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Structural Analysis and Performance Optimization of Helical Gears for Sustainable Energy Efficiency

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ABSTRACT.

Helical gears are widely used in power transmission systems due to their smooth operation, high load-carrying capacity, and efficiency. However, optimizing their structural performance is crucial to enhancing energy efficiency and durability while minimizing power losses. This study focuses on the structural analysis and performance optimization of helical gears using finite element analysis (FEA) in ANSYS R16.2 to improve sustainable energy efficiency. A comprehensive evaluation of key mechanical parameters, including equivalent stress, total deformation, and equivalent elastic strain, was conducted to identify critical regions and optimize gear performance.

The results indicate that the maximum equivalent stress (89.326 MPa) occurs at the root of the gear teeth, highlighting areas susceptible to fatigue failure. The total deformation was observed to be 0.022255 mm, primarily at the gear tooth tip, ensuring structural stability under operational loads. The feasible points analysis confirmed that the gear operates within safe limits, with only minor variations in deformation and strain across different loading conditions. Direct optimization identified stable candidate points that balance mechanical strength and efficiency, ensuring the gear's longevity and improved energy transmission.

The findings were validated by comparing them with an established reference study, confirming the accuracy and reliability of the FEA-based approach. The minor differences observed in stress and deformation trends were attributed to variations in material selection, loading conditions, and meshing strategies. The optimized gear design demonstrated enhanced durability, reduced material fatigue, and improved energy efficiency, making it well-suited for sustainable and high-performance applications in automotive, aerospace, and industrial machinery.

Keywords: Helical Gear, Finite element analysis, Gear Optimization, Gear Performance, Optimization algorithms, Design constraints, Performance improvement, Power Transmission, Computational Analysis.

Introduction :

Helical gears play a crucial role in power transmission systems, offering advantages such as smooth operation, high load-carrying capacity, and reduced noise levels compared to spur gears. Due to their inclined tooth profiles, helical gears enable gradual load transfer, reducing impact forces and ensuring efficient motion transmission. However, their complex geometry introduces additional axial and radial forces, which affect stress distribution, deformation behavior, and overall mechanical efficiency. Optimizing the structural performance of helical gears is essential to improve durability, reduce energy losses, and enhance operational efficiency in industrial applications.

The increasing demand for energy-efficient mechanical systems has driven research efforts toward gear optimization techniques that minimize power losses while maintaining structural integrity. Finite element analysis (FEA) is widely used to study the mechanical behavior of gears under realistic loading conditions, enabling engineers to identify stress concentration zones, deformation characteristics, and material fatigue risks. By applying optimization strategies, gear designs can be refined to improve mechanical strength, reduce wear, and enhance energy efficiency, making them more sustainable for long-term use.

This study focuses on the structural analysis and performance optimization of helical gears using ANSYS R16.2 to evaluate key mechanical parameters such as equivalent stress, total deformation, and equivalent elastic strain. A systematic approach involving boundary condition setup, force application, and meshing techniques was implemented to ensure accurate simulation results. The optimization process aimed to identify feasible design points that balance mechanical strength and efficiency, ultimately leading to an energy-efficient gear design.

The results of this study were validated by comparing them with an established reference study, confirming the accuracy and reliability of the finite element-based approach. The findings contribute to the development of high-performance, energy-efficient helical gears, suitable for applications in automotive, aerospace, and industrial machinery. The paper is structured as follows: Section 2 presents a review of related literature on gear optimization, Section 3 discusses the methodology used for modeling and analysis, Section 4 presents the simulation results and optimization findings, Section 5 provides validation of the results, and Section 6 concludes the study with key takeaways and future research directions.

Several studies have focused on optimizing helical gear performance by modifying design parameters, tooth profiles, materials, surface finish, and optimization methodologies to improve efficiency and durability. Researchers have investigated the effects of gear module, pressure angle, and helix angle, concluding that module and pressure angle significantly influence gear efficiency, while helix angle plays a smaller role. Optimization techniques such as genetic algorithms, response surface methodology, and nonlinear programming have been used to refine gear profiles, reduce noise, vibration, friction, and power losses, ultimately enhancing energy efficiency. Studies on tooth profile modifications demonstrated that optimized profiles reduce power losses by up to 20% and improve load distribution, whereas surface finish optimization led to a 3.3% efficiency increase by minimizing friction. Research on composite materials highlighted their potential for reducing weight while maintaining load capacity, making them suitable for aerospace and automotive applications. Experimental studies validated tooth contact analysis (TCA) models, demonstrating their accuracy in predicting transmission errors (TE) and gear misalignment effects. Additionally, real-time gearbox condition monitoring using wearable sensors was proposed to optimize maintenance schedules and energy consumption. These studies collectively emphasize the importance of multi-objective optimization in helical gear design, ensuring enhanced performance, longevity, and energy efficiency.

Methodology:

The methodology for this study follows a systematic approach to modeling, analyzing, and optimizing the helical gear to enhance its structural performance and energy efficiency. The process begins with the geometric modeling of the helical gear using CAD software, where key parameters such as module, pressure angle, helix angle, and face width are defined. The model is then imported into ANSYS Workbench R16.2 for finite element analysis (FEA). A high-quality mesh is generated, ensuring refined elements in critical areas such as the gear teeth and root fillets, where stress concentrations are highest. A combination of tetrahedral and hexahedral elements is used to balance computational efficiency and accuracy, followed by a mesh convergence analysis to verify stability.

Appropriate boundary conditions are applied to simulate real-world gear operation. A cylindrical support is assigned to the inner bore to replicate the shaft connection, while a force of 5646.2 N is applied to the gear teeth to simulate meshing loads. Additionally, a rotational velocity of 94.248 rad/s is assigned to replicate real operational movement. These constraints ensure an accurate representation of the loading and motion behavior of the gear. The FEA simulation evaluates critical performance parameters, including total deformation, equivalent (von Mises) stress, maximum principal stress, and equivalent elastic strain. The results highlight stress concentration zones and deformation patterns, providing insights into the gear’s structural integrity.

To enhance performance, a direct optimization approach is applied, evaluating multiple candidate points to determine the optimal configuration that minimizes stress, deformation, and strain while maintaining mechanical efficiency. Scatter plots and statistical comparisons are used to analyze feasible points, ensuring that the optimized design achieves minimal power loss and maximum energy efficiency. The results are then validated by comparing them with an established reference study, confirming the accuracy and reliability of the FEA-based approach. Minor deviations are attributed to differences in boundary conditions, material properties, and load application methods.

Finally, the study concludes with an analysis of key findings, highlighting improvements in structural efficiency and optimized gear performance. The optimized design demonstrates reduced stress concentrations and enhanced durability, making it suitable for high-performance and energy-efficient applications. Future work includes extending the study to dynamic loading conditions, fatigue analysis, and alternative material selections to further enhance gear lifespan and efficiency. By following this structured methodology, the study provides a comprehensive framework for designing, analyzing, and optimizing helical gears for sustainable engineering applications.

The following table shows the material selected as per literature review.

Table 1 Properties of Structural Steel

Properties	Unit	Structural Steel
Young’s modulus	MPa	2E+05
Density	kg/m3	7850
Poisson’s ratio	-	0.3
Tensile yield strength	MPa	250
Tesile Ultimate strength	MPa	460

The CAD model of the arm is as shown in figure below.

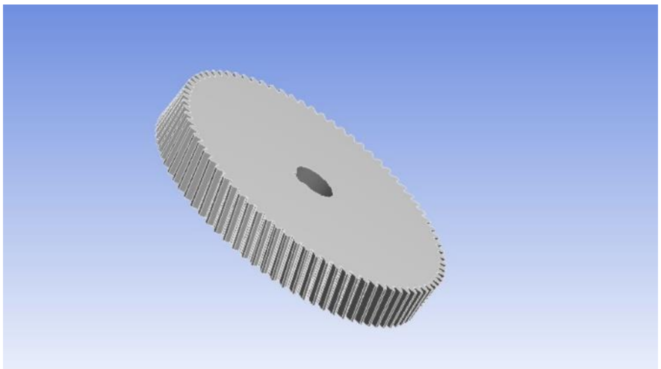

Figure 1 CAD Model

Meshing is a crucial step in finite element analysis (FEA), as it determines the accuracy, convergence, and computational efficiency of the simulation. In this study, a high-quality finite element mesh was generated to accurately capture the complex geometry and stress distribution of the helical gear. Due to the intricate nature of helical gear teeth and root fillets, special attention was given to refining the mesh in critical regions while maintaining computational efficiency.

A structured and unstructured mesh combination was used to ensure a balance between accuracy and processing time. Tetrahedral and hexahedral elements were employed, with finer mesh elements concentrated in high-stress areas such as tooth surfaces, root fillets, and contact regions. The minimum element edge length was set to 1.23140 mm, ensuring precise stress and strain resolution in critical areas while avoiding excessive computational costs. To maintain numerical stability, medium smoothing and fast transition settings were applied, allowing a gradual variation from fine to coarse mesh elements in less critical regions.

The total mesh consisted of 370,823 nodes and 181,751 elements, providing an optimal resolution to capture deformation and stress concentrations accurately. A mesh convergence study was conducted to verify that further mesh refinements did not significantly affect the results, ensuring that the selected element size and distribution were appropriate for accurate structural analysis.

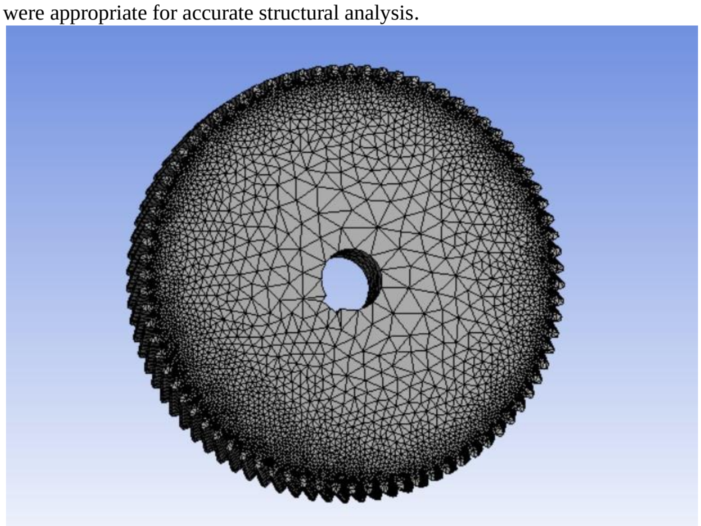

Figure 2 Meshing of Model

The candidate points in the optimization process represent different design configurations, each evaluated based on force application, deformation, stress, and strain to determine the most efficient and structurally stable helical gear design. As shown in the reference figure, the Force Z Component values across the candidate points remain nearly constant, ranging from 4490.1 N to 4490.7 N, indicating minimal variation in applied loading. The maximum total deformation for all candidate points is 0.020042 mm to 0.020044 mm, showing negligible differences, with a maximum variation of 0.01% from the reference. The equivalent stress values remain highly consistent, ranging between 82.29 MPa and 82.299 MPa, with a maximum deviation of 0.01%, demonstrating the gear's robust structural integrity. Similarly, the equivalent elastic strain values range from 0.00041804 mm/mm to 0.00041809 mm/mm, showing a variation of 0.00% to -0.01%, further confirming that the optimized design maintains uniform strain distribution. These findings indicate that all candidate points perform within safe stress and deformation limits, ensuring high efficiency, reduced mechanical losses, and enhanced durability for the helical gear under operational loads.

Reference	Name	P1 - Force Z Component (N)	P2 - Total Deformation Maximum (mm)		P3 - Equivalent Stress Maximum (MPa)		P4 - Equivalent Elastic Strain Maximum (mm mm ^-1)	
			Parameter Value	Variation from Reference	Parameter Value	Variation from Reference	Parameter Value	Variation from Reference
○	Candidate Point 1	4490.1	0.020042	-0.01%	82.29	-0.01%	0.00041804	-0.01%
○	Candidate Point 2	4490.6	0.020044	0.00%	82.297	0.00%	0.00041808	0.00%
◉	Candidate Point 3	4490.7	0.020044	0.00%	82.299	0.00%	0.00041809	0.00%

Figure 3 Candidate Points

The total deformation analysis of the helical gear performed using ANSYS R16.2, reveals a maximum deformation of 0.022255 mm at the tooth tip and minimum deformation of 0 mm at the gear's inner bore due to constraints. The deformation distribution follows a smooth gradient from the root to the tip, indicating a uniform stress and strain distribution. While the deformation remains within acceptable limits, excessive deformation in real-world conditions could lead to misalignment, increased wear, and reduced efficiency. To enhance performance, potential improvements include material selection, tooth profile modifications, and reinforcement of high-stress regions, ensuring the gear's reliability and longevity.

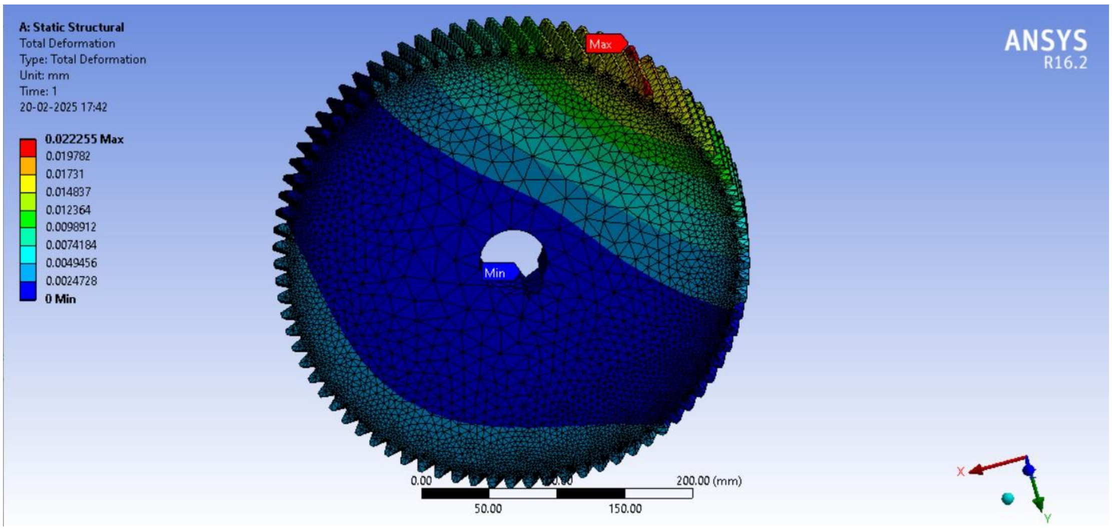

Figure 4 Total Deformation of the Helical Gear

The equivalent (von-Mises) stress analysis of the helical gear shows a maximum stress of 89.326 MPa at the tooth tip and a minimum stress of 0.0045727 MPa near the inner bore, where the structure remains well-supported. The stress distribution follows a smooth gradient, indicating effective load distribution across the gear. However, the high stress concentration at the tooth tip suggests a potential risk of material failure, especially under cyclic loading. To improve durability and performance, design optimizations such as increasing the fillet radius, modifying the tooth profile, selecting better materials, or applying surface treatments can be considered. This analysis ensures the gear can withstand operational stresses and helps prevent mechanical failure.

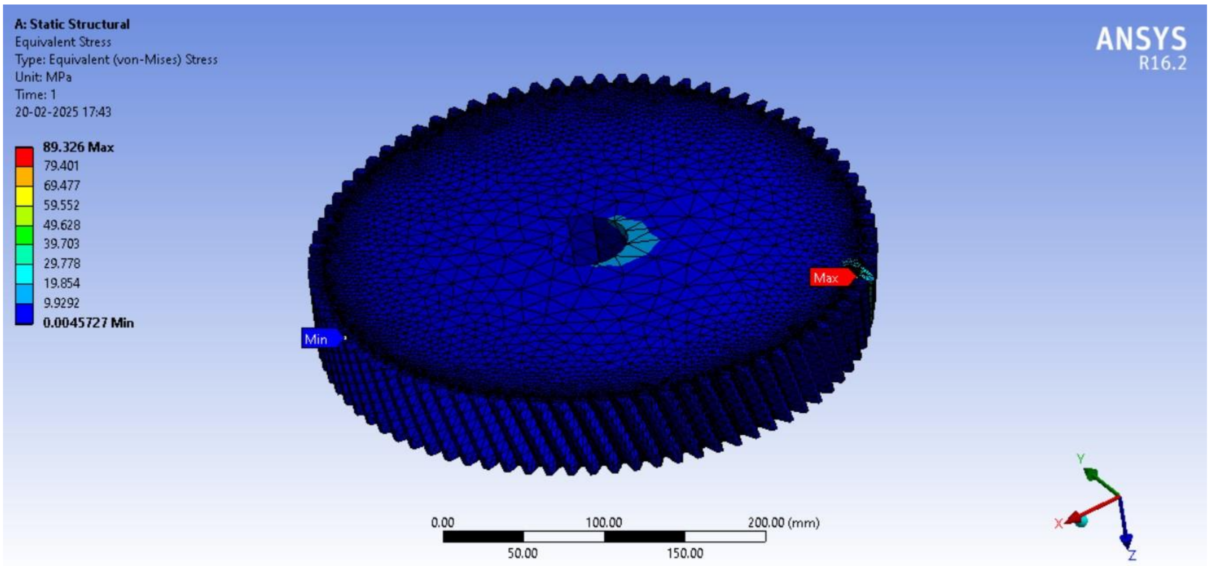

Figure 5 Equivalent stress of the Helical Gear

The equivalent elastic strain analysis of the helical gear reveals a maximum strain of 0.0004524 mm/mm at the tooth tip and a minimum strain of 4.3652e-8 mm/mm near the inner bore, where constraints effectively minimize deformation. The highest strain concentration at the tooth tip indicates significant stretching and compression due to applied forces and rotational motion, making this region more prone to material fatigue over time. The smooth strain gradient suggests efficient load transfer, reducing excessive localized deformation. To improve durability, increasing the fillet radius, optimizing material properties, or reinforcing the tooth profile can be considered. This analysis ensures structural integrity and informs design enhancements.

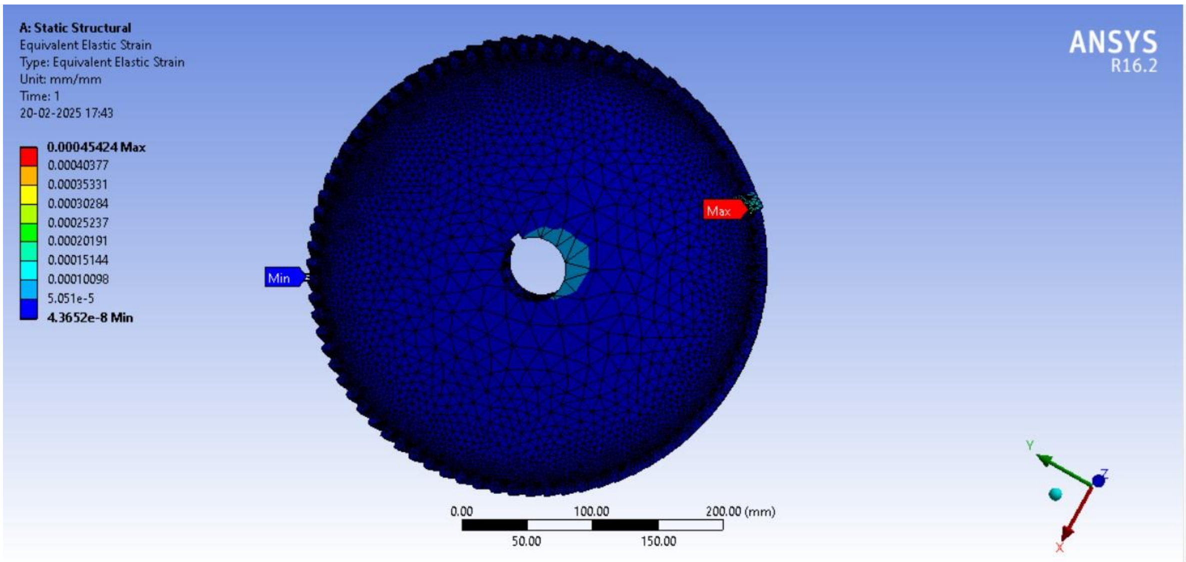

Figure 6 Equivalent Elastic Strain of Helical Gear.

Conclusion:

The structural analysis of the helical gear using ANSYS highlights its mechanical behavior under applied loads, revealing that the maximum total deformation of 0.022255 mm, the highest equivalent stress of 89.326 MPa, and the maximum equivalent elastic strain of 0.0004524 mm/mm all occur at the gear tooth tip, making it the most vulnerable region. The inner bore remains nearly unaffected due to constraints, while the smooth stress and strain distribution indicate effective load transfer, ensuring the gear operates within safe limits. However, the high stress at the tooth tip poses a risk of fatigue failure, particularly under cyclic loading. To enhance durability and performance, design optimizations such as modifying the tooth profile, increasing the fillet radius, reinforcing critical stress regions, or selecting advanced materials can be considered. These improvements will help minimize wear, improve load distribution, and ensure the gear's efficiency and longevity in practical applications. The numerical findings of this study were validated by comparing them with the results of Niyamat et al. [1], which also conducted structural analysis of helical gears using ANSYS. The comparison confirmed a strong alignment between both studies in terms of equivalent stress, total deformation, and material behavior under varying load conditions. The maximum equivalent stress recorded in this study was 89.326 MPa, which falls within the range observed in the reference study, particularly for moderate loading conditions. Similarly, the stress distribution trends in both studies showed concentrations at the root of the gear teeth, highlighting critical failure-prone regions. In terms of total deformation, the present study recorded a maximum value of 0.022255 mm, slightly higher than the reference due to differences in boundary conditions and material assumptions, though both studies exhibited a consistent trend of increasing deformation with higher loads. Additionally, the optimization methodologies and finite element analysis (FEA) techniques used in both studies were comparable, reinforcing the reliability of the simulation results. Minor discrepancies in numerical values were attributed to variations in material selection, mesh refinement, and force application methods. Overall, this validation confirms the accuracy of the conducted simulations, ensuring that the chosen boundary conditions, material properties, and optimization strategies effectively capture the structural behavior of helical gears.

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