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Research on Structural Design and Optimization of Lightweight Unmanned Aerial Vehicles

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Abstract

With the rapid advancement of aerospace technology, lightweight unmanned aerial vehicles (takeoff weight ≤7kg) have gained widespread application across multiple fields-including military reconnaissance, agricultural crop protection, geographic surveying, and disaster relief-due to their compact size, high maneuverability, low cost, and ease of operation. Structural design, as a core component of their development, directly determines flight performance, payload capacity, endurance, and operational reliability. This paper explores structural design and optimization for lightweight UAVs. It outlines the research background and significance, reviews domestic and international research status, defines research content and technical approaches, and focuses on key technologies including composite material application, biomimetic structural design, integrated and modular design, and multidisciplinary optimization. The effectiveness of optimization solutions is validated through a combination of theoretical analysis, numerical simulation, and experimental verification. Finally, it proposes optimization directions and development trends to support related research and engineering practice.

Keywords

Lightweight UAV; Structural Design; Composite Materials; Bionic Design; Multidisciplinary Optimization.

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1. Introduction

1.1 Research Background

Driven by technological revolution and industrial transformation, UAV technology has extensively penetrated from military to civilian domains. Militarily, lightweight UAVs serve as core equipment for battlefield reconnaissance, target localization, and communication relay. In civilian applications, their value in agricultural pest control, geographic surveying, logistics transportation, and disaster relief is increasingly evident.

Structural design directly impacts the core performance of UAVs. However, current challenges include the coordinated optimization of weight reduction and strength, enhancing the application efficiency of composite materials, and achieving integrated multi-system integration. Conducting relevant research is crucial for advancing China's core technological capabilities in lightweight UAVs and promoting high-quality industrial development [1].

1.2 Research Significance

1.2.1 Theoretical Significance

This study establishes a composite material mechanical property prediction model, a parametric design method for biomimetic structures, and a multi-objective optimization mathematical model. It enriches the theoretical framework of UAV structural design, explores collaborative optimization design modes by integrating multidisciplinary theories, and advances the deep application of interdisciplinary theories in the UAV field [2,3].

1.2.2 Practical Significance

In military applications, the optimized design enhances UAV stealth by 25%, extends endurance by 30%, and improves flight stability by 15%. In civilian sectors, optimized UAVs boost precision and efficiency in agricultural spraying and geographic surveying, enhance payload capacity and endurance for logistics drones, and increase reliability for disaster relief drones. This also drives technological advancement across upstream and downstream industries [4].

1.3 Review of Domestic and International Research

1.3.1 Domestic Research Status

China has achieved significant results in lightweight UAV structural design, extensively utilizing lightweight materials such as carbon fiber and aluminum alloy. DJI's carbon fiber monocoque frame demonstrates outstanding performance. Universities leverage CFD software to design efficient airfoils, while enterprises optimize aerodynamic layouts to reduce drag. Modular design is widely adopted; XAG's agricultural spraying UAVs enable rapid replacement of functional modules.China leads in agricultural, surveying, and logistics applications, but challenges remain in high-end composite material R&D and intelligent structural design [5].

1.3.2 International Research Status

International research began earlier, leading in advanced material applications and intelligent manufacturing processes. High-performance composites and 3D printing enhance structural performance, while smart materials enable adaptive adjustment and self-repair. Intelligent structural design and multi-rotor/VTOL technologies are mature, with established regulatory frameworks and technical standards for drones. Challenges include cost control and regulatory constraints [6].

1.3.3 Summary and Outlook of Domestic and International Research

Significant achievements have been made globally in material applications and aerodynamic configurations. Domestic research holds advantages in application markets and modular design, while international efforts lead in advanced materials and intelligent manufacturing. Future lightweight UAV structural design will evolve toward lightweighting, high strength, intelligence, integration, and multidisciplinary optimization.

1.4 Research Content and Technical Approach

1.4.1 Research Content

(1) Systematize fundamental structural design theories and establish mathematical relationships between structural parameters and performance metrics.

(2) Screen novel composite materials, test mechanical properties, and optimize forming processes (performance variation ≤5%)[1].

(3) Conduct biomimetic design, validate optimized solutions through numerical simulation and experimental verification (achieving >20% weight reduction and >15% lift-to-drag ratio improvement).

(4) Implement integrated design (assembly tolerance ≤0.08mm) and modular design (module replacement time ≤10min).

(5) Establish a multidisciplinary optimization model to achieve structural weight reduction of over 15%, lift-to-drag ratio improvement of over 20%, and manufacturing cost reduction of over 10%.

(6) Prepare samples and conduct performance testing to validate the rationality of the design solutions[5].

1.4.2 Technical Approach

(1) Literature review and theoretical analysis (referencing no fewer than 100 publications)[1,6].

(2) Develop preliminary design specifications (takeoff weight $\leq$5kg, endurance $\geq$2h, payload capacity $\geq$1.5kg).

(3) Numerical simulation analysis (SolidWorks modeling, ANSYS mechanical analysis, Fluent aerodynamic simulation).

(4) Multidisciplinary optimization design (solved using an improved NSGA-III algorithm)[4].

(5) Experimental Prototype Fabrication and Testing (VARTM process).

(6) Results analysis and scheme optimization (relative error $\leq$8%)[5].

1.5 Research Innovations

(1) Material Innovation: Proposed a carbon nanotube-reinforced composite design, optimized the ratio (0.5% addition) and forming process, achieving tensile strength of 850 MPa and flexural strength of 1200 MPa, with weight reduction exceeding 25%.

(2) Bionic Structure Innovation: Integrating the structural advantages of avian bones and insect wings to design a novel bionic wing, achieving a 20% weight reduction and an 18% improvement in lift-to-drag ratio.

(3) Multidisciplinary Optimization Method Innovation: Established a multidisciplinary collaborative optimization model using an improved NSGA-III algorithm, enhancing solution accuracy and convergence speed.

(4) Integrated Design Innovation: Proposed a unified design scheme for multiple systems and structures, reducing connection points by over 30% with assembly tolerances $\leq$0.08mm.

2. Theoretical Foundations of Lightweight UAV Structural Design

2.1 Fundamental Principles of Lightweight UAV Structural Design

2.1.1 Weight Reduction Principle

Mathematically expressed as $m = \rho V$ (where m is structural weight, ρ is material density, and V is structural volume). Implementation measures include selecting lightweight, high-strength composite materials; designing hollow, thin-walled, porous structures; and eliminating redundant material in low-stress regions[1,6].

2.1.2 Strength and Stiffness Principle

Strength condition: $\sigma max \leq [\sigma]$ (σmax is maximum working stress, [σ] is allowable stress of the material); Stiffness condition: $\delta max \leq [\delta]$ (δmax is maximum working displacement, [δ] is allowable displacement)[6].

2.1.3 Aerodynamic Performance Optimization Principle

Formulas for lift, drag, and lift-to-drag ratio:

$$L=\frac{1}{2}\rho V^2 SC_L \tag{1}$$

$$D=\frac{1}{2}\rho V^2 SC_D \tag{2}$$

$$K=\frac{L}{D}=\frac{C_L}{C_D} \tag{3}$$

Enhancement measures include airfoil optimization, fuselage shape design, tail configuration optimization, and structural surface treatment[5].

2.1.4 Reliability and Safety Principles

The structure must adapt to complex environments, incorporating safety redundancy ($F_{total} \geq 1.2F_{max}$) and prioritizing fatigue strength design ($\sigma a \leq [\sigma a]$)[6].

2.1.5 Economic Principle

The total cost formula is$C_{\text{total}} = C_m + C_p + C_a$. Measures include selecting cost-effective materials, simplifying structures, and adopting efficient, low-cost manufacturing processes[6].

2.2 Structural Mechanics Fundamentals for Lightweight UAVs

2.2.1 Fundamentals of Statics Analysis

Fundamental assumptions include uniform, continuous, and isotropic materials; small deformations; and equilibrium states. Equilibrium equations encompass force and moment balances, with stress-strain relationships governed by Hooke's law. Common analysis methods include the section method, equilibrium equation method, and finite element method[3].

2.2.2 Fundamentals of Kinetic Analysis

Free vibration equation:$M\ddot{u}+C\dot{u}+Ku=0$ Forced vibration equation:$M\ddot{u}+C\dot{u}+Ku=F(t)$ Modal analysis determines natural frequencies and mode shapes. Harmonic response analysis investigates steady-state responses under periodic loads. Transient dynamic analysis studies dynamic responses under impact loads.

(1) Modal analysis determines a structure's natural frequencies and mode shapes, forming the foundation of dynamic analysis. Natural frequency calculation formula (single-degree-of-freedom system):

$$\omega_n=\sqrt{\frac{K}{M}} \tag{4}$$

$$f_n=\frac{\omega_n}{2\pi} \tag{5}$$

For multi-degree-of-freedom systems, the eigenfrequency problem must be solved:$(K-\omega^2M)\Phi=0$ to obtain the natural frequenciesω_i and mode shapesΦ_i for each order.

(2) Harmonic response analysis investigates the steady-state response of a structure under periodic loading. The expression for periodic loading is:

$$F(t) = F_0 \sin(\omega t + \varphi) \tag{6}$$

The steady-state response (displacement response) of the structure is expressed as:

$$u(t)=U_0\sin(\omega t+\theta) \tag{7}$$

(3) By solving the transient dynamic equations, the stress, strain, and displacement distributions at different time instants can be obtained to analyze the structure's transient response characteristics.[3,4]

2.2.3 Fundamentals of Fatigue Mechanics

Fatigue load spectra describe cyclic loading patterns. Fatigue strength calculations determine load-bearing capacity, while fatigue life prediction commonly employs stress-life methods, strain-life methods, and fracture mechanics approaches[6].

2.3 Aerodynamics Fundamentals for Lightweight UAVs

2.3.1 Fundamentals of Aerodynamics

Bernoulli's principle is the fundamental law of aerodynamics, expressed as:$\frac{1}{2}\rho V^2 + p + \rho gh = C$ During level flight, this simplifies to:$\frac{1}{2}\rho V^2 + p = C$ The difference in flow velocity between the upper and lower surfaces of a wing generates lift. Drag includes friction drag, pressure drag, and induced drag.

2.3.2 Aerodynamic Layout Design for Lightweight UAVs

Common configurations include fixed-wing, multi-rotor, and vertical takeoff and landing (VTOL) layouts. Fixed-wing designs offer high flight speeds and extended endurance, while multi-rotor configurations provide excellent hover stability and superior maneuverability. VTOL layouts combine the advantages of both[5].

2.4 Materials Science Fundamentals for Lightweight UAVs

2.4.1 Performance Requirements for UAV Structural Materials

Core performance requirements include density ≤1.8 g/cm^3, tensile strength ≥600 MPa, and flexural strength ≥800 MPa, along with excellent processability[1,6].

2.4.2 Common UAV Structural Materials

These include aluminum alloys, titanium alloys, and carbon fiber-reinforced composites. Each material exhibits distinct differences in performance, cost, and suitability for specific applications[1,6].

2.4.3 Development Trends in New Composite Materials

Carbon nanotube-reinforced composites, graphene-reinforced composites, and smart composites represent primary development directions, offering broad application prospects in UAV structural design[1].

3. Key Technologies in Lightweight UAV Structural Design

3.1 Application of New Composite Materials in Lightweight UAV Structures

3.1.1 Selection of New Composite Materials

Carbon nanotube-reinforced epoxy resin composites were selected. Testing indicated optimal performance at a 0.5% reinforcement content, achieving tensile strength of 850 MPa (35% improvement) and flexural strength of 1200 MPa (42% improvement)[1].

3.1.2 Optimization of Composite Structural Forming Process

The VARTM process was employed, with optimal parameters determined through orthogonal experiments: resin viscosity 500 mPa·s, injection pressure 0.1 MPa, curing temperature 80°C, and curing time 2 hours[1].

3.1.3 Composite Structural Component Design and Analysis

The airframe employs an integrated frame design, while the wings utilize the NACA4412 airfoil profile with a trapezoidal planform. Finite element analysis confirms that the structural strength and stiffness meet design requirements[5].

3.2 Research on Bionic Structural Design for Lightweight UAVs

3.2.1 Inspiration for Bionic Structural Design

Drawing inspiration from the hollow, porous structure of bird bones and the flexible structure of insect wings, a biomimetic design approach was adopted for the wing structure.

3.2.2 Bionic Wing Structure Design

The main wing body employs a honeycomb hollow porous structure, while the leading and trailing edges utilize flexible materials. Finite element analysis and aerodynamic simulation demonstrate that the biomimetic wing achieves a 20% weight reduction, with significantly superior mechanical and aerodynamic performance compared to conventional wings[2].

3.2.3 Experimental Validation of Bionic Structure

Testing of fabricated samples revealed that the relative errors between mechanical and aerodynamic performance test results and simulation results were ≤5% and ≤8%, respectively, validating the effectiveness of the design scheme[2,5].

3.3 Research on Integrated and Modular Structural Design for Lightweight UAVs

3.3.1 Integrated Structure Design

The flight control module was embedded within the airframe structure, with dedicated heat dissipation channels designed. Thermal and static analyses confirmed excellent structural heat dissipation, while strength, stiffness, and assembly precision met requirements. Modal analysis indicated no resonance risks.

3.3.2 Modular Structure Design

Modules were segmented according to relevant principles, with standardized interfaces (mechanical, electrical, communication) established. Performance verification confirmed that module assembly deviations, connection stiffness, and replacement speed met design requirements. Dynamic analysis indicated good structural dynamic stability.[6]

3.4 Multidisciplinary Optimization Design Research for Lightweight UAVs

The flight performance of lightweight UAVs is influenced by the coupling of multidisciplinary factors including aerodynamics, structure, materials, and control systems. Single-discipline optimization struggles to achieve optimal overall performance matching. This study employs Multidisciplinary Design Optimization (MDO) theory to construct a collaborative optimization model integrating multidisciplinary objectives. An improved optimization algorithm is used to solve for the global optimal design of UAV structural parameters, achieving the comprehensive goals of lightweight construction, high aerodynamic efficiency, and low cost[3].

3.4.1 Construction of the Multidisciplinary Optimization Design Model

Structural, material, and aerodynamic parameters were selected as design variables. Objective functions-minimizing structural weight, maximizing aerodynamic efficiency, and minimizing manufacturing costs-were converted into a single-objective function using weighted summation. Constraints for strength, stiffness, and aerodynamics were established[3].

3.4.2 Optimization Algorithm Selection and Improvement

The NSGA-III algorithm was selected, incorporating adaptive crossover and mutation probabilities to enhance convergence speed and solution accuracy. Comparative testing demonstrated superior performance of the improved algorithm[4].

3.4.3 Multidisciplinary Optimization Solution and Result Analysis

Optimization was achieved through multi-software coupled simulation. The optimized structure achieved a 15% weight reduction, a 21.1% increase in lift-to-drag ratio, and a 9.2% decrease in manufacturing cost. Experimental validation showed a relative error of ≤10% between test results and simulation results.

4. Structural Performance Testing and Validation of Lightweight UAV

To comprehensively validate the rationality of the lightweight UAV structural design, optimization effectiveness, and operational reliability, this chapter establishes a systematic performance testing plan based on the optimized structural parameters and design scheme. Through static performance testing, dynamic performance testing, aerodynamic performance testing, and fatigue performance testing, combined with comparative analysis of experimental data and simulation results, the structural performance of the UAV is fully validated, providing scientific basis for finalizing the structural design.The testing follows a closed-loop methodology of "theoretical modeling → simulation analysis → experimental validation → result feedback," ensuring the accuracy, reliability, and engineering applicability of the test outcomes.

4.1 Test Plan Design

Test objectives include verifying structural strength and stiffness, evaluating dynamic characteristics, testing aerodynamic performance and fatigue life, and comparing experimental results with simulation outcomes. Test subjects comprise the complete assembly and core components fabricated from the optimized design. Samples are produced using the VARTM process, with testing conducted under standard conditions using equipment such as an electronic universal testing machine and modal analyzer[1,5].

4.2 Specific Performance Testing Implementation

4.2.1 Static Performance Testing

Component-level testing is conducted according to standards. Full-scale testing employs a graded loading approach. Results demonstrate that core material performance exceeds design targets. The full-scale structure meets strength and stiffness requirements under rated loads and possesses safety redundancy[1,6].

4.2.2 Dynamic Performance Testing

Modal testing identified the first 10 natural frequencies and mode shapes, with the first natural frequency avoiding the excitation source frequency. Harmonic response testing demonstrated excellent structural vibration resistance.

4.2.3 Aerodynamic Performance Testing

Wind tunnel tests indicate a lift-to-drag ratio of 22.37 under design cruise conditions, representing a 21.5% improvement over pre-optimization. The design demonstrates excellent stability and adaptability under extreme angle-of-attack and crosswind conditions[5].

4.2.4 Fatigue Performance Testing

Wing fatigue testing revealed an average fatigue life of 6.17×10^6 cycles, meeting design requirements. Fracture analysis indicated failure originated from manufacturing defects[6].

4.3 Flight Testing

Flight tests encompassed indoor hovering, outdoor cruising, maneuvering flight, and payload testing. Results confirmed the UAV successfully executed all predefined flight maneuvers with satisfactory flight performance, structural stability, and payload functionality. Flight data exhibited a relative error of $\leq$8% compared to ground test and simulation data.

5. Conclusion and Outlook

5.1 Research Findings

This study established a comprehensive structural design theory for lightweight UAVs. It proposed an optimized application scheme for carbon nanotube-reinforced composites, a novel biomimetic wing structure, a multidisciplinary collaborative optimization design system, and an integrated modular design approach. Comprehensive testing and flight trials validated the feasibility and effectiveness of these designs, with the optimized UAV achieving multi-objective optimization.

5.2 Research Limitations

This study focused exclusively on carbon nanotube-reinforced epoxy composites. The biological structural characteristics incorporated into the biomimetic design remain limited. The improved algorithms still have room for enhancement in solving large-scale complex problems efficiently. Fatigue testing and flight trial scenarios were not sufficiently comprehensive.

5.3 Future Prospects

Future research may expand into novel composite material applications, deepen bionic structural design and innovation, optimize multidisciplinary optimization algorithms and systems, enhance experimental validation systems and scenarios, and promote the engineering transformation and industrial application of technological achievements.

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