Frontiers in Computing and Intelligent Systems
ISSN: 2832-6024 | Vol. 14, No. 1, 2025

Lightweight Design of Automotive Driveshaft Flange Fork Under High Torque Conditions Using ANSYS

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Abstract: With the rapid development of the automotive industry and increasingly stringent environmental requirements, lightweight design has become a key technological direction in automotive manufacturing. As a critical component of the vehicle's power transmission system, the structural rationality, lightweighting level, and manufacturing process reliability of the drive shaft flange fork directly impact transmission efficiency, vehicle reliability, and fuel economy. Optimizing its performance is of great significance for vehicle energy conservation and emission reduction. This study employs ANSYS Workbench software to conduct finite element analysis and structural optimization of automotive drive shaft flange forks, evaluating stress and strain under high torque conditions of 24,000 N·m. Analysis reveals that while pre-optimization safety factors exceed industry standards, material redundancy exists. To address this, structural optimization was implemented through material reduction techniques. After optimization, the flange fork achieved approximately 9% weight reduction while maintaining safety factors that still meet requirements. This study validates the effectiveness of finite element analysis in lightweight design for drive shafts, providing theoretical basis and practical reference for automotive component optimization.

Keywords: Driveshaft; Flange Fork; ANSYS; Structural Optimization; Lightweighting.

1. Introduction

The booming automotive industry has energized the global economy, yet it also poses challenges of energy consumption and environmental pollution. By the end of September 2025, China's vehicle ownership reached 363 million units, with motor vehicle ownership at 465 million units. Traditional fuel-powered vehicles remain dominant, and their energy consumption and emissions issues are increasingly prominent. Research indicates that a 10% reduction in vehicle mass can decrease fuel consumption by 6%–8% and emissions by 4%. [1] Consequently, lightweight design has become the core pathway for the automotive manufacturing industry to achieve energy conservation and emission reduction. The Made in China 2025 strategy prioritizes lightweighting as a key direction, aiming to enhance vehicle dynamic performance and environmental benefits. As a critical component in power transmission, the driveshaft transfers engine torque to the drive wheels while accommodating angular and distance variations during vehicle motion. Under high-speed, high-torque conditions, lightweighting the propeller shaft not only reduces material costs but also decreases rotational inertia, thereby improving transmission efficiency. However, domestic propeller shafts lag behind international counterparts in material strength (tensile strength generally below 480 MPa) and structural design, necessitating performance enhancements through optimization. [2]

This study focuses on the flange fork of commercial vehicle drive shafts, employing ANSYS Workbench finite element analysis software for structural optimization design. Research objectives include: (1) establishing an accurate model of the drive shaft flange fork; (2) evaluating performance through static analysis; (3) implementing material reduction optimization in stress concentration zones; (4) verifying the feasibility and effectiveness of the optimized design. The findings provide data support for drivetrain shaft lightweighting and advance automotive component technology upgrades.

2. Current Status of Lightweighting Research for Automotive Driveshaft Flange Forks

The application of lightweighting technology in the automotive field began in the 1950s. In 1953, General Motors launched the first composite body vehicle, the Chevrolet Corvette, pioneering material lightweighting. As the automotive industry evolves toward "lightweighting, high performance, and low cost," flange forks face numerous challenges in controlling structural stress concentration, adapting to multi-material lightweighting, and ensuring consistency in complex manufacturing processes. Shang Guosheng [3] established a quantitative logic for flange fork structural design by focusing on critical dimensions such as fork ear hole diameter, retaining ring groove spacing, and center height. Yang Chunyong [4] and colleagues analyzed fracture causes using fishbone diagrams to optimize flange fork structures. Xu Huafu [5] optimized the structural lightweighting and fatigue life of end-face gear flange forks and welded forks, providing lightweighting solutions for other drive shaft components. Overseas research primarily focuses on advanced material applications. S.A. Mutasher [6] found optimal torque transmission at a fiber winding angle of 45°; Arun Ravi [7] determined via SolidWorks modeling and ANSYS analysis that high-strength carbon/epoxy composite drive shafts are 24% lighter than steel shafts. However, domestic drive shafts still lag behind foreign products in fatigue strength and weight, primarily due to insufficient material strength and process limitations [8]. Research on weight reduction of flange forks under high-torque conditions for automotive drive shafts remains scarce. Therefore, this paper addresses existing research gaps by initiating structural optimization combined with finite element simulation.

3. Working Principle and Modeling of Drive Shaft Flange Fork

The core function of a driveshaft is to transmit torque in dynamic environments while compensating for relative displacement between the power source and driven components. The driveshaft assembly comprises flange forks, splined shaft forks, universal joint forks, and cross shafts. The flange structure on the driveshaft typically serves to connect and transmit power. Flange forks are bolted, pinned, or otherwise fastened together to transmit torque and power. The flange fork modeling is shown in Figure 1.

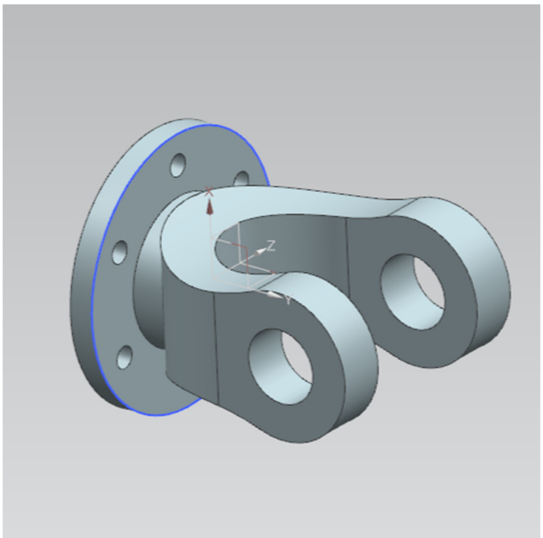


Figure 1. Drive Shaft Flange Fork Structure

4. Static Analysis of Drive Shaft Flange Fork

4.1. Mesh Generation and Material Selection

Table 1. Transmission Shaft Flange Fork Mesh Partitioning

Type	Maximum Mesh Size	Minimum Mesh	Average Mesh Quality
Flange Fork	0.99984	0.10172	0.81857

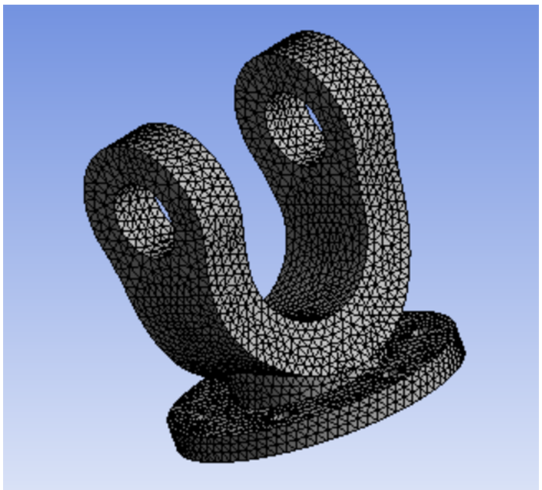


Figure 2. Mesh Partitioning of the Drive Shaft Flange Fork

A tetrahedral mesh with a size of 2 mm was employed, with critical regions refined to 1 mm. Mesh quality is detailed in Table 1. The material selected is 40Cr steel for the drive shaft, with a density of 7.85 g/cm³, elastic modulus of 211 GPa, and Poisson's ratio of 0.3.

4.2. Static Analysis Results

Boundary conditions for bench test simulation: Apply 24,000 N·m torque at the lug holes, with fixed constraints on the end face or spline tooth surfaces. The static analysis results are shown in Figure 3: The maximum stress on the flange fork is 329.6 MPa (located at the junction between the flange wall and the disc body), with a safety factor of 1.81; the maximum deformation is 0.18227 mm. The component's safety factor exceeds 1.5, meeting industry standards.

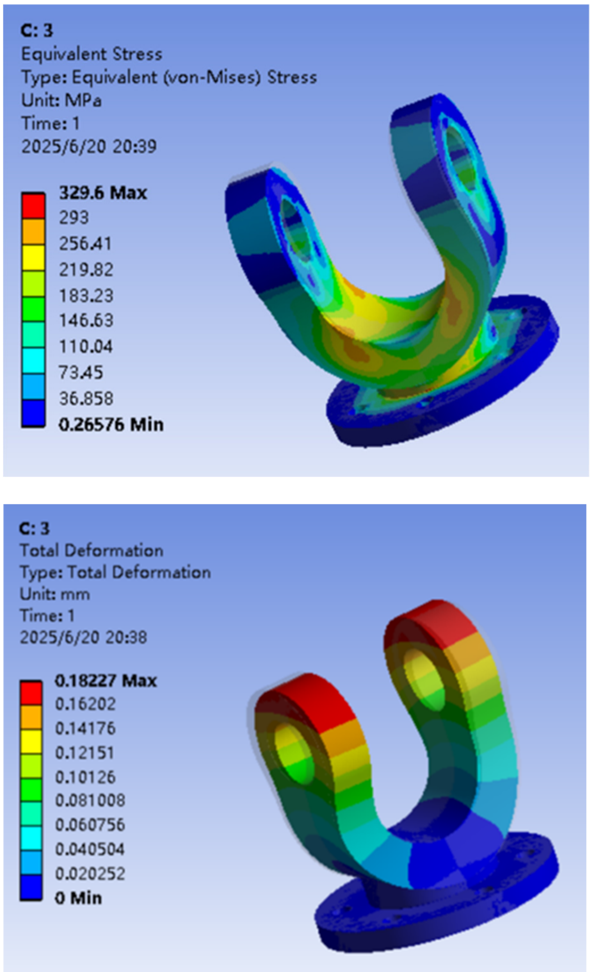


Figure 3. Static Analysis of Automotive Driveshaft Flange Fork

5. Lightweight Structural Optimization of Flange Fork

The goal of lightweighting is to reduce weight while ensuring safety. Research indicates that a 10% reduction in vehicle weight can decrease fuel consumption by 6-8%. Lightweighting significantly improves fuel economy and aligns with increasingly stringent global emission regulations (e.g., Euro VI, China VI standards). This study focuses on material removal optimization in low-stress regions. The maximum stress in the flange fork is concentrated at the junction between the ear wall and the bottom plate, while the bottom exhibits lower stress and material redundancy. Therefore, material removal design is implemented at the bottom.

The first material reduction design involved hollowing out a square hole with 10 cm sides along both the x and z axes on the bottom plane. The second design created a rectangular hole measuring 12 cm along the x-axis and 14 cm along the z-axis on the bottom plane, as shown in Figure 4. The equivalent stress and equivalent strain plots for the flange fork optimized through two distinct structural iterations using ANSYS Workbench are shown in Figure 5.

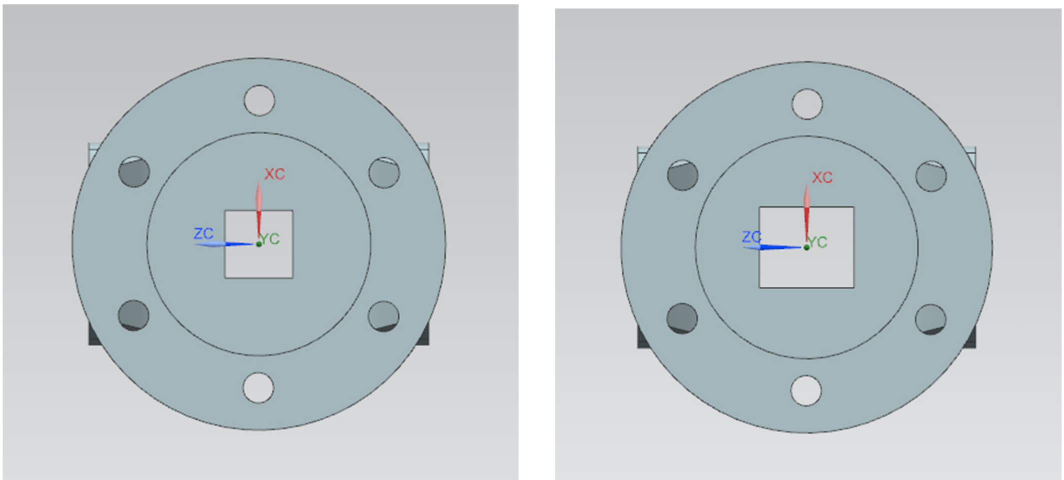
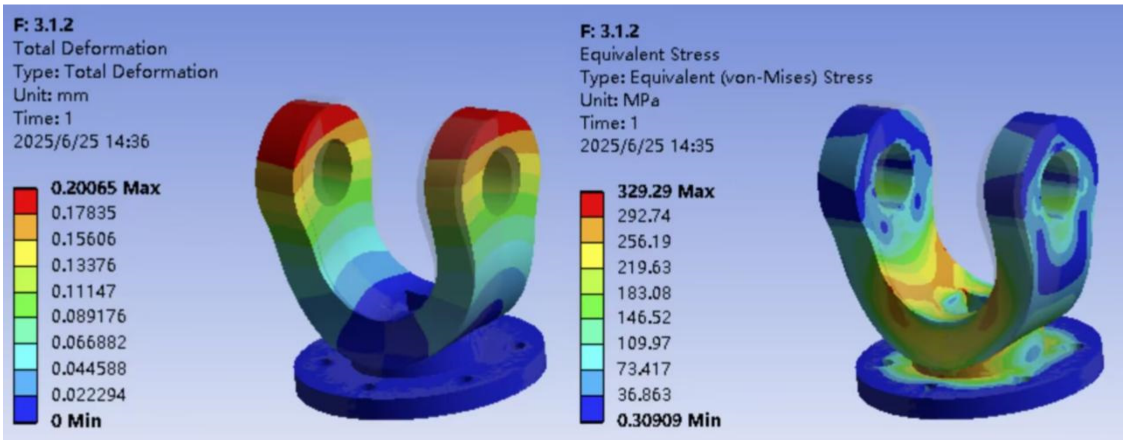
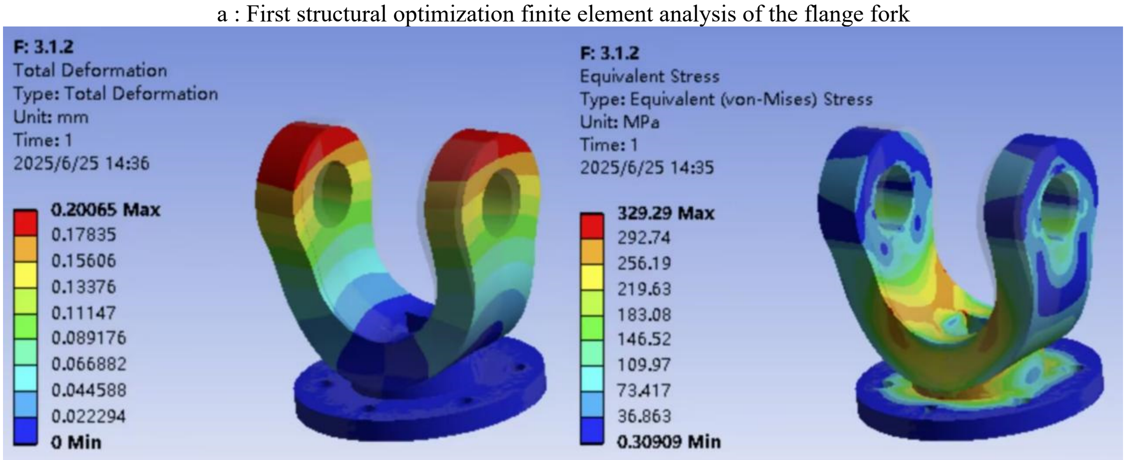


Figure 4. Optimization scheme for the drive shaft flange fork



a : First structural optimization finite element analysis of the flange fork



b : Second structural optimization finite element analysis of the flange fork

Figure 5. Finite Element Analysis of Optimized Drive Shaft Flange Fork Design

Three distinct structural configurations: stress increases with optimized structure, strain increases with optimized structure, safety factor decreases with optimized structure, weight decreases with optimized structure. All results remain within permissible limits, with safety factors exceeding 2, meeting industry requirements as shown in Table 2.

Table 2. Results of Different Structural Optimization Schemes

Type	Stress/MPa	Strain/mm	Safety Factor	Weight/kg
Original	329.6	0.18227	2.3817	0.29852
First Structural Optimization	329.23	0.20065	2.3839	0.28461
Second Structural Optimization	383.74	0.21673	2.0457	0.27061

After the first structural optimization, the weight ratio was 94% of the original. After the second optimization, while ensuring safety, the weight ratio was 91% of the original, resulting in a total weight reduction of 9%.

6. Summary

Under high-torque operating conditions, the transmission shaft flange fork achieved significant weight reduction (9% for the flange fork) through bottom structure optimization, while maintaining the required safety factor. Stress concentration zones showed no deterioration, indicating the rationality of this material reduction approach. However, the optimized component exhibits slightly reduced stiffness, necessitating further validation of fatigue life under dynamic loading conditions. This study achieved a balance between structural optimization and weight reduction for the drive shaft flange fork through systematic finite element analysis. Bench testing was conducted to compare simulation and actual measurement data. Future research directions include exploring multi-objective optimization (e.g., shape and topology co-optimization) and investigating composite material applications to further enhance weight reduction potential, thereby advancing lightweight structural design for automotive drive shaft flange forks under high-torque conditions.

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