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Structural Optimization Design and Strength Verification of Reducer

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Abstract: As the core component of mechanical transmission systems, the performance of reducers directly determines the overall equipment's reliability, efficiency, and service life. Under the stringent demands of modern industry for high power density, lightweight design, low noise, and high reliability, traditional empirical design methods can no longer meet the requirements. This paper aims to systematically explore advanced strategies for the structural optimization design of reducers and scientifically rigorous strength verification methods. The article first elaborates on the objective system for reducer structural optimization and the importance of multi-physics coupling analysis. Secondly, it provides an in-depth analysis of modern structural optimization design strategies based on topology optimization, size optimization, shape optimization, and parametric modeling. Thirdly, it discusses in detail the theories and methods for static strength, fatigue strength, contact strength, and stiffness verification of key components such as gears, shaft systems, and housings. Finally, it offers an outlook on the development trends in the field of reducer design. Research indicates that deeply integrating advanced optimization algorithms, precise multi-physics simulations, and a comprehensive strength verification system is the key pathway to achieving high-performance and high-reliability reducer design.

Keywords: Reducer; Structural Optimization; Topology Optimization; Strength Check

Introduction

The reducer, as a key mechanical device for transmitting power, reducing speed, and increasing torque, is widely used in equipment fields such as transportation. Currently, the global manufacturing industry is transforming towards intelligent and high-end production, placing higher demands on reducer performance: they must be compact and lightweight to improve power density, while also possessing high load capacity, long service life, smooth operation, and reliability under extreme conditions in complex environments. Traditional design relies on empirical formulas and physical prototype testing, which has limitations such as long cycles, high costs, difficulty in achieving global optimization, and insufficient prediction of complex nonlinear problems. Since the 21st century, emerging technologies such as Computer-Aided Engineering (CAE), modern optimization algorithms, and advanced materials science have brought revolutionary changes to reducer design. Structural optimization design aims to optimize performance indicators while satisfying functional, performance, and manufacturing constraints; strength verification ensures the design is safe and reliable, requiring comprehensive consideration of multiple loads and environmental factors. Therefore, the combination of efficient structural optimization and precise strength verification forms the core of modern forward design for high-performance reducers. This paper will establish a universal theoretical framework from a systems engineering perspective, define optimization objectives and constraints, explore optimization strategies, construct a methodology for strength verification, and outlook future trends.

1. Objective System and Constraints of Reducer Structural Optimization

Reducer structural optimization is a typical complex engineering problem involving multiple objectives and constraints. The optimization objectives are diverse and mutually restrictive, including minimizing mass to reduce costs, improve dynamic response, achieve lightweight design and high power density; minimizing volume to accommodate space-constrained scenarios; maximizing transmission efficiency to reduce energy loss and support energy conservation and emission reduction; optimizing dynamic performance to reduce vibration and noise while avoiding resonance zones; and optimizing cost to cover the entire lifecycle. These objectives often require coordinated handling through specific methods to seek compromise solutions. Simultaneously, optimization must be conducted under strict constraints, such as strength and stiffness constraints to ensure component safety, geometric constraints to guarantee manufacturability, kinematic and dynamic constraints to ensure proper meshing and motion, thermal constraints to prevent lubrication failure, and manufacturing process constraints to ensure the solution can be realized with existing technologies [1]. Clearly quantifying objectives and constraints forms the foundation for efficient and reliable optimization design.

2. Speed Reducer Structural Optimization Design Strategy

2.1 Topology Optimization

Topology optimization represents the highest level of structural optimization methodology, addressing the fundamental question: "Where should material be placed?" Under given design spaces, loading conditions, boundary constraints, and design limitations, topology optimization algorithms iteratively compute to automatically identify the optimal material distribution scheme, aiming to achieve specific objectives (such as minimizing compliance—equivalent to maximizing stiffness—or maximizing frequency). For complex load-bearing structures like reducer housings, topology optimization is particularly effective. It removes redundant material that contributes negligibly to load-bearing capacity, generating lightweight configurations with bionic characteristics and the clearest load-transfer paths. Common topology optimization methods include the Homogenization Method, the Solid Isotropic Material with Penalization (SIMP) method, and the Level Set Method. Among these, the SIMP method is widely adopted due to its conceptual clarity and ease of implementation [2]. However, topology optimization results often exhibit gray areas (intermediate-density elements between solid and void) and complex geometric forms, making them difficult to use directly in manufacturing. Consequently, post-processing is typically required, involving result interpretation (converting grayscale images into clear binary images), geometric reconstruction (fitting smooth solid models using CAD software), and redesign that accounts for manufacturing constraints.

2.2 Size Optimization

Dimensional optimization is conducted after the structural topology and basic shape have been determined, involving adjustments to specific dimensional parameters of various components (such as the modulus, tooth width, and pressure angle of gears; the diameter and length of shafts; the wall thickness of housings, and the thickness and height of ribs) to further enhance performance. This is a relatively mature field of optimization, where design variables are typically continuous or discrete scalars. Dimensional optimization problems can generally be formulated as nonlinear programming problems and solved using gradient-based algorithms (such as Sequential Quadratic Programming, SQP) or gradient-free algorithms (such as Genetic Algorithms, GA, or Particle Swarm Optimization, PSO). Due to the relatively clear relationship between design variables and performance indicators, dimensional optimization offers high computational efficiency and is one of the most widely used optimization methods in engineering practice.

2.3 Shape Optimization

Shape optimization lies between topology optimization and size optimization, focusing on the fine-tuning of structural boundary contours. Its goal is to improve local stress concentration, enhance fatigue life, or optimize fluid dynamic performance by adjusting the positions of boundary nodes. For example, optimizing the transition curve at the root of a gear tooth can significantly reduce bending stress at the tooth root, while optimizing the contour around a bearing seat hole in a housing can improve stress distribution. The design variables in shape optimization are typically the coordinates of boundary nodes, which are numerous. During the optimization process, mesh quality must be maintained to prevent distortion [3]. Therefore, parametric boundary description methods (such as B-spline curves) are often used to reduce the number of design variables, combined with mesh adaptation or mesh mapping techniques to ensure computational stability.

2.4 Parametric Modeling and Multidisciplinary Design Optimization (MDO)

Modern gearbox design is a complex process involving multiple disciplines such as structural mechanics, rotor dynamics, thermodynamics, fluid mechanics, and control theory. To achieve global optimization, it is essential to break down disciplinary barriers and adopt a Multidisciplinary Design Optimization (MDO) framework. The core of MDO lies in establishing an integrated parametric digital model capable of automatically coordinating data transfer between various disciplinary analysis tools (e.g., Finite Element Analysis FEA, Multibody Dynamics MBD, Computational Fluid Dynamics CFD). Through parametric modeling, designers can define a set of master parameters (such as center distance, total transmission ratio, input power, etc.), and the system will automatically update all associated geometric and simulation models. On this basis, MDO algorithms (e.g., Collaborative Optimization CO, Multidisciplinary Feasible MDF) can efficiently explore the design space to identify optimal solutions that simultaneously meet multidisciplinary performance requirements. This strategy significantly enhances the systematic and forward-looking nature of design, representing an inevitable trend in the development of high-end gearboxes.

3. Strength Verification Methods for Key Components of Reducers

3.1 Gear Strength Check

3.1.1 Tooth Contact Strength Verification

When gears mesh, the tooth contact area experiences extremely high Hertzian contact stress. Under cyclic loading, the tooth surface material may undergo fatigue failures such as pitting and spalling. Internationally, standards like ISO 6336 or AGMA 2101-D04 are commonly used for verification. The core principle involves calculating the maximum contact stress σH generated during the meshing process and comparing it with the material's contact fatigue limit σHlim. After applying various correction factors (such as life factor, lubrication factor, speed factor, roughness factor, etc.), it is ensured that the safety factor $S_H \geqslant 1$.

$$\sigma_H = Z_H Z_E Z_\epsilon \sqrt{\frac{F_t}{d_1 b} \bullet \frac{u+1}{u}} < \frac{\sigma_{Hlim}}{S_H}$$

Here, Z_H is the regional coefficient, Z_E is the elasticity coefficient, Z_ϵ is the coincidence coefficient, F_t is the tangential force, d_1 is the pitch diameter of the pinion, b is the face width, and u is the gear ratio.

3.1.2 Tooth Root Bending Strength Verification

When transmitting torque, the gear teeth roots are subjected to the maximum bending stress, making them prone to fatigue cracks. The verification also follows the aforementioned standards, calculating the maximum bending stress σF at the tooth root and comparing it with the material's bending fatigue limit σFlim.

$$\sigma_F = \frac{F_t}{bm_n} Y_F Y_S Y_\epsilon Y_\beta \leq \frac{\sigma_{Flim}}{S_F}$$

Among these, m_n is the normal module, Y_F is the tooth form factor when the load acts on the tooth tip, Y_S is the stress correction factor, Y_ϵ is the contact ratio factor, and Y_β is the helix angle factor. In addition to standard methods, for non-standard tooth profiles or special working conditions, the finite element method (FEM) is often used for precise stress analysis, particularly for detailed evaluation of stress concentration in the tooth root transition curve area [4].

3.2 Shafting Strength and Stiffness Verification

3.2.1 Static Strength Check

Based on the bending moment M and torque T acting on the shaft, calculate the equivalent bending moment Me according to the fourth strength theory (maximum distortion energy theory), and verify whether the stress at the critical section is within the allowable range.

$$M_e = \sqrt{M^2 + (\alpha T)^2}$$

Among them, α is the conversion coefficient determined based on the torque characteristics (pulsating, symmetrical cyclic).

3.2.2 Fatigue Strength Verification

The shaft is subjected to alternating bending stress during rotation. Its fatigue strength verification must consider factors such as stress concentration, size effect, and surface condition. A common method involves plotting the limiting stress diagram of the component and comparing it with the working stress point to calculate the safety factor.

3.2.3 Stiffness Check

Excessive shaft deformation can lead to poor gear meshing, accelerating wear and increasing noise. Therefore, it is essential to check the shaft's deflection (y) and torsion angle (φ) under load to ensure they remain below the allowable values [y] and [φ]. This is typically calculated using the superposition method from material mechanics or the finite element method.

3.2.4 Critical Speed Verification

To avoid resonance, the operating speed of the shafting should be kept away from its first-order, second-order, and other critical speeds. Critical speeds can be accurately determined using Rayleigh's method, Dunkerley's formula, or rotor dynamics simulation.

3.3 Box Strength and Stiffness Verification

3.3.1 Static Strength Check

The housing primarily bears the reactive forces from the bearings. By establishing a finite element model of the housing and applying the bearing forces as boundary loads, the stress distribution across the entire housing can be obtained. Key attention should be paid to high-stress areas such as the bearing seats, anchor bolt holes, and the mating surfaces between the housing cover and base. It is essential to ensure that the maximum stress in these regions remains below the material's yield strength while maintaining an adequate safety margin.

3.3.2 Stiffness Check

Insufficient stiffness of the housing can cause relative displacement in the bearing bores, disrupting the proper meshing of gears. Therefore, it is necessary to verify the relative displacement of the bearing bores (including radial displacement and angular deflection) under load to ensure it remains within the permissible installation error range of the gear pair. This is also accomplished through finite element analysis.

3.3.3 Modal Analysis

Perform modal analysis on the housing to obtain its first few natural frequencies and mode shapes. The objective is to ensure these natural frequencies are sufficiently separated from the primary excitation frequencies of the reducer (such as gear meshing frequency and its harmonics), thereby avoiding resonance.

3.4 Bolt Connection and Bearing Verification

3.4.1 Bolt Connection Verification

The bolt connections at the box cover and base, bearing end covers, and other locations must be checked to ensure that the preload is sufficient to withstand working loads, preventing separation or slippage of the joint surfaces. Additionally, the strength of the bolts themselves under combined tensile and shear loads should be verified.

3.4.2 Bearing Life Verification

Based on the radial force Fr and axial force Fa acting on the bearing, calculate the equivalent dynamic load P. Then, determine the basic rating life L10 using the Lundberg-Palmgren theory or ISO 281 standard, ensuring it exceeds the design life requirement.

Conclusion

This paper systematically constructs a theoretical framework for the structural optimization design and strength verification of reducers, emphasizing that their high-performance design relies on a multidimensional, integrated methodological system. This system is guided by multi-objective optimization, incorporates multi-level optimization strategies, and uses multidimensional strength verification as the safety foundation. Looking ahead, the field of reducer design will exhibit three major trends: deep empowerment by artificial intelligence, where machine learning and deep learning will build high-precision surrogate models to accelerate the optimization process and uncover failure modes to inform design; design freedom driven by additive manufacturing, as the maturity of 3D printing technology enables the direct fabrication of complex structures from topology optimization, giving rise to a new generation of reducer configurations; and digital twins spanning the entire lifecycle, where high-fidelity model-based digital twins can real-time map the state of physical reducers, achieving closed-loop optimization and health management across the entire chain. Reducers serve as the "joints" of industry, and enhancing their design level is a crucial reflection of a nation's high-end equipment manufacturing capability. It is essential to continuously promote the integrated innovation of design, analysis, and manufacturing technologies to develop high-performance, high-reliability reducers.

References

[1] Guan Weijian, Liao Jianqiang, Liu Hua, et al. Design Analysis of Die-Casting Mold for Automotive Reducer Housing[J]. Foundry Equipment & Process, 2025, (05): 9-13.

[2]Zhong Quanneng. Structural Optimization Design and Analysis of New Energy Vehicle Reducer[J]. Agricultural Machinery Use & Maintenance, 2024, (06): 36-38.

[3] Zhao Binghao. Lightweight Design and Fatigue Life Analysis of Automotive Wheel Reducer Housing[D]. Henan University of Science and Technology, 2023. DOI:10.27704/d.cnki.ghnkj.2023.000068.

[4] Li Jian, Wang Xiaomei, Shen Yichen. Design and Finite Element Analysis of Reducer for Electric Vehicles[J]. Auto & Driving Maintenance (Maintenance Edition), 2021, (05):70-71.