Design Optimization of Composite Curved Rod for Wind Tunnel Virtual Flight Test Based on Multi-island Genetic Algorithm

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Abstract. The curved rod of carbon fibre composite is the key component of the large angle three degree of freedom virtual flight test device. This article takes the composite curved rod as the research object, establishes a finite element analysis model and analyzes its strength and stiffness under the initial design conditions, the RSM response surface approximation model and the multi-island genetic algorithm are used to optimize the carbon fibre composite angle of each layer of the composite curved rod, so that the maximum deformation displacement of the curved rod is minimized, as far as possible, the influence of the center of mass of the virtual flight test model on the wind tunnel test data should be reduced. The optimization results show that relative to the initial design, the failure factor of the composite curved rod is reduced by 65.4%, the rigidity is increased by 35.94%, and the maximum deformation is reduced by 44.5%. In order to realize the simulation of flight motions close to 90° angle of attack in a horizontal wind tunnel, it provides equipment guarantee for the research of stall deviation, initial phase of spin and stable spin.

1. Introduction

Wind tunnel virtual flight technology is a typical test method for non-linear aerodynamic problems. It can more realistically simulate the maneuvering flight process and better reveal the aerodynamic/motion coupling mechanism. The technology was first proposed by Americans and the first virtual flight demonstration experiment was conducted by Magill et al. At the 42in × 43in (1in = 25.4mm) wind tunnel in Georgia [1-4], and similar studies have been carried out in other countries since then. Bristol University in the United Kingdom designed a three degree of freedom and five degree of freedom dynamic device for a low-speed wind tunnel, and realized the rolling motion of the model around the velocity vector [5-9]. The three degree of freedom device developed by Sohi in Russia carried out the experimental study of the stable tail spin of a typical fighter, but there was no theoretical modeling analysis of the system dynamics. The influence of the motion curved rod and friction torque in the mechanism on the test results has not been involved [10]. Russia's TsAGI has proposed a three degree of freedom back support device, which uses robust control methods to suppress the wing sway problem [11]. The China Aerodynamics Research and Development Center has also established a virtual flight test technology for high-mobility missiles in the 2.4 meter transonic wind tunnel [12], and a virtual flight test technology for fixed-wing aircraft in the Φ 3.2 meter low speed wind tunnel. The maximum angle of attack reached by the test is close to 30° [13].
The wind tunnel virtual flight test technology has the characteristics of multiple degrees of freedom, large angle range, and free rotation of the model. It can be used in the early stage of aircraft development to study the characteristics of high angle of attack and stall spin. In order to expand the test capability and further carry out the simulation research on the whole process of high angle of attack stall / deviation / spin, a large-angle three degree of freedom virtual flight test device (Figure 1) needs to be developed to achieve close to 90° in a horizontal wind tunnel Simulation of flight motion at an angle of attack, and research on stall deviation, initial stage of spin, and stable spin. One end of the curved rod is connected with the rotary hinge, and it can rotate freely around the central axis of the wind tunnel; the other end is fixedly connected with the cross universal joint. The universal joint is placed inside the model to support the model, through the joint action of the rotary hinge and the universal joint It can realize the free rotation of the model in a large range of three directions of pitch, yaw and roll (Figure 2). According to GuoLinliang's previous study [14], the inertia of the curved rod does not affect the characteristic parameters such as the mean value of the model's spin motion, rotation rate, etc., but it will prolong the model's entry into the spin process and affect the oscillation amplitude of the spin parameter. It is recommended to control the ratio of the inertia of the curved rod and the model along its own X axis to within 1:10; the deformation of the curved rod under load causes the displacement of the model's center of mass to affect the oscillation amplitude of the model's wake motion. It is recommended to control the offset.

Therefore, according to the inertia requirements of the X-axis of the curved rod itself, the design of the curved rod is made of carbon fiber composite material, the thickness of the layer is 5.64mm, and the layering method is 24 layers.

![Figure 1. Schematic of virtual flight test rig.](image1.png)

![Figure 2. Sketch of the velocity-vector roll on the test rig.](image2.png)

In this paper, the curved rod is taken as the research object, and the finite element analysis model is established to analyze the strength and stiffness of the curved rod under the initial lay angle; For the purpose, the angle of the composite material of curved bar is optimized. Minimize the influence of the center of mass displacement of the curved rod on the wind tunnel test data as much as possible.

2. Establishment and Analysis of Finite Element Model

2.1. Meshing

In order to ensure the accuracy of the calculation, this device uses a 4-node quadrilateral element to divide the curved rod (see Figure 3).

![Figure 3. Mesh diagram of Curved Rod](image3.png)
The shape of the grid, that is, the quality of the grid, has a great influence on the calculation accuracy. Through the finite element pre-processing software, the unit is divided and the quality of the unit is checked, and the unit that does not meet the quality standard is modified until the finite element model fully meets the requirements of high precision. The final finite element model is divided into: 7833 quadrilateral elements.

2.2. Definition of Material Properties and Boundary Conditions
Using T800 carbon fiber reinforced composite material, material properties are shown in Table 1. The load applied to the curved rod is the aerodynamic load on the aircraft model.

| Mechanical parameters of T800 carbon fiber reinforced composites |
|---------------------------------------------------------------|
| Elastic modulus/GPa  | Shear modulus/GPa  | Poisson’s ratio  |
| $E_1$              | $E_2$              | $E_3$              |
| 195                | 8.58               | 8.58               |
| $G_{12}$           | $G_{13}$           | $G_{23}$           |
| 4.6                | 4.6                | 2.9                |
| $\nu_{12}$         | $\nu_{13}$         | $\nu_{23}$         |
| 0.33               | 0.33               | 0.48               |

| Tensile strength/MPa | Compression strength/MPa | Shear strength/MPa |
|----------------------|--------------------------|--------------------|
| $X_T$                | $Y_T$                    | $Z_T$              |
| 3071                 | 88                       | 88                 |
| $X_C$                | $Y_C$                    | $Z_C$              |
| 1747                 | 271                      | 271                |
| $S_{12}$             | $S_{13}$                 | $S_{23}$           |
| 143                  | 143                      | 143                |

2.3. Finite Element Static Analysis and Results

2.3.1. Stiffness analysis. From Figure 4, the maximum displacement of the model is 9.96mm.

![Figure 4](image)

Figure 4. Deform contours of the model.

2.3.2. Modal analysis and results. From the perspective of resonance, all modes with natural frequencies within the range of external load frequency should be kept at least. Generally, higher order frequencies will appear when the operating frequency is more than 10 times of the operating frequency.

![Figure 5](image)

Figure 5. Deform contours of the model.
Inside. The modal changes are shown in Figure 5 below. Table 2 shows the natural frequency and mode of each order.

**Table 2. Result of mode analysis**

| Mode | Frequency | 1 | 2 | 3 | 4 | 5 | 6 |
|------|-----------|---|---|---|---|---|---|
|      |           | 7.93 | 8.96 | 5.85 | 76 | 293 | 374 |

2.3.3. Model composite failure analysis and results. According to the actual working conditions, it is assumed that any layer of the curved rod is damaged, and the model is deemed to be damaged. The failure judgment criterion *Tsai–Wu* adopts the failure criterion widely used in composite materials \[15-16\]. The conditions under which the material does not damage are:

\[
FI = F_1\sigma_1 + F_2\sigma_2^2 + F_3\sigma_1^2 + F_4\sigma^2 + F_6\tau^2 + 2F_2\sigma_1\sigma_2 \leq 1
\]

In the formula: \(FI\) is the failure index;

\[
F_1 = \frac{1}{X_t}, \quad F_2 = \frac{1}{Y_t}, \quad F_3 = \frac{1}{X_c}, \quad F_4 = \frac{1}{Y_c}, \quad F_6 = \frac{1}{S^2}, \quad F_2 = \frac{1}{\sqrt{X_tX_cY_t}}
\]

Generally taken \(F_1^* = -\frac{1}{2}, X_t \) and \(X_c\). Where is the longitudinal tensile and compressive ultimate strength; \(Y_t\) and \(Y_c\) is the lateral tensile and compressive ultimate strength, \(S\) is the in-plane shear ultimate strength.

Using the failure criterion *Tsai–Wu* to conduct failure analysis, it can be seen from Figure 6 that the maximum failure index \(FI\) is 0.243.

![Figure 6. Failure contours of the model.](image)

3. Optimization Method

3.1. Approximate Model

The approximate model is also called the proxy model. It obtains a certain number of variables and response values by means of simulation and experiment, and uses different algorithms to obtain the mapping relationship between variables and response values, that is, the mathematical model, instead of the original actual model. Commonly used approximate models mainly include RSM model, Kriging model and RBF model.

The general form of RSM model relationship is: \(y = f(x_1, x_2, \cdots, x_n) + \epsilon\).

In the formula \(\epsilon\) is random error, it is generally assumed that it meets the normal distribution with a mean value of 0, \(x_1, x_2, \cdots, x_n\) is a design variable, \(n\) is the number of design variables, and \(f()\) is the response, the RSM model is often used for regression analysis of first, second, third or fourth order polynomials, because the input and output are highly nonlinear, and the fourth degree polynomial is used to improve the calculation accuracy. The response surface equation is:

\[
f(x) = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \sum_{i=1}^{n} \beta_{ii} x_i^2 + \sum_{i=1}^{n} \beta_{ii} x_i^2 + \sum_{i=1}^{n} \beta_{iii} x_i^4 + \sum_{i=1}^{n} \beta_{jj} x_i^4 + \sum_{i<j}^{n} \beta_{ij} x_i x_j
\]
3.2. Mathematical Model for Optimal Design

There are three elements of optimal design, namely design variables, objective function, and constraints. Design variables are a set of parameters that change during the optimization process to improve structural performance; the objective function is the optimal performance required, which is a function of the design variables; the constraints are the constraints on the design, the design variables and other performance requirements. The mathematical model of optimized design\cite{17} can be expressed as:

$$\min f(X) = f(x_1, x_2, \ldots, x_n)$$

$$s.t. \quad g_j(X) \leq 0, \quad j = 1, 2 \cdots m$$

$$d.v. \quad l_i \leq x_i \leq u_i, \quad i = 1, 2 \cdots n$$

In the formula, $X = x_1, x_2, \ldots, x_n$ is a design variable; $f(X)$ is an objective function, $g(X)$ is a constraint; $l_i \leq x_i \leq u_i$ indicates the value range of the design variable, the upper corner $L$ indicates the lower limit, and the upper corner $U$ indicates the upper limit.

3.3. Error Analysis

This paper uses the credibility index $R^2$ as the evaluation index to detect the global and local approximation accuracy of the approximate model. The closer to 1, the more accurate, $R^2 > 0.9$ can meet the needs of engineering applications. It is defined as:

$$R^2 = 1 - \frac{\sum_{j=1}^{n}(f_j - \bar{f}_j)^2}{\sum_{j=1}^{n}(f_j - \bar{f})^2}$$

In the formula: $f_j$, $\bar{f}_j$, $\bar{f}$ are the true response value, approximate response value and average response value of the verification test sample point.

3.4. MIGA Optimization Algorithm

MIGA is improved on the basis of traditional genetic algorithm. Individuals of each population are divided into several islands. On each island, genetic operations such as cross variation are independently selected for the subpopulation according to the traditional genetic algorithm, and they are periodically randomized on each island. Select some individuals to migrate to other islands. This migration operation maintains the diversity of optimized solutions and improves the chance of including the global optimal solution.

4. Curved Rod Optimization Design

4.1. Establishment and Verification of Approximate Model

The RSM model is used to simulate the input-output relationship of the finite element model. The establishment of approximate models mainly includes the following:

(1) Define input parameters $x_i$ (different ply angles of composite material curved rods). The layup can take 8 angles of $-45^\circ$, $-30^\circ$, $-15^\circ$, $0^\circ$, $30^\circ$, $45^\circ$, $75^\circ$ and $90^\circ$, a total of 8 input variables.

(2) Define the output parameters $y_j$. The results of the finite element calculation: the maximum deformation displacement value $d_{\text{max}}$, the first order natural frequency $f_{\text{freq}1}$, and the failure index $FI$ are set as output variables.

(3) Use the optimal Latin hypercube test design method to obtain a certain number of sample points, and then establish the RSM model. The approximate model error analysis results (Table 5) can be seen that the RSM model has good performance in fitting curved rods.
Table 3. Error calculation result.

| Evaluation index | \( R^2 \) |
|------------------|-----------|
| \( d_{\text{max}} \) | 0.901     |
| \( \text{freq} \) | 0.957     |
| \( FI \)        | 0.948     |

5. Optimized Calculation

Under the premise of meeting the requirements of the strength and natural frequency of the composite material, with the minimum deformation amount as the goal, the MIGA algorithm is used to optimize the angle distribution of the composite material.

Define input parameters. A total of 8 variables are design parameters, and output variable parameters are defined as responses.

Define the optimization problem:

\[
\begin{align*}
\text{Minimize: } & d_{\text{max}} \\
\text{s.t. } & FI \leq 1, \ \text{freq} \geq 7 \\
& x_i \in [-45^\circ, -30^\circ, -15^\circ, 0^\circ, 30^\circ, 45^\circ, 75^\circ, 90^\circ]
\end{align*}
\]

Input the approximate model according to the value of the initial plan, and iterate through the 1001 step of the MIGA algorithm. The optimized results are shown in Table 4, and the Rod displacement optimization process is shown in Figure 7, the Rod displacement was optimized from 9.96mm to 5.52mm from the initial design.

Table 4. Values after design parameter optimization.

| Input parameter         | Initial value | Optimized value |
|-------------------------|---------------|-----------------|
| Layer 1 ply angle       | 0             | -30             |
| Layer 2 ply angle       | 0             | 15              |
| Layer 3 ply angle       | 0             | -15             |
| Layer 4 ply angle       | 0             | -30             |
| Layer 5 ply angle       | 0             | 0               |
| Layer 6 ply angle       | 0             | 30              |
| Layer 7 ply angle       | 0             | -30             |
| Layer 8 ply angle       | 0             | 0               |

Table 5. Optimization results.

| Output parameter | Initial value | Optimized value | Value relative to initial value% |
|------------------|---------------|-----------------|---------------------------------|
| \( d_{\text{max}} \) | 9.96          | 5.52            | -44.5%                          |
| \( \text{freq} \) | 7.93          | 10.78           | 35.94%                          |
| \( FI \)        | 0.243         | 0.084           | -65.4%                          |

It can be seen from Table 5 that after optimization of the composite curved rod, the failure factor is reduced by 65.4%, the stiffness is increased by 35.94%, and the maximum deformation is reduced by 44.5%.
6. Conclusions
In this paper, the key component of the three degree of freedom virtual flight test device in the lowspeed wind tunnel is used as the research object for the optimization simulation. The following conclusions can be drawn:
According to the inertia requirement of the X axis of the curved rod itself, the layer thickness of the curved rod was originally designed to be 5.64 mm, and the paving method was 24 layers in total. Taking the composite material curved rod as the research object, a finite element analysis model is established to analyze the strength and stiffness of the curved rod under the initial lay angle; using the RSM response surface approximation model and the multi-island genetic algorithm, the maximum deformation displacement of the curved rod is targeted, To optimize the angle of the composite material curved bar. Minimize the influence of the center of mass displacement of the curved rod on the wind tunnel test data as much as possible. After optimization of the composite curved rod, the failure factor is reduced by 65.4%, the stiffness is increased by 35.94%, and the maximum deformation is reduced by 44.5%. It satisfies the need to realize the simulation of flight motions close to 90° angle of attack in a horizontal wind tunnel, and to carry out research on stall deviation, initial phase of spin, and stable spin.

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