

Study on the Impact Response Characteristics of Hollow Fan Blades under Near-Real Bird Strike (Postprint)

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Abstract

Wide-chord hollow fan blades of aero-engines are prone to significant vibration during high-speed rotation and face an increased risk of structural damage under bird impact during operation. Based on images of bird postures, this study proposes a method for constructing realistic bird structural models, and establishes a two-layer cavity fan blade model for a certain aero-engine. A fluid-structure coupling approach is employed to investigate the vibration characteristics of the blade and its response to impact by a realistic bird model. The effectiveness of the proposed near-real bird model is validated through bird strike tests on flat plates, showing that, compared with the traditional simplified bird model, it can reproduce bird strike loads more realistically and effectively. The results indicate that, through analysis of blade resonance margin using a Campbell diagram, the appropriate rotational speed range for the blade is determined to be 2900-3800 r/min. When a realistically shaped bird impacts frontally at 100 m/s on the fan blades rotating at 3344 r/min, the axial deformation of blades No. 2, 3, and 4 is relatively large, with a maximum value of 78.3 mm. During the bird cutting process, stress concentration first appears at the leading edge of the blade, reaching 2000 MPa, and subsequently propagates over the entire blade. The findings can provide a basis for the bird-strike-resistant design and optimization of fan blades.

Full Text

Research on Impact Response Characteristics of Hollow Fan Blades Against Near-Real Bird Strikes

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Abstract

Wide-chord hollow fan blades in aeroengines are prone to significant vibration problems during high-speed rotation and face higher structural damage risks when subjected to bird strikes during operation. This study proposes a methodology for constructing realistic bird structural models based on bird posture images and develops a two-cavity fan blade model for a certain aeroengine. Using a fluid-structure interaction approach, the vibration characteristics and anti-realistic bird impact response of the blade are investigated. The effectiveness of the proposed near-real bird model is verified through bird strike plate experiments, which demonstrate that compared with traditional simplified bird models, the near-real model can more authentically and effectively reflect bird strike loads. Results show that through Campbell diagram analysis of blade resonance margins, the reasonable operating speed range is determined to be 2,900–3,800 r/min. When a real-shaped bird strikes the blade head-on at 100 m/s with a rotational speed of 3,344 r/min, blades No. 2, 3, and 4 exhibit relatively large axial deformation with a maximum value of 78.3 mm. During the bird cutting process, stress concentration first appears at the blade leading edge, reaching 2,000 MPa, and subsequently spreads throughout the entire blade. The research findings can provide a basis for the design and optimization of fan blades against bird strikes.

Keywords: hollow fan blade; vibration characteristic; real-shaped bird; impact response; fluid-structure interaction

1. Construction of Bird Finite Element Model

Simplified regular geometric structures such as spheres and cylinders cannot effectively characterize the biological structural differences among various bird species, yet these structural differences significantly affect simulation results. Figure 2 illustrates the construction process of the near-real shape bird geometric model proposed in this study. Using photographic images containing specific bird postures and basic views, an image length measurement tool is employed to measure characteristic parameters of key body parts. By obtaining the characteristic parameters of each key part and the proportional relationships between parameters in different parts, the real bird structural solid model is drawn using methods such as sweeping and proportional scaling. The bird is divided into five key parts: beak, neck, torso, wings, and legs. Based on corresponding contour features, each part is simplified into rotational geometries including cones and cylinders. A method is established that can generate real bird solid structural models of any species and mass simply by providing photographic images containing specific bird postures and basic views. Finally, this study selects a 1.8

kg real grey crane bird model for subsequent bird strike blade simulations. The geometric model is imported into ANSYS Workbench for finite element meshing. Lagrange particles are generated at corresponding positions with a particle spacing of 4 mm, slightly smaller than the fan blade mesh size. This approach both preserves the biological characteristics of the bird and ensures acceptable computational time, with a total of 28,200 particles.

2. Construction of Blade Finite Element Model

Figure 3 shows the construction process for the structural and fluid domain mesh models of an aeroengine fan blade. Based on the physical blade model, the geometric model is constructed to obtain individual fluid domain and structural domain solid entities. The structural domain blade entity is a hollow blade. For convenience in meshing, the connection between stiffeners and the hollow blade is set as bonded contact. Figure 4 presents the mesh independence verification of the finite element model. The structural finite element analysis primarily simulates the maximum blade stress under centrifugal force at 4,000 r/min. When the fluid domain mesh size is 15 mm and the structural domain mesh size is 4 mm, the computational requirements are satisfied. The meshed blade contains 15,254 elements. The discrete error is calculated, and the results show that setting the fluid domain mesh size to 15 mm can maintain stable computational results, with 1,061,663 fluid domain elements at this configuration.

For fluid domain construction, a periodic flow channel for a single fan blade is created. To simplify calculations, the blade tip clearance is set to 1 mm, meaning tip leakage is not considered. Since the flow field geometry contains complex curved surfaces, polyhedral meshes are used for flow field division, with mesh orientation aligned as much as possible with the airflow direction. Boundary layers are established to capture near-wall flow. The turbulence model calculation accuracy has specific requirements for mesh size. The rotational speed is set to 4,000 r/min, and the flow field mesh independence verification is shown in Figure 4.

3. Material Models and Parameters

Bird soft tissue exhibits fluid-like characteristics when impacting hard objects at speeds exceeding 100 m/s, primarily because the stress generated during impact far exceeds material strength. Bird bodies are generally considered flexible bodies. This study uses the *MAT_{Null} material model in LS-DYNA combined with a polynomial equation of state to characterize bird deformation behavior at high speeds. The equation of state is given by [equation], with bird equation-of-state parameters shown in Table 1, where μ represents relative volume and E represents internal energy per unit volume.

The fan blade rotor is made of titanium alloy (TC4). The Johnson-Cook elastoplastic material model is used to describe its dynamic constitutive behavior, with the strength equation given by [equation]. Corresponding material param-

eters are shown in Table 2, where A represents yield stress, B represents strain hardening parameter, C represents strain rate strengthening parameter, n represents material thermal softening parameter, $\bar{\epsilon}$ represents equivalent plastic strain, and T^* represents dimensionless temperature.

4. Validation of Bird Model Effectiveness

Traditional simplified bird models commonly use cylindrical birds, which differ significantly in geometric shape from the real bird model proposed in this study. Cylindrical birds primarily represent simplified torso sections. When these two bird types strike a plate equivalently, they produce different stress distributions and damage areas on the plate. Therefore, comparative analysis of dynamic responses during impact is necessary.

To verify the flexible body and fluid-like deformation process of birds during high-speed impact, plate experiments are commonly used to validate finite element methods. Wilbeck's bird strike plate experimental data is used for validation. Wilbeck launched real bird projectiles using an air compression cannon onto a metal plate and recorded pressure changes at the impact center. For numerical simulation verification of the bird strike plate process, a 60 cm diameter, 6 cm thick metal plate model is established, with the plate material changed to titanium alloy to match fan blade material properties. The real bird model is scaled geometrically to control its mass at 1 kg, while the cylindrical bird's length-to-diameter ratio is set to 2. Both bird types are initially positioned 1 mm from the plate, with the impact location at the plate center.

Figure 5 shows the pressure-time curves at the plate center for both bird types at an initial impact velocity of 116 m/s. Figure 6 illustrates the bird strike plate process. The figure shows that both bird types correspond to the three impact deformation stages summarized by Wilbeck. First is the initial impact stage where the bird first contacts the plate and generates stress waves. This stage's stress peak is called the Hugoniot peak. As stress waves propagate to the bird's rear, an adverse pressure gradient forms on the bird's side, accelerating particles outward and releasing unloading waves into the shock decay stage. After unloading wave transmission, bird deformation gradually proceeds at a stable velocity and pressure, entering the constant flow stage. As unloading waves continuously weaken stress waves, bird deformation gradually ends, reaching the impact conclusion.

The cylindrical bird model produces a first peak pressure at the plate center far exceeding experimental data, while the real bird model's results are much closer to experimental values, especially during the initial impact stage. This is primarily because the real bird model's structural characteristics better match biological bird structures. The real bird's length exceeds that of the cylindrical bird at the same mass, resulting in longer impact duration on the plate and greater model splashing than the cylindrical bird. The real bird can more accurately characterize bird behavior compared to traditional simplified birds.

5. Fluid-Structure Coupling Analysis of Blade Pre-stress

During normal operation, fan blades are subjected to multiple loads including centrifugal force and aerodynamic force, plus structural constraints. After long-term operation, blade mechanical performance and behavior degrade, potentially causing blade fracture. Blades should operate at speeds that can withstand centrifugal and aerodynamic loads. This study first determines the maximum speed blades can withstand through fluid-structure coupling strength analysis, then performs blade vibration characteristic analysis.

For fan blade surface aerodynamic force calculation, the basic control equations of the flow field adopt steady compressible Reynolds-Averaged Navier-Stokes (RANS) equations. To improve calculation accuracy for adverse pressure gradient boundary layer flow and separation states, the $k-\omega$ SST (Shear Stress Transport) two-equation model is used as the turbulence model closure. When an aeroengine fan operates, the air flow rate through a single blade can reach 14 kg/s, making aerodynamic force effects significant. Therefore, blade surface aerodynamic pressure distribution and its impact on blades must be analyzed.

Figure 7 shows the aerodynamic pressure distribution on the fan blade surface at 4,000 r/min. When air flows over the blade surface, the pressure surface's root section experiences large aerodynamic pressure due to its geometry. The blade's twist angle is large, and the blade leading edge faces the incoming flow directly, resulting in substantial airflow. The blade's middle suction surface experiences smaller aerodynamic pressure because its geometry causes fast air velocity at that location.

Figure 8 presents the stress distribution of the hollow fan blade under fluid-structure interaction at 4,000 r/min. Under combined centrifugal and aerodynamic forces, maximum blade stress concentrates at the middle-lower section of the suction surface, reaching 837 MPa, which exceeds the titanium alloy yield stress of 950 MPa. Maximum stress distributes near the root skin on both suction and pressure surfaces. During design, appropriately increasing skin and stiffener thickness at the root can enhance blade load-bearing capacity. Since the blade's maximum stress under fluid-structure coupling at 4,000 r/min has reached 1.10 times the material yield stress, this study focuses on fan blade speeds from 0 to 4,000 r/min to determine appropriate operating ranges.

6. Blade Vibration Characteristic Analysis

By solving the nodal characteristic equation for eigenvalues and corresponding eigenvectors, blade natural modes can be obtained. Combined with excitation force calculations and blade natural frequencies, Campbell diagrams can be plotted to identify reasonable operating speed ranges. Generally, only the first five orders of natural frequencies are considered for frequency margin analysis.

This study performs modal analysis on blades from 0 to 4,000 r/min. Figure 9 shows the Campbell diagram under fluid-structure coupling for aeroengine

fan blades. The figure shows no frequency testing below 2,000 r/min, primarily because fan blades generally don't remain at startup and shutdown speeds for extended periods. Therefore, this study mainly considers vibrations between 2,000 and 4,000 r/min. When fan blades operate at resonance points for extended periods, resonance occurs. To avoid resonance and find reasonable operating intervals, blade resonance frequency margins must be calculated.

Figure 10 shows the frequency margin diagram for the first five orders of the fan blade from 0 to 4,000 r/min. Since frequency margins from sixth order and above are greater than 15%, higher-order vibrations are not considered. The fan blade can quickly accelerate through low-order resonance points to 2,900 r/min, then operate in the 2,900–3,800 r/min range where frequency margins for first, second, and third orders exceed 10%, and fourth and fifth order frequency margins also exceed 10%. For fan blades, lower modal orders produce the most dangerous vibrations, so engineering practice focuses on the first five orders. Therefore, the blade can operate safely and stably in the 2,900–3,800 r/min interval.

7. Blade Anti-Bird Strike Impact Response Analysis

The fan blade's cruise speed of 3,344 r/min is taken as the operating speed. Bird initial velocity is set at 100 m/s. According to the empirical probability formula established by Ma Li et al., the blade tip region at radial distance R from the fan rotor axis has the highest bird strike risk. Before explicit dynamic analysis of bird strike, pre-stress is applied to the fan blade. The centrifugal and aerodynamic forces obtained from the previous section serve as pre-stress loads. The impact location is set at the blade tip region, with motion applied to the entire blade rotor. Contact between bird particles and fan blade finite element mesh is defined as impact contact using coupling algorithms to simultaneously describe load transfer between bird particles and Lagrange elements.

Figure 11 shows the finite element model and boundary conditions for aeroengine fan blade bird strike. Since other rotor components exist behind the fan blade, axial displacement of impacted blades must be primarily monitored. When blades first contact the bird, blade stress and deformation are small. This study selects blades No. 2, 3, and 4, which primarily cut the bird torso, to investigate axial displacement changes at the blade trailing edge tip during bird strike.

Figure 12 shows axial displacement curves for blades No. 2, 3, and 4. All three blades exhibit oscillation and rebound phenomena during deformation. Blade No. 2 shows the most severe deformation with significant displacement fluctuations. Blade No. 2 first cuts the bird, so its first displacement peak appears earliest at 6.4 ms, reaching 45.7 mm. Blades No. 3 and 4 mainly cut the bird neck, showing local stress and beginning deformation at 6.8 ms with axial displacement of 50.8 mm. After 8.0 ms, the bird is completely cut and no longer impacts blades, yet blades No. 2, 3, and 4, most affected by bird strike, show axial displacement that first decreases then increases, reaching secondary peaks at 12.1 ms that exceed primary peaks. This occurs because after bird impact,

blades begin periodic deformation trends moving back and forth while blade stiffness decreases. However, centrifugal force persists as the blade continues rotating, making blade operation unstable and showing axial oscillation.

Figure 13 shows the equivalent stress evolution process on blades at different moments after bird strike. High stress regions first appear locally when blades contact the bird, with maximum stress reaching 2,000 MPa. As impact continues, stress waves diffuse from local regions to the entire blade, causing significant overall blade stress increase. After bird cutting, due to fragmented bird particle splashing, stress peaks transfer from the leading edge to pressure surface regions.

Figure 14 shows the equivalent strain evolution process on blades at different moments. Contact regions produce high strain areas. Blade No. 2's leading edge shows local strain because it primarily cuts the bird neck. Blade No. 3's leading edge shows local curling deformation. Blade No. 4's deformation begins from the pressure surface. After bird cutting, blade leading edge stress levels no longer increase, but overall blade stress continues rising as blades contact scattered bird fragments.

Figure 15 illustrates the complete process of birds being cut by blades. From 0 to 5.0 ms, the neck is primarily cut. At 5.0 ms, the bird neck is basically cut through, with the torso half-cut. At 6.0 ms, blades complete the cutting process. At 8.0 ms, bird fragment particles begin flying away and gradually leave the fan blade flow channel under their axial velocity.

8. Conclusions

This study constructs a real bird model containing biological features from bird posture images and investigates the vibration characteristics and bird strike impact response of wide-chord hollow fan blades for a certain aeroengine using fluid-structure interaction methods. The main conclusions are:

1. For titanium alloy wide-chord hollow fan blades, frequency margins for the first five orders exceed 10% in the 2,900-3,800 r/min range. The blade has good resonance avoidance characteristics and can prevent resonance-induced structural damage in this speed range.
2. When a real-shaped grey crane bird strikes at 100 m/s against a fan blade rotating at 3,344 r/min, blades No. 2, 3, and 4 cutting the bird exhibit significantly greater axial displacement than other blades, with a maximum of 78.3 mm. These blades may further collide with downstream rotor blades.
3. During bird cutting, stress concentration first appears at the blade leading edge, reaching 2,000 MPa, then spreads throughout the blade, causing significant overall deformation. After cutting, due to fragmented bird impact, stress peaks transfer from the leading edge to pressure surface regions.

The research results provide reference for anti-bird strike design of hollow fan blades. To reduce bird strike loads and improve blade survivability, blade geometry optimization can be considered, such as increasing leading edge thickness to enhance impact resistance or adjusting leading edge angle to reduce strike loads. External protective devices like guard cables can also be considered to break up birds before blade contact, ensuring engine safety and stability.

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Figures

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Figure 1

Figure 1: Figure 1

Figure 2

Figure 2: Figure 2

Figure 3

Figure 3: Figure 3

Figure 4

Figure 4: Figure 4

Figure 7

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Figure 8

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Figure 12

Figure 7: Figure 12

Figure 13

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Figure 14

Figure 9: Figure 14