Optimization of Wing Structure Based on Fluid-solid Coupling and Vibration Model

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Abstract: With the development of ages, human beings have made more efforts to develop the sky, and aircraft is widely used as the main tool for human beings to set foot in the sky. Therefore, optimizing wing structure is positive for saving resources and improving efficiency. In this paper, by establishing the conventional wing structure model and the wing model after changing its rib density, we compared results based on fluid-solid coupling and vibration mode analysis. It is found that: The wing structure optimization should appropriately increase or decrease the wing-rib aperture (i.e., increase/decrease by 10%) based on ensuring the flight performance of the wing, and it can effectively reduce the overall deformation of the wing and ensure the flight performance of the wing, which provides a valuable reference for the design of the wing structure.

Keywords: fluid-solid coupling, structural optimization, vibration model, finite element analysis.

1. Introduction

The wing is one of the most important components of the aircraft, and its primary role is to provide lift and maintain the stability of the aircraft. Therefore, in order to improve wing performance, wing reliability analysis is often carried out. Among them, the most commonly used analysis process for wing reliability analysis is to perform a fluid simulation of the aircraft wing, calculate the stress, resistance, or lift, and then conduct modal analysis or vibration analysis based on this force. By comparing the stress and strain nephogram, the overall evaluation of its structure is carried out, and the optimization scheme is proposed. Many experts and scholars have made achievements in wing mechanics analysis.

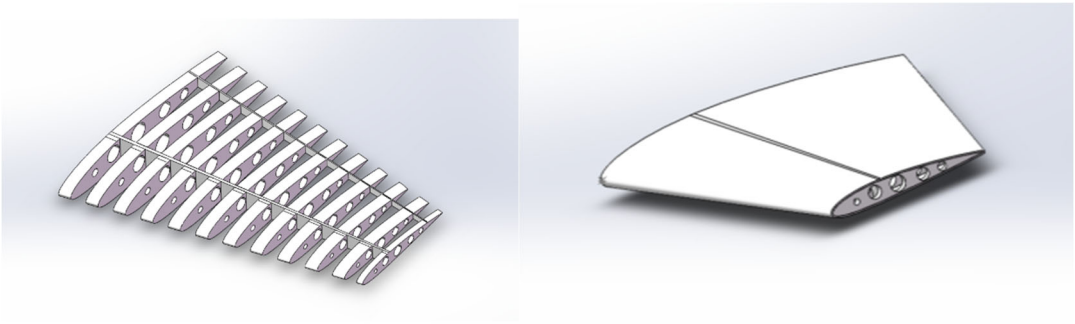
Up to now, the commonly used methods for wing mechanical analysis include finite element simulation analysis, wing aerodynamic analysis, wing structure topology optimization design, algorithm optimization, or optimization of wing structure layout to reduce wing weight. Zhou Zhiqiang and Hu Zonghao[1] used a genetic algorithm to carry out topological optimization design of aircraft wing structure; Liu Bingfei and Zhang Chao[2] studied the design optimization of deformable wing driven by shape memory alloy; Wang and Sun[3] integrated optimization method and simulation of wing structure based on finite element model; A A G Hanif et al.[4] carried out the optimization design of an aircraft wing structure by response surface method; Raphael T. Haftka[5] studied the structural optimization of flexible wings constrained by strength and induced resistance; Venkayya V. B. et al.[6] carried out the optimization design of multi-frequency constrained wing structure; Zhu[7] used the finite element method to make a model analysis of the wing mechanism model, and finally gave the solution. Phyo Wai Aung et al.[8] focused on the structural optimization of light aircraft composite wings. These studies either employ a single research method for wing structure optimization, or investigate the influence of materials on wing structure, so as to propose optimization schemes. Therefore, the shortcomings of the previous wing optimization research are summarized. In this paper, the wing structure is thoroughly analyzed using fluid-solid coupling and modal analysis, and the optimization scheme is proposed, making the research more scientific and feasible.

In this paper, the optimization analysis of wing structure based on unidirectional fluid-solid coupling and vibration modal analysis is made, that is, the unidirectional fluid-solid coupling simulation and vibration modal analysis are carried out on the conventional wing model, and the wing rib aperture increase 10 % model and the wing rib aperture decrease 10 % model, respectively. It is expected that the deformation degree of bending and torsion can be reduced under changing the wing rib density, to optimize the wing structure.

2. Modeling and methods

2.1 Model Establishment

The analysis of multiaxial fatigue analysis of ABAQUS/FE-SAFE wing structure by Sun Miao and Xu Ying[9] is as follows. The wing airfoil used in this paper is NACA2412 airfoil. Since only the overall mechanical effect of the wing is studied, the established wing model only includes wing beams, wing ribs, skin, other structures, and other fine structures that are not reflected. Now, this paper uses SolidWorks software to import NACA2412 airfoil data in Profili to establish the wing model. The model is as follows（Fig.1.） :

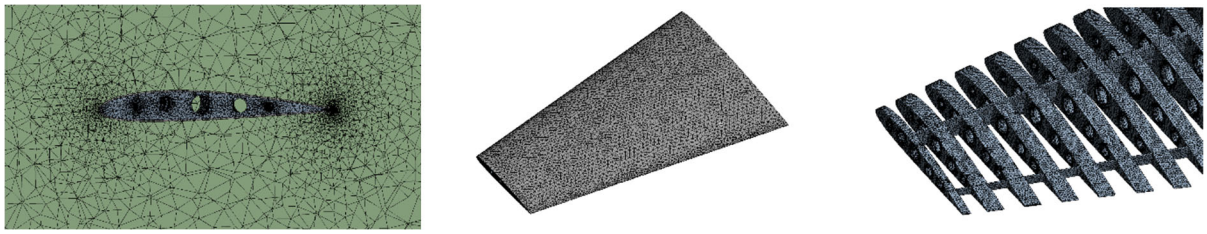


（a）Wing skeleton model (b) Wing model with skin

Fig.1. Wing model

The conventional wing model is used for one-way fluid-solid coupling and vibration modal analysis. The other two wing models are established by changing the fin density of the wing to increase the fin aperture by 10 % and decrease the fin aperture by 10 %, and then used for one-way fluid-solid coupling and vibration modal analysis, and the optimization scheme of the wing structure is given.

2.2 Method



(a) Schematic diagram of mesh division section of fluid domain

(b) Mesh division of skin

(c) Mesh division of wing ribs

Fig.2. Mesh division

In this paper, the Fluent / Transient module in ANSYS Workbench is used to conduct unidirectional fluid-structure interaction on the wing. The unidirectional fluid-structure interaction method results are used to verify that the wing structural strength analysis results are safer than those of the

bidirectional coupling[10]. Then, the static performance of the wing with different opening sizes is compared by changing the size of the rib hole. The mesh division in the flow field and the wing mesh division in the transient structure are shown below(Fig.2.).

The material used in this paper is 6061 aluminum alloy, and its mechanical properties are as follows (Table 1).

TABLE1. Mechanical Properties of 6061 Aluminum Alloy

Material	Young 's modulus / MPa	Poisson ratio	Tensile strength /MPa
6061 Aluminum alloy	6904	0.33	259.20

The Fluent software is used to establish the flow field model. The flight speed is 50 m/s, and the attack angle of the wing is 5º. The standard K-EPSILON model was selected. The turbulence intensity was set to 5 %, the turbulence viscosity ratio was 10, and the fluid material was Air. The obtained results were imported into the transient structure, and fixed support was set at one end of the wing near the fuselage.

Then the 1 to 4 order modal diagram of the wing structure is made by ANSYS. The wing material is 6061 aluminum alloy, and its mechanical properties are consistent with the previous. This problem belongs to the modal analysis problem in dynamics. When calculating the inherent dynamic characteristics of the structure, only a few low-order modes need to be calculated for analysis. Consequently,, fewer grids can be chosen to improve the calculation efficiency while maintaing the accuracy of the calculation results.

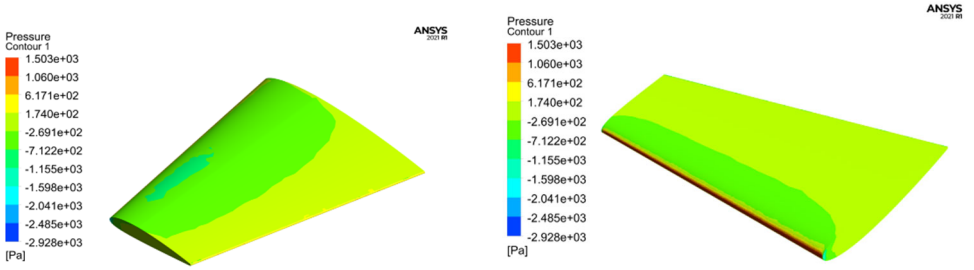
When imposing constraints on the model, because a wing section needs to be fixed on the fuselage, all nodes at the large end of the wing structure model are selected to impose displacement and rotation constraints. On the basis of this constraint, the low-order modal diagrams of the wing model conditions are plotted, and suggestions for structural optimization and improvement are proposed according to the structure.

At the same time, in order to prove that the modal analysis of the wing structure model in this paper is also applicable to the actual situation, the lifting force obtained by fluid simulation is equivalent to the force on the static structure, and is loaded on the wing structure model to simulate the vibration mode in the actual state.

Then the low-order modal diagram of the wing model is drawn by changing the hole size (10 % increase or decrease of the hole diameter) and keeping the same variable. The effect of aperture on the maximum deformation of wing model caused by vibration is studied under different vibration frequencies

3. Results and discussion

3.1 Fluid-solid Coupling



Upper surface (b) Lower surface

Fig.3. Wing surface pressure diagram

The surface pressure distribution of the wing under the above working conditions can be intuitively seen from the obtained surface pressure nephogram of the wing. The pressure on the front wing is the largest, while the pressure on the upper surface of the wing (Fig.3.a) is less than that on the lower surface of the wing (Fig.3.b).

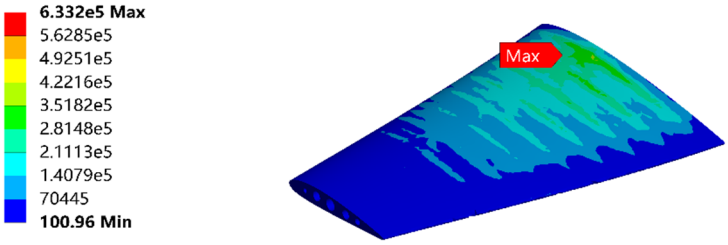


Fig.4. Wing stress diagram

The one-way fluid-solid coupling is completed in the transient structure based on the computed result. The Von-Mises yield strength criterion is used to check if the strength meets the standard. As shown in the equivalent stress distribution map (Fig.4.), it can be seen that the maximum stress above is within the allowable value of the material (259.20 MPa).

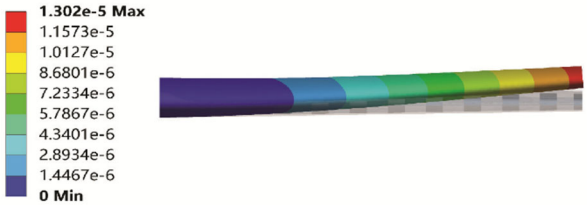
After changing the win rib aperture size, the fluid-solid coupling is solved by the same method as above. It can be found that compared with the original structure (Fig.5.a), the maximum displacement of the wing always occurs at the tip of the wing, and the maximum deformation value of the wing is proportional to the rib aperture. This indicates that the wing with the smallest aperture has the least deformation at the wing tip (Fig.5.c). However, from the overall deformation degree, the overall deformation degree of the wing with a larger rib aperture is smaller (Fig.5.b). The structural strength of both materials is within the allowable range.



(a) Original size

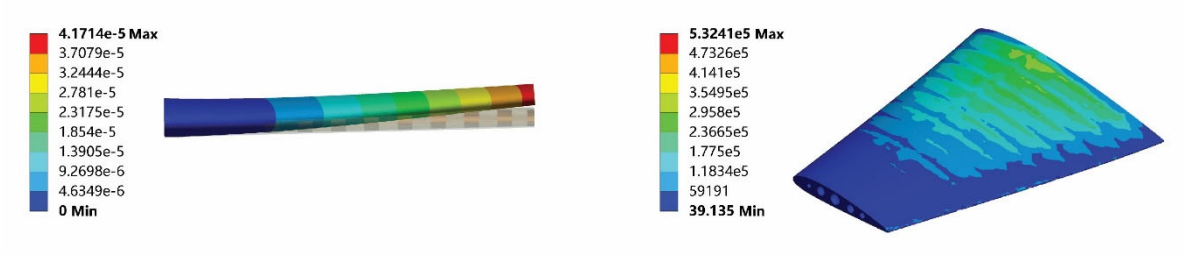


(b) Aperture+10%



（c）Aperture-10%

Fig.5. Wing displacement diagram



(a) Displacement (b) Stress

Fig.6. Results after using carbon fiber materials

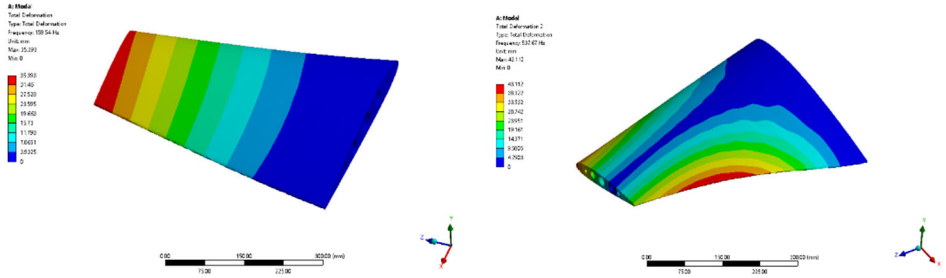
The material of the wing with a 10 percent increase in apertures on ribs is replaced with unidirectional carbon fiberboard (230GPa), and the results are obtained after unidirectional fluid-solid coupling (Fig.6). It can be seen that although the degree of wing deformation increases, the maximum stress value is also significantly reduced, and the tensile strength of the material is generally greater than 3500Mpa, much larger than the traditional alloy material. It has the characteristics of small density and good collision energy absorption [11], as well as excellent fatigue resistance and high fatigue threshold value [12], making the material more suitable for extreme scenarios.

3.2Vibration Analysis

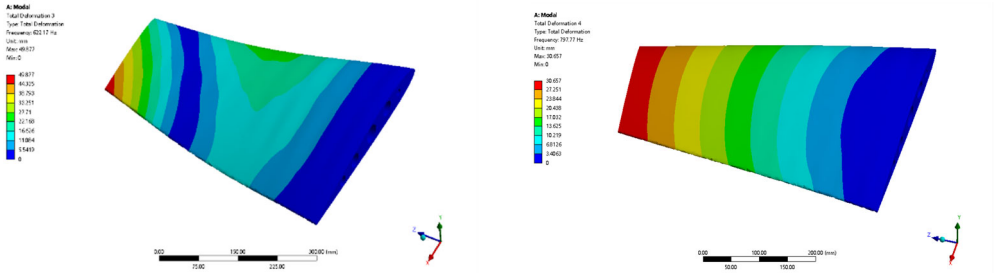
Based on Zhang Hongcai and He Bo[13], using ANSYS13.0 finite element analysis, this paper has the following analysis: on the basis of the above analysis, ANSYS is used to make the 1 to 4 order modal diagram of the wing structure model to explore the influence of wing structure change on the mode and give the optimization direction. After changing the pore size by increasing 10 % and decreasing 10 %, the 1 to 4 order modal diagram is still made for comparison and exploration, and the optimization suggestions are put forward according to the comparison results. Then, the lift obtained from the fluid simulation part is equivalent to the force on a static structure, which is loaded at the center of the wing structural model, and the 1 to 4 order modal diagram is made again to simulate the actual operation state. Finally, the results are analyzed, and optimization suggestions are put forward.

3.2.1 Low-order Vibration Mode Analysis of Wing Structure

According to the above method, the modal diagrams and natural frequencies of each wing order are plotted. The values and images are shown in Fig7. and Table 2.



（a）First-order (159.54Hz) mode diagram （b）Second-order (537.67Hz) mode diagram



（c）Third-order (622.17 Hz) modal diagram （d）fourth-order (797.77 Hz) modal diagram

Fig.7. Low-order modal diagram of wing model

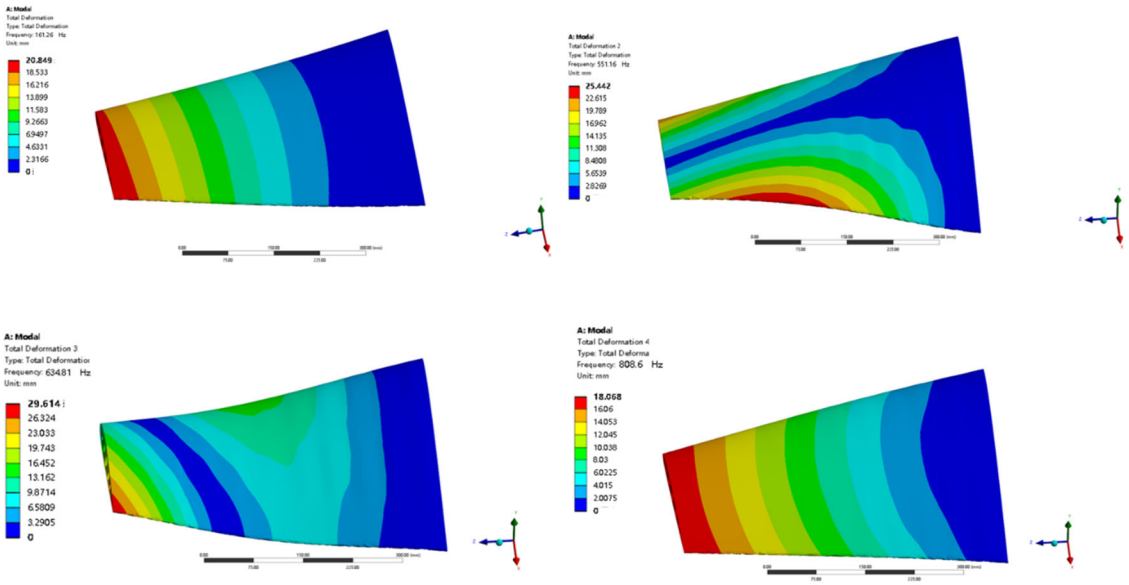
Table 2 Natural frequencies of wing model

Rank（SET）	1	2	3	4
Frequency（Hz）	159.54	537.67	622.17	797.77

It can be seen in the figure that under the first-order (159.54Hz) and fourth-order (797.77Hz) vibration modes, the wing mainly occurs bending deformation, and it can be seen that the farther away from the fixed end, the greater the deformation. Under the third-order (622.17Hz) vibration mode, the wing has to bend deformation and slight torsional deformation, and the maximum deformation occurs at the corner of the section. Under the second-order (537.67Hz) vibration mode, the wing mainly undergoes torsional deformation, and the maximum deformation occurs at the midpoint of the wing side, with the maximum deformation value of 43.112 mm.

The bending of the wing is mainly applied to the beam of the wing, while the torsional deformation is primarily applied to the rib and skin of the wing. Therefore, for the first and fourth-order vibration, the wing can strengthen the strength of the beam to avoid excessive bending deformation. For second-order vibration, wing ribs can be strengthened, or integral panels can be used to avoid excessive shape changes caused by torsional deformation. Due to many types of deformation, the third-order vibration can be adjusted according to the actual situation. If the aeroelastic frequency is within this range, the design of the airfoil needs to be changed to avoid such vibration.

The lift force obtained by fluid simulation is equivalent to the force on the static structure (F = 21N), which is loaded on the wing structure model to simulate the vibration mode in the actual state. The low-order modal diagram is shown in Figure 8.



（a）First order (161.26Hz) mode diagram under loading

（b）Second order (651.16Hz) mode diagram under loading

（c）The third-order (634.81Hz) mode diagram under loading

（d）The fourth-order (808.6Hz) mode diagram under loading

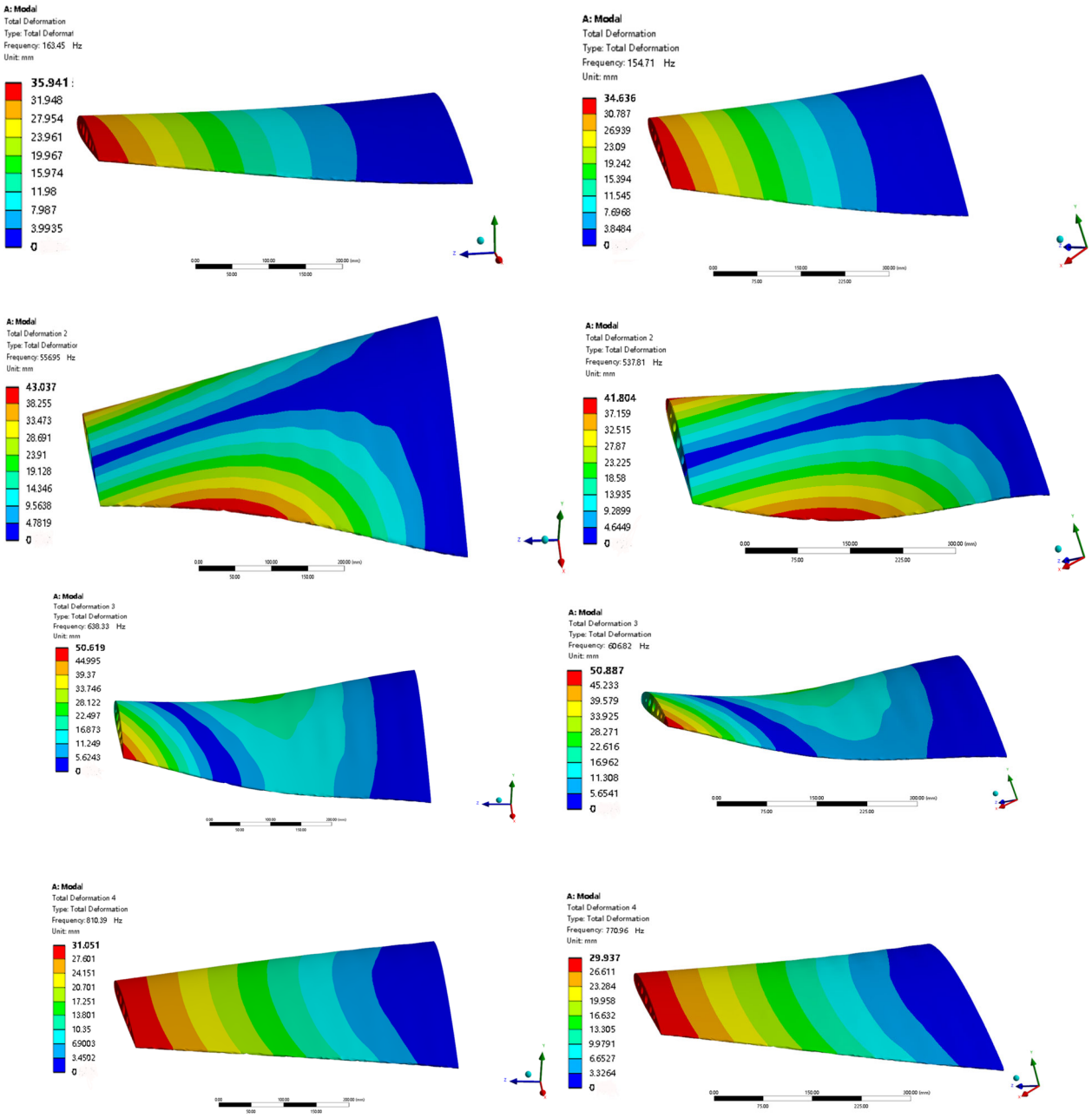
Fig. 8. Low-order modal diagram of wing model under loading

It can be seen from the low-order modal diagram of the wing structure under loading that the main deformation form has not changed under each order of vibration mode, and only the deformation degree has changed. Therefore, the optimization conclusion given above is still applicable.

3.2.2 Effect of aperture on modal analysis

After adjusting the aperture size on the wing rib, ANSYS is used again to make the low-order modal diagram to explore the influence of aperture size on the structural modal of the wing.

When the aperture is increased by 10 % and decreased by 10 %, the 1 to 4 order modal diagram is drawn as shown in Figure 9, and the maximum deformation degree of each order when changing aperture size is shown in Figure 10 and Table 3.



（a.1）First-order (163.45 Hz) modal diagram after adding 10 % aperture

（a.2) First-order (154.71 Hz) modal diagram after reducing 10 % aperture

（b.1) Second-order (556.95 Hz) modal diagram after adding 10 % aperture

(b.2) Second-order (537.81 Hz)modal diagram after reducing 10 % aperture

（c.1) Third-order (556.95 Hz) modal diagram after adding 10 % aperture

(c.2) Third-order(537.81 Hz)modal diagram after reducing 10 % aperture

（d.1) Fourth-order (556.95 Hz) modal diagram after adding 10 % aperture

(d.2) Fourth-order(537.81 Hz)modal diagram after reducing 10 % aperture

Fig. 9 Comparison of low-order modal diagrams with a 10 % increase and decrease in aperture

Keeping the amount of aperture unchanged and increasing or decreasing the aperture by 10 %, it can be seen from the 1 to 4 order modal diagram at this time that with the change of aperture, the main deformation form does not change under each order vibration mode, but the deformation degree changes. With the decrease of aperture, the deformation degree decreases under the first and fourth-order vibration modes, with the smallest deformation occurring when the aperture decreases by 10 % under the second-order vibration mode.

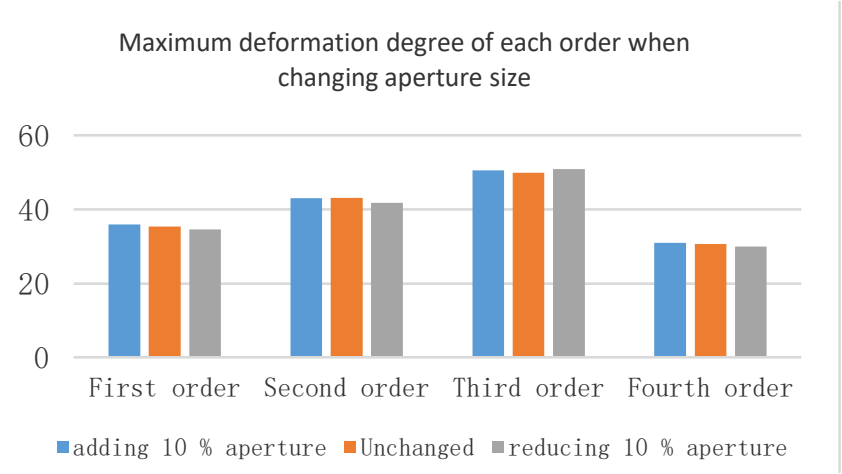


Fig.10 Maximum deformation degree of each order when changing aperture size

Table 3 Maximum deformation degree of each order when changing aperture size

Rank（SET） maximum deflection（mm）	1	2	3	4
The aperture increases by 10 %	35.941	43.037	50.619	31.051
The aperture is constant	35.393	43.112	49.877	30.657
The aperture decreases by 10 %	34.636	41.804	50.887	29.937

Therefore, for the first-order or fourth-order vibration, the deformation degree of vibration can also be controlled by appropriately reducing the aperture size.

It can be seen from this section that under different vibration frequencies, the wing structure has different modes, different deformation types, and different deformation sizes. In the design process of the actual wing structure, the frequency of aeroelasticity in the flight environment should be considered to avoid excessive deformation. In the case of first-order and fourth-order vibrations, the strength of the strengthened beam can be used for optimization. In the case of second-order vibration, the reinforced wing rib or the overall panel can be used for optimization while avoiding its third-order vibration. If the aeroelastic frequency is within this range, the airfoil needs to be changed and further analyzed according to the actual situation. In addition, according to the vibration frequency range, the aperture size of the wing model can be appropriately adjusted to reduce the deformation degree and optimize the structure. For example, for the first-order or fourth-order vibration, the deformation degree of vibration can be controlled by appropriately decreasing the aperture size.

4. Conclusion

In this paper, three wing models with different rib densities are analyzed by unidirectional fluid-solid coupling simulation and vibration modal analysis, and the optimization scheme is finally given:

The one-way fluid-solid coupling simulation shows that the maximum deformation value of the wing is proportional to the diameter of the wing rib, but from the overall deformation degree, the larger

the diameter of the wing rib, the smaller the overall deformation degree of the wing. Meanwhile, the effects of aluminum alloy materials and carbon fiberboard materials on the wing structure are also analyzed and compared. It is found that carbon fiberboard materials have the characteristics of small density and good collision energy absorption, and they have excellent fatigue resistance and high fatigue threshold value. They are more suitable for high-performance occasions, and can be used as wing materials to optimize the wing performance. Therefore, in order to reduce wing deformation and optimize the wing structure, the aperture of the wing rib should be increased as much as possible while ensuring wing's performance is not affected. In addition, carbon fiber materials can be added to the selection of materials to increase the wing performance.

After the modal vibration analysis, it can be seen that compared with the normal wing, the main deformation forms of the two wings (i. e., the increase and decrease of the rib aperture of the wing by 10 %) after the rib density change do not change under different vibration modes, but the deformation degree changes. With the decrease of the rib aperture, the deformation degree decreases under the first-order and fourth-order vibration modes, and the deformation is the smallest when the rib aperture decreases by 10 % under the second-order vibration mode. Therefore, in the case of first-order and fourth-order vibration, the optimization of the wing structure can be carried out by strengthening the strength of the beam. In the case of second-order vibration, the optimization can be carried out by strengthening the wing rib or utilizing the overall panel, while avoiding its third-order vibration. In conslusion, for different vibration frequencies, the wing aperture size can be appropriately adjusted to reduce the degree of deformation.

References

[1] Zhou Zhiqiang, Hu Zonghao, Xing Bendong, Cui Can. Topology optimization design method of aircraft wing structure based on genetic algorithm [J].Internal combustion engine and accessories, 2021 (24) : 16-18.DOI : 10.19475 / j.cnki.issn1674-957x.2021.24.006.

[2] Liu Bingfei, Zhang Chao, Zhang Wei. Design Optimization of Shape Memory Alloy Driven Deformable Wings [J]. Journal of Civil Aviation University of China, 2021,39 (03) : 34-38.

[3] Wang Fei, Sun Peijie. Integrated optimization method and simulation of wing structure based on finite element model [J]. Electronic design engineering, 2021,29 (09) : 41-45.DOI : 10.14022 / j.issn1674-6236.2021.09.009.

[4] A A G Hanif,Hanif A A G,Li H S,Raza M A,Kamran M,Abdullah M. Optimization Design of an Aircraft Wing Structure based on Response Surface Method[J]. IOP Conference Series: Materials Science and Engineering,2020,887(1).

[5] Raphael T. Haftka. Optimization of flexible wing structures subject to strength and induced drag constraints[J]. AIAA Journal,1977,15(8).

[6] Venkayya V. B.,Grandhi R. V.. Optimum Design of Wing Structures With Multiple Frequency Constraints[P]. ASME 1987 Design Technology Conferences,1987.

[7] Zhu Zhicheng. Modal analysis of wing structure based on finite element [J].China high-tech, 2019 (05) : 64-66.DOI : 10.13535 / j.cnki.10-1507 / n.2019.05.17.

[8] Phyo Wai Aung,Oleg Tatarnikov,Naing Lin Aung. Structural optimization of a light aircraft composite wing[J]. IOP Conference Series: Materials Science and Engineering,2020,709(4).

[9] Sun Miao, Xu Ying, Li Long. Multiaxial fatigue analysis of wing structure based on ABAQUS / FE-SAFE [J].Failure analysis and prevention, 2016,11 (01) : 1-5 + 12.

[10] Liu Jihai, Yi Yuecheng, Xie Ke, Song Yuyu, Long Yixing, Guo Dong. Application analysis of unidirectional and bidirectional fluid-solid coupling method in unmanned wing [J / OL]. Applied science and technology : 1-9 [2022-07-20].http://kns.cnki.net/kcms/detail/23.1191.U.20220526.1143.002.html

[11] Liu Xiang, Xu Wei, Liang Yao, Zhang Zhihua, Wu Sumei. Integrated carbon fiber composite molding and its application in the field of unmanned aerial vehicles [J]. Chemical fiber and textile technology, 2021,50 (07) : 97-98.

[12] Feng Zhenyu, Zou Tianchun, Hao Peng, Du Hongzeng, Tian Xiuyun. Method for determining structural materials and design allowable values of composite aircraft [J]. Astronautical material process, 2011,41 (05) : 15-17 + 39.

[13] Zhang Hongcai, He Bo. Finite Element Analysis - ANSYS 13.0 From Introductory to Actual Combat. Beijing. Machinery Industry Press. 2011.9