Vibration analysis and simulation of composite fan blades with various laminate configurations

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ABSTRACT

Composite blades, known for their exceptional specific strength, stiffness, and damping characteristics, are pivotal in addressing blade fatigue issues in aero-engines. This paper designs and manufactures eight composite fan blades with various lay sequences, examining the effects of ply ratio and lay sequence on the blades' vibration characteristics. A vibration test platform was constructed, subjecting the eight blades to varying levels of sinusoidal, random, and impact excitations. The vibration responses were measured using an accelerometer (A3), a displacement sensor (X1), and a strain gauge (S1). The measured blade vibration modes and natural frequencies were compared with finite element simulation results. The study reveals that blades without 90° plies exhibit significantly higher natural frequencies than those with 90° plies. The comparison shows that the error between simulation and experiment is less than 8% for the first five modes, demonstrating the finite element simulation model's effectiveness. Additionally, different stacking sequences at the same ply ratio influence the natural frequencies. The first vibration mode frequency decreases with increasing excitation magnitude, indicating a certain degree of nonlinearity in the blades.

Keywords: Composite fan blades, Modal test; Lay sequence, Vibration analysis

1. INTRODUCTION

Composite materials, characterized by high specific strength, specific modulus, and customizable properties, exhibit excellent fatigue and impact resistance. These attributes make them highly suitable for applications in aerospace, marine, weaponry, automotive, and construction industries[1-3]. The use of composite fan blades in aero engines effectively reduces rotor mass and centrifugal load, thereby enhancing bypass ratios and thrust-to-weight ratios[4-6]. However, the operational environment for these blades is extremely challenging, involving mechanical excitations from other components, impacts from external objects (e.g., birds, ice), friction-induced mechanical excitations, and aerodynamic excitations from turbulence, vortices, and distorted airflow. These conditions can induce high-frequency vibrations[7], leading to fatigue fractures and compromising aircraft safety. Therefore, there is a critical need for fan blades with superior vibration characteristics. Studies have shown that the layup sequence of composite materials has a certain impact on the vibration characteristics of the blades under the same structural conditions [8-9]. This study designed and fabricated eight blades with different layup sequences and conducted various excitation tests alongside simulation analyses to validate the experimental and simulation results.

Chen et al.[10] explored the dynamic response of wide-chord composite fan blades using multiple macro fiber composite

(MFC) actuators, analyzing the vibration characteristics under complex excitation forces. Wang et al.[11] investigated the vibration of wide-chord fan blades using pin test methods and random broadband excitation on a vibration table. Wollmann et al.[12] designed a composite compressor blade and conducted numerical predictions and experimental validation of the blade modal parameters. Kee et al.[13] studied the impact of advanced tip shapes on the free vibration of composite blades. Teter[14] and Yang[15] conducted modal tests on composite blades and rotating wind turbine blades using multi-point scanning laser vibrometers. Rand[16] researched the free vibration behavior of rotating thin-walled composite blades. Yoo and Pierre[17] examined the rotor's vibration behavior, detailing eigenvalue trajectory deflection and mode shape crossover phenomena. In these studies, traditional pin test methods, vibration table excitations, and MFC actuators were commonly employed to investigate blade vibrations. Some researchers complemented these methods with simulation analyses, corroborating the simulation effectiveness with experimental data.

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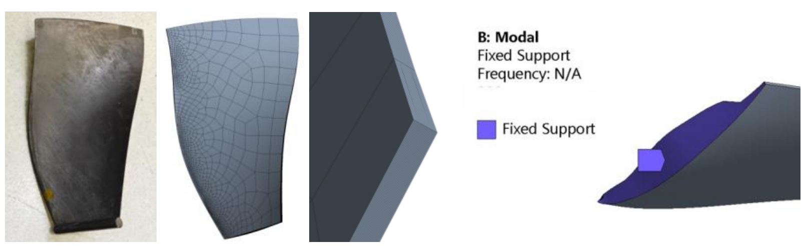
Albanesi et al.[18] introduced a novel optimization tool combining genetic algorithms and inverse finite element methods to optimize the layup sequence, number of layers, and layer drops for composite laminate wind turbine blades, achieving a 15% weight reduction while satisfying mechanical and manufacturing constraints. Dal et al[19] developed a coupled optimization program to finalize the layup of fan blades, enhancing aerodynamic performance and mechanical integrity. Li et al. [20] proposed a two-step online automatic structural optimization method for composite turbine blades based on particle swarm optimization, which reduced blade weight and improved load-bearing capacity. Thuan et al. [21] designed and manufactured a fan blade with a 54.5% [0/90] layer proportion and a 45.5% [45/−45] layer proportion, proposing a numerical analysis method for fiber drape deformation analysis that showed strong agreement between simulated and experimental results.

In the aforementioned studies, the optimization of composite laminate layups was primarily achieved using genetic algorithms or particle swarm algorithms. These simulations enhanced the mechanical properties of composite fan blades or reduced their weight. Thuan Ho-Nguyen-Tan et al.[21] designed and manufactured a fan blade and compared the simulated and experimental blade deformations. However, existing research predominantly focuses on vibration tests for a single blade type, lacking comparative modal analyses for blades with varying lay-up configurations. This study builds upon these foundations by designing and manufacturing composite blades with eight distinct layup schemes. And conducted vibration response tests under various excitations (sine, random, and impact), and compared the results with finite element simulations to further validate our approach.

2. FINITE ELEMENT(FE) MODELING OF COMPOSITE BLADES

The composite fan blade analyzed in this study is constructed from 72 layers of T800 carbon fiber prepreg, laminated and cured under pressure. The blade measures approximately 25 centimeters in length, as shown in Figure 1(a). The Volume Fill module in Fibersim composite design software was utilized to complete the volume filling ply design, resulting in a high-fidelity finite element model established in ANSYS Figure 1(b). This model comprises 91,944 elements and 99,288 nodes. The material properties incorporated into the finite element model are detailed in Table 1. E11, E22, and E33 are the Young's moduli in the 11, 22, and 33 directions, respectively. The 11-axis aligns with the 0-degree fiber, the 22-axis is perpendicular to the 0-degree fiber, and the 33-axis is perpendicular to the ply plane. G12, G13, and G23 are the shear moduli for the 12, 13, and 23 planes, respectively, while ν12, ν13, and ν23 represent the Poisson's ratios for these same planes. The blade root and blade connection are fixedly constrained, as shown in Figure 1(c).



(a) (b) (c)

Figure 1. Composite Fan Blade and Finite Element Model Images: (a) Composite Fan Blade; (b) Finite Element Model; (c) Boundary Conditions.

Table 1. Material properties.

Properties	Value
E11	173Gpa
E22	11.4Gpa
E33	11.4Gpa
G12	3.97Gpa
G13	3.97Gpa

Properties	Value
G23	2.97Gpa
ν12	0.22
ν13	0.22
ν23	0.4

Using this finite element model, the natural frequencies, mode shapes, and modal strains of different lay-up schemes (Eight categories) were calculated. The model's accuracy was verified through comparisons with experimental data.The design of composite material layups must account for structural, strength, and manufacturing considerations.Drawing from extensive theoretical analysis, experimental validation, and industry experience, numerous scholars have proposed guiding design principles. Based on these principles, we designed eight layup schemes as outlined in Table 2.The first four schemes include 90° layers, while the latter four do not. In Scheme 1, the proportions of -45° and 90° layers are each 16.7%, and the proportions of 45° and 0° layers are each 33.3%. In Scheme 2, all four layer orientations are equally proportioned at 25%. Scheme 3 features -45° and 90° layers at 14.3%, 0° layers at 28.6%, and 45° layers at 42.8%. Scheme 4 includes 90° layers at 14.3%, with 0° and ±45° layers each at 28.6%. Schemes 5 and 7 both allocate 25% to 45° and -45° layers, and 50% to 0° layers, with the positions of ±45° layers reversed. Scheme 6 assigns 20% to -45° layers and 40% each to 0° and 45° layers. Scheme 8 distributes 16.7% to 45° and -45° layers, and 66.7% to 0° layers.

Table 2. Lamination Scheme

Scheme	Ply Sequence	Scheme	Ply Sequence
1	[-45/0/45/90/45/0]ns	5	[45/0/-45/0]ns
2	[45/0/-45/-45/0/45/90/90]ns	6	[45/0/-45/0/45]ns
3	[45/90/45/0/-45/0/45]ns	7	[-45/0/45/0]ns
4	[-45/0/45/90/45/0/-45]ns	8	[45/0/0/-45/0/0]ns

3. THE TEST SYSTEM OF COMPOSITE BLADES

The composite blade vibration test system and solid blades is shown in Figure 2. This system comprises a high-frequency large-thrust electric vibration test bench, power amplifier, vibration controller, data acquisition instrument, and laser vibrometer. The vibration bench has a maximum thrust of 30000N, a maximum excitation acceleration of 100g, and a frequency range of 2-6500Hz. It supports various excitation functions, including sinusoidal, random, and typical shocks (half-sine, triangular, and rectangular wave shocks).

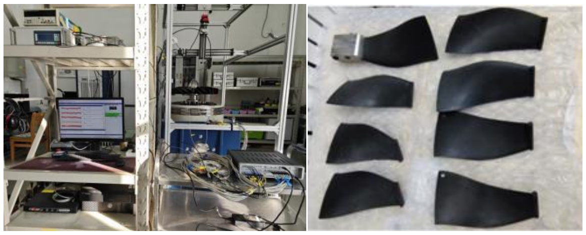


Figure 2. Composite Material Fan Blade Vibration Test System And Blades

For the vibration characteristic tests of the eight blades with different layup schemes, an accelerometer (A1) was mounted on the surface of the vibration table to control the excitation acceleration. A strain gauge (S1) was attached at the blade root to measure root strain, and a reflective strip was placed at the blade tip, with a laser displacement sensor (X1) aimed at this point to measure tip vibration displacement. Additionally, a miniature accelerometer (A3) was affixed to the blade tip to capture the vibration acceleration response.

4. DISCUSSION OF VIBRATION TEST RESULTS

4.1 Testing of natural frequency and harmonic response under different sine excitations

In the sine excitation tests for determining the natural frequency of the blades, a steady-state excitation force was precisely applied to the blades. The frequency of this excitation force was adjustable, inducing vibrations in the blades. The magnitude and phase of the excitation force across various frequencies, as well as the corresponding responses at multiple test points, were meticulously measured.

In this section, various magnitudes of sine excitations were applied to eight composite material blades. The excitations were introduced at the blade roots, where strain gauges (S1) were attached. Additionally, laser displacement sensors (X1) and micro accelerometers (A3) were placed at the blade tips to measure vibration responses under different excitations. The sine excitations, ranging from 0.2g to 5.0g, are illustrated in Figure 3.

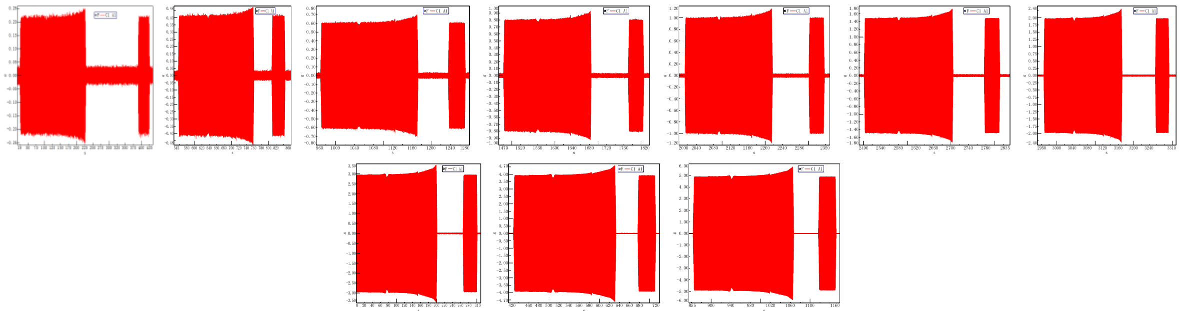


Figure 3. Sinusoidal Excitations of Different Sizes

Figure 4 shows the natural frequencies of eight types of blades under sinusoidal excitation of different amplitudes. It is evident from the figure that the natural frequencies for Scheme 5 and Scheme 8 are significantly higher than those for the other schemes. Additionally, the natural frequency values for the 90° layup schemes(schemes 1,2,3,4) are markedly lower than those for the non-90° layup schemes(schemes 5,6,7,8). Specifically, the natural frequencies for the first four layup schemes are considerably lower than those for the last four schemes. All layup schemes exhibited a decrease in natural frequency values with increasing external excitation force, highlighting the nonlinearity of these composite blades.

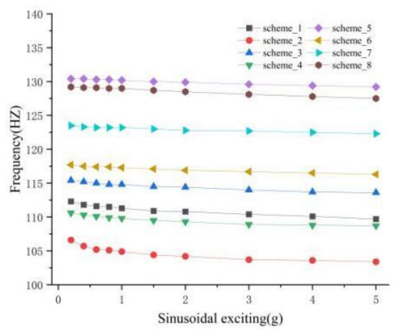


Figure 4. Natural frequencies of eight blades under different sinusoidal excitation forces

4.1 Modal vibration mode results and simulation comparison of the blade

Based on the geometry of the composite material blades, a quadrilateral scan grid with forty-eight nodes was generated, enabling the separate measurement of the vibration displacement at each node. This process yielded the first five mode shapes of the eight types of composite material fan blades. In table 3, the results indicated that the modal test results (with minimal excitation) were slightly higher than the first mode measured under 0.2g sinusoidal excitation, suggesting a certain degree of nonlinearity in the blade.

Figures 5 illustrate the comparison between the experimental and finite element simulation results for the first five modes' natural frequencies and mode shapes of Scheme 8. The discrepancy in the natural frequencies of the first three modes of the composite fan blades is less than 4%, while the error for the first five modes is under 8%. The mode shapes of the first five modes in the simulation align well with the experimental results, indicating the high-fidelity finite element model's accuracy in predicting low-order natural frequencies and mode shapes. However, improvements are needed for higher-order natural frequencies and mode shapes. Table 3 compares the experimental and simulation values of the first mode for the eight types of fan blades, including the damping ratios tested in the experiments. The results are consistent with the patterns observed under sinusoidal excitation, with Scheme 5 and 8 exhibiting significantly higher natural frequencies than the others. The discrepancy in the first mode between experiments and simulations for all blades does not exceed 4%. Table 4 compares the experimental and simulation results for the first five modes of Scheme 8 composite fan blades, including the damping ratios. The comparison shows that the error between simulation and experiment is less than 4% for the first four modes and less than 8% for the fifth mode, demonstrating the finite element simulation model's effectiveness, especially for low-order modes. Errors between experiments and simulations for the other schemes are also within 8%, although they are not listed individually here.

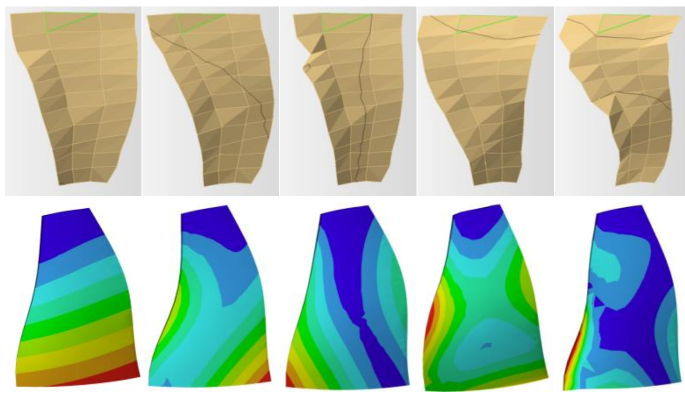


Figure 5. The first five test and FE mode shapes of Scheme 8

Table 3. Comparison of blade modal test values and FE values

	Modal testing		Freq. (FE)(Hz)	Difference(%)
	Freq. (HZ)	**Difference (%)**		
Scheme 1	114.277	0.67	113.646	0.55%
Scheme 2	104.182	3.55	107.320	3.01%
Scheme 3	116.334	0.57	115.745	0.50%
Scheme 4	109.892	1.45	110.707	0.74%
Scheme 5	131.392	0.38	127.658	2.84%
Scheme 6	117.169	0.47	117.206	0.03%
Scheme 7	122.922	0.43	119.166	3.05%
Scheme 8	130.975	0.23	130.191	0.60%

Table 4. Test frequency and FE simulation frequency of Scheme 8

Mode	Modal testing		Freq. (FE)(Hz)	Difference(%)
	Freq. (HZ)	**Difference (%)**		
1	130.975	0.23	130.191	0.60%
2	530.070	0.30	551.842	4.11%

Mode	Modal testing		Freq. (FE)(Hz)	Difference(%)
	Freq. (HZ)	Difference (%)		
3	614.741	0.19	614.078	0.11%
4	1184.227	1.05	1177.787	0.54%
5	1847.227	0.73	1968.255	6.55%

5. CONCLUSION

In this study, based on existing processing experience and composite material layup design guidelines, eight types of blade layup sequences were designed, processed, and subjected to vibration tests under various excitation conditions. The natural frequencies of the tested blades were compared with simulations. The findings are as follows:

(1) The natural frequencies and the influence patterns of the layup on blade dynamics obtained from finite element simulation and vibration tests under various excitation conditions are highly consistent. This indicates that the vibration tests and the high-fidelity finite element model developed in this study are highly accurate.

(2) The natural frequency test results for schemes 5 and 7 clearly demonstrate that, with an identical ply proportion, the ply sequence also influences the blade's natural frequency.

(3) The natural frequencies of schemes 5 and 8 are significantly higher than those of other schemes, and the natural frequencies of layup schemes with 90-degree(schemes 1,2,3,4) layers are significantly lower than those without 90-degree(schemes5,6,7,8) layers.

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