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Simplification and Performance Analysis of Biomimetic Flapping-wing Aircraft Wing Model

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***Abstract*:** This study aims to simplify the wing model of a biomimetic flapping-wing aircraft and assess the performance of the simplified model through mechanical analysis. The results show that by removing finer parts of the wing veins, the error between the natural frequencies of the simplified model and the actual flapping frequency of dragonflies is within 3%, meeting the design requirements for flapping-wing aircraft. Modal analysis indicates that the simplified wing model closely matches the actual flapping frequency of dragonfly wings, fulfilling the design criteria for biomimetic flapping-wing aircraft. Transient dynamic analysis reveals that the displacement variation of the wing corresponds well with static analysis results, demonstrating the simplified biomimetic wing model's favorable dynamic response characteristics. Thus, the findings of this study hold significant implications for the further design and optimization of biomimetic flapping-wing aircraft.

Keywords: *biomimetic flapping-wing aircraft, wing model, mechanical analysis, modal analysis*

I. INTRODUCTION

Micro Air Vehicles (MAVs) are currently in a rapid development phase, with wide-ranging applications in both military and civilian sectors. MAVs can be classified into fixed-wing aircraft, rotary-wing aircraft, and flapping-wing aircraft based on their wing motion characteristics. Among these, flapping-wing aircraft, unlike the former two, have not been widely used despite the fact that the majority of flying organisms in nature employ flapping-wing flight[1]. In recent years, biomimetic flapping-wing aircraft have gradually gained attention, with dragonflies being a typical example of insects utilizing flapping-wing flight and exhibiting excellent flight capabilities, thus becoming a focal point in the research of biomimetic flapping-wing aircraft.

The wing structure of a dragonfly is unique, composed of tubular wing veins and wing membranes with certain rigidity at the microscopic level. The wing veins are hollow and distributed in a network pattern, dividing the wing membrane into geometric structures such as triangles, quadrilaterals, and pentagons[2,3]. The wing veins are formed by layers of chitin and protein, while the wing membrane is primarily composed of protein[4]. As a crucial component and the source of propulsion for biomimetic flapping-wing aircraft, the wing plays a significant role in determining the flight performance through its material, shape, structure, and flapping motion during the design process.

Research has shown that the wing morphology of dragonflies significantly influences their flight behavior. Researchers have been studying the performance of wings using finite element analysis since the end of the last century[5]. In 2008, Ying Li et al. investigated the microstructure of dragonfly wing veins using finite element analysis, providing a biomimetic perspective for constructing micro air vehicles[6]. In 2015, Praveena Nair Sivasankaran et al. studied the feasibility of manufacturing artificial dragonfly-like wing frames using materials commonly used in drones (light wood, black graphite carbon fiber, and red pre-impregnated glass fiber)[7]. In 2017, Dan Hou et al. investigated passive deformation under aerodynamic loads and active flapping of wings, summarizing the role of soft vein joints in dragonfly flight[8]. In 2022, He Yuanyuan et al. employed principal component analysis to elucidate the correlation between the bending stiffness of insect wings and their geometric morphological parameters[9]. Currently, research on dragonfly wings mainly focuses on their structural and aerodynamic aspects, with relatively fewer studies on practicality and application rationality[10-12]. This paper conducts finite element analysis on the established wing model based on the characteristics of dragonfly wings, compares the mechanical properties of wing models under different material parameters, selects the optimal model, simplifies the model, and analyzes the mechanical performance of the simplified model, providing insights for further research on biomimetic dragonfly wings.

II. PRINCIPLE OF FINITE ELEMENT ANALYSIS OF DRAGONFLY WING

The material properties of biomimetic wings have a significant impact on the performance of aircraft. In this study, a biomimetic wing model was established based on the characteristics of dragonfly forewings by collaborating group members.

Based on finite element theory, a finite element mechanics analysis was performed on a forewing model. This analysis involved comparing the static and modal analyses of three distinct materials to ascertain the stiffness and vibration attributes of the wings, including their natural frequencies and mode shapes. Furthermore, the model was simplified, and the mechanical performance and dynamic response of the simplified model were analyzed.

The basic principle of the finite element method involves dividing the model into elements and then using a mathematical model to describe the interactions between the elements, which mainly consists of pre-processing, solving, and post-processing. In this study, ANSYS software was used for finite element analysis to investigate the mechanical performance of wings, including static analysis, modal analysis, etc.

Modal analysis describes how the model vibrates through essential features such as natural frequencies and mode shapes. It is one of the main methods for studying the dynamic characteristics of the model and forms the basis of dynamic analysis. The dynamic control equation for modal analysis is shown in (1).

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=\{F(t)\} \qquad (1)$$

Where $[M]$ is the mass matrix of the model, $[C]$ is the damping matrix, $[K]$ is the stiffness matrix, $\{F(t)\}$ is the external force load function changing with time, and $\{x\},\{\dot{x}\},\{\ddot{x}\}$ are the displacement vector, velocity vector, and acceleration vector of the node respectively.

Since external forces do not need to be considered in modal analysis, the dynamic control equation of modal analysis can be expressed as (2).

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=\{0\} \qquad (2)$$

Moreover, under ideal conditions, damping effects are neglected during the vibration process of the model, known as free vibration. Therefore, modal analysis can also be described as (3).

$$[M]\{\ddot{x}\}+[K]\{x\}=\{0\} \qquad (3)$$

Assuming the free vibration is a harmonic response, $x=x_0\sin(2\pi ft)$ represents the natural frequency of the model, the above equation can be described as (4).

$$([M](2\pi f)^2-[K])\{x\}=\{0\} \qquad (4)$$

Solving this equation yields the characteristic value f^2, whose square root is f, representing the natural frequency, or vibration frequency, of the model.

Transient mechanics analysis is used to analyze the structural dynamic response of loads varying with time. The motion equation used for transient dynamic analysis is consistent with the general motion (5), representing the most general form of transient dynamic analysis. The load can be any function of time, and modal superposition method is used for solving. Modal superposition method is based on modal analysis and represents node displacement y_i as a linear combination of modal coordinates $\{u\}$, specifically formulated as (5).

$$\{u\}=\sum_{i=1}^{n}\{\phi_i\}y_i \qquad (5)$$

Where $\{\phi_i\}$ is the *i*-th mode shape, and *n* is the number of modes extracted.

III. DRAGONFLY WING FINITE ELEMENT MODELING AND ANALYSIS

Analysis of dragonfly wing materials

Different materials have a significant impact on the mechanical performance of wings, and studying the characteristics of wings under different materials is crucial for the design of subsequent biomimetic flapping-wing aircraft. Based on the composition of dragonfly wings, materials with parameters similar to those of the wings are selected for simulation[13]. Polyester resin (PET), epoxy resin (EP), and nylon are chosen for comparative analysis of the mechanical performance of biomimetic wings under these three materials, aiming to identify the optimal material for the subsequent design of biomimetic wing models.

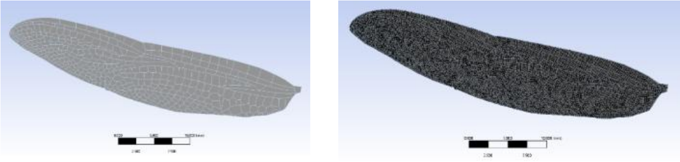
Since each material's parameters vary within a certain range, the specific parameters of the three materials studied in this paper are shown in TABLE I.

TABLE I. THREE MATERIAL PARAMETERS

Material	***Density (kg/m^3)***	***Young's Modulus (GPa)***	***Poisson's Ratio***
Polyester resin	4	0.3	1380
Epoxy resin	1	0.38	1300
Nylon	3.5	0.28	1150

A. *Physical characteristic parameters of wing membrane*

The model consists of dragonfly forewings with mesh partitioning. The wing veins are modeled using PIPE16 elements, which are single-axis elements suitable for stretching, twisting, and bending analyses. Each node of the PIPE16 element has six degrees of freedom. This element is based on a three-dimensional beam element, simplified by symmetrically utilizing standard pipe cross-sections. The wing membranes are represented by SHELL63 elements, capable of both bending and membrane actions, capable of withstanding in-plane and normal loads. Each node of the SHELL63 element has six degrees of freedom. The mesh partitioning size for both wing veins and membranes is set to 0.125mm. The specific model and mesh partitioning are illustrated in Fig. 1.

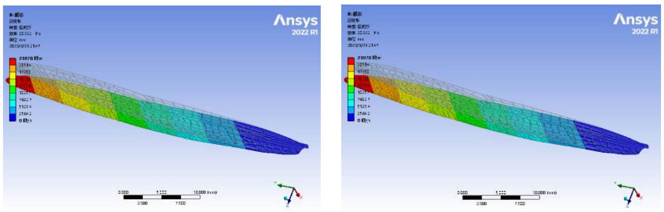


(a) wings model figure (b) mesh generation

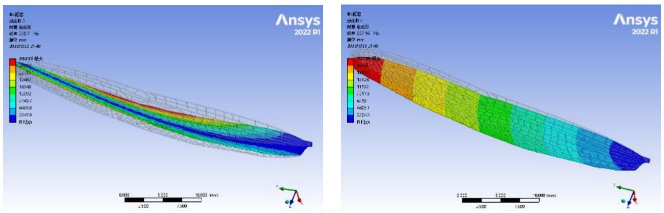
Fig. 1. Model building

B. *Model Solution*

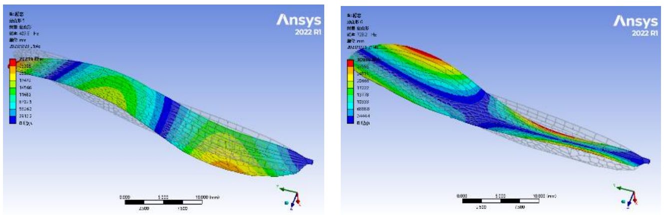
Modal analysis was conducted on the wing models made of three different materials. The first step was to determine the loads and boundary conditions. In typical modal analysis processes, only zero displacement constraints are considered as effective loads. Therefore, for the modal analysis of biomimetic wings, zero displacement constraints were applied only at the wing root. Modal expansion was then performed, as shown in Fig. 2, and after computation, the first six natural frequencies for each material were obtained, as shown in TABLE II.



first order second order



third order fourth order



fifth order sixth order

Fig. 2. Figure of the first six modes of polyester resin material

TABLE II. FIRST SIX NATURAL FREQUENCIES OF THE MODEL

Order	Modal frequency（Hz）					
	First order	*second order*	*third order*	*fourth order*	*fifth order*	*sixth order*
Polyester resin	20.992	134.17	220.7	339.16	409.8	728.2
Epoxy resin	7.9186	50.161	80.911	125.3	154.38	266.17
Nylon	16.569	105.9	174.19	267.69	323.44	574.75

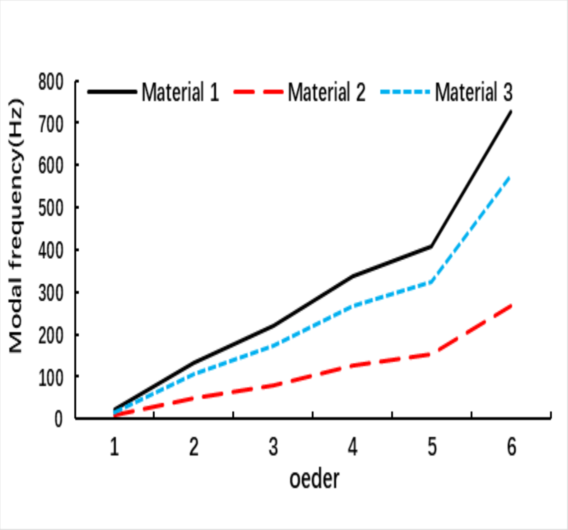


Fig. 3. The first six natural frequencies of three materials

Comparing the modal analysis results of the three materials reveals that the first mode is characterized by bending deformation, while the second mode exhibits torsional deformation. The variation curves of the first six modal frequencies for the three materials are illustrated in Fig. 3. Comparing the first mode frequencies of the three materials, which represent the natural resonant frequencies of the wing model under different materials, indicates a significant influence of material choice on the wing model's natural frequencies.

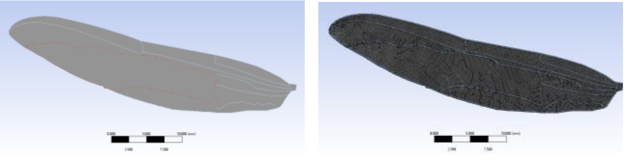
C. *Results Analysis*

By comparing different material parameters and observing wing deformations, it is evident that the degree of deformation in the wing model can be adjusted by tuning the material parameters under specific model conditions. For the static and modal analyses of the biomimetic dragonfly wing model conducted in this study using three selected materials, stiffness and the first natural frequency of each material model were obtained. Based on the actual flight conditions of dragonflies, a material that closely resembles their flight state was chosen as a reference for subsequent research. Considering the actual flapping frequency of dragonflies and the composition of their wings, nylon material was selected for further study.

IV. WING VEIN SIMPLIFIED SIMULATION ANALYSIS

A. *Wing Vein Simplified Model*

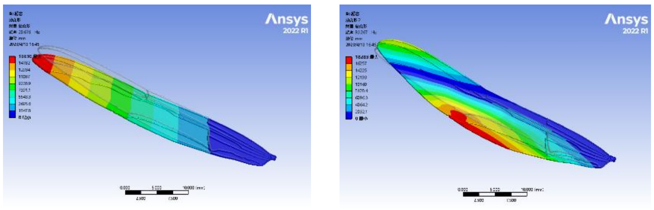
Considering the practical constraints at the root of the wing and the necessity to minimize the weight of micro flapping-wing aircraft due to the challenges in actual machining, the wing veins need to be simplified. Based on the deformation and stress distribution of the model under uniform loads, most of the main veins of the wing are retained while the thinner wing veins are removed. Since wing veins are hollow tubular structures, they are simplified to solid structures. The simplified model and mesh division results are illustrated in Fig. 4.



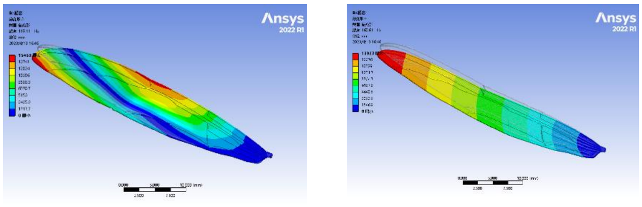
(a) simplified model (b) mesh generation

Fig. 4. The simplified model and its mesh division

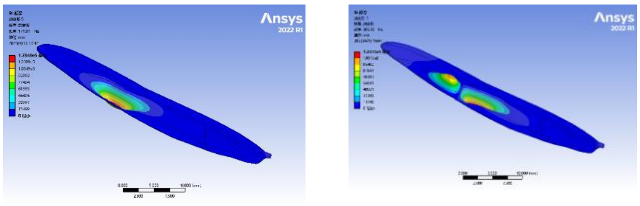
Mechanical performance analysis is conducted on the simplified model using nylon material. To ensure the reliability of the results, the parameters for mesh division of the model are kept consistent with those set for the original model. Similarly, the loading and boundary conditions for modal analysis are also kept consistent with those of the original model. The specific settings are shown in Fig. 5 and TABLE III.



first order second order



third order fourth order



fifth order sixth order

Fig. 5. Modal analysis results of simplified model

TABLE III. THE FIRST SIX NATURAL FREQUENCIES OF THE SIMPLIFIED MODEL

	First order	*second order*	*third order*	*fourth order*	*fifth order*	*sixth order*
frequency	20.676	93.267	119.11	160.61	171.81	205.38

Transient Dynamic Analysis of the Model, In transient dynamic analysis, it is essential to determine the excitation function driving the biomimetic wing structure. Considering a sinusoidal function with time-varying characteristics, the function is defined as (6).

$$F = A\sin(2 * \pi * f * t) \tag{6}$$

The primary focus is on examining the influence of natural frequencies on the vibration characteristics of the wing model. Therefore, referring to the first natural frequency of the simplified wing model, with f set to 20 Hz, we investigate the dynamic response of the model at this frequency. This calculation neglects the effects of air resistance. Based on the previous simulation calculations of the wing model, the load steps and sub-steps are determined as shown in Table IV.

TABLE IV. LOAD STEP AND SUBSTEP SETTING

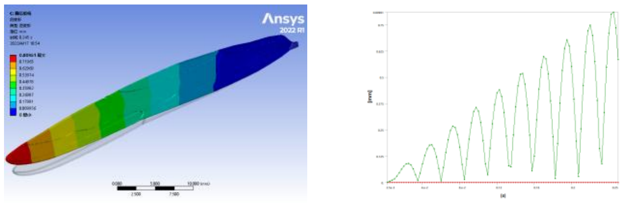
excitation frequency f(Hz)	*period T（s）*	*Step end time 5T（s）*	*time stepping T/20（s）*
20	0.05	0.25	0.0025

For the biomimetic wing model, the nodes where displacement and stress responses are maximized under sinusoidal excitation load are the most critical points of concern. Typically, the location with the maximum displacement response is at the rear of the wing model, farthest from the wing root. Conversely, the location with significant stress response tends to be near the wing root. Given the simplification of the wing model in this section, it's observed that stress distribution tends to be uniform, with a primary concentration near the center of the wing model. The dynamic response outcomes are detailed in TABLE V.

TABLE V. DYNAMIC RESPONSE RESULT

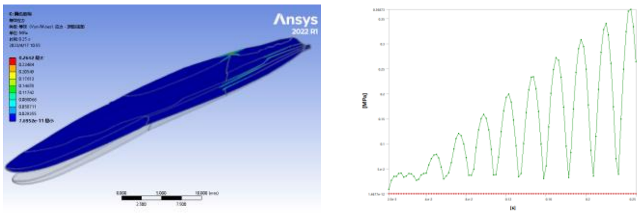
excitation frequency（Hz）	*total deformation（mm）*	*equivalent stress（MPa）*
20	0.80961	0.36873

Based on the finite element analysis calculations, deformation and stress contour plots for the front wing model were obtained.



displacement nephogram

time history curve of maximum displacement point



stress nephogram

time history curve of the point of maximum stress

Fig. 6. Dynamic response of the simplified model

For the biomimetic wing model, the focus lies on the nodes exhibiting maximum displacement and stress responses under sinusoidal excitation load. The maximum displacement node is typically located at the wing structure's tip, while the maximum stress node is situated near the wing root region, as depicted in Fig. 6.

B. Comparison Analysis Before and After Wing Vein Simplification

Comparing the modal analysis results of the wing model before and after simplification, the results are shown in TABLE VI and Fig 7.

By removing most of the finer wing veins of the wing model, there have been certain changes in the first and second natural frequencies after simplification. Since the flapping frequency of dragonfly wings is typically between 10-20Hz, the error between the natural frequencies of the simplified wing model and the actual flapping frequency of dragonflies is around 3%. This error is relatively small and meets the requirements for the design of flapping-wing aircraft.

TABLE VI. COMPARISON OF MODAL FREQUENCIES BEFORE AND AFTER SIMPLIFICATION

	First order	*second order*	*third order*	*fourth order*	*fifth order*	*sixth order*
Before Simplification	7.9186	50.161	80.911	125.3	154.38	266.17
After Simplification	20.676	93.267	119.11	160.61	171.81	205.38

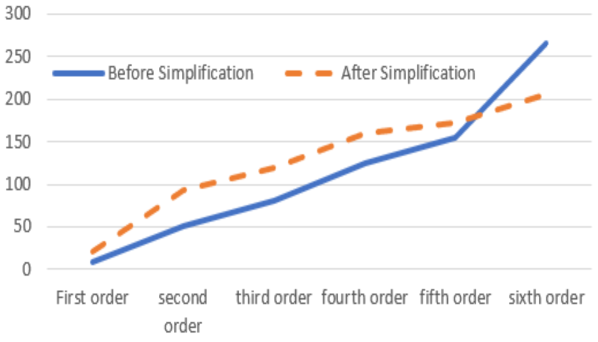


Fig. 7. Simplified before and after modal frequency comparison diagram

In this section, the wing model was simplified, and the mechanical performance of the simplified model was analyzed. From the modal analysis results, the simplified wing model is closer to the actual flapping frequency of dragonfly wings, thus better meeting the design requirements for biomimetic flapping-wing aircraft. Regarding the transient dynamic analysis results, the displacement variation of the wing is consistent with the static analysis results, with displacement changes starting from the wing root and increasing as one moves away from the root. This indicates a high degree of similarity in the dynamic response of displacement and stress for biomimetic wings, highlighting the significant impact of wing model characteristics on its dynamic properties.

V. CONCLUSION

This study simplified the wing model of a biomimetic flapping-wing aircraft and evaluated the simplified model through mechanical performance analysis. The results indicate that by removing finer portions of the wing veins, the error between the natural frequencies of the simplified model and the actual flapping frequency of dragonflies is within 3%, meeting the requirements for the design of flapping-wing aircraft. Modal analysis results demonstrate that the simplified wing model is closer to the actual flapping frequency of dragonfly wings, aligning well with the design requirements for biomimetic flapping-wing aircraft. Transient dynamic analysis results show that the displacement variation of the wing is consistent with static analysis results, indicating that the simplified biomimetic wing model possesses good dynamic response characteristics consistent with real-world scenarios. Therefore, the findings of this study are of great significance for further designing and optimizing biomimetic flapping-wing aircraft.

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