Fatigue analysis of airfoil under different working conditions

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Abstract. Within the flight mission envelope, the wing receives different aerodynamic loads in each mission stage, which results in bending and torsion alternating stress, which is prone to deformation or fatigue damage, threatening flight safety. Therefore, it is necessary to predict the fatigue life of the wing structure and maintain it in time to avoid accidents. Fluent software is used to analyze the aerodynamic load state of the wing when the lift-to-drag ratio is the largest under the three conditions of the climb, level flight, and landing, as the loading load of the wing, analyze the stress and strain of the dangerous points at each stage based on the finite element analysis platform, and determine Multiaxial fatigue state. The Brown-Miller multiaxial fatigue analysis method based on the critical surface was adopted, and the fatigue life analysis was carried out using the Fe-safe software and the Abaqus software. The results show that the minimum lifespan first appears at the root of the wing. In the Fe-safe analysis, the design life of the given wing structure is 40000 cycles, and the minimum life of the wing structure is calculated to be 58420 cycles, longer than the design life, and the life safety factor is 1.078, basically in line with the actual situation.

1. Introduction
The wing is the most important aerodynamic component of the aircraft. It is subjected to the alternating stress of bending and torsion during flight, easy to deform or result in fatigue damage, which directly affects the structural life and safety of the aircraft. By predicting the fatigue life of the wing structure, the safety status of the wing structure can be understood in time, and corresponding repairs or replacements can be made quickly to avoid major accidents [1]. Therefore, it is very important to perform fatigue analysis on the wing structure.

In the process fatigue analysis process of the wing structure, there are many factors that affect fatigue and the problems are complex, and it is difficult to find a universally applicable fatigue analysis method. Maksimovic M developed a program for the analysis of damaged aircraft structural components in terms of fatigue and fracture mechanics to estimate the residual life of aircraft structural components under cyclic loading, verified by fatigue test of representative aircraft structural elements [2]. Chen Liang and others studied the operational characteristics of UCAV based on the experience of manned aircraft load spectrum compilation technology, the compilation principle of UCAV load spectrum is established, and the omission method of high load truncation and low amplitude period is studied, which lays a foundation for structural fatigue analysis and life [3]. Deepashri N V found the best equation for predicting the stress concentration factor, and a large number of finite element (FE) analyses involved in determining the stress concentration factor are optimized [4]. Main B found that accurate and reliable prediction depends on the availability of high-fidelity short crack rate data and the appropriate stress intensity solution, thus the reliability of the existing fatigue life simulation is improved [5].
In the fatigue analysis of the wing structure, this paper divides the aircraft into three stages: climb (condition I), level flight (condition II), and landing (condition III). The basic Brown-Miller multi-axis fatigue analysis method uses Abaqus, Fe-safe and other software to perform finite element analysis of strength and stiffness, and analyzes the fatigue life of the wing structure. Compared with the traditional fatigue analysis method, this method takes into account the existence of multi-directional stress (strain) and is more in line with the actual situation of the wing in service under multi-axial stress.

2. Brown-Miller Critical Surface Multiaxial Fatigue Analysis

The critical surface method proposed by Brown-Miller is based on the location of the failure surface and the stress-strain relationship on the failure surface [6, 7, 8]. The maximum shear strain and the influence of the normal normal strain on the crack are mainly considered, and the maximum shear strain and the normal normal strain are used as the parameter to replace the equivalent strain parameter for life estimation, the expression is:

\[
\frac{V_{\gamma_{\text{max}}}}{2} + k \varepsilon_n = 1.65 \frac{\sigma_\text{r}}{E} (2N_r)^{\delta} + 1.75 \varepsilon_1^\prime (2N_r)^{\delta}
\]

Where \( \frac{V_{\gamma_{\text{max}}}}{2} = V (\varepsilon_1 - \varepsilon_3) \), normal strain: \( \varepsilon_n = \frac{V (\varepsilon_1 - \varepsilon_3)}{2} \), \( k \) is constant.

Through research, it can be known that the critical surface theory takes into account the magnitude and direction of stress and strain when selecting damage parameters, so it has certain physical significance. This theoretical method is closer to the real situation and provides a guarantee for the accuracy of multi-axis fatigue life prediction.

3. Multiaxial Fatigue State Analysis of Wing Structure

This section analyzes the aerodynamic characteristics of the wing structure under the three working conditions of the climb, level flight, and landing, and determine the aerodynamic external loading characteristics of the wing structure in each working condition that best match the actual flight state. The stress and maximum displacement distribution cloud diagram of the wing under various conditions, find out the maximum stress and displacement position, and analyze the distribution characteristics of the stress and displacement on the wing, and propose specific locations that should be targeted when improving the strength and stiffness of the wing. Identify the dangerous point, analyze the degree of the principal stress and strain at the dangerous point as the working conditions change and determine the multi-axial fatigue state, to prepare for the multiaxial fatigue life prediction of the wing structure.

3.1. External Load Characteristics Analysis of Wing

In this paper, the CFD software Fluent is used to calculate the lift/drag force of the wing structure under conditions I, condition II and condition III. In each working condition, the same incoming flow velocity and different angles of attack are given. Compare the lift-drag ratio at different angles of attack, and select the lift/drag calculation result that best fits the actual flight situation as the external load of the wing structure. The wing airfoil adopts NACA2415 airfoil. The model only considers the overall mechanical performance of the wing, and does not consider the local secondary stress and local structure of the wing. Therefore, the wing can be simplified to a double-beam structure, and the wing is ultimately simplified into the skin, ribs, and beams (because the fuselage is an auxiliary part in the research process, it is simplified to a plate connecting with the wing). NACA2415 is selected for the airfoil, and a three-dimensional solid model is established using CATIA software.

Use Gambit to mesh the wing and import the established computational domain mesh model into Fluent for lift/drag calculation. In condition I, the incoming flow velocity is set to 0.3 Ma, and the angle of attack value is 7°-9°. In working condition II, set the incoming flow velocity to 0.4Ma and the
angle of attack value to be 0°~10°. In working condition III, the incoming flow velocity is set to 0.25Ma and the angle of attack value to be 6°~9°.

In each condition, the actual flight angle of attack is selected when the lift-drag ratio is the largest. Operating condition I is 7°, operating condition II is 5°, and operating condition III is 6°. The corresponding lift/drag calculation results under the three working conditions are shown in Table 1.

Table 1. The calculation results of external load on each condition (unit: N)

| Condition   | Lift    | Drag    | Lift    | Drag    | Lift    |
|-------------|---------|---------|---------|---------|---------|
| Condition I | 47925.2 | 5202.2  | 41653.1 | 4450.0  | 29569.1 |
| Condition II| 29569.1 |         | 29569.1 |         |         |
| Condition III| 1919.2 |         |         |         |         |

3.2. Static Analysis of Wing Structure Under Three Working Conditions

Hypermesh software is used to mesh the 3D model of the wing established in CATIA V5. The meshing strategy is a trade-off between calculation accuracy and speed. The mesh at the junction of the wing and the fuselage is refined, and other parts are meshed normally. For the loading strategy, the wings are fully constrained and fixed to the fuselage simplified to a plate.

The lift/drag force in Table 1 is loaded by the loading method of concentrated force evenly dispersed on the acting surface. The drag force is averagely loaded on the leading edge of the wing, and the lift force is averagely loaded on the lower surface of the wing.

According to Table 1, the loading conditions during the climbing stage show that the lift is 47925.2 (N) and the resistance is 5202.2 (N). The finite element solution results of the wing structure can be used to obtain the stress and deformation cloud diagrams in the Abaqus post-processing. Figure 1 shows the overall Mises stress and the maximum displacement cloud diagram in the condition I.

![Figure 1. The stress(left) and displacement(right) distribution cloud diagram on condition I](image)

According to the results of the finite element analysis of the climbing phase, it can be seen that when the external load is uniformly distributed on the wing from point to surface during the climbing phase, the resulting larger stresses are mainly distributed at the root of the wing and the connection near the root of the wing, and the stress value gradually decreases from wing root to wing tip. The maximum stress value at the wing root is 300.6Mpa. The maximum displacement of the wing structure occurs at the wing tip, and contrary to the stress distribution, it gradually decreases from the wing tip to the wing root. Comparing the finite element analysis results with the material yield value, it can be seen that the maximum stress value of the wing structure during the climb phase does not exceed the yield value of material aluminum 2024. In this case, the external load will not affect the static strength of the wing structure, so the wing structure is safe under this condition and can work normally.

Use the same method to analyze working conditions II and III, except for the maximum stress at the root of the wing, the other distributions are the same as those of working condition I. The maximum stress value at the root of the second wing in the working condition II is 262Mpa, and the maximum stress value at the root of the third wing in the working condition III is 151.3Mpa, which does not exceed the yield value of the material aluminum 2024. Table 2 shows the analysis results.
Table 2. Analysis of simulation results under various conditions

| Item                      | Condition I   | Condition II  | Condition III  |
|---------------------------|---------------|---------------|----------------|
| Maximum Stress            | 300.6Mpa      | 262Mpa        | 151.3Mpa       |
| Position                  | Wing Root     | Wing Root     | Wing Root      |
| Maximum Displacement      | Wing Tip      | Wing Tip      | Wing Tip       |
| Position                  |               |               |                |

3.3. Analysis of Principal Stress and Strain Synthesizing Three Conditions

Although the maximum strain is at the wing tip, its essence is deflection, because it is at the far end of the cantilever beam, and the strain of each section is superimposed. In actual situations, the bending moment of the wing is borne by the equal section spar, larger stress larger strain. Therefore, the static analysis of the wing structure under three working conditions shows that the dangerous part under each working condition is at the wing root. In the previous finite element analysis, the 14096, 15499, and 14698 nodes are three nodes with higher stress. Figure 2, 3, 4 are respectively the first, the second and the third principal stress and the corresponding three principal strain curves of the three nodes.

Figure 2. First principal stress (left) and first principal stress (right)

Figure 3. Second principal stress (left) and second principal stress (right)

Figure 4. Third principal stress (left) and third principal stress (right)

Synthesizing the change characteristics of the principal stresses and principal strains under the three working conditions, it can be known that the magnitude and direction of the principal stresses at these nodes are constantly changing, so the fatigue state of the wing structure under the three working conditions is multiaxial fatigue state.
4. Fatigue Life Prediction of Wing Structure

Through the previous static analysis of the wing structure under three working conditions, it is known that it is in a multi-axial fatigue state. This paper uses the critical surface method to predict the fatigue life of the wing. The Fe-safe fatigue analysis software adds the Brown-Miller multiaxis fatigue algorithm based on the critical surface method, which facilitates the work of this paper [9, 10, 11, 12]. The results obtained from the Fe-safe analysis are post-processed by Abaqus, and finally the fatigue life cloud image and the fatigue safety factor cloud image are obtained.

4.1. Fe-safe Dataset and Analysis Process Settings

When calculating fatigue life in Fe-safe software, it is necessary to obtain the load steps generated under different working conditions. In Abaqus's finite element analysis of the wing structure, the finite element results analyzed under the three working conditions are relatively independent, but the fatigue life analysis of the wing structure requires the formation of continuous load steps of the three working conditions. The load steps of the three working conditions are combined and imported into the Fe-safe software. Correspond the compiled loads with the load steps under the three working conditions one by one, and establish a fatigue cycle sequence set, considering the stress and strain effects at the same time. Set the stress cycle and the strain cycle separately, condition I → condition II as a small cycle, condition II → condition III as another small cycle. A cycle of the two sequence sets constitutes a complete take-off and landing flight. The load steps and load cycle settings under each working condition are shown in Figure 5.

The Brown-Miller algorithm is selected for the multiaxial fatigue calculation of the wing structure. The calculation process constitutes three sequent parts. First part, the shear strain and normal strain on the critical surface can be obtained from the principal strains of the relevant nodes. Second part, the average stress effect can be corrected according to the fatigue load time history. Third part, solve the calculation to get the fatigue life value and FOS value.

4.2. Results of Fatigue Life Analysis

The multiaxial fatigue life results of the wing structure obtained in the Fe-safe software, shown in figure 6, are post-processed and read through the Abaqus software. The life cloud diagram and the safety factor cloud diagram of the wing structure can be obtained, also shown in figure 6.

Through the life cloud diagram of the wing structure, the partial diagram of the minimum life and the fatigue life safety factor cloud diagram, it can be known that after the multiaxial fatigue life analysis of the wing structure, the minimum life span 58420 cycles first appeared at the root of the wing, but longer than the design value 40000 cycles, minimum life safety factor reaching 1.078 at the root of the wing. The weak part of the fatigue life obtained by the fatigue life analysis of the wing structure is consistent with the maximum stress position obtained in the previous static analysis, which is in line with the actual situation.
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Figure 6. The Fe-safe analysis results (top). The life (left) and the safety factor (right) cloud diagram

5. Conclusion

This paper first analyzes and confirms the actual aerodynamic load characteristics of the wings during takeoff, level flight, and landing, and then compares the static characteristics of the wings under aerodynamic loads under various working conditions, and concludes that the wings are in multiaxis fatigue state. Finally, the Brown-Miller critical surface multiaxis fatigue algorithm in Fe-safe is used to analyze the multiaxis fatigue life of the wing structure. The fatigue life value obtained is also within a reasonable range of aircraft takeoffs and landings, which is comparable to the maximum corresponding takeoff and landing cycles of civil aircraft, indicating that the multi-axis fatigue analysis method based on the critical surface method is reliable for the fatigue life computation of wing structure. It can provide a new analysis method for the fatigue life analysis of the wing structure and provide a reference for estimating the service life of the wing during wing design.

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