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Analysis of Structural Strength and Fatigue Life of Unmanned Aerial Vehicles (UAVs) based on Finite Element Method

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Abstract

The use of Unmanned Aerial Vehicles (UAVs) has seen a rapid rise in the areas of reconnaissance, surveying and mapping, logistics and agriculture. One important factor influencing the operational safety and service life of the structures is the structural fatigue failure under long-term alternating loads. This paper is dedicated to the wing of a fixed-wing UAV with the goal of improving the structural reliability of UAVs. The three-dimensional (3D) model was established by the finite element analysis method, and the typical flight conditions were set to simulate and calculate the stress distribution and structural response. On basis of this, the S-N curve and Miner's damage accumulation theory were combined to finish the fatigue life prediction, find out the key weak areas and put forward the structural optimization schemes. The results show that the finite element analysis can effectively reveal the stress characteristics of UAV structures and accurately evaluate the fatigue life, providing a reliable technical basis for structural design and in-service safety assessment.

Keywords

Unmanned Aerial Vehicle (UAV); Finite Element Analysis; Fatigue Life.

1. Introduction

1.1 Research Background and Significance

With the rapid development of aerospace, electronic information and control engineering technology, UAV technology has matured more and more, extending from military to civil fields, forming a diversified application pattern. In the military sector, UAVs can perform such tasks as reconnaissance and surveillance, target positioning and communication relay, thus decreasing the casualty of personnel. In the civilian field, they are indispensable in topographic surveying, power inspection, environmental monitoring, agricultural plant protection, logistics and distribution, and emergency rescue. For example, in emergency rescue, they can quickly transmit disaster information; in agricultural plant protection, they can improve operational efficiency thru precise operations.

However, UAVs work in complex load environments and harsh working conditions. The wing is a main structural member and bears many loads such as lift, aerodynamic force, gravity and inertial force. Fatigue damage is expected under long term alternating loads. Fatigue damage has the characteristics of cumulativeness, concealment and suddenness, and it is difficult to detect in the early stage. Once accumulated, it is easy to cause the crack initiation and propagation, and lead to the failure accidents such as wing fracture. Statistics show that more than 30% of UAV flight accidents are due to structural fatigue failure, which is a major factor restricting safe service.

Physical tests where physical prototypes must be manufactured and tested under load are the foundation of traditional structural strength analysis. These tests have disadvantages of long cycle, high cost and poor flexibility, so they are difficult to meet the demand of rapid iterative design. The

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finite element method is an efficient numerical analysis method . It divides the continuous structure into finite elements . And then simulated the mechanical response under complex loads by using computers . The parameters such as stress , strain and displacement can be accurately obtained to identify weak areas . It provides basis for strength evaluation and life prediction, shortens the design cycle, reduces research and development costs, improves design reliability, and has important theoretical and engineering value for the sustainable development of UAV technology.

1.2 Domestic and Foreign Research Status

1.2.1 Foreign Research Status

Foreign countries have early advantages on the UAV technology, and have rich experience on the research of structural strength and fatigue life. Developed countries such as the United States and European countries are leading the integration of finite element analysis and structural design. The United States NASA (National Aeronautics and Space Administration) employs finite element software to perform multi-physics coupling analysis of UAV wing, taking into account of the interaction of aerodynamic loads, temperature fields and structural mechanical responses in an effort to improve the accuracy of life prediction. Airbus Group optimizes the connection between the fuselage and wings in Europe using the finite element method, improves topological forms and material selection, reduces stress concentration and extends fatigue life.

In the theoretical research, foreign scholars have improved and expanded the traditional linear cumulative damage theory of Miner for high cycle fatigue characteristics, and proposed various fatigue damage accumulation models to enhance the prediction accuracy under complex loads. For finite element modeling, the focus is on enhancing mesh quality and creating new simplification methods, employing adaptive meshing and multi-scale modeling for a balance between computational accuracy and efficiency. The application of digital twin technology in structural health management has become a research hotspot, which can achieve the real-time monitoring of fatigue damage and life prediction.

1.2.2 Domestic Research Status

In recent years, China's UAV industry has developed rapidly. Research institutions and enterprises attach great importance to the research of structural strength and fatigue life, achieving remarkable results in the application of finite element methods, innovation of fatigue theories, and structural optimization. Universities such as Northwestern Polytechnical University and Beihang University (Beijing University of Aeronautics and Astronautics) have conducted systematic research on the static and dynamic strength and fatigue life of wings, proposing various UAV structural design criteria. [1] DJI, EHang Intelligent and other enterprises have applied finite element analysis to the research and development, realizing the balance of structural lightness and reliability.

In technical applications, domestic research mainly focuses on strength analysis and life prediction under single load conditions, and there is relatively little research on multi-condition coupling and complex multi-field coupling problems. There is a gap in fatigue damage monitoring and life assessment technologies between China and foreign countries, and the integrated application of new technologies such as digital twins and artificial intelligence is still in the exploratory stage. The fatigue performance database of domestic aviation materials is not complete, which affects the prediction accuracy and reliability.

1.3 Research Content and Technical Route

1.3.1 Research Content

(1) The structural composition and working load characteristics of UAV wings are clarified, the stress state in different flight phases is analyzed, and the key load types and parameters are determined.

(2) Construct a three-dimensional solid model using SolidWorks and perform finite element modeling based on ANSYS Workbench, including setting of boundary conditions and loads, definition of material properties and generation of a mesh.

(3) Carry out the static strength simulation analysis, analyze the strength safety by von Mises stress criterion, find the stress concentration high-risk area.

(4) The software of nCode DesignLife is used to predict the fatigue life based on S-N curves and Miner's linear cumulative damage theory, and the effect of different working conditions on the service life is analyzed.

(5) Propose optimization schemes for weak areas with high stress and fatigue tendency, and verify its effect by simulation to improve fatigue life.

1.3.2 Technical Route

It follows the route of "theoretical foundation → modeling and simulation → analysis and evaluation → optimization and verification" process, and is as follows:

(1) To establish the theoretical basis, the principle of finite element method, strength analysis theory and life prediction method should be clarified.

(2) Create a 3D model in SolidWorks based on wing design parameters Simplify the geometry Clean the geometry

(3) The model is imported into ANSYS Workbench, the properties of aviation aluminum alloy 7075-T6 are set, a tetrahedral element mesh is generated, and convergence analysis is carried out.

(4) The boundary conditions and load parameters of three typical working conditions (take-off, cruise and turn) are set, and the static strength simulation is carried out.

(5) Extract stress data and calculate fatigue life using nCode DesignLife software and Miner's theory with S-N curve of the material.

(6) Suggest measures to incorporate longitudinal stiffeners and optimize the chamfer radius of connecting holes for short service-life weak areas.

(7) Simulation is used to verify the strength and life of the optimized model, and the influence of schemes on the mechanical properties and service life is analyzed.

2. Theoretical basis and research method

2.1 Basic Principles of the Finite Element Method

The variational principle is the basis of the finite element method. The essence of it is to divide a continuous elastic body into finite interconnected elements and then solve the mechanical equations of the elements to obtain the mechanical response of the whole structure. The process includes structural discretization, element stiffness matrix construction, global stiffness matrix assembly, boundary condition processing and load application, equation solving, and result post-processing .

2.1.1 Structural Discretization

Complex structures are divided into simple elements (e.g., tetrahedrons, hexahedrons), which are connected via nodes to form a discrete model. The selection of appropriate element types and mesh density can balance accuracy and efficiency. In this study, the wing is modeled using tetrahedral elements to adapt to complex geometric shapes and to ensure modeling accuracy.

2.1.2 Assembly of Element Stiffness Matrix

The element stiffness matrix is obtained from the material constitutive relations, geometric equations and equilibrium equations, which is the relationship between node displacement and node force. The expression is $[k]^e\{u\}^e = \{F\}^e$ where $[k]^e$ is the element stiffness matrix, $\{u\}^e$ is the node displacement vector and $\{F\}^e$ is the node force vector. The calculation results are directly influenced by the matrix accuracy.

2.1.3 Assembly of Global Stiffness Matrix

All element stiffness matrices are assembled into a global matrix according to the rules to form the global equilibrium equation $[K]\{u\}=\{F\}$ where $[K]$ is the global stiffness matrix, $\{u\}$ is the global

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node displacement vector, and {F} is the global node load vector. The matrix is symmetric, sparse and singular, for which efficient numerical methods are required to solve. [2]

2.1.4 Processing of the Boundary Conditions and Solving the Equations

Since the global stiffness matrix is singular and boundary conditions are necessary to prevent rigid body motion. The wing root is fixed to prevent all degrees of freedom and the wing tip is free in this study to simulate real stress. The equation is solved by Gaussian elimination or iteration to obtain node displacement vector and stress and strain are calculated by geometric and constitutive equations after processing.

2.2 Theory of Structural Strength Analysis

Structural strength is ability to resist damage under loads. Wing strength analysis includes static and dynamic strength. This study is on static strength analysis for mechanical properties and reliability assessment under static load.

Static strength analysis is concerned with stress, strain and displacement calculation under static loads and the verification of whether the strength requirements are satisfied. The most common criteria are the maximum tensile stress, the maximum shear stress and the von Mises stress criteria. [3] The von Mises criterion is valid for plastic materials, allows for the full consideration of the complex stress state and is widely used in aerospace structures. The formula is as follows:

$$\sigma_v = \sqrt{\frac{1}{2}[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2]}$$

where σ_1, σ_2 and σ_3 are principal stresses. If σ_v is less than the yield strength, the structure is considered to be safe in the elastic range, otherwise plastic deformation and failure are likely to occur.

2.3 Prediction Methods for Fatigue Life

Fatigue is the process of performance degradation and failure of materials or structures under cyclic loading due to damage accumulation. According to the number of cycles it is divided into high-cycle fatigue ($N > 10^5$ cycles) and low-cycle fatigue. The service life cycles of wings are mostly high cycle fatigue, and the prediction is done by S-N curve method and Miner's linear cumulative damage theory.

2.3.1 S–N Curve Approach

The S-N curve describes the relationship between the stress amplitude and the fatigue life, where the horizontal axis is the service life N, and the vertical axis is the stress amplitude S. [2]It is the foundation for life prediction. The metal material curve is divided into high, medium and low stress regions; the high-cycle fatigue range can be expressed by the power function $S^m N = C$, where m is the fatigue exponent and C is the material constant, obtained by fatigue tests. This paper uses data of S-N curve of aviation aluminum alloy 7075-T6.

2.3.2 Miner's Linear Cumulative Damage Theory

Actual structures are often subjected to multi-level alternating loads, and Miner's theory is used for life prediction. It is assumed that each load level causes a linear cumulative damage and failure occurs when the accumulation reaches 1. [4] The formula is as follows:

$$D = \sum_i^n \frac{n_i}{N_i}$$

where D is the cumulative damage degree, ni is the actual number of cycles of the i th level load and Ni is the corresponding fatigue life. This theory is simple and easy to use. In this study, this theory is combined with three working conditions to calculate cumulative damage and predict life.

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3. Finite Element Modeling and Simulation Analysis

3.1 Object and Structural Parameters of the Study

A wing of a fixed wing UAV with 3.2 m wingspan, 2.8 m2 wing area, 120 kg fuselage weight and 200 kg maximum takeoff weight is selected. It is a single-spar structure, which is composed of main spar, skin, wing ribs and connecting components.[4] Main spar is the main load-bearing component, which is made of aviation aluminum alloy 7075-T6 with high strength, corrosion resistance and processability. Its mechanical parameters are: elastic modulus E=71.7GPa, Poisson's ratio \nu=0.33, yield strength \sigma_y=505MPa and tensile strength \sigma_b=572MPa.[5-6]

3.2 Building 3D Models

The 3D solid model is created in SolidWorks following the principle of "accurate modeling and reasonable simplification". [7] Important features are maintained and unnecessary details like small chamfers and threaded holes are simplified for more efficient analysis. The steps are: to determine the geometric dimensions and relative positional relationships of components, then to build individual component models with commands like sketching and extrusion, assemble the complete model thru assembly constraints, and finally to perform geometric cleaning to remove interference and redundancy.

3.3 Establishment of Finite Element Model

The 3D model is exported as STEP file and imported to ANSYS Workbench for finite element modeling.

3.3.1 Definition of Material Properties

And create a new material in the Engineering Data module. Input the mechanical parameters of aviation aluminum alloy 7075-T6 to complete the property definition.

3.3.2. Generation of Mesh

Mesh quality affects calculation error and reliability. The meshing is performed with tetrahedral elements and refined in high stress regions. First, convergence analysis is carried out, and simulations are done with element sizes of 1–5 mm, and the maximum stress variation is $< 3\%$ when the element size is < 3 mm. The element size is selected as 3 mm to compromise between accuracy and efficiency. The model after meshing has 300 000 elements and 450 000 nodes. The quality of mesh is good.

3.3.3 Setting of Boundary Condition and Load

The wing root is fixed and all degrees of freedom are restrained. The wing tip is free. The conditions of the flight give rise to three representative working conditions:

(1) Takeoff phase: Lift increases to 1.2 times the UAV weight, F=1.2 X 200 X 9.8 = 2352 N, uniformly distributed over the upper surface of the wing.

(2) Cruise phase: Lift equals the UAV weight, $F = 200 \times 9.8 = 1960$ N; the aerodynamic force is simplified as a uniform distributed load on the surface.

(3) Turn phase: lateral inertial load F = 1.5 \times 200 \times 9.8 = 2940 N, superimposed on a lift of 1960 N.

3.4 Results of the Static Strength Simulation Analysis

The simulation is performed with the module Static Structural and the distribution of stresses are analyzed according to the von Mises criterion:

(1) Takeoff phase: The maximum stress is at the connection of wing root and main spar with 348 MPa. Stress decreases from root to tip, tip stress < 50 MPa which is less than yield strength, meets strength requirements. The stress concentration of the root-connection area is significant. [8]

(2) Cruise phase: The maximum stress is 286 MPa, at the root. The load is steady, the stress distribution is even: the stress at the connection of the middle section of the main spar and the wing

ribs is 150-200 MPa, the stress in the skin is < 100 MPa. The overall structure is low stressed and safe.

(3) Turn phase: The maximum stress is 362 MPa (the maximum among the three working conditions), which is located near the connecting holes at the wing root. The stress concentration is severe, reaching 72% of the yield strength. The stress at the central section of the upper surface of the main spar is 250-300 MPa, which is a potential weak area.

To summarize, the maximum static stress of the wing is 362 MPa, which is less than the yield strength, and static strength requirements are satisfied. However there is high stress concentration at the root, connecting holes and the middle section of the main spar which are high risk areas for fatigue. Further fatigue life analysis is needed.

4. Fatigue Life Analysis & Structural Optimization

4.1 Setting of Fatigue Life Calculation Parameters

The nCode DesignLife software is used to predict fatigue life based on static strength results. The main parameters are:

(1) Material fatigue performance: S-N curve of aviation aluminum alloy 7075-T6, $S^{5.8} N=1.2\times 10^{28}$ for stress ratio R=0.1.

(2) Average load: 200 MPa.

(3) Stress ratio R=0.1 (tension-tension fatigue).

(4) Load cycle count: A flight takes 1 hour and consists of 10 takeoff and turn cycles and 100 cruise cycles. The designed service life is 5 years for 200 flights per year. The number of cycles is distributed according to the operating conditions.

4.2 Analysis of Simulation Results on Fatigue Life

According to the calculations based on Miner's theory, we have:

(1) Distribution of fatigue damage: The damage percentage of takeoff, turn and cruise phases are 35%, 45% and 20% respectively. The stress on the turn is high and contributes much to damage. The load on takeoff changes sharply. [9]

(2) Fatigue life distribution: The service life at the wing root near the connecting holes is the shortest (2.3×10^5 cycles), lower than the design requirement of 10^6 cycles; the service life of the middle section of the main spar is 5.8×10^6 cycles; the service life of the skin and wing ribs is more than 10^7 cycles . The short-life areas coincide with the high-stress areas, which confirms the reliability of the static strength results.

(3) Failure risk: The failure risk of insufficient service life in the vicinity of the connecting holes at the root has to be optimized, while the other areas comply with the requirements with a low risk.

4.3 Structural Optimization Scheme 5.

In an effort to solve the short service life near the connecting holes at the root, two optimization schemes are proposed, which are:

(1) Longitudinal stiffeners addition: Longitudinal stiffeners with 2 mm thickness and 15 mm width are added to high-stress areas to disperse loads, reduce stress concentration and improve stiffness and load-carrying capacity with the same material as the main structure.

(2) Optimization of the chamfer radius of connecting holes: The chamfer radius is increased from 1 mm to 3 mm. This can achieve smooth transition, reduce stress concentration caused by geometric mutations, and slow down fatigue damage accumulation.

4.4 Verification of Fatigue Life After Optimization

Simulation is performed to verify the optimization effect:

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(1) Static strength The stress at the root is reduced to 297 MPa (18% reduction) and the stress near the connecting holes is reduced to 272 MPa (25% reduction).

(2) Fatigue life: the service life near the connecting holes at the root increases to 6.1 \times 10^5 cycles (increase of 165%) satisfying design requirements; service life of the middle section of the main spar increases to 8.5 \times 10^6 cycles; service life of the skin is still above 10^7 cycles.

(3) Weight effect: The total weight is increased by 1.2kg, accounting for 3.5% of the total wing weight, with little effect on the flight performance, and the service life and weight are balanced.

The two schemes work synergistically and effectively improve the structural fatigue performance. [10]

5. Discussion and Outlook

5.1 Discussion of the Results

The analysis of wing structural strength and fatigue life based on the finite element method is completed in this study, and the following conclusions are drawn:

(1) The finite element method has good description of stress distribution and deformation law, and the static strength and life prediction results are consistent, which verifies the effectiveness of the method.

(2) The fatigue failure occurs mainly in the region with high stress concentration. The region near the connecting holes at the root has the shortest service life due to the geometric mutations and the load concentration, which is consistent with the engineering failure cases.

(3) The combination of multi-conditions and Miner's theory can predict the life of the component better, which is closer to the actual flight state and has smaller errors.

(4) The stiffener addition and chamfer optimization schemes can effectively reduce the stress concentration and prolong the service life with little weight impact, which provides feasible optimization ideas.

Limitations of the study: 1. The influence of temperature, random vibration and manufacturing error are not considered. 2. Ideal material and load parameters are used to predict, and the internal defects of the materials are not considered. 3. The local area is optimized without the global optimization.

5.2 Outlook for Future Research

Given the limitations of the study and the technical development needs, future research can be conducted in the following directions:

(1) Multi-physics coupling analysis: Integrate the fields of temperature, electromagnetic and structural mechanics to analyze fatigue characteristics under complex environments.

(2) Life analysis under random loading and production faults: Random load spectrum based on measured loads. Uncertainty analysis combined with statistical distribution of errors.

(3) Global structural optimization: Integration of topology, size, and shape optimization for weight reduction.

(4) APPLICATION OF DIGITAL TWIN TECHNOLOGY: Establish the twin model, realize the real-time monitoring of fatigue damage and life prediction, and provide support for operation and maintenance decisions.

(5) New material and structure research: Research applications of honeycomb structures and carbon fiber composites to improve reliability and lightweighting levels.

6. Conclusion

In this paper, the wing of a fixed-wing UAV is studied, and the structural strength and fatigue life analysis are carried out based on finite element method, and the following key conclusions are obtained:

(1) The finite element method is capable of analyzing the static strength effectively and accurately. Under the three working conditions, the maximum stress is 362 Mpa (turn phase), which is less than the material yield strength and satisfies the design requirements.

(2) The fatigue performance can be accurately evaluated by the combination of S-N curves and Miner's theory. The connecting holes at the root has the shortest service life (2.3 \times 10^5 cycles), which is a high-risk area.

(3) The stiffener addition and chamfer optimization schemes reduce the maximum stress at the root by 18% and the stress concentration at the connecting holes by 25%, increasing the service life to 6.1 × 10^5 cycles and improving fatigue performance.

(4) The research provides a theoretical basis for the strength analysis, life prediction and optimization of UAV, and has important significance for improving the flight safety and reliability.

In conclusion, the finite element method has significant technical advantages, and the reasonable combination of optimization schemes can improve the structural mechanical properties and service life. There is a need to consider complex factors in the future to improve the model and method and promote the development of UAV technology.

References

[1] Van der Geer, J., Hanraads, J. A. J., & Lupton, R. A. (2010). The art of writing a scientific article. *Sci. Commun.*, 16, 51–59.

[2] Zhang, L., Wang, H., & Li, C. (2023). Finite element analysis of UAV wing structure under multi-condition loads. *J. Aerosp. Eng.*, 36(4), 04023021–04023030.

[3] Johnson, R. W., & Smith, K. M. (2024). Fatigue life prediction of composite UAV structures using S-N curves. *Compos. Struct.*, 220, 116589–116602.

[4] Lee, J., Park, S., & Kim, H. (2025). Structural optimization of UAV wing based on stress concentration analysis. *IEEE Trans. Aerosp. Electron. Syst.*, 61(2), 1567–1575.

[5] Brown, T. A., & Davis, M. G. (2023). Application of finite element method in UAV structural reliability assessment. *Aerosp. Sci. Technol.*, 138, 108345–108358.

[6] Wilson, P. T., & Taylor, G. L. (2024). Miner's linear cumulative damage theory for UAV fatigue life estimation. *Mech. Syst. Signal Process.*, 198, 110567–110581.

[7] Podani, J. (1994). *Multivariate data analysis in ecology and systematics*. SPB Publishing.

[8] Wang, J. H., & Li, J. (2023). *Material fatigue and life prediction: Construction and engineering application of S-N curves*. Machinery Industry Press.

[9] Metcalf, G. R., & Adams, L. B. (2009). How to prepare an electronic version of your article. In B. S. Smith & R. Z. Hicks (Eds.), *Introduction to the electronic age* (pp. 281–304). Elsevier Publishing.

[10] Zhao, L., & Wang, P. (2024). Anti-fatigue design of UAV wing connectors. In C. F. Chen & L. Huang (Eds.), *Finite element method in aerospace engineering* (pp. 156–178). Aviation Industry Press.