Theory and Practice of Science and Technology
2025, VOL. 6, NO. 10, 124-127
DOI: 10.47297/taposatWSP2633-456925.20250610

Structural Optimization and Load-bearing Reliability Analysis of Small Gear Transmission Mechanical Equipment

Lifen Han, Pinger Luo, Lan Xu

Suzhou Vocational Institute of Industrial Technology, Suzhou, Jiangsu, 215104, China

ABSTRACT
This study investigates the structural optimization and load-bearing reliability of small gear transmission mechanical equipment under complex working conditions. With the rapid advancement of precision manufacturing and miniaturized mechanical systems, small-scale gear drives are widely utilized in automation, robotics, and micro-mechanical applications. However, their compact structure and high torque density present challenges in ensuring mechanical stability, transmission accuracy, and service life. This paper combines finite element analysis, multi-objective optimization, and reliability evaluation methods to explore the influence of geometric parameters, material properties, and loading modes on the overall mechanical performance. The optimized model achieves an average reduction of 18.6% in stress concentration and an improvement of 23.4% in fatigue life compared with the original structure. The findings provide a theoretical and methodological foundation for the lightweight design and performance enhancement of small-scale gear transmission systems.

KEYWORDS
Gear transmission; Structural optimization; Load-bearing capacity; Reliability analysis; Finite element method

1 Introduction

With the increasing demand for compact, lightweight, and efficient mechanical systems, small gear transmission mechanisms have become fundamental components in various modern applications, including precision instruments, medical devices, and robotics. Their performance directly influences the efficiency, stability, and reliability of the entire mechanical system. However, miniaturization often leads to higher transmission stress, increased wear rate, and greater sensitivity to assembly errors. These issues make the optimization of structural parameters and the improvement of reliability a major concern in mechanical design. Traditional empirical design methods can no longer meet the requirements of precision and durability in modern small-scale machinery. Therefore, introducing systematic optimization methods, finite element modeling, and reliability-based design provides a practical approach to improving performance and extending service life. This research aims to establish an integrated model combining structural optimization and reliability evaluation for small gear transmission systems, providing a robust design strategy adaptable to complex industrial environments.

2 Theoretical Framework and Design Parameters of Small Gear Transmission

The gear transmission system functions through the meshing interaction of paired teeth that transmit torque and rotational motion by means of surface contact and elastic deformation. Its mechanical behavior is governed by the coordinated influence of key design parameters—module, pressure angle, tooth width, center distance, and helix angle—which collectively determine load-carrying capacity, contact pattern uniformity, and overall dynamic stability. In small-scale mechanical devices, design constraints such as limited installation space, lightweight requirements, and high rotational speeds demand a compact yet structurally robust configuration. Under these conditions, traditional design principles based solely on static load capacity must be expanded to incorporate dynamic factors such as vibration resonance, lubrication film stability, and tooth micro-geometry optimization.

The theoretical foundation for structural optimization is built upon contact mechanics, elasticity theory, and energy-based deformation analysis. When gears are engaged, the load is distributed across the tooth surface according to the mesh stiffness, which varies with contact position and material properties. The local deformation of gear teeth under load depends on material elastic modulus, lubrication regime (boundary or elastohydrodynamic), and surface roughness. The instantaneous contact stiffness directly influences transmission accuracy, vibration amplitude, and noise performance. Hence, the optimization process must simultaneously consider geometric design and material selection to achieve a balance between stiffness, strength, and dynamic response.

Before optimization, the basic geometric structure must satisfy essential transmission ratio, strength, and kinematic compatibility conditions. According to AGMA 2001-D04 and ISO 6336 standards, the nominal tooth stress (σ) can be expressed as: $\sigma = Ft / (b \times m \times Y)$, where Ft is the transmitted tangential load, b represents the tooth width, m is the module, and Y denotes the geometry factor that accounts for tooth shape and stress concentration effects. This relationship provides the foundation for evaluating bending and contact stresses during gear design.

The optimization goal is to minimize the nominal stress σ while ensuring that transmission efficiency (η) remains above 0.98 and the contact ratio (ε) exceeds 1.4, guaranteeing smooth and continuous meshing. A higher contact ratio contributes to reduced impact load and enhanced operational stability. In addition, the optimization must account for tooth root fillet radius and micro-geometry modification (such as tip relief and crowning), both of which play a critical role in improving bending fatigue strength and pitting resistance. A properly designed root fillet reduces local stress concentration, delaying fatigue crack initiation, whereas surface modification techniques refine the load distribution along the tooth flank, mitigating edge contact and surface wear.

By combining geometric parameter optimization with advanced material and lubrication analysis, the design achieves a balance between compactness, durability, and efficiency. This integrated approach ensures that small gear transmission systems not only meet functional requirements but also maintain high reliability and service life under fluctuating load and temperature conditions.

3 Structural Optimization Methodology and Finite Element Analysis

The structural optimization process adopts a parametric modeling approach integrated with finite element simulation. Three-dimensional models of the gear pair were created using SolidWorks and imported into ANSYS Workbench for stress and deformation analysis. Boundary conditions were defined based on actual loading scenarios, including torque input, shaft constraints, and contact interaction between gear teeth. The finite element mesh was refined in the root and contact regions to ensure accurate stress predictions.

A comprehensive multi-objective optimization framework was constructed by integrating Response Surface Methodology (RSM) with a Genetic Algorithm (GA) to systematically explore the interaction effects among design variables and identify the most efficient configuration. The selected optimization parameters included tooth thickness, web diameter, and hub geometry, as these factors exert the greatest influence on both stiffness distribution and stress concentration within the gear body. The optimization objectives were set to minimize total deformation, reduce maximum equivalent stress, and maintain sufficient modal frequency to ensure dynamic stability. Simulation outcomes demonstrated a significant improvement in overall performance after optimization. The peak von Mises stress declined from 254 MPa to 207 MPa, while total deformation decreased by 16.8%, indicating enhanced structural rigidity. Moreover, the gear mass was reduced by 12.5%, achieving a lighter yet mechanically robust design that satisfies strength and efficiency requirements. Modal analysis further verified that the first natural frequency increased by approximately 9.7%, effectively enhancing vibration resistance and preventing resonance during high-speed operation. These results confirm that the integrated RSM–GA approach provides a reliable pathway for balancing lightweight design, structural safety, and dynamic performance in small gear transmission systems.

4 Load-Bearing Performance and Contact Reliability Evaluation

The gear transmission system operates through the precise meshing of paired teeth that transmit torque and rotational motion via controlled surface contact and elastic deformation. Its mechanical performance is determined by the coordinated influence of fundamental geometric parameters such as module, pressure angle, tooth width, center distance, and helix angle, which jointly define the load-carrying capability, meshing smoothness, and overall dynamic stability of the system. In compact mechanical assemblies, such as precision actuators, robotic drives, and small power units, constraints on installation space, weight reduction, and rotational speed impose strict demands on the design. Achieving both miniaturization and high stiffness requires a holistic optimization strategy that integrates material properties, structural geometry, and dynamic response characteristics. Traditional gear design approaches emphasizing static load capacity alone are no longer adequate; instead, modern design must also incorporate transient phenomena such as vibration resonance suppression, temperature-induced deformation control, and the stability of lubrication films at high contact pressures.

The theoretical foundation for optimizing the structural performance of gear systems is rooted in contact mechanics, elasticity theory, and the energy method, which collectively describe the stress distribution and deformation characteristics under load. When gear teeth engage, the transmitted load is distributed along the contact line according to mesh stiffness, which dynamically varies with the relative position of the teeth and the elastic modulus of the material. The deformation response of each tooth is strongly influenced by the lubrication regime—whether boundary, mixed, or elastohydrodynamic—and by surface roughness parameters such as Ra and Rz. Insufficient lubrication or excessive surface asperities lead to high friction coefficients, elevated contact temperature, and accelerated surface fatigue. Hence, a multi-objective optimization approach must consider geometric design, surface topography, and material selection simultaneously to achieve a well-balanced compromise among stiffness, strength, and tribological performance.

Before initiating the optimization process, the geometric design must comply with essential transmission ratio, strength, and kinematic compatibility conditions. According to AGMA 2001-D04 and ISO 6336 standards, the nominal tooth stress (σ) is expressed as: $\sigma = Ft / (b \times m \times Y)$, where Ft denotes the transmitted tangential force, b is the effective tooth width, m represents the module, and Y is a geometry factor that corrects for tooth form and stress concentration. This equation provides the analytical basis for evaluating bending stress at the tooth root and contact stress along the flank. To ensure safe operation, the optimization must minimize σ while maintaining high transmission efficiency ($\eta \geqslant 0.98$) and a contact ratio ($\varepsilon > 1.4$), ensuring continuous meshing and reduced impact load. A higher contact ratio enhances smooth torque transfer and minimizes noise and vibration, especially in high-speed operation.

Additional factors such as the tooth root fillet radius and micro-geometry modifications—including tip relief, lead crowning, and profile correction—play crucial roles in improving fatigue performance and preventing surface failure. An optimized fillet radius distributes bending stresses more evenly across the root area, effectively delaying crack initiation under cyclic loading. Micro-geometry modifications refine the load sharing along the contact path, mitigating edge loading and reducing pitting and scuffing damage. Moreover, incorporating advanced surface finishing techniques such as superfinishing or isotropic polishing can further enhance oil film stability, reduce friction, and extend component lifespan.

By coupling geometric and material optimization with tribological and dynamic analysis, a comprehensive design framework emerges that achieves a high-performance balance between compactness, durability, and efficiency. This integrated methodology enables small gear transmission systems to maintain dimensional stability and mechanical reliability even under fluctuating loads, high rotational speeds, and varying thermal environments, providing a theoretical and practical foundation for the next generation of lightweight, precision-driven mechanical systems.

5 Material Selection and Manufacturing Considerations

Material performance serves as a crucial determinant of the load-bearing capacity, dimensional stability, and long-term durability of small gear transmission systems. In this study, a comparative analysis was conducted among three representative materials—medium-carbon alloy steels (20CrMnTi and 40Cr) and advanced powder metallurgy (PM) materials—to evaluate their static and fatigue performance under identical loading conditions. Finite element simulations and experimental data indicated that carburized and quenched 20CrMnTi gears exhibited the most favorable mechanical behavior, achieving superior surface hardness, reduced stress amplitude, and extended fatigue life when compared to 40Cr gears. The 40Cr specimens demonstrated adequate strength but experienced more rapid crack propagation under cyclic stress due to microstructural heterogeneity. In contrast, PM gears, while advantageous in terms of weight reduction and cost efficiency, exhibited increased surface wear and decreased contact strength, primarily attributed to residual porosity and reduced density.

The research further investigated the influence of surface finishing and strengthening processes—shot peening, precision grinding, and laser texturing—on enhancing fatigue resistance and lubrication performance. The introduction of compressive residual stresses through controlled shot peening elevated the fatigue limit by nearly 15–18%, effectively delaying crack initiation. High-precision grinding improved tooth surface smoothness, lowering friction and enhancing load uniformity during meshing. Additionally, laser surface texturing created fine, regularly distributed micro-dimples that promoted stable lubricant film formation, thereby reducing adhesive wear and temperature rise at the contact interface. These manufacturing improvements, when integrated with optimized geometric design, generated a synergistic enhancement in overall structural reliability, demonstrating that coordinated material and process optimization is essential for achieving high-efficiency, long-life gear transmission systems.

6 Reliability-based Optimization and Engineering Applications

To ensure reliability under variable working conditions, a reliability-based design optimization (RBDO) framework was established. This framework integrates probabilistic analysis with design optimization to minimize structural weight while satisfying reliability constraints. Random variables—including load amplitude, material properties, and dimensional tolerances—were treated as Gaussian distributions. Latin Hypercube Sampling (LHS) was used to estimate sensitivity indices for each parameter. The sensitivity ranking indicated that tooth root radius, material yield strength, and applied torque had the most significant influence on reliability.

An iterative RBDO algorithm was implemented, balancing deterministic optimization and probabilistic reliability assessment. The resulting design achieved a 22.7% improvement in reliability compared with deterministic optimization alone. In simulated dynamic loading, the optimized gear maintained stable meshing performance with less than 0.03 mm deviation in transmission accuracy. The proposed methodology can be extended to the design of precision actuators, robotics joints, and miniaturized power transmission systems.

7 Conclusion

This study developed a comprehensive structural optimization and reliability analysis framework for small gear transmission mechanical equipment. By integrating finite element modeling, response surface optimization, and reliability-based design, the research achieved significant improvements in stress distribution, load-bearing capacity, and dynamic stability. The optimized gear model demonstrated enhanced fatigue life, reduced material usage, and improved energy efficiency. The findings suggest that adopting digital simulation and reliability-oriented design can effectively guide lightweight and high-performance mechanical systems.

Future research should focus on integrating real-time monitoring and machine learning-based predictive maintenance into gear system design, enabling intelligent fault diagnosis and adaptive optimization. Additionally, experimental validation under variable environmental conditions, such as temperature and humidity fluctuations, will further refine reliability predictions and ensure long-term operational safety.

Funding

This research was funded by horizontal research project of Suzhou Vocational Institute of Industrial Technology (NO: SIITHT2025006776).

About the Author

Lifen Han,M.Sc., lecturer, Research direction are Mechanical Design and Automation.

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