

DAMAGE ASSESSMENT OF SPUR GEAR THROUGH INTEGRATED OIL, WEAR, AND VIBRATION TECHNIQUES

DHARMENDER



**Department of Mechanical Engineering
INDIAN INSTITUTE OF TECHNOLOGY DELHI
JULY 2023**

©Indian Institute of Technology Delhi (IITD), New Delhi, 2023

DAMAGE ASSESSMENT OF SPUR GEAR THROUGH INTEGRATED OIL, WEAR, AND VIBRATION TECHNIQUES

by

DHARMENDER

Department of Mechanical Engineering

Submitted

in fulfillment of the requirements of the degree of DOCTOR OF PHILOSOPHY

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

JULY 2023

Dedicated to

My parents (**Sh. Rajmal** and **Smt. Shakuntla**), and my brother (**Atul Jangra**)

and

(All the teachers)

Especially to my supervisor/s **Prof. Ashish K. Darpe** and **Prof. Harish Hirani**

and

My schoolteacher Lecturer **Anil Panchal**

“A teacher helps us breach the fog of ignorance through guidance and teachings.”

Certificate

This is to certify that the thesis entitled “**DAMAGE ASSESSMENT OF SPUR GEAR THROUGH INTEGRATED OIL, WEAR, AND VIBRATION TECHNIQUES**” being submitted by **Mr. Dharmender** 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 supervision and the candidate has fulfilled the requirements for the submission of this thesis. This thesis, in our opinion, meets the requirements for granting a Ph.D. degree from this institution. 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 the granting of a degree or certificate.

Dr. Harish Hirani

Professor

Department of Mechanical Engineering

Indian Institute of Technology Delhi

New Delhi- 110016, India

Date.....

Dr. Ashish K. Darpe

Professor

Department of Mechanical Engineering

Indian Institute of Technology Delhi

New Delhi- 110016, India

Date.....

Acknowledgments

"Success is sweet: the sweeter if long delayed and attained through manifold struggles and defeats." -Unknown

"A person never fails; the agreement between him and the result that fails." -Unknown

I owe a huge debt of gratitude to my advisors **Prof. Ashish K. Darpe** and **Prof. Harish Hirani**, for offering me the opportunity to work on this project and for their understanding, patience, encouragement, and guidance throughout this research. During my time at the Indian Institute of Technology Delhi, their professional demeanor aided my professional development and maturation.

I acknowledge all the support **Prof. M. R. Ravi** (Head, Department of Mechanical Engineering) provided in completing the thesis. I am highly thankful to **Prof. N. Tandon** (External expert in SRC), Centre for Automotive Research and Tribology, Indian Institute of Technology Delhi, for his valuable suggestions and essential feedback during presentations. I would like to express my sincere gratitude to internal Student Research Committee (SRC) members, especially **Prof. J. K. Dutt** and **Prof. R. K. Pandey**, for their valuable technical suggestions and help.

I would also like to acknowledge the help provided by **Prof. K. Gupta** and **Prof. S. P. Singh** during the perusal of this study. Especially, **Prof. K. Gupta** for the unwavering support and encouragement provided during my darkest days of depression and anxiety. Your words of motivation were like medicine to my soul, reminding me of my potential even when I couldn't see it myself.

I would like to express my heartfelt gratitude to **Mr. K. N. Madhu** for his moral support and assistance in performing research. I would also like to thank **Mr. Abhishek**

Rana and all my lab mates (**Dr. Anvesh Reddy, Dr. Jaskarn Singh, Dr. Asjad M., Hridin Pradeep, Gyan Setu, Sarthak Mittal, Anuj Dhaiya**) and friends (**Hardeep Jinjjhar, Dr. Abhinava Chatterjee, Dr. Devershi Mourya, Dr. Rajeev L., Jagat, Dr. Vickey Nandal, Kuldeep Yadav, Sandeep Yadav, Dr. Nimish Joseph, Dr. Mainendra Dewangan, Dr. Saurabh Chandrakar, Ashok, Dr. Ajay Lodhi, Dr. Vinay Kumar, Dr. Hariom Singh, Dr. Surojit Poddar, Dr. Deepak Chauhan, Dr. Jayant Kumar, Milan Kumar, Kishan Nath Sidh and Jaswant Hirwani**) for their help and encouragement.

I appreciate **Anil Patidar, Pavan Kumar, Dr. Faisal Rahmani,** and **Dr. Pradeep Kundu** from the bottom of my heart for providing me with moments of respite during a hard day's work.

I would like to express my heartfelt gratitude to my parents, my wife '**Asha Rani**' and all my family (**Atul Jangra, Jyoti Jangra** and **Neha Singh**) for their support and encouragement, especially my mother '**Shakuntla Devi**' and my father '**Rajmal Jangra**' for their support and substantial encouragement from the time I was in my primary school till now. To fill my life with hope and joy, I would like to thank my darling nephew '**Siddhant Jangra**', who was born during my studies. I will never forget the time we spent together. *The time I spent in Delhi during my Ph.D. years at the Indian Institute of Technology, Delhi, will always be in my memory.*

Above all, I pray to God to strengthen and keep me motivated throughout this journey.

Dharmender

Date:

Place: IIT Delhi, New Delhi

Abstract

Gears are the critical components for motion and power transmission in the desired ratio and high efficiency. These factors can be satisfactorily achieved if the gears have no faults. Whenever a fault or defect occurs in a gear system (e.g., wear, scuffing, plastic deformation, Hertzian fatigue, crack, fracture, and bending fatigue), the performance of the gears deteriorates. The demanded motion and power cannot be transferred under deteriorated conditions—the early detection of these defects results in saving of catastrophic failure and substantial economic losses. The condition-based maintenance (CBM) helps in the early detection of machinery faults so that the appropriate action can be taken before failure and the system's reliability can be improved. In the literature, various reasons were reported for the gearbox failure, like misalignment, lubricant deterioration, bearing failure, foreign particles contamination, etc. Out of these reasons, misalignment and lubricant deterioration play an important role in gear failure. Misalignment may result from installation errors, manufacturing errors in gears, distortion of the gearbox housing, excessive radial spacing in bearings, excessive stresses and thermal effects, design failure, etc. The lubricant degradation may result from contamination from foreign particles, water ingress, oxidation, etc.

In the present work, a mathematical expression is developed for the effect of different types of misalignments (angular, radial, and axial) on the surface wear of gears. Misalignment leads to a change in contact pattern and load distribution, which results in increased surface wear that further leads to the change in contact pattern. The resulting mathematical model results were validated with the existing literature and experimentally obtained wear results. Additionally, the effect of different parameters (module, pressure angle, number of teeth on the pinion, and gear ratio) on wear

resistance is studied. It was found that the load share ratio in the double teeth pair region increases with an increase in the module, gear ratio, and number of teeth on pinion and decreases with an increase in pressure angle. The wear depth decreases at the transition from double teeth pair region to single pair region with an increase in module, gear ratio. The wear depth decreases at the initiation of the contact point and overall mesh cycle with increased pressure angle and the number of teeth on the pinion, respectively.

Further, run-to-failure experiments were conducted on a single-stage spur gear test rig developed in-house. The real-time vibration, wear debris, and oil quality have been obtained. The classical time synchronous averaging was used to denoise the vibration data, and statistical features were obtained from the denoised signal. These vibration features were then compared with the online wear progression. It was observed that the wear debris progression provides early detection of the fault progression compared to the vibration signature. The oil samples were collected periodically for offline analysis. Scanning electron microscopy (SEM) imaging of the wear debris harvested from the oil samples was done to study the wear debris morphologies. It was observed that the morphology of the wear debris changes from a fiber-like structure to a more spherical one as the wear progresses.

Further, the study extends to see the effect of nano-lubricants on degraded lubricant and the wear of the spur gears. An artificial lubricant ageing by chemical degradation (mixing the aqueous HCl (36.46% HCl + 63.54% aqueous) is proposed to simulate the ageing process of gear lubricants. The pH value of the oil is used to estimate the ageing time of the lubricant. The oil samples were analyzed using ATR-FTIR spectroscopy by monitoring the degradation of additives, level of moisture, and sludge formation. The aged gear lubricant was tested on the developed gear test setup. Initially, three nano-additives were selected: graphite, graphene and “graphene oxide

functionalized with silicon oxide (GO@SiO₂)". A preliminary study on the chosen nano-additives (two levels of each nano-additives) was conducted using L8 orthogonal array to estimate the performance and interaction of nano-additives. Based on the analysis of variance (ANOVA), graphene was eliminated due to its least (0.31%) contribution. The L16 (four levels of graphite and GO@SiO₂) orthogonal array was used to optimize the percentage of nanoparticles. Finally, the optimum percentage of nano-additives (Graphite:0.125% w/w, GO@SiO₂: 0.15% w/w) was applied for the experimental study on the gearbox test rig. ATR-FTIR studies have been performed to understand nano-additives' effect on the fresh and degraded gear lubricant.

Overall current work analyses the significance of misalignment in gear and oil degradation on the wear behavior of spur gear in lubricated conditions. Further, the study identified the effect of variation in pH value as a critical aspect of oil deterioration which leads to accelerated wear. Also, this thesis portrays the effect of different parameters on spur gear surface wear for effective detection and quantification. Furthermore, the different mode of wear detected by this study clarifies the understanding of gear designing for the reliability of the transmission systems.

सार

वांछित अनुपात और उच्च दक्षता में गति और शक्ति संचरण के लिए गियर्स महत्वपूर्ण घटक हैं। इन कारकों को संतोषजनक ढंग से प्राप्त किया जा सकता है यदि गियर में कोई दोष न हो। जब भी गियर सिस्टम में कोई दोष या दोष होता है (जैसे, घिसाव, खरोंच, प्लास्टिक विरूपण, हर्ट्ज़ियन क्लान्ति, दरार, फ्रैक्चर और झुकने क्लान्ति), तो गियर का प्रदर्शन बिगड़ जाता है। मांग की गई गति और शक्ति को खराब परिस्थितियों में स्थानांतरित नहीं किया जा सकता है - इन दोषों का शीघ्र पता लगाने से विनाशकारी विफलता और पर्याप्त आर्थिक नुकसान की बचत होती है। कंडीशन-बेस्ड मॉनिटोरिंग (CBM) मशीनरी की खराबी का जल्द पता लगाने में मदद करता है ताकि विफलता से पहले उचित कार्रवाई की जा सके और सिस्टम की विश्वसनीयता में सुधार किया जा सके। साहित्य में, गियरबॉक्स की विफलता के लिए विभिन्न कारणों की सूचना दी गई थी, जैसे मिसलिग्न्मेंट, स्नेहक क्षय, वहन विफलता, विदेशी कण संदूषण, आदि। इन कारणों में से, मिसलिग्न्मेंट और स्नेहक क्षय गियर विफलता में महत्वपूर्ण भूमिका निभाते हैं। मिसलिग्न्मेंट इंस्टॉलेशन त्रुटियों, गियर्स में निर्माण त्रुटियों, गियरबॉक्स हाउसिंग की विकृति, बीयरिंगों में अत्यधिक रेडियल रिक्ति, अत्यधिक तनाव और थर्मल प्रभाव, डिज़ाइन विफलता आदि के परिणामस्वरूप हो सकता है। स्नेहक अवक्रमण बाहरी कणों, जल प्रवेश, ऑक्सीकरण से संदूषण के परिणामस्वरूप हो सकता है, वगैरह।

वर्तमान कार्य में, गियर की सतह घिसाव पर विभिन्न प्रकार के मिसलिग्नमेंट (कोणीय, रेडियल और अक्षीय) के प्रभाव के लिए एक गणितीय अभिव्यक्ति विकसित की गई है। मिसलिग्नमेंट से संपर्क पैटर्न और भार वितरण में परिवर्तन होता है, जिसके परिणामस्वरूप सतह के घिसाव में वृद्धि होती है जो आगे संपर्क पैटर्न में परिवर्तन की ओर ले जाती है। परिणामी गणितीय मॉडल के परिणाम मौजूदा साहित्य और प्रयोगात्मक रूप से प्राप्त घिसाव के परिणामों के साथ मान्य किए गए थे। इसके अतिरिक्त, घिसाव के प्रतिरोध पर विभिन्न मापदंडों (मॉड्यूल, दबाव कोण, पिनियन पर दांतों की संख्या और गियर अनुपात) के प्रभाव का अध्ययन किया जाता है। यह पाया गया कि दोहरे दांत जोड़े क्षेत्र में लोड शेयर अनुपात मॉड्यूल, गियर अनुपात और पिनियन पर दांतों की संख्या में वृद्धि के साथ बढ़ता है और दबाव कोण में वृद्धि के साथ घटता है। मॉड्यूल, गियर अनुपात में वृद्धि के साथ दोहरे दांत जोड़ी क्षेत्र से एकल जोड़ी क्षेत्र में संक्रमण पर घिसाव की गहराई कम हो जाती है। घिसाव की गहराई संपर्क बिंदु और समग्र जाल चक्र की शुरुआत में दबाव कोण और क्रमशः पिनियन पर दांतों की संख्या के साथ घट जाती है।

आगे, इन-हाउस विकसित सिंगल-स्टेज स्पर गियर टेस्ट रिग पर रन-टू-फेलर प्रयोग किए गए। रीयल-टाइम कंपन, घिसाव का मलबा और तेल की गुणवत्ता प्राप्त की गई है। प्रतिष्ठित समय तुल्यकालिक औसत का उपयोग कंपन डेटा को निरूपित करने के लिए किया गया था, और सांख्यिकीय विशेषताओं को निरूपित संकेत से प्राप्त किया गया था। इन कंपन सुविधाओं की तुलना ऑनलाइन घिसाव की प्रगति से की गई थी। यह देखा गया कि वाइब्रेशन

सिग्नेचर की तुलना में वियर डेब्रिस प्रोग्रेस फॉल्ट प्रोग्रेशन का शीघ्र पता लगाने में मदद करता है। ऑफ़लाइन विश्लेषण के लिए समय-समय पर तेल के नमूने एकत्र किए गए। तेल के नमूनों से निकाले गए घिसाव के मलबे की स्कैनिंग इलेक्ट्रॉन माइक्रोस्कोपी (SEM) इमेजिंग घिसाव के मलबे के आकारिकी का अध्ययन करने के लिए की गई थी। यह देखा गया कि जैसे-जैसे घिसाव बढ़ता है घिसे हुए मलबे की आकारिकी फाइबर जैसी संरचना से अधिक गोलाकार में बदल जाती है।

आगे, अध्ययन का विस्तार निम्नीकृत स्नेहक और स्पर गियर्स के घिसाव पर नैनो-स्नेहक के प्रभाव को देखने के लिए किया गया है। गियर स्नेहक की उम्र बढ़ने की प्रक्रिया को अनुकरण करने के लिए रासायनिक गिरावट (जलीय एचसीएल (36.46% एचसीएल + 63.54% जलीय) को मिलाकर एक कृत्रिम स्नेहक उम्र बढ़ने का प्रस्ताव किया गया है। तेल के पीएच मान का उपयोग स्नेहक के उम्र बढ़ने के समय का अनुमान लगाने के लिए किया जाता है। तेल के नमूनों का विश्लेषण एटीआर-एफटीआईआर स्पेक्ट्रोस्कोपी का उपयोग करके एडिटिक्स के क्षरण, नमी के स्तर और कीचड़ के गठन की निगरानी करके किया गया था। वृद्ध गियर स्नेहक का परीक्षण विकसित गियर टेस्ट सेटअप पर किया गया था। प्रारंभ में, तीन नैनो-एडिटिक्स का चयन किया गया था: ग्रेफाइट, ग्रेफीन और "ग्राफीन ऑक्साइड सिलिकॉन ऑक्साइड के साथ कार्यात्मक (GO@SiO₂)"। नैनो-एडिटिक्स के प्रदर्शन और परस्पर प्रभाव का अनुमान लगाने के लिए L8 ऑर्थोगोनल सारणी का उपयोग करके चुने हुए नैनो-एडिटिक्स (प्रत्येक नैनो-एडिटिक्स के दो स्तर) पर एक प्रारंभिक अध्ययन किया गया था। आधारित विचरण (ANOVA)

के विश्लेषण पर, इसके कम से कम (0.31%) योगदान के कारण ग्राफीन को हटा दिया गया था। L16 (ग्रेफाइट के चार स्तर और GO@SiO₂) ऑर्थोगोनल सारणी का उपयोग नैनोपार्टिक के प्रतिशत को अनुकूलित करने के लिए किया गया था। अंत में, गियरबॉक्स टेस्ट रिग पर प्रायोगिक अध्ययन के लिए नैनो-एडिटिव्स (ग्रेफाइट: 0.125% w/w, GO@SiO₂: 0.15% w/w) का इष्टतम प्रतिशत लागू किया गया था। ताजा और खराब गियर लुब्रिकेंट पर नैनो-एडिटिव्स के प्रभाव को समझने के लिए एटीआर-एफटीआईआर अध्ययन किया गया है।

कुल मिलाकर वर्तमान कार्य लुब्रिकेटेड स्थितियों में स्पर गियर के घिसाव के व्यवहार पर गियर और तेल के क्षरण में मिसलिग्न्मेंट के महत्व का विश्लेषण करता है। इसके अलावा, अध्ययन ने तेल के क्षरण के एक महत्वपूर्ण पहलू के रूप में पीएच मान में भिन्नता के प्रभाव की पहचान की जिससे त्वरित घिसाव होता है। इसके अलावा, यह थीसिस प्रभावी पहचान और प्रमाणीकरण के लिए स्पर गियर सरफेस वियर पर विभिन्न मापदंडों के प्रभाव को चित्रित करती है। इसके अलावा, इस अध्ययन द्वारा पता लगाए गए घिसाव के विभिन्न तरीके ट्रांसमिशन सिस्टम की विश्वसनीयता के लिए गियर डिजाइनिंग की समझ को स्पष्ट करते हैं।

Table of Contents

Certificate	i
Acknowledgments	iii
Abstract.....	v
सार.....	ix
Table of Contents	xiii
List of Figures.....	xix
List of Tables	xxvii
List of Abbreviation.....	xxxi
Chapter 1 Introduction.....	1
1.1 Research Motivation	3
1.2 Background.....	4
1.3 Condition monitoring	7
1.4 Gear misalignment.....	9
1.5 Nano-additives	10
1.6 Scope of the study.....	11
1.7 Organization of Thesis	11

Chapter 2	Literature Review.....	15
2.1	Gear Failure Modes	17
2.1.1	<i>Wear.....</i>	17
2.1.2	<i>Scuffing</i>	19
2.1.3	<i>Plastic deformation</i>	20
2.1.4	<i>Hertzian fatigue.....</i>	20
2.1.5	<i>Crack.....</i>	21
2.1.6	<i>Fracture</i>	21
2.1.7	<i>Bending fatigue</i>	22
2.2	Surface Wear Modelling and Role of Misalignment.....	23
2.2.1	<i>Surface wear modeling</i>	24
2.3	Condition-Based Monitoring Techniques and Their Role in Early Detection of Gear Failures.....	28
2.3.1	<i>Fault diagnosis using vibration</i>	28
2.3.1.1	Time-Domain Analysis	30
2.3.1.2	Frequency Spectrum Analysis.....	35
2.3.1.3	Joint Time-Frequency Approaches	36
2.3.1.4	Order Analysis	38
2.3.1.5	Independent Component Analysis (ICA).....	38
2.3.1.6	Bounded Component Analysis (BCA)	38
2.3.1.7	Principal Component Analysis (PCA).....	39
2.3.1.8	Empirical Mode Decomposition (EMD).....	39

2.3.2 <i>Fault diagnosis using wear debris analysis</i>	41
2.3.2.1 Morphology of wear particles.....	44
2.3.3 <i>Role of Lubrication Mechanism and Nano- additives on Protection of Gear Failure</i>	47
2.4 Conclusive Remark from the Literature	52
2.5 Objective of Thesis	53
2.5.1 <i>Research Questions</i>	53
2.6 Novelty of this Thesis	54
Chapter 3 Misalignment Effect on Surface Wear of Spur Gear Pair	55
3.1 Development of Mathematical Model for the Radial, Axial, and Angular Misalignment	57
3.2 Computation of the Contact Pressure	60
3.3 Computation of Sliding Distance	65
3.4 Computation of Wear Depth	66
3.4.1 <i>Computation of the wear coefficient</i>	67
3.5 Selection of the Load Model	72
3.6 Simulation Scheme	75
3.7 Validation of Methodology	80
3.7.1 <i>Validation with FEM Results</i>	80
3.7.2 <i>Experimental Results</i>	83

3.8 Concluding Remarks.....	86
Chapter 4 Effect of Different Design Parameters on Surface Wear of Spur Gear Pairs.....	87
4.1 Wear Depth on Perfectly Aligned and Misaligned Spur Gear Pair – a Comparison	89
4.2 Influence of Design Parameters	101
<i>4.2.1 Influence of Module.....</i>	<i>102</i>
<i>4.2.2 Influence of Pressure Angle.....</i>	<i>104</i>
<i>4.2.3 Influence of Gear Ratio.....</i>	<i>105</i>
<i>4.2.4 Influence of Number of Pinion Teeth.....</i>	<i>105</i>
4.3 Effect of Angular Misalignment.....	115
4.3 Concluding Remarks.....	119
Chapter 5: Experimental Investigation of Surface Wear of Spur Gear Through Vibration, Wear Debris and Wear Debris Morphological Studies ..	121
5.1 Experimental Setup and Instrumentation	123
<i>5.1.1 Description of sensors and instruments.....</i>	<i>125</i>
5.1.1.1 Accelerometer and proximity sensor	125
5.1.1.2 Metallic wear debris sensor and oil sensor suite	127
5.1.2 Experimental procedure	128
5.1.2.1 Processing of the vibration data.....	129
5.1.2.2 Processing of the wear debris data	133

5.2 Results and Discussions	139
<i>5.2.1 Wear debris particle and vibration result and discussion</i>	<i>139</i>
5.2.1.1 Vibration spectral analysis.....	149
5.2.1.2 Online wear debris analysis.....	152
<i>5.2.4 Wear Debris Morphological Studies.....</i>	<i>153</i>
5.3 Concluding Remarks.....	169
Chapter 6: Experimental Investigation on the Wear Performance of Nano-additives on Degraded Gear Lubricant	171
6.1 Experimental Setup and Instrumentation	173
<i>6.1.1 pH value and TAN value measurement</i>	<i>174</i>
<i>6.1.2 Lubricant</i>	<i>175</i>
<i>6.1.3 Experimental procedure.....</i>	<i>176</i>
6.2 Results and Discussions	176
<i>6.2.1 Case 1.....</i>	<i>176</i>
<i>6.2.2 Case 2.....</i>	<i>179</i>
6.2.2.1 Artificial Ageing Simulation.....	179
<i>6.2.3 Case 3.....</i>	<i>182</i>
6.2.3.1 Selection of Nano-additives.....	182
6.2.3.2. Experimental Design for Tribological Performance of Nano-Additives Doped in Lubricant.....	186
6.2.3.3. Orthogonal Array Design and Optimisation of the Concentration of Nano-Additives.....	188

6.2.4 <i>Effect of Nano-additive doped in lubricant on spur gear wear</i>	199
6.2.4.1. Online Wear Debris Analysis.....	199
6.3 Conclusions.....	201
Chapter 7 Conclusions and Scope for Future Work.....	203
7.1 Consolidated Conclusions.....	205
7.2 Recommendation based on consolidated conclusions	207
7.3 Future Scope of Work.....	208
References	211
Appendix	A

List of Figures

Figure 1.1 Different types of gears (Image source: [3])	4
Figure 1.2 Application of gear in different machines (Image source: [2,6])	6
Figure 1.3 Typical faults associated with gears [1,5]	7
Figure 2.1 Wear on gear flank [1, 5]	18
Figure 2.2 Scuffing wear in gears [1]	19
Figure 2.3 Different forms of plastic deformation [1, 5]	20
Figure 2.4 Pitting failure in gears [a:1 and 5, b: 32]	20
Figure 2.5 Crack failure of the gear tooth [1]	21
Figure 2.6 SEM images of (a) brittle fracture of gear teeth and (b) ductile fracture of gear teeth [1]	22
Figure 2.7 Bending fatigue of the spur gear [1, 5]	23
Figure 2.8 Gear failure modes [46]	25
Figure 2.9 Relationship of wear mechanism between gear teeth [47]	25
Figure 2.10. (a) Typical flank wear profile of the gear tooth [10], and (b) rolling and sliding in gear contact [48]	25
Figure 2.11. Variation in wear rate with running time [144-146].	42
Figure 2.12. Schematic representation of gear flank wear.	42
Figure 2.13. Relationship between particle size, morphology, and wear mechanisms [129, 141, 149, 154-155, 159-162].	45
Figure 2.14. Geometrical categorisation of wear particle shape and wear mode and their correlation [21, 48, 129, 134,154-155,157,159,161,163-166].	45

Figure 2.15. (a) Surface interaction of gear surfaces under EHL lubrication (b) Formation of protective tribefilms to avoid direct metal-to-metal contact (c) metal-to-metal contact under depleted additives leading to surface wear.	48
Figure 3.1. Schematic diagram of gear under combined misalignment (radial, axial, and angular misalignment).	60
Figure 3.2 The schematic diagram showing (a) slicing of the gear tooth, (b) contact patch when the gears are perfectly aligned, and (c) contact patch under radial, axial, and angular misalignment.	62
Figure 3.3 The normal load shared in (a and c) perfectly aligned and (b and d) combined (axial, radial, and angular) misaligned gear pair.	63
Figure 3.4 (a) Lubricity tester schematic diagram and (b) Lubricity tester test setup	69
Figure 3.5. Theoretically estimated (a) peripheral velocities (mm/sec) and (b) contact pressure (MPa) at “40Nm” applied torque and “1200 rpm”.	70
Figure 3.6 The effect of different (a) load sharing factors on the (b) contact pressure (MPa), (c) wear depth on gear profile, and (d) wear depth on pinion profile for a torque of “40Nm” and pinion speed of “1200 rpm”.	73
Figure 3.7. Photographs of the gear and pinion used for experiments (material EN24)	74
Figure 3.8. Optimization of the number of points along the involute profile (a) contact pressure (MPa), (b) % variation and the number of slices along the face width, (c) % variation, (d) mean contact pressure (MPa), and (e) comparison for contact pressure for optimized values.	76-78

Figure 3.9. Computational flow chart of overall solution scheme.	79
Figure 3.10. Load sharing model used in the current model and Zhang et al.	81
Figure 3.11. The comparison of contact pressure (MPa) results for the current model and the model used by Zhang et al.	82
Figure 3.12. The wear depth in the addendum and dedendum region of the driver gear teeth for experimental and theoretical; (a) SEM image of the cut tooth, (b) and (c) modeled wear depth without and with misalignment, respectively.	85
Figure 4.1. Different types of misalignments (radial, axial, angular, and combined) and the contact patch generated during a mesh cycle.	89
Figure 4.2. Influence of different types of misalignments on (a) contact pressure, (b) semi-Hertzian contact width, (c-d) sliding distance variation ((c) pinion and (d) gear), and (e-f) wear depth ((e) pinion and (f) gear) for equal contact patch during a mesh cycle.	94-99
Figure 4.3. Influence of module on combined (radial, axial, and angular) misaligned gear pair	103
Figure 4.4. Influence of pressure angle on combined (radial, axial, and angular) misaligned gear pair	107
Figure 4.5. Influence of gear ratio on combined (radial, axial, and angular) misaligned gear pair	108
Figure 4.6. Influence of the number of teeth of the pinion on combined (radial, axial, and angular) misaligned gear pair	109

Figure 4.7. Influence of the angular misalignment about coupling position on gear pair	116-117
Figure 5.1 (a) Photograph of the experimental setup, (b) different sensor locations, and (c) schematic representation of the experimental setup and instrument used in the study.	124-125
Figure 5.2 (a) Calibration of the accelerometer and (b) proximity probe.	126
Figure 5.3 Photograph of (a) metallic wear debris sensor and (b) oil sensor suite.	127-128
Figure 5.4 Flow chart for calculating the TSA signal, filtered signal (difference signal, residual signal, and regular signal)	130
Figure 5.5 Synchronous time-averaged signal	131
Figure 5.6 Filtered signal from the raw vibration signal (a) TSA signal and filtered signal from TSA signal (b-d) residual signal, difference signal, regular signal.	132
Figure 5.7 Wear particle extraction from the oil sample.	134
Figure 5.8. Image analysis steps using ImageJ software.	135
Figure 5.9. Example problem for validation from reference [165].	136
Figure 5.10 Schematic to understand different wear particle morphological parameters.	137
Figure 5.11. Oil and vibration parameters obtained for the first set of the experiment (a) Oil wear debris particle per minute, (b) Energy ratio, (c) FM0, (d) RMS, (e) Kurtosis, (f) Crest factor, (g) CCR. The vibration parameters (b), (c), (d), (e), (f), and (g) are obtained at input and output bearing positions, respectively.	140-142

Figure 5.12. Oil and vibration parameters obtained for the second set of the experiment (a) Oil wear debris particle per minute, (b) Energy ratio, (c) FM0, (d) RMS, (e) Kurtosis, (f) Crest factor, (g) CCR. The vibration parameters (b), (c), (d), (e), (f), and (g) are obtained at input and output bearing positions, respectively.	142-144
Figure 5.13. Percentage variation of oil and vibration parameters (a) Run-in to normal wear, (b) Normal wear to medium wear, and (c) Medium wear to severe wear	148
Figure 5.14 Waterfall spectral plots for (a-b) input and output bearing position of experiment 1 and (c-d) input and output bearing position of experiment 2.	150-151
Figure 5.15. Distribution of Fe PPM and wear mass for experiments 1 and 2.	152
Figure 5.16. Ferrous particle size distribution for experiments 1 and 2.	153
Figure 5.17. The SEM images and surface plot images of the wear debris particles at different stages (experiment 1) (a) stage 1, (b) stage 2, (c) stage 3, and (d) stage 4.	155-158
Figure 5.18. The SEM images and surface plot images of the wear debris particles at different stages (experiment 2) (a) stage 1, (b) stage 2, (c) stage 3, and (d) stage 4.	160-163
Figure 5.19. The variation of morphological parameters from stage 1 to stage 4 over the operation time.	166-167
Figure 6.1. Photograph of pH meter (Metrohm)	175
Figure 6.2. Variation in pH value during running conditions	177
Figure 6.3. The effect of aqueous HCl addition on oil. (a) Oil samples for fresh and aqueous HCl-mixed and (b) ATR-FTIR spectra of fresh and aqueous HCl-mixed (0.0025% v/v) oil.	178

Figure 6.4. (a) Effect aqueous HCl concentration on pH value of lubricant and (b) effect of aqueous HCl concentration on ageing life of the lubricant.	180-181
Figure 6.5. Variation of pH under mechanical shearing for the chemically aged lubricant.	182
Figure 6.6. SEM images of the nano-additives (a) Graphene, (b) Graphite, (c) GO@SiO ₂ , and (d) the Raman spectra recorded at 532 nm excitation wavelength for the graphite, graphene, and GO@SiO ₂ .	185
Figure 6.7. Effect of weight concentration on particle sedimentation.	186
Figure 6.8. Theoretically estimated (a) peripheral velocities and (b) contact pressure for gear at “50Nm” applied torque and “483.52 mm/s”.	187
Figure 6.9. Variation in pH value of the aged lubricant doped with nano-lubricant	194
Figure 6.10. ATR-FTIR spectra of the three tests Case 1 (fresh oil), Case 2 (0.0025% v/v aqueous HCl mixed oil), and Case 3 (0.0025% v/v aqueous HCl-mixed + nano-additive-mixed oil).	195
Figure 6.11. ATR-FTIR of test 3 (0.0025% v/v HCl + nano-additives) for every 10 minutes and compared with the fresh oil and fresh oil mixed with 0.0025% v/v aqueous HCl.	198
Figure 6.12. Distribution of Fe PPM and wear mass for test 1 (without aqueous HCl), test 2 (with 0.0025% v/v aqueous HCl-mixed), and test 3 (with 0.0025% v/v aqueous HCl mix + nano-additive-mixed).	200
Figure 6.13. Ferrous particle size distribution for test 1 (without aqueous HCl), test 2 (with 0.0025% v/v aqueous HCl-mixed), and test 3 (with 0.0025% v/v aqueous HCl mix + nano-additive-mixed).	200

- Figure A1.** Effect of radial misalignment on (a) pitch point, (b) working pressure angle and its variation along the tooth profile, (c) contact ratio, and (d) circular pitch. A-B
- Figure B1.** Lab report of TAN measurement for (a) fresh oil June 2021, (b) fresh oil March 2022, (c) fresh oil doped with 0.0025%v/v HCl, (d) after '90 minutes' mechanical shearing of fresh oil , and (e) after '90 minutes' mechanical shearing of HCl doped oil. F-G
- Figure B2.** The effect of different aqueous HCl concentrations on gear lubricants. H
- Figure B3.** The effect of nano-additives on the aqueous HCl-doped gear lubricants. H
- Figure B4.** Lubrication mechanism for (a) without aqueous HCl, a perfect layer of lubricant is formed, (b) aqueous HCl damage the lubricant layer, and (c) the damaged lubricant layer is partially repaired by the combined action of graphite (activated in shear) and GO@SiO₂ (head is spherical attached to the surface and provide rolling). I

List of Tables

Table 1.1 Types and function of spur, helical, bevel, and worm gears [4]	5
Table 2.1. Corresponding frequency components with different faults	29
Table 2.2 The vibrational frequency and associated functional groups [186-189]	50
Table 3.1. Expression for various forces acting on gear tooth [35]	64
Table 3.2. The effect of load sharing factor on mean contact pressure and maximum wear depth	74
Table 3.3. Parameter used for the comparison (Taken from Zhang et al. [20])	81
Table 3.4. Comparison between the current model and Zhang et al.	83
Table 3.5. Experimental test specification	83
Table 3.6. Variation in experimental and theoretical wear depth in pinion addendum and dedendum	84
Table 4.1. Values of different misalignment for the equal contact patch area ($A_{1cp} = 90\%$ of A_{cp}).	91
Table 4.2. Comparison between the different types of misalignments based on contact pressure, wear depth, sliding distance, and semi-Hertzian contact width.	100-101
Table 4.3 Geometric design considerations to avoid the gear failure according to ANSI/AGMA 101-F14 [1]	102

Table 4.4. Effect of design parameters (module, pressure angle, gear ratio, and number of teeth on pinion) on contact pressure, wear depth, sliding distance width, and semi-Hertzian contact width of combined misaligned gear pair.	110-114
Table 4.5. Effect on angular misalignment on contact pressure, wear depth, sliding distance, and semi-Hertzian contact width.	117-118
Table 5.1 Test specifications	128
Table 5.2 Comparison of wear particle morphological result of the Peng et al. [165] with the current study.	136
Table 5.3 Different morphological parameters and their definition [154,165-166,193]	138
Table 5.4. Values of the oil and vibration parameters for the two experiments in different stages of wear	146
Table 5.5. The percentage variation in values of oil and vibration parameters in wear stages transition	147
Table 5.6. The mean and standard deviation values of the particle morphological parameters for particles in each stage of gear wear (experiment 1)	159
Table 5.7. The mean and standard deviation values of the particle morphological parameters for particles in each stage of gear wear (experiment 2)	164
Table 5.8. The mean and standard deviation values of the particle morphological parameters for particles in each stage of gear wear	165

Table 6.1. Parameters and their levels for wear analysis (for Lubricity Tester)	173
Table 6.2: Test Specification for gearbox test rig	174
Table 6.3 Variables and their levels for wear analysis	189
Table 6.4 Experimental plan for wear analysis with the response using L8 orthogonal array	190
Table 6.5 ANOVA for wear analysis (First stage experiments (L8))	192
Table 6.6: Experimental plan using L16 orthogonal array for wear analysis	193
Table A1. Misalignment measured by the Laser alignment Kit.	B
Table B1. Properties of the tested gear lubricant (provided by OEM).	C
Table B2. L8 Orthogonal array with factors and their interactions [223]	C
Table B3. Experimental plan using L16 (4^5) orthogonal array [223]	D
Table B4. ATR-FTIR peaks and their corresponding functional groups	D-E

List of Abbreviation

A	Area of the wear particle (μm^2)
a	Axial misalignment (mm)
AGMA	American gear manufacturing association
A_k	Amplitude of k^{th} harmonic
ATR-FTIR	Attenuated total reflectance-Fourier transform infrared spectroscopy
a_H, b	Half semi-Hertzian contact width (mm)
A_{cp}	Contact patch area (m^2)
AR	Aspect ratio
BCA	Bounded Component Analysis
CBM	Condition based maintenance
CF	Crest factor
CCR	Correlation coefficient of residual signal
CD	Center distance between gear and pinion (mm)
CD_I	New center distance after misalignment (mm)
d	Difference signal
\bar{d}	The mean of the difference signal
EDAX/ EDX	Energy dispersive X-ray spectroscopy
EHL	Elastohydrodynamic lubrication
EMD	Empirical Mode Decomposition
E^*	Equivalent Young's modulus (N/mm^2)
ER	Energy ratio

FTIR	Fourier transform infrared spectroscopy
FEM	Finite element method
F_m	Gear mesh frequency
F_t	Tangential force acting on gear teeth (N)
F_a	Force acting in axial direction (N)
F_r	Force acting in radial direction (N)
GO	Graphene oxide
H	Hardness of the material (N/mm ²)
HCl	Hydrochloric acid
h	Wear depth (mm)
ICA	Independent Component Analysis
IPCA	Integrated Particle Coverage Area
K	Dimensionless wear coefficient
k	Index number of samples
L	The position of the pinion from coupling center ‘O’ in ‘mm’
M	Current reading number
N	The number of samples
O	Coupling position
OVLf	Online visual ferrography
PCA	Principal Component Analysis
PDSC	Pressure differential scanning calorimetry
PV	Peak value
P_{pr} and G_{pr}	Pitch radius of the pinion and gear in ‘mm’

P_{t_r} and G_{t_r}	Tip radius of the pinion and gear in ‘mm’
P_{mean}	Maximum pressure on gear tooth
RMSDS	The standard deviation of the difference TSA signal
RMS	Root mean square
RPVOT	Rotating pressure vessel test
RH	Residual vibration signal during the healthy state
\overline{RH}	Mean of the healthy residual signal
R, r	Residual signal
$\overline{R}, \overline{r}$	Mean of the residual signal
Ra	Average roughness (μm)
Rq	Root means square value of roughness (μm)
R_P and R_G	The instantaneous radius of curvatures at contact points (mm)
R^*	Equivalent radius of curvature (mm)
R_f	Rotational harmonic
r	Radial misalignment (mm)
SD	Standard deviation
SEM	Scanning electron microscopy
SNR	Signal to noise ratio
SK	Spectral Kurtosis
STFT	Short-Time Fourier Transform
TAN	Total acid number
TBN	Total base number
TGA	Thermogravimetric analysis

TSA	Time synchronous averaging
T_b	The gear bulk temperature (°C)
T_c	Total contact temperature (°C)
T_f	The flash temperature (°C)
Torq	Torque (Nm) acting on the gear shaft (Nm)
V	Volume of worn-out material (m ³)
V_P and V_G	Peripheral velocities of the pinion and gear (mm/sec)
WT	Wavelet Transform
WVD	Winger- Ville Distribution
$W_x(t,f)$	Denotes the WVD of the signal
w_{eff}	Effective width in contact (mm)
w	Width of the pinion/gear in ‘mm’
$w(t)$	Moving window function
X_G-X_G and X_P-X_P	axis of rotation of the gear and pinion
x-y	Coordinate of the coupling center
$x_{max}(t)$	Maximum vibration signal amplitude
x^*	Complex conjugate
y	Raw vibration signal
y_{pk-pk}	The peak-to-peak amplitude of the signal
\bar{y}	Mean of the signal
y_k	k th sample point in the signal
$y_{rms}(d)$	RMS value of difference TSA signal
$y_{rms}(r)$	RMS value of the harmonics TSA signal

ϕ	Pressure angle in degrees
ϕ_{new}	New pressure angle in degrees
θ_1	Angular misalignment in degree
ω_P and ω_G	The angular velocities of the pinion and gear in ‘rad/sec’
$\psi(\cdot)$	A wavelet function

