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Modal analysis and experimental verification of a seaplane based on a piecewise elastic model

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Abstract

Large Seaplane Typically Use Piecewise Elastic Models for Modal Analysis and Scale Model Testing, but There Are Discrepancies Between the Dynamic Response of the Scale Model and the Full-Scale Vehicle. To Validate the Test Results of the Scale Model, Finite Element Modal Analyses Were Conducted on the Fuselage, Wings, and Full Aircraft. Additionally, Ground Resonance Tests Were Performed on the Scale Model to Obtain the Low-Order Mode Shapes and Natural Frequencies. By Comparing the Finite Element Simulation Results of the Full Aircraft with the Experimental Results of the Scale Model in the Horizontal and Vertical Directions, the Similarity of Dynamic Responses Between the Scale Model and the Full-Scale Aircraft Was Verified. Furthermore, the Causes of Data Discrepancies Between the Simulation and Test Methods Were Analyzed. The Results of the Modal Analysis and Experimental Verification Indicate That the Wave Sliding Load Characteristics Obtained from the Scale Model in the Towing Tank Provide a Reasonable Reference for the Full Aircraft's Wave Testing.

Keywords: Scale Model; Finite Element Modal Simulation; Modal Testing; Natural Frequency

1. Introduction

Ground Vibration Test (GVT) is an essential method in aerospace engineering used to measure various modal parameters of an aircraft, including modal frequencies, mode shapes, and damping. The modal data obtained through this test can be used to validate and correct the aircraft's finite element model, ensuring the accuracy and reliability of the predicted dynamic response. These test results provide the foundation for the correction of the full aircraft's finite element model, structural dynamics analysis, and flight quality analysis, making them one of the critical references for the maiden flight and certification of a new aircraft[1].For large and complex structures like aircraft, modal testing is commonly employed to gain a deep understanding of their dynamic characteristics, and based on this, the finite element model is optimized[2]. With the advancement of technology, modal testing has been widely applied in engineering practices across various industries due to its high accuracy[3-5]. If further analysis of the structure, such as aeroelastic analysis or structural response analysis, is required, modal testing becomes an essential step.

The design concepts and performance characteristics of elastic aircraft and rigid aircraft differ significantly. Compared to traditional rigid aircraft, elastic aircraft often use lightweight materials, such as composites. Additionally, elastic design can reduce the need for some traditional rigid structures. This not only ensures structural strength but also reduces the overall weight of the aircraft. On the other hand, elastic materials possess better toughness and impact resistance, enabling the aircraft to better withstand sudden external impacts, such as bird strikes or collisions with debris during flight. Furthermore, these materials can deform upon impact, absorbing shock energy and protecting the internal structure and the safety of the occupants.The piecewise elastic model test is a widely used hydrodynamic testing method. This model is constructed by segmenting the hull and connecting the segments with a keel beam to

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simulate the actual stiffness distribution[6]. The hull transmits fluid dynamic loads to the keel beam, and the segments are sealed with elastic materials, such as rubber[6]. This method is easy to manufacture and allows for accurate measurement of the hull profile loads.

The determination of the wave sliding load for seaplanes is fundamental to optimizing their structural design. During the aircraft development phase, it is necessary to design relevant models for the analysis of wave sliding load characteristics[7]. To ensure that the model's dynamic characteristics in the waves accurately map to the full-scale aircraft, and that the experimental and computational results of the aircraft model are reliable, detailed modal testing and computational analysis must first be conducted. The key to this process is ensuring that the model's natural frequency is similar to that of the actual aircraft. This similarity allows the experimental and numerical simulation results to truly reflect the dynamic characteristics of the aircraft. The similarity in natural frequencies is the basis for ensuring that the model can effectively simulate the vibration response encountered by the actual aircraft during flight, thus providing accurate data support for the aircraft's design and optimization.

However, in practical engineering, the structure of large aircraft is often constrained by site limitations and costs, making it difficult to conduct full-scale model tests. To address this issue, engineers apply the principle of similarity to scale down the aircraft model proportionally. This scaling not only involves reducing the geometric dimensions but also requires the model to retain dynamic characteristics similar to those of the full-scale aircraft. Therefore, the design of the scaled model needs to ensure structural similarity while ensuring that its lower-order modes align with the design requirements of the full-scale aircraft. Only when these modes are similar can the scaled model accurately reflect the vibration characteristics and dynamic response of the actual aircraft[8,9].

This paper obtained the natural frequencies of various mode shapes through finite element simulation and experimental measurements. By comparing the calculated values of the full-scale aircraft with the experimental values of the scaled model, it was found that the natural frequencies of the scaled model closely match the theoretical values of the full-scale aircraft. This indicates that the towing tank tests can provide valuable reference data for the dynamic response of the full-scale aircraft in waves and are also beneficial for subsequent structural optimization design.

2. Materials and Methods

In this study, the modal analysis of the model was conducted using the ABAQUS commercial software, with the scale ratio λ of the model to the full-scale aircraft set at 1:10. The mesh was generated using the HYPERMESH commercial software, employing a hybrid mesh of linear hexahedral and quadratic tetrahedral elements. Due to the small thickness and complex curvature variations of the aircraft skin, shell elements were used for modeling, with quadrilateral elements as the primary shape for the mesh. For internal structures such as beams and frames, hexahedral elements were predominantly used. Since the beams are variable cross-section hollow beams and the wall thickness of both beams and frames is small, the mesh size was reduced appropriately to ensure mesh quality. The total number of mesh elements was 792,572.

The modal analysis method employed was the Lanczos method, which is suitable for symmetric structures, efficiently calculating eigenvalues and eigenvectors with low memory usage and good parallelism. This method is ideal for vibration and modal analysis applications. Given that this model is a symmetric structure and a complex assembly with numerous components, the Lanczos method was chosen for solving the modes.

For the modal test, the Siemens LMS system was used, employing a multi-excitation point and single measurement point method to obtain the low-order mode shapes of the scaled model. A total of 112 excitation points were arranged, avoiding the rubber connection areas. The testing equipment included a data acquisition device (LMS SCADAS Mobile), a force hammer (PCB 086C03), and accelerometers (PCB 333B50). The measurement and analysis software used was Simcenter Testlab. The test was conducted using an installation method where the model was mounted with beeswax bonding.

The modal test simulated the free-body modes of the fuselage, with the model suspended using elastic ropes. To ensure the reliability of the test results, the rigid body mode frequencies of the aircraft in the elastic rope suspension state had to be less than 1 Hz. Due to uncertainties in the supporting stiffness and boundary conditions, which resulted in poor repeatability, multiple measurements were taken, and the average value was used for analysis.

3. Elastic Model Structural Design

3.1. Overall Design

The elastic deformation of slender bodies, such as ships and aircraft, is coupled with the fluid loads they experience. Since seaplanes are relatively light in weight and have low stiffness, they cannot be treated as rigid bodies. Therefore, it is essential to study them using elastic test models. Elastic models have already been well developed and applied in the motion of hulls and wave loads, and extending these methods to aircraft-related tests is feasible.

Elastic models can generally be divided into two categories: global elastic models and piecewise elastic models. While global elastic models can reflect both the overall and local elastic responses, their practical application is limited due to difficulties in finding suitable materials for the scale model, especially when considering the scale ratio. For slender hulls and aircraft structures, the piecewise model is highly effective in simulating the overall deformation of the hull or aircraft and is easier to implement. This deformation is typically measured using a keel centerline beam arranged inside the hull, which is why piecewise elastic models are widely applied in hull wave load testing.

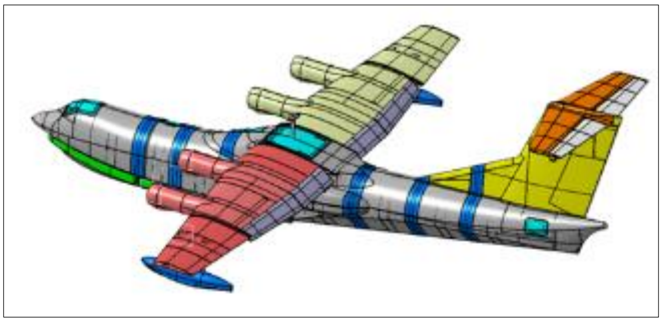


Figure 1 Full-Scale Aircraft Scale Model

The full-scale aircraft scale model is shown in Figure 1. It consists of several components, including the fuselage, wings, horizontal tail, vertical tail, and others. The fuselage is designed using a piecewise approach, while the wing is designed as a single, integrated unit.

3.2. Airframe design

The fuselage structure is designed based on the mass distribution, stiffness, and natural frequencies of the full-scale aircraft. The fuselage adopts a piecewise structure, consisting of 7 segments in total. To prevent adjacent segments from colliding during testing due to elastic deformation of the keel beam, a small gap is left at the cut-off locations. After the structural design, optimization is performed to ensure that the model satisfies the mechanical similarity with the original prototype structure.

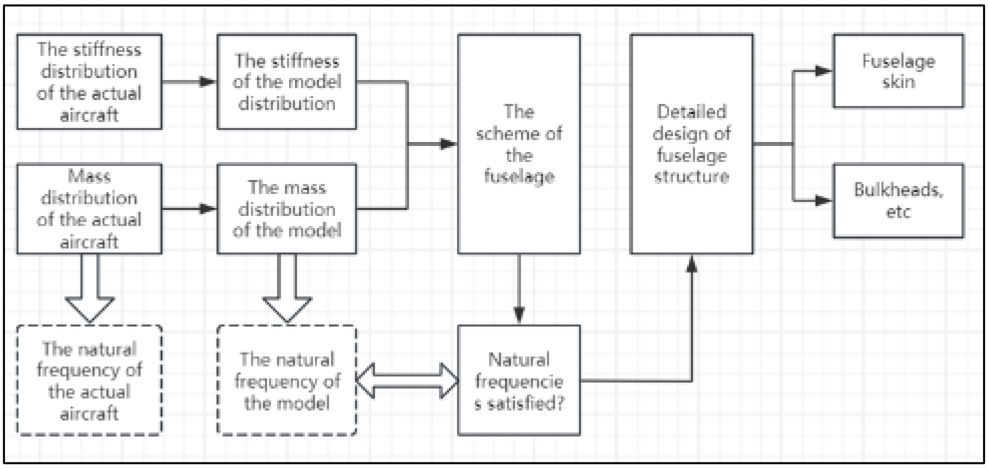


Figure 2 Fuselage Design Flowchart

The fuselage structure is shown in Figure 3. It is primarily composed of variable cross-section keel beams, frame supports, and bulkheads. Since the skin does not provide stiffness, the stiffness is mainly provided by the keel beams. The external skin has 6 cut-outs, dividing the fuselage into 7 segments. To prevent adjacent segments from colliding during testing due to elastic deformation of the keel beams, a small gap is left at the cut-out positions. The blue areas in the figure represent rubber, which serves both to connect the different segments of the fuselage and to provide an effective waterproofing function.

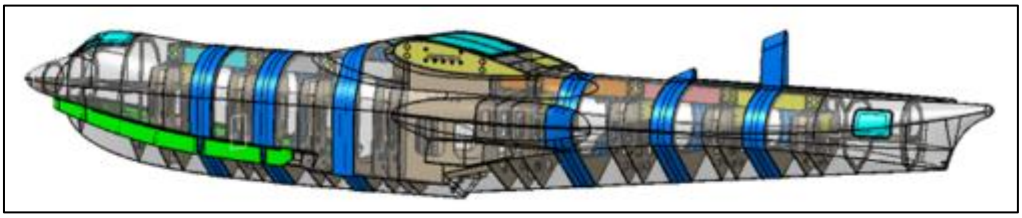


Figure 3 Fuselage Structure Diagram

3.3. Wing design

The wing model of the aircraft adopts a "metal beam + composite skin" beam-and-frame structure. The metal beam mainly simulates the stiffness characteristics of the wing, while the composite material's ribbed structure simulates the wing's shape and provides a relatively lower model stiffness. The mass characteristics of the wing are simulated by the model's structure and counterweight mass. The advantage of this structural form is that the primary characteristics of the wing are simulated by relatively independent model components, minimizing mutual interference and improving the design accuracy of the model.

To ensure that the structural dynamics of the model closely match those of the full-scale aircraft, NASTRAN is used for structural optimization, and the optimization process is shown in Figure 4.

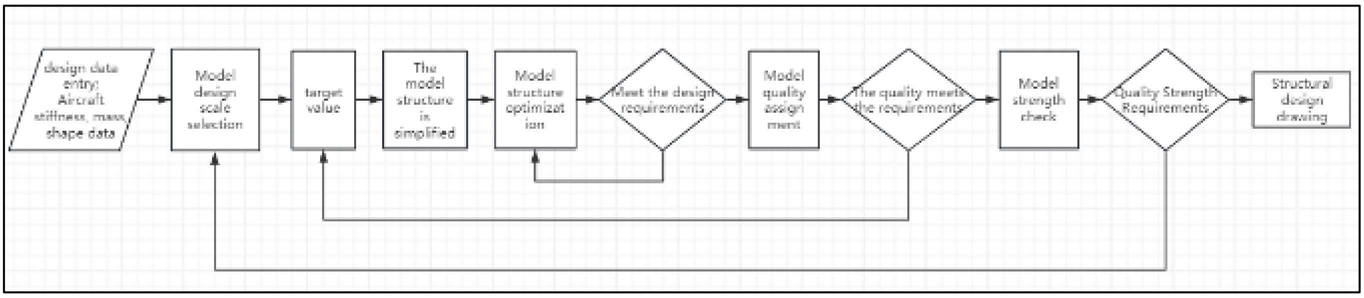


Figure 4 Wing Optimization Flowchart

The optimized wing structure is shown in Figure 5.

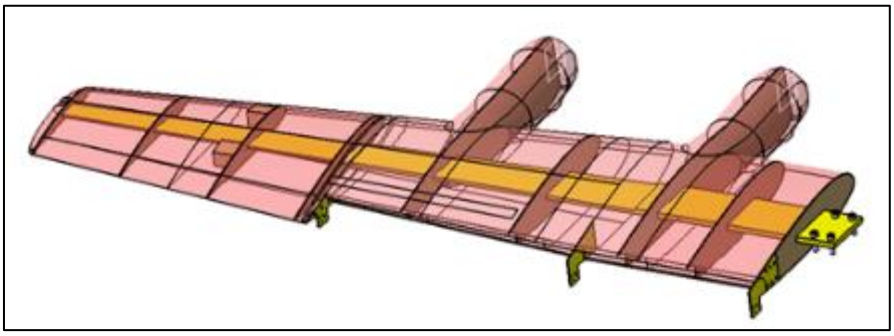


Figure 5 Wing Structure Diagram

4. Full-Scale Aircraft Modal Analysis

4.1. Finite Element Model

Since the full-scale aircraft is composed of multiple components and has a complex structure, with several openings at various locations, it is difficult to obtain the system's natural frequencies through theoretical calculations. In this study, finite element simulation was used to obtain the modal parameters of the full-scale aircraft. The modal frequencies and mode shapes of the fuselage, wings, and the entire aircraft were calculated. First, a finite element model of the full-scale aircraft was established, as shown in Figure 6. The scale ratio λ of the model to the full-scale aircraft is 1:10.

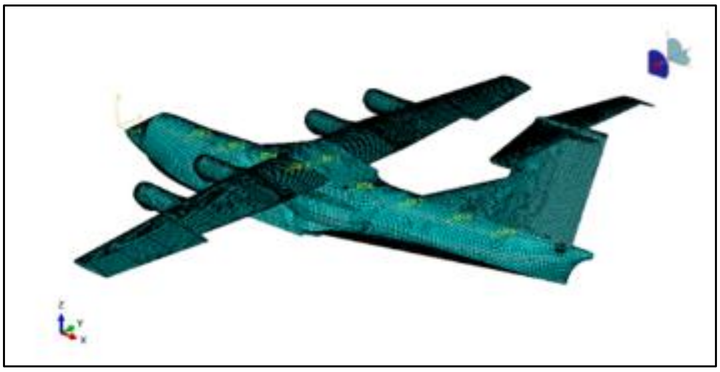


Figure 6 Full Aircraft Finite Element Model

A mixed mesh of linear hexahedrons and quadratic tetrahedrons was used. The fuselage skin, due to its small thickness and complex curvature, was modeled using shell elements, with the mesh predominantly consisting of quadrilateral elements. For the internal structure, such as beams and bulkheads, hexahedral mesh elements were mainly used. Since the beams are variable cross-section hollow beams and both the beams and bulkheads have small wall thicknesses, the element size was appropriately reduced to ensure mesh quality.

4.2. Solution Method

In the analysis step, frequency analysis was selected under linear perturbation. ABAQUS software provides three solving methods: Lanczos, Subspace, and AMS. Compared to the latter two methods, the Lanczos method has the following advantages:

- 1.Efficiency: Designed specifically for symmetric systems, the Lanczos method is particularly well-suited for symmetric or Hermitian matrices. It can efficiently find eigenvalues and eigenvectors, especially when dealing with sparse matrices. In the case of structural symmetry, the Lanczos method converges more quickly[10].
- 2.Low Memory Usage: The Lanczos method typically requires less memory, making it suitable for large sparse systems. It only needs to store a small number of vectors rather than the entire matrix[11].
- 3.Parallel Computation: The Lanczos algorithm can be parallelized, which allows it to achieve better performance on modern computing architectures such as multi-core processors or GPU[12].

In summary, the Lanczos method is suitable for symmetric structures, offering efficient computation of eigenvalues and eigenvectors with low memory usage and good parallelization, making it ideal for vibration and modal analysis applications. Given that this model is a symmetric structure with a complex assembly, the Lanczos method was chosen to solve the modal analysis.

4.3. Results Processing

Since the natural frequencies of the full-scale aircraft and the model cannot be directly compared, according to the theory of structural vibration similarity[13], it is known that..

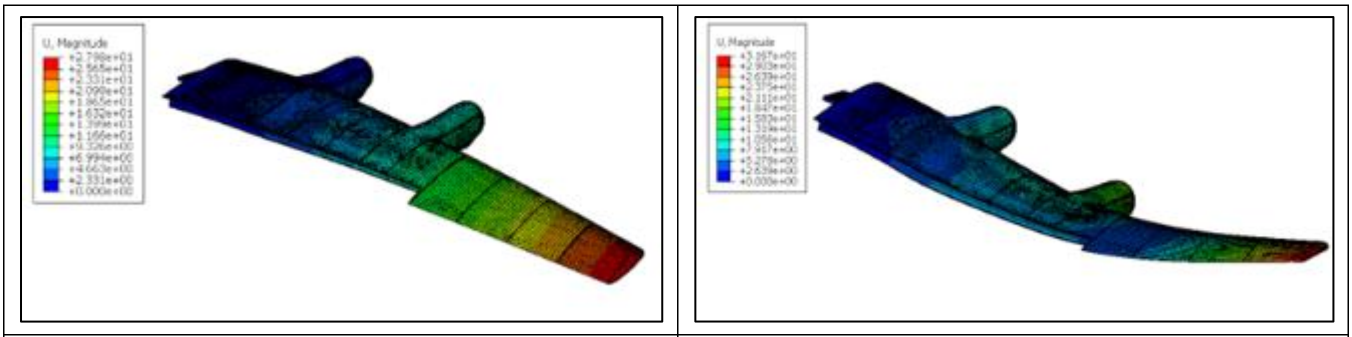
$$f_m = f_s / \sqrt{\lambda} \quad \text{................(1)}$$

Where f_m is the natural frequency of the model, λ is the scale ratio, and f_s is the natural frequency of the full-scale aircraft. In this study,λ=0.1.

4.4. Finite Element Results

4.4.1. Wing Modal Analysis

The first and second-order bending mode shapes of the wing are shown in Figure 7, with the processed natural frequencies being 5.77 Hz and 28.93 Hz, respectively.

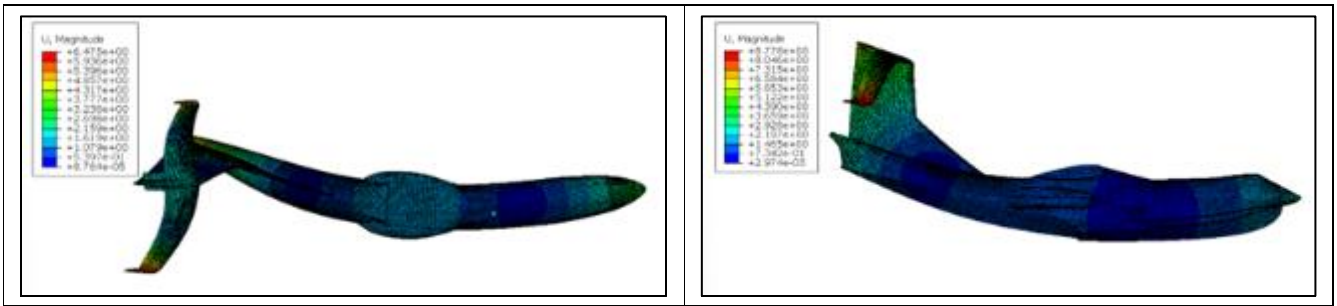


(a)First-order bending　　(b) Second-order bending

Figure 7 Wing Finite Element Modal Shapes

4.4.2. Fuselage Modal Analysis

The first-order horizontal and vertical mode shapes of the fuselage are shown in Figure 8, with the processed natural frequencies being 20.73 Hz and 12.57 Hz, respectively.



(a) First Order Horizontal　　(b)First Order Vertical

Figure 8 Fuselage Finite Element Modal Shapes

4.4.3. Full Aircraft Modal Analysis

The symmetric first-order mode shape of the full aircraft is shown in Figure 9, with the processed natural frequency being 6.37 Hz.

Figure 9 Symmetric First-Order Mode of the Entire Aircraft

The above are the calculated modes for the full-scale aircraft. Although the calculated modes of the optimized model are the same as those of the full-scale aircraft, there may be certain discrepancies between the stiffness data obtained through the computational methods and the actual conditions. This could lead to errors in the natural frequencies, especially in the areas where the wings and fuselage, as well as the horizontal and vertical tails and fuselage, are connected, where the discrepancies may be more significant. Therefore, it is necessary to make corrections based on the results of the full aircraft ground vibration test, which will also provide a basis for subsequent model optimization.

5. Scaled Model Modal Test

5.1. Test Conditions

The modal test was conducted using Siemens' LMS system, employing a multi-excitation point, single measurement point method to obtain the low-order mode shapes of the scaled model. Considering the large size of the model, a total of 112 excitation points were arranged to more effectively present the mode shapes in a three-dimensional manner, avoiding the rubber connection areas. The test equipment included a data acquisition system (model LMS SCADAS Mobile), a hammer (model PCB 086C03), and an accelerometer (model PCB 333B50). The measurement and analysis software used was Simcenter Testlab.

The test simulated the fuselage modes in a free state, where the aircraft model was fixed at a certain height above the ground using elastic ropes. This setup ensured that the model remained horizontal, with both the pitch and roll angles of the aircraft set to zero. The actual suspension method is shown in Figure 10.

(a) Full Aircraft Test Suspension Diagram

(b) Wing test diagram

(c) Fuselage test hoisting drawing

Figure 10 Model Testing Diagram

To measure the modal frequencies of the model in its free state, it is necessary to ensure that the rigid body motion frequencies of the test aircraft (heave, pitch, and roll) under elastic support are less than one-third of the aircraft's lowest natural frequency. This condition allows the aircraft to simulate a free-free state[14,15]. According to the frequency formula of a single-degree-of-freedom vibration system, it is known that:

$$\omega_s = \sqrt{\frac{k_s}{m_s}} \quad \text{..................(2)}$$

In this context, ω_s represents the support frequency, k_s is the total stiffness of the elastic ropes, and m_s is the mass of the tested object.

In the current experiment, the rigid body mode frequencies of the aircraft in the elastic rope suspension state were all less than 1 Hz, ensuring the reliability of the test results.

5.2. Test results

5.2.1. Wing modality

The geometry of the wing constructed in the software's Geometry module is shown in Figure 11. A total of 12 excitation points are arranged on one side of the wing, with the accelerometer attached to the right wing at point 7.

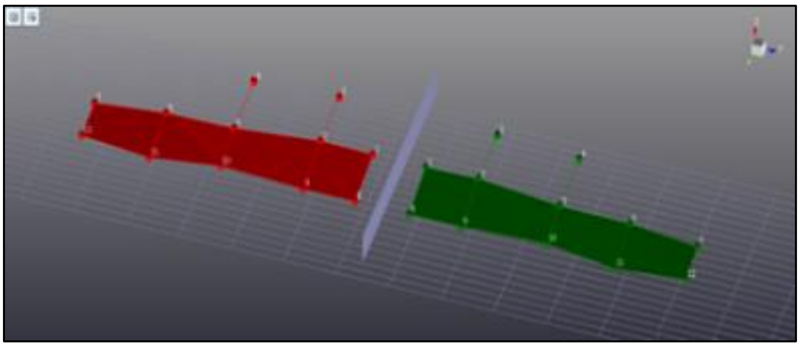


Figure 11 Wing Test Geometry Diagram

The wing measurement data was imported, and since the primary focus is on the low-frequency modes of the model, a frequency bandwidth of 0 to 100 Hz was selected. The poles were chosen based on the steady-state plot, as shown in Figure 12. However, not all poles correspond to the global modes; some poles may correspond to local modes. It is necessary to determine the corresponding mode shapes for each pole to make an accurate judgment.

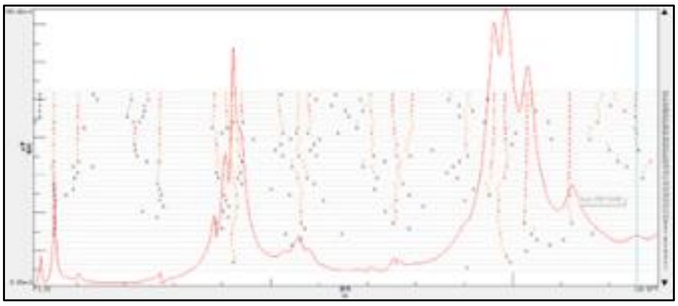
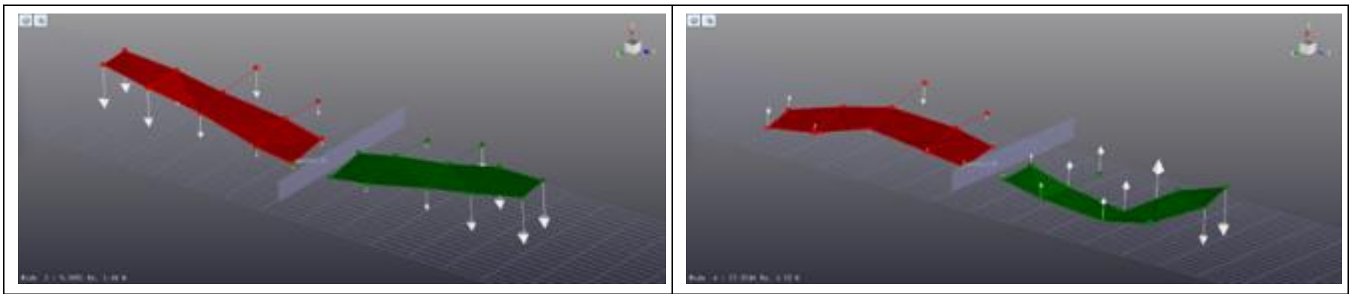


Figure 12 Wing Steady-State Diagram

The first and second-order bending mode natural frequencies of the wing are 5.38 Hz and 27.22 Hz, respectively. The mode shapes are shown in Figure 13.

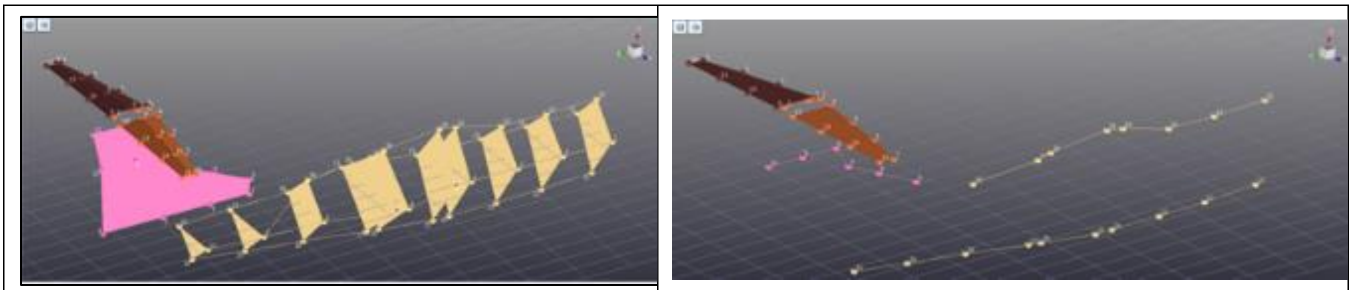


(a)First-order bending	(b) Second-order bending

Figure 13 Wing Test Mode Shapes

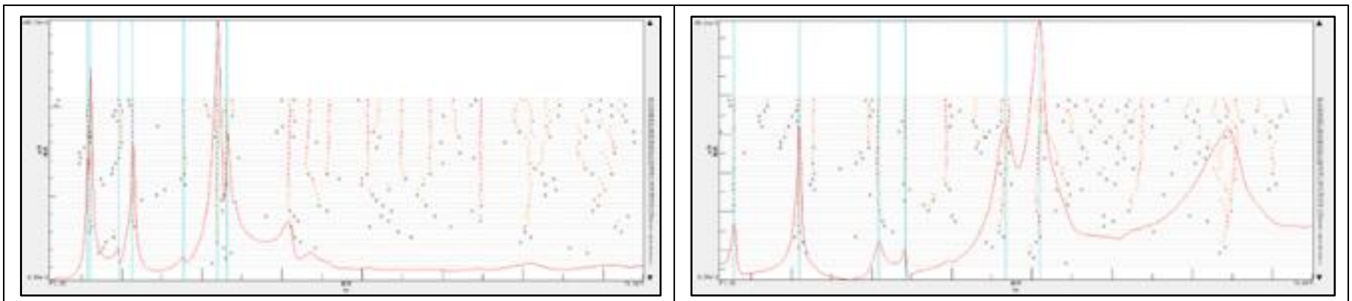
5.2.2. Fuselage modality

A total of 78 excitation points were arranged for measuring the horizontal mode of the fuselage, and 43 excitation points were arranged for measuring the vertical mode. The fuselage geometry is shown in Figure 14, and the steady-state plot of the fuselage is shown in Figure 15.



(a) Horizontal modal geometry	(b) Vertical modal geometry

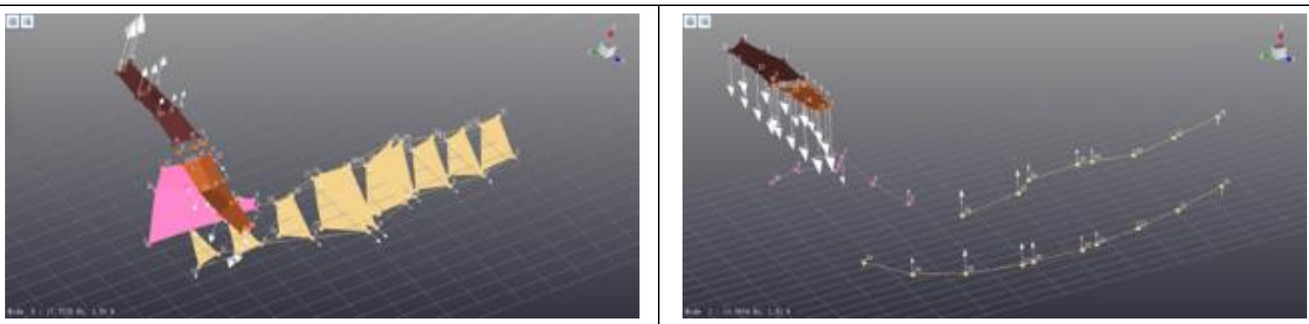
Figure 14 Geometry of the fuselage test



(a) Horizontal steady state diagram	(b) Vertical steady-state diagram

Figure 15 Steady state diagram of the fuselage

The first-order horizontal and vertical mode shapes of the fuselage were selected from the mode shape plots corresponding to each pole, as shown in Figure 16, with frequencies of 17.76 Hz and 10.96 Hz, respectively.



First Order Horizontal	First Order Vertical

Figure 16 Mode shape of the fuselage test

5.2.3. Full aircraft modality

A total of 112 excitation points were arranged for the entire aircraft. The geometry of the entire aircraft is shown in Figure 17. The measurement data for the entire aircraft was imported, and the steady-state plot of the entire aircraft modal is shown in Figure 18.

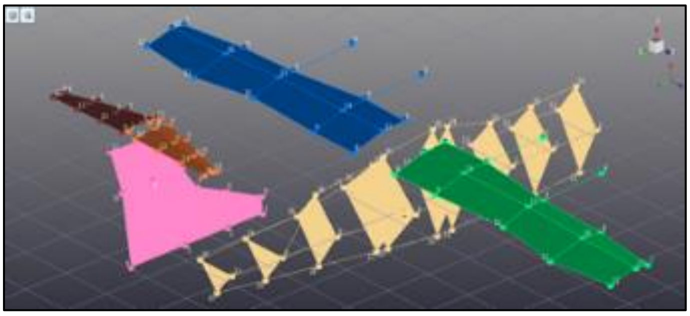


Figure 17 Geometry of the Full aircraft test

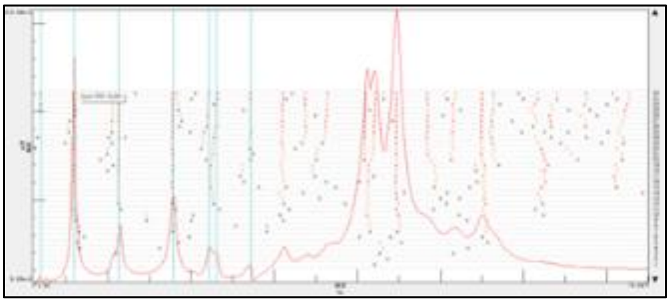


Figure 18 Steady-state diagram of the Full aircraft

The symmetric first-order mode shape of the entire aircraft is shown in Figure 19, with a frequency of 5.92 Hz.

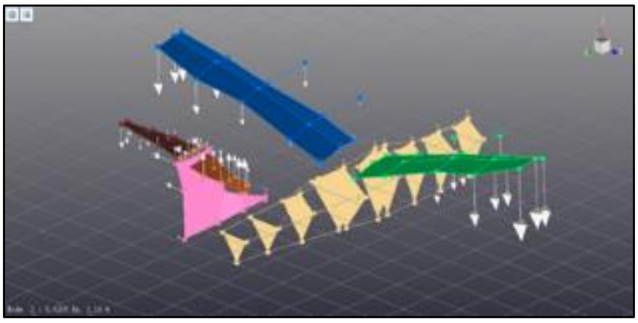


Figure 19 Symmetrical first-order mode shape of the whole machine

6. Results and Error Analysis

Table 1 presents a comparison between the full-scale aircraft simulation results and the experimental results of the scaled model.

Multiple repeated measurements were taken, and it was observed that the experimental values were consistently lower than the simulation values. After inspection, it was found that the model's actual weight was approximately 44 kg, exceeding the theoretical design weight by 1.7 kg. Specifically, the wing portion was overweight by 0.6 kg, and the fuselage portion was overweight by 1.1 kg. The primary cause of this excess weight was the overuse of epoxy resin. On the other hand, in the real structure, many components are connected using bolts, which results in a certain degree of elasticity at the connections, rather than perfectly rigid connections. However, during finite element analysis (FEA), this elasticity is generally ignored, and the connections are assumed to be perfectly rigid.

In addition, there are many possible reasons for the error of modal test and simulation results, such as deviation of material properties, installation error of the specimen, the influence of environmental conditions (such as temperature and humidity), and the small shaking of the model itself during data acquisition.

According to Table 1, the comparison between the finite element analysis results and the experimental results shows that the low-order modal frequencies for the wing, fuselage, and entire aircraft are in close agreement, with relatively small errors. This suggests that the scaled model of the segmented elastic body aircraft satisfies the basic condition of having similar natural frequencies to the full-scale aircraft. The results from the scaled model provide a reliable foundation for the dynamic characteristics to be mapped onto the full-scale aircraft in future wave slippage tests. This will, in turn, support subsequent theoretical analyses and structural optimization design.

Table 1 Finite Element Simulation vs Experimental Results Comparison

	Mode Shape	**Finite Element Simulation Values (Post-Processing) / Hz**	**Test Modal Value / Hz**	**Error**
Wing	First-order bending	5.77	5.38	-6.8%
	Second-order bending	28.93	27.22	-5.9%
Fuselage	First Order Horizontal	20.73	17.76	-14.3%
	First Order Vertical	12.57	10.96	-12.8%
Full aircraft	Symmetric First Order	6.37	5.92	-7.1%

7. Conclusion

This study conducted a finite element modal analysis on a segmented elastic body aircraft and performed modal tests on its scaled model to obtain the low-order modal shapes and natural frequencies. A comparison was made between the simulation results for the full-scale aircraft and the experimental results of the scaled model, leading to the following conclusions:

- Structural Design of the Scaled Model: Based on the mass distribution, stiffness distribution, and natural frequencies of the full-scale aircraft, the model was structurally designed with a segmented fuselage. After optimization, the natural frequencies of the model matched the calculated values of the full-scale aircraft.
- Modal Analysis and Test Comparison: Modal analysis was performed on the full-scale aircraft, and modal tests were conducted on the scaled model. The experimental data were compared with the finite element modal results. The main source of error was found to be the overweight of the model during manufacturing, though factors such as material properties and environmental influences may also contribute to the discrepancies.
- Validation of the Scaled Model: The natural frequency results of the full-scale aircraft and the scaled model were close in value, confirming that the scaled model can provide dynamic response data closely resembling that of the real aircraft. The experimental results from the scaled model were cross-validated with the finite element simulation results for the full-scale aircraft. The similarities between the modal analysis and experimental verification results indicate that the scaled model's performance in the towing pool, particularly its wave slippage load characteristics, can serve as a reliable reference for the full-scale aircraft in wave-based testing.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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