profile modifications on tribodynamics of gearsets	12

2.1.3	Influence of lubrication on tribodynamics of gearsets	12
2.1.4	Effects of damping particles on tribodynamics of gearsets	14
2.2	Techniques for improving tribodynamic performance of grease lubricated spur gearsets	14
2.3	Tribodynamic studies of generic textured concentrated contacts	17
2.4	Surface texturing techniques	18
2.5	Numerical modelling of elastohydrodynamically lubricated concentrated line/teeth contact of gearsets	19
2.6	Conclusions of literature review	21
2.7	Objectives of thesis	22
Chapter 3	Experimental Study of Tribodynamic behaviours of Oil Lubricated Conventional/Textured Spur Gearsets	23-69
3.1	Experimental Details	24
3.1.1	Textured gears	24
3.1.2	Test rig setup and experimentation	28
3.1.3	Lubricating oil	31
3.1.4	Experimental procedure	31
3.2	Results and discussions	33
3.2.1	Fully flooded lubrication	33
3.2.1.1	Film formation and temperature rise	33
3.2.1.2	Teeth surface investigation	39
3.2.1.3	Vibrations	41
3.2.2	Starved Lubrication	50
3.3	Accelerated Testing	54
3.3.1	Experimental description	54

3.3.1.1	Selection of test gears, lubricating oil and creation of texture	54
3.3.1.2	Measurement of vibrations, film temperature rise and surface topography	57
3.3.1.3	Experimental Procedure	57
3.3.2	Results and discussions	58
3.3.2.1	Vibration Investigation	58
3.3.2.2	Oil film temperature rise and worn surface investigation	62
3.4	Concluding Remarks	67
Chapter 4	Experimental Investigation of Tribodynamic Performances of Grease Lubricated Conventional/Textured Spur Gearsets	69-101
4.1	Experimental Details	70
4.1.1	Spur gearset and surface texturing	70
4.1.2	Grease samples	74
4.1.3	Description of Experimental Setup	77
4.1.4	Test procedure	81
4.2	Results and discussions	82
4.2.1	Film formation in terms of electrical resistance	82
4.2.2	Temperature rise and teeth surface topography	86
4.2.3	Vibrations	95
4.3	Concluding remarks	101
Chapter 5	Lubrication Governing Equations and Computational Procedure	102-116
5.1	Description of geometry of gearset	103
5.2	Governing equations for evaluation of performance parameters	104
5.2.1	Reynolds equation	104

5.2.2	The film thickness expression	106
5.2.3	Rheological relation	107
5.2.4	Steady state and dynamic pressure equations	108
5.2.5	Stiffness and damping coefficients	111
5.2.6	Miscellaneous equations	112
5.3	Computational procedure and flowchart	113
5.4	Validation of numerical model	115
5.5	Concluding remarks	116
Chapter 6	Numerical Analysis of Lubricated Conventional/Textured Line contacts of Gears	117-135
6.1	Numerical input data	117
6.2	Influence of surface texture on film thickness	118
6.3	Influence of surface texture on coefficient of friction	130
6.4	Effects of surface texture on side leakage	131
6.5	Effects of surface texture on dynamic coefficients	132
6.6	Concluding remarks	134
Chapter 7	Conclusions and Scope of further Research	136-140
7.1	Conclusions	136
7.1.1	Experimental study of tribodynamic behaviours of oil lubricated conventional/textured spur gearsets	136
7.1.2	Experimental investigation of tribodynamic performances of grease lubricated conventional/textured spur gearsets	138
7.1.3	Lubrication governing equations and computational procedure	139

7.1.4	Numerical analyses of lubricated conventional/textured line contacts of gearsets	139
7.2	Scope for further research	140
References		141-153

List of Figures

Fig. no.	Description	Page no.
1.1	Lubrication in gearsets [1]	1
1.2	(a) Rolling and rolling/sliding motions at the typical meshed gear teeth; (b) High slip zones over a tooth face	2
1.3	Schematic diagram showing the isochromatic (shear stress distributions) at the concentrated line contact (it simulates the line contact found in spur gearset)	3
1.4	Photographic views of failed gears' teeth mainly due to high friction and associated vibrations [5-7]	4
1.5	Various texture shapes (a) circular, (b) elliptical, (c) triangular, (d) rectangular, (e) groove and (f) chevron-like [8]	5
1.6	Patterns of surface textures created on (a) polyimide sheets using laser texturing; (b) 100Cr6 steel using micro-coining [9]	7
1.7	Surface texture (a) view of dimples with ablated material around the edges; (b) view of dimples after lapping [10]	7
3.1	CAD model of textured gear teeth surfaces	26
3.2	(a) Textured teeth surface, (b) SEM image of textured surface, (c) 2D profile of dimple	27
3.3	SEM images of textured surfaces involving vertically oriented ellipsoidal dimples, horizontally oriented ellipsoidal dimples and hemispherical dimples	28
3.4	Description of experimental set up (a) CAD model of gear test rig (b) front view of test gear box showing the scheme of contact resistance and vibration measurement	30
3.5	Photographic illustration of test gear mountings	30
3.6	Comparison of contact resistance at the interface of conventional and textured gear sets at different loads; (a) 4m/s, (b) 8m/s	35

3.7	Teeth contact patterns in textured gear sets; (a) vertically oriented ellipsoidal dimples, (b) horizontally oriented ellipsoidal dimples	36
3.8	Schematic representation of the mechanisms accountable for the performance improvement due to the presence of texture at the interface of teeth	37
3.9	Comparison of temperature rise at the interface of conventional and textured gear sets at different loads; (a) 4m/s, (b) 8m/s	38
3.10	SEM micro-images of teeth surfaces ($p_H = 0.7\text{GPa}$, 8m/s)	40
3.11	SEM/EDXS images of teeth surfaces of pinions, (a) conventional teeth; (b) textured surface with vertically oriented ellipsoids; (c) textured surface with horizontally oriented ellipsoids; (d) textured surface with hemispheres; at $p_H = 0.7\text{GPa}$ and 8m/s	41
3.12	Vibration response of conventional and textured gear sets in time domain at 4m/s (a) Load = 30 N/0.4 GPa, (b) Load = 90N/0.7GPa	44
3.13	Vibration response of conventional and textured gear sets in frequency domain at 4m/s (a) Load = 30 N/0.4 GPa, (b) Load = 90N/0.7GPa	45
3.14	Schematic representation of physical contact/interface (a) conventional pinion, (b) textured pinion	46
3.15	Vibration response of conventional and textured gear sets in time domain at 8m/s (a) Load = 30 N/0.4 GPa, (b) Load = 90N/0.7GPa	47
3.16	Vibration response of conventional and textured gear sets in frequency domain at 8m/s (a) Load = 30 N/0.4 GPa, (b) Load = 90N/0.7GPa	48
3.17	Comparison of vibration acceleration amplitudes at gear mesh frequency at different loads and velocities	49
3.18	Vibration responses of conventional and textured gear sets in time and frequency domain at $p_H = 0.7\text{GPa}$ and 4m/s for starved lubricating condition	51

3.19	SEM images of teeth surfaces of conventional and textured pinions at $p_H = 0.7\text{GPa}$ and 4m/s for starved lubricating condition	52
3.20	SEM images of counter mating gear teeth surfaces for conventional and textured pinions at $p_H = 0.7\text{GPa}$ and 4m/s for starved lubricating condition	53
3.21	SEM/EDXS images of teeth surfaces of pinions under starved lubricated condition, (a) Conventional teeth surface; (b) textured teeth surface; at $p_H = 0.7\text{GPa}$ and 4m/s	53
3.22	Textured teeth surface; (a) Schematic view, (b) Photographic view, (c) SEM image	56
3.23	Comparisons of vibration velocity spectra with conventional and textured gearsets [Velocity= 4m/s , $p_H = 0.2, 0.4, 0.5, 0.6$, and 0.7GPa]	60
3.24	Comparisons of vibration velocity spectra of conventional and textured gearsets [Velocity= 8m/s , $p_H = 0.2, 0.4, 0.5, 0.6$, and 0.7GPa]	61
3.25	Vibration (velocity) amplitudes at the gear mesh frequencies at different loads and two velocities; (a) Velocity = 4m/s , (b) Velocity = 8m/s	62
3.26	Comparison of average film temperature rise during meshed gearset; (a) Velocity = 4m/s , (b) Velocity = 8m/s	63
3.27	Temperature images captured by FLIR camera at $p_H = 0.4\text{GPa}/30\text{N}$ [Distance= 0.5m , $T_{\text{refl}} = 20^\circ\text{C}$, $\epsilon = 0.96$]	63
3.28	SEM images of teeth surfaces [Load= 90N ($p_H = 0.7\text{GPa}$), Velocity = 8m/s]	65
3.29	SEM images with EDS analysis of teeth surfaces; (a) Conventional gear (b) Textured gear [Load= 90N ($p_H = 0.7\text{GPa}$), Velocity = 8m/s]	66
3.30	Comparison of microscopic 3-D and 2-D views of dimples of fresh and used textured surfaces (a) 3-D view of fresh textured surface (b) 3-D view of used textured surface [Load= 90N ($p_H = 0.7\text{GPa}$), Velocity = 8m/s] (c) 2-D profile of fresh dimple (d) 2-D profile of used dimple [Load= 90N ($p_H = 0.7\text{GPa}$), Velocity = 8m/s]	66

4.1	Texture details; (a) CAD model of a textured pinion tooth, (b) Photographic view of textured teeth, (c) SEM image of textured tooth surface (after texturing), (d) SEM image of textured surface (after lapping), (e) 2D profile of ellipsoidal dimple in X-direction, (f) 2D profile of ellipsoidal dimple in Y-direction	73
4.2	Comparison of microscopic 3D and 2D views of fresh conventional and textured pinion teeth surfaces; (a) 3D surface topography of fresh conventional tooth, (b) 3D surface topography of fresh textured tooth after lapping, (c) 2D roughness profile of conventional surface, (d) 2D roughness profile of fresh textured surface	74
4.3	TEM micro-images of soap fibers of fresh and MoS ₂ blended greases	77
4.4	(a) Schematic illustration of top view of experimental setup; (b) Photographic views of mounted test gearset, (c) Coated and uncoated sides of test gear	80
4.5	Variation of electrical contact resistance at the interfaces of conventional and textured gearsets at different torques	84
4.6	Schematic depiction of the mechanisms responsible for improving the tribodynamic performance in presence of texture/MoS ₂ flakes at the interface of teeth	86
4.7	Variation of maximum temperature rise at the interfaces of conventional and textured gearsets at applied torques	87
4.8	Maximum temperature rise at the interfaces of conventional and textured gearsets [Duration of test= 3.5 hours, Applied torque =40.5 N-m]	88
4.9	SEM and EDXS micro-images of teeth surfaces of conventional and textured pinions at location-1 (towards addendum) after running time of 3.5 hr [Torque=40.5 N-m]	91
4.10	SEM and EDXS micro-images of teeth surfaces of conventional and textured pinions at location-2 towards dedendum [Torque=40.5 N-m, Test duration=3.5 hours]	92
4.11	SEM micro-images of surfaces of counter meshing gear tooth [Torque=40.5 N-m, Test duration=3.5 hours]	93

4.12	3D surface topographies of counter meshing tooth [Torque=40.5 N-m, Test duration=3.5 hours]	94
4.13	TEM micro-images of soap fibers of used greases [Torque=40.5 N-m, Test duration=3.5 hours]	95
4.14	Vibrations of conventional and textured gear sets, (a) Time domain, (b) Frequency domain [torque= 13.5 N-m, test duration=30 min]	97
4.15	Vibrations of conventional and textured gear sets (a) Time domain, (b) Frequency domain [torque= 40.5 N-m, test duration=30 min]	98
4.16	Variation of vibration amplitudes at GMF of conventional and textured gear sets at different torques	99
4.17	Vibrations of conventional and textured gearsets, (a) Time domain, (b) Frequency domain [torque=40.5 N-m, test duration= 3.5 hours]	100
5.1	CAD model of gear tooth (a) conventional gear tooth (b) Representation of mating spur gear faces by cylinders (c) textured gear tooth	103
5.2	Line contact and its geometry (a) two cylinders; (b) equivalent contact	104
5.3	Illustration of three-dimensional ellipsoidal dimple with co-ordinate system	107
5.4	Flow chart of computational procedure	114
5.5	Validation of the present model with prior published work; (a) elastic deformation profile with the result of authors [153] (Input data: $p_H = 0.3$ GPa, radius of hertz circle = 0.104061 mm, elastic modulus=115.9739 GPa), (b) film thickness profile with the result of authors[154] (Input data: $U=6 \times 10^{-11}$, $R_x=12.7$ mm, $L=12.7$ mm, $\eta_0=0.08$ Pa-s, $\rho_0=870$ kg/m ³ , $G= 5000$), (c) comparison of Coefficient of friction with results of authors [154] (Input data: $R_x=12.7$ mm, $L=12.7$ mm, $\eta_0=0.08$ Pa-s, $\rho_0=870$ kg/m ³ , $G= 5000$)	115
6.1	3-D computational domains of contact, (a) conventional, (b) textured	118

6.2	Variation of minimum film thickness for conventional and textured contact at different speeds; (a) applied load, $p_H = 0.3\text{GPa}$, (b) applied load, $p_H = 0.5\text{ GPa}$, and (c) applied load, $p_H = 0.7\text{ GPa}$	120
6.3	Pressure profile illustrations: (a) 3-D pressure profile of conventional contact, (b) 3-D pressure profile of textured contact, (c) comparison of pressure profiles of conventional and textured contact at mid-length ($Z=0$), film thickness profile illustrations: (d) 3-D film thickness profile of conventional contact, (e) 3-D film thickness profile of textured contact, and (f) comparison of film thickness profiles of conventional and textured contact at mid-length ($Z=0$) [$p_H = 0.3\text{ GPa}$, speed = 2 m/s]	121
6.4	Pressure profile illustrations: (a) 3-D pressure profile of conventional contact, (b) 3-D pressure profile of textured contact, (c) comparison of pressure profiles of conventional and textured contact at mid-length ($Z=0$), film thickness profile illustrations: (d) 3-D film thickness profile of conventional contact, (e) 3-D film thickness profile of textured contact, and (f) comparison of film thickness profiles of conventional and textured contact at mid-length ($Z=0$) [$p_H = 0.3\text{ GPa}$, speed = 4 m/s]	122
6.5	Pressure profile illustrations: (a) 3-D pressure profile of conventional contact, (b) 3-D pressure profile of textured contact, (c) comparison of pressure profiles of conventional and textured contact at mid-length ($Z=0$), film thickness profile illustrations: (d) 3-D film thickness profile of conventional contact, (e) 3-D film thickness profile of textured contact, and (f) comparison of film thickness profiles of conventional and textured contact at mid-length ($Z=0$) [$p_H = 0.3\text{ GPa}$, speed = 8 m/s]	123
6.6	Pressure profile illustrations: (a) 3-D pressure profile of conventional contact, (b) 3-D pressure profile of textured contact, (c) comparison of pressure profiles of conventional and textured contact at mid-length ($Z=0$), film thickness profile illustrations: (d) 3-D film thickness profile of conventional contact, (e) 3-D film thickness profile of textured contact, and (f) comparison of film thickness profiles of conventional and textured contact at mid-length ($Z=0$) [$p_H = 0.5\text{ GPa}$, speed = 2 m/s]	124
6.7	Pressure profile illustrations: (a) 3-D pressure profile of conventional contact, (b) 3-D pressure profile of textured contact, (c) comparison of pressure profiles of conventional and textured contact at mid-	125

	length ($Z=0$), film thickness profile illustrations: (d) 3-D film thickness profile of conventional contact, (e) 3-D film thickness profile of textured contact, and (f) comparison of film thickness profiles of conventional and textured contact at mid-length ($Z=0$) [$p_H = 0.5$ GPa, speed = 4 m/s]	
6.8	Pressure profile illustrations: (a) 3-D pressure profile of conventional contact, (b) 3-D pressure profile of textured contact, (c) comparison of pressure profiles of conventional and textured contact at mid-length ($Z=0$), film thickness profile illustrations: (d) 3-D film thickness profile of conventional contact, (e) 3-D film thickness profile of textured contact, and (f) comparison of film thickness profiles of conventional and textured contact at mid-length ($Z=0$) [$p_H = 0.5$ GPa, speed = 8 m/s]	126
6.9	Pressure profile illustrations: (a) 3-D pressure profile of conventional contact, (b) 3-D pressure profile of textured contact, (c) comparison of pressure profiles of conventional and textured contact at mid-length ($Z=0$), film thickness profile illustrations: (d) 3-D film thickness profile of conventional contact, (e) 3-D film thickness profile of textured contact, and (f) comparison of film thickness profiles of conventional and textured contact at mid-length ($Z=0$) [$p_H = 0.7$ GPa, speed = 2 m/s]	127
6.10	Pressure profile illustrations: (a) 3-D pressure profile of conventional contact, (b) 3-D pressure profile of textured contact, (c) comparison of pressure profiles of conventional and textured contact at mid-length ($Z=0$), film thickness profile illustrations: (d) 3-D film thickness profile of conventional contact, (e) 3-D film thickness profile of textured contact, and (f) comparison of film thickness profiles of conventional and textured contact at mid-length ($Z=0$) [$p_H = 0.7$ GPa, speed = 4 m/s]	128
6.11	Pressure profile illustrations: (a) 3-D pressure profile of conventional contact, (b) 3-D pressure profile of textured contact, (c) comparison of pressure profiles of conventional and textured contact at mid-length ($Z=0$), film thickness profile illustrations: (d) 3-D film thickness profile of conventional contact, (e) 3-D film thickness profile of textured contact, and (f) comparison of film thickness profiles of conventional and textured contact at mid-length ($Z=0$) [$p_H = 0.7$ GPa, speed = 8 m/s]	129

6.12	Variation of coefficient of friction for conventional and textured contact at different speeds; (a) applied load, $p_H = 0.3\text{GPa}$, (b) applied load, $p_H = 0.5\text{ GPa}$,and (c) applied load, $p_H = 0.7\text{ GPa}$	131
6.13	Variation of side leakage for conventional and textured contact at different speeds; (a) applied load, $p_H = 0.3\text{GPa}$, (b) applied load, $p_H = 0.5\text{ GPa}$, and (c) applied load, $p_H = 0.7\text{ GPa}$	132
6.14	Variation of stiffness contact for conventional and textured contact at different speeds; (a) applied load, $p_H = 0.3\text{GPa}$, (b) applied load, $p_H = 0.5\text{ GPa}$, and (c) applied load, $p_H = 0.7\text{ GPa}$	133
6.15	Variation of damping coefficient for conventional and textured contact at different speeds; (a) applied load, $p_H = 0.3\text{GPa}$, (b) applied load, $p_H = 0.5\text{ GPa}$, and (c) applied load, $p_H = 0.7\text{ GPa}$	134

List of Tables

Table no.	Description	Page no.
3.1	Input parameters and geometrical details of test gearset	25
3.2	Physical properties of lubricating oil (SAE-90)	31
3.3	Comparison of percentage reduction in amplitudes of vibration at gear mesh frequencies and its harmonics of textured gear sets with respect to conventional	43
3.4	Properties of lubricating oil (SAE-15W40)	55
3.5	Dimple/texture details	56
4.1	Geometrical and material details of test gearset	72
4.2	Dimple/texture details	72
4.3	Properties of lubricating fresh and MoS ₂ greases	76

Nomenclature

a	Half hertzian width, m
β	Bulk modulus, N/m ²
c_p	Specific heat capacity of lubricant, J/kg-K
D	Deformation, m
E'	Reduced modulus of elasticity, Pa
E	Modulus of elasticity, Pa
f	Friction force, N
F	Dimensionless friction force, $f / \frac{E' R_x L}{2}$
g	Switch function
h	Film thickness, m
h_m	Minimum film thickness, m
h_{ell}	Film thickness for ellipsoidal dimple, m
H	Dimensionless film thickness, h/R_x
H_m	Dimensionless minimum film thickness, h/R_x
h_{st}	Minimum film thickness for steady state condition, m
H_{st}	Normalized film thickness for steady state condition, h_{st}/R_x
ΔH	Perturbation parameter-fluid film displacement
$\Delta \dot{H}$	Perturbation parameter-velocity
k	Stiffness, N/m
K	Stiffness coefficient, $\frac{k}{\frac{E' a L}{2 R_x}}$
p	Pressure in lubricating film, Pa

P	Dimensionless pressure in lubricating film, p/E'
P_c	Cavitation pressure, N/m ²
p_H	Hertzian pressure, Pa
p_{st}	Steady state pressure in lubricating film, Pa
P_{st}	Dimensionless steady state pressure in lubricating film, p_{st}/E'
P_H	Dimensionless perturbed pressure for stiffness
$P_{\dot{H}}$	Dimensionless perturbed pressure for damping
R_x	Equivalent radius in x-y plane, m
R_z	Equivalent radius in y-z plane, m
r_x	Ellipsoidal dimple radius in x-direction, m
r_y	Dimple depth, m
r_z	Ellipsoidal dimple radius in z-direction, m
u	Velocity in x-direction, m/s
v	Velocity in y-direction, m/s
w	Velocity in z-direction, m/s
u_1	Velocity of bounding solid-1 in x-direction, m/s
u_2	Velocity of bounding solid-2 in x-direction, m/s
u_{avg}	Average rolling velocity in x direction $((u_1 + u_2)/2)$, m/s
$\bar{u}$	Dimensionless average velocity, $\frac{u_{avg}}{\left(\frac{R_x^2 E'}{\eta_0 a}\right)}$
ω	Angular velocity, s ⁻¹
W	External applied load, N
w_{int}	Load (achieved by pressure integration in domain), N
W_{int}	Dimensionless load, $\frac{w_{int}}{\frac{E' a L}{2}}$

x	Coordinate axis in rolling direction
X	Dimensionless coordinate in rolling direction, x/a
y	Coordinate axis in film thickness direction
z	Coordinate axis across rolling direction
Z	Dimensionless coordinate across rolling direction, $z/(L/2)$
Z'	Roelands exponent
ΔX	Dimensionless grid spacing in x direction
ΔZ	Dimensionless grid spacing in z direction
α	Pressure viscosity coefficient of lubricant, Pa^{-1}
γ	Thermal expansivity coefficient of lubricant, K^{-1}
ζ	Temperature viscosity coefficient of lubricant, K^{-1}
η	Viscosity of lubricant, $\text{Pa}\cdot\text{s}$
η_0	Viscosity of lubricant at ambient temperature, $\text{Pa}\cdot\text{s}$
$\bar{\eta}$	Dimensionless viscosity of lubricant, η/η_0
λ	Dimensionless parameter, $\frac{\eta_0 \alpha^2 \omega_p}{R_x^2 E'}$
μ	Friction coefficient (F/W_{int})
ρ	Density of lubricant, kg/m^3
ρ_0	Density of lubricant at ambient condition,
$\bar{\rho}$	Dimensionless density of lubricant, ρ/ρ_0
ρ_c	Density within cavitated region
ϕ	Nondimensional density in full film, ρ/ρ_c
	Fractional film content in cavitation region
ν	Poisson's ratio