

Article

Multiple-Bird-Strike Probability Model and Dynamic Response of Engine Fan Blades

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Abstract: Bird strikes pose one of the most significant threats to aviation safety, often leading to substantial loss of life and economic damage. Many bird strike incidents involve multiple birds. However, in previous bird strike studies, the problem of multiple bird strikes has often been neglected. In this paper, the bird slicing process of a rotating engine fan is examined, and a probability model is introduced to assess the risk of multiple impacts on the fan blades. In addition, this paper utilized an implicit–explicit calculation method. The parameters of blade root stress, tip displacement, plastic deformation, and energy were selected to investigate the effects of the time interval and strike position of a bird strike on the dynamic response of and damage to the blades. The results indicated that the position of bird strikes has a more pronounced effect on blade damage compared to the time interval between impacts. Damage to a blade is most severe when the blade root is struck multiple times. Multiple bird strikes may not always lead to a significant increase in maximum blade tip displacement, and may even have a dampening effect.

Keywords: bird strike; SPH method; impact dynamic; probability model; multiple bird strike



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1. Introduction

The term “bird strike” most commonly denotes a collision between birds and aircraft. The problem of bird strikes is one of the major threats faced by airplanes during takeoff and landing. Research estimates suggest that approximately 90% of instances involving foreign-object damage (FOD) to aircraft structures are attributable to bird encounters [1]. Data from the Federal Aviation Administration (FAA) indicate that bird strikes result in considerable downtime and economic losses to the aviation industry [2]. Scholars are currently working to address this issue in two main ways:

1. Scientific and comprehensive assessments of the risk of bird strikes to prevent bird strikes;
2. Predicting the response of and damage to aeronautical structures after bird strikes to improve bird strike resistance.

In the domain of bird strike risk assessment, numerous scholars have been continuously engaged in conducting studies from innovative perspectives. Budgey et al. [3] introduced a methodology to evaluate the risk of bird strikes within flocks, employing a stereo camera for flock photography to ascertain flock density and bird distribution. Lopez-Lago et al. [4] devised a real-time bird strike risk assessment model grounded in pertinent factors, including bird detection radar and flight data. Coccon et al. [5] formulated generalized linear models (GLMs) with a binomial distribution to further quantify the level of risk associated with bird strikes at airports. Metz et al. [6] calculated bird strike risk by predicting bird flights and evaluating the severity of collisions. Additionally, they assessed the impact on airport safety and capacity when implementing a bird strike advisory system.

According to statistics, accidents resulting from engine strikes by birds constitute 44% of all bird strikes [7]. Fan blades, which are a critical component of an engine, are situated at the forefront of the engine and are particularly vulnerable to bird strikes during aircraft

take-off, landing, and flight. Bird strikes can result in various forms of damage to the blades, including craters, tears, and curling, which may lead to more serious aviation accidents [8]. Many scholars have extensively investigated the responses and damage issues related to bird strikes on fan blades. Prakash et al. [9] conducted numerical simulations of the bird strike response of rotating blades with and without convex shoulders. Their findings suggest that blades with convex shoulders exhibit reduced deformation damage at the strike position compared to those without. Zhang et al. [10] utilized the SPH method to create a detailed bird model and studied the impact response of and damage to a rotating engine fan struck by a bird, considering bird geometry and impact direction. Liu et al. [11] examined the effects of the bird strike problem on rotating fan blades through a combination of experiments and numerical simulations, with a focus on impact parameters affecting engine blade damage. Their study revealed that bird mass and engine blade rotational speed significantly influenced the deformation of and damage to the fan blades. Puneeth et al. [12] investigated the effect of bird mass and impact height on blade response, identifying the critical impact height of the fan blades under study. Yella et al. [13] explored the bird strike resistance of hybrid fiber composite blades, particularly emphasizing the impact of the bird's position and the length of the combined region of the two materials on the blade's response.

Prior studies on bird strike response damage in aerostructures have predominantly centered on single bird strikes. However, in actuality, aircraft are frequently confronted with flocks of birds. The Federal Aviation Administration (FAA) reported 141,067 bird strikes from 1990 to 2020, revealing that multiple bird strikes constituted 13.8% of total incidents [14]. A prominent example is the 1975 incident involving an American Overseas Airlines DC10 airliner, which tragically crashed in New York following the ingestion of a flock of seagulls during takeoff [15]. This accident further reinforced the concern about the airworthiness of high-bypass-ratio turbofan engines for bird-absorbing. Simultaneously, the U.S. authorities issued FAR 33.77 AMDT6, further refining the criteria governing the weight and quantity of birds used in airworthiness verification tests for bird ingestion, thereby enhancing the standards [16]. In 2000, the FAA issued AMDT20, mandating the execution of engine bird ingestion validation tests with a mass ranging from 1.5 to 2.5 lb and a maximum of six birds, determined by parameters such as the engine's windward area. Parameters such as the engine's windward area were used to establish the test requirements [17]. Subsequently, in 2007, AMDT23/24 elevated the performance criteria post bird ingestion and introduced validation for ingesting large flocks of birds [18]. A number of scholars have also carried out studies related to multiple bird strikes. Wu et al. [19] investigated the effects of bird flock strikes on an engine rotor system under a variety of scenarios. Rezaei et al. [20] redesigned an aircraft windshield to improve its mechanical resistance against simultaneous bird strikes. It is evident that in recent years, researchers have increasingly focused on the issue of multiple bird strikes, and there has been a gradual enhancement in the standards of related airworthiness verification experiments.

In a multiple-bird-strike incident, a single fan blade is prone to experiencing multiple bird strikes. Existing studies on bird strike risk assessment predominantly address the aircraft as a unified structure, lacking a recognized systematic approach to assess the risk of multiple fan blade impacts. Current blade strength designs often overlook the possibility of multiple bird strikes, which can lead to damage in real multiple-bird-strike accidents. Random bird placement is primarily employed in airworthiness verification experiments, making it challenging to simulate the most hazardous impact scenarios. Additionally, the issue of blade impact by multiple birds is more intricate, involving the accumulation of blade damage and dynamic response coupling after each impact. There is also very limited research on the dynamic response of fan blades struck by multiple birds.

This paper investigates the aforementioned issues. The paper begins by introducing the bird slicing process and subsequently proposes a probability model for assessing the risk of multiple impacts on fan blades. Subsequently, a simulation model for bird strikes is established, with validation accomplished through the solution of rotational prestressing of

the blade and its impact on the rigid flat plate. Ultimately, this paper considers factors such as bird strike position and impact time interval, which may influence the dynamic response of the blade. The effects of these factors on a blade's dynamic response are investigated through numerical simulation.

2. Methodology

2.1. Probability Modeling of Multiple Bird Strikes on Blades

2.1.1. Bird Slicing Process

In bird strike tests and numerical simulations, the geometry of a bird is frequently approximated as a cylinder [11]. During bird strikes, birds are cut by the blades in the V_r direction into pieces of various sizes and shapes. The middle parts of the birds are cut by the fan blades into several large bird pieces of similar thickness, with the head and tail pieces having less thickness and mass. Furthermore, the impact velocity of birds exhibits considerable variation depending on the height at which they collide with the blades. Therefore, it is essential to consider the strike position's height s when assessing the dynamic response to bird strikes. Figure 1 provides an illustrative representation of the process of bird slicing [21], where V_a denotes the speed of the bird relative to the aircraft along the engine axis; V_r denotes the speed of the bird relative to the blade; H and ω are the height and angular velocity of the blades, respectively; $R(s)$ and $V(s)$ represent the radius of rotation and tangential velocity of the impacted position of the blade, respectively, while $\varphi(s)$ signifies the torsion angle of the blade at this specific position; B_L and D are the length and width of the bird, respectively; B_S indicates the thickness of the large bird piece; and α is the angle of incidence for birds and can be expressed by the following equation:

$$\alpha = \arctan \frac{V_a}{V(s)} \quad (1)$$

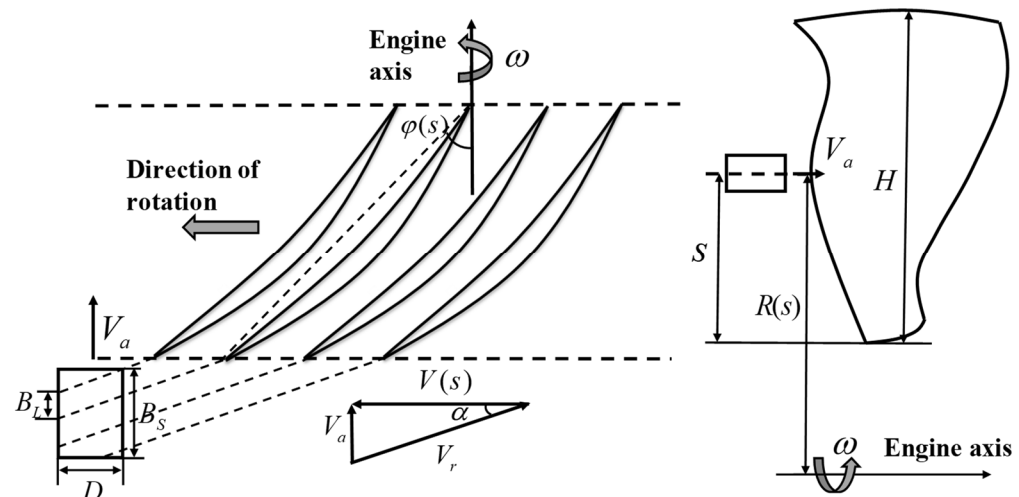


Figure 1. Bird slicing process.

Then, the following angular relationship is satisfied:

$$\alpha < \frac{\pi}{2} - \varphi(s) \quad (2)$$

Bird pieces initially strike the concave surface of the fan blades, then proceed to slide along this surface. Throughout the sliding process, the impact load from the bird fragments continues to exert force on the fan blades until they ultimately slide out along the blades' end. This scenario is most common in actual bird strikes, so it is studied in this paper.

2.1.2. Probability Model

Overall, the impact of engine suction on the airflow rate and direction around the air intake is generally much less significant than the influence exerted by the aircraft's own speed [22]. We disregard the effects of engine suction and bird evasive maneuvers against the aircraft, assuming that birds colliding with the engine are positioned directly in front of it. The variable n symbolizes the number of birds impacting the fan blades when the aircraft passes through the flock, and can be represented as

$$n = V_a S \rho t \quad (3)$$

where ρ is the bird density of the flock, and t is the time taken by the airplane to cross the entire flock. These two parameters need to be determined through a survey of common bird species causing aircraft strikes in the area and an assessment of flock characteristics. S is the engine fan projection surface area and can be expressed as

$$S = \pi(R(H))^2 - \pi(R(0))^2 \quad (4)$$

During the bird slicing process, the thickness of a large bird piece can be expressed as [21]

$$B_s = \frac{2\pi V_a}{\omega N_b} \quad (5)$$

where N_b represents the total number of fan blades within the engine. There are two factors to consider when studying this problem: the count of blades impacted by an individual bird N , and the total number of birds involved in the entire impact process n . If the bird strikes at position $R(s)$, N can be expressed as

$$N = \frac{B_L + D \tan \alpha}{B_S} = \left(\frac{B_L \omega}{V_a} + \frac{D}{R(s)} \right) \frac{N_b}{2\pi} \quad (6)$$

Birds are assumed to impact with equal probability at various positions on the windward side of the engine fan. As illustrated in Figure 2, N can be further expressed as

$$N = \int_{R(0)}^{R(H)} \frac{2\pi R(s)}{S} \left(\frac{B_L \omega}{V_a} + \frac{D}{R(s)} \right) \frac{N_b}{2\pi} d(R(s)) = \left(\frac{B_L \omega}{V_a} + \frac{D}{\frac{R(H) + R(0)}{2}} \right) \frac{N_b}{2\pi} = \left(\frac{B_L \omega}{V_a} + \frac{D}{R(\frac{H}{2})} \right) \frac{N_b}{2\pi} \quad (7)$$

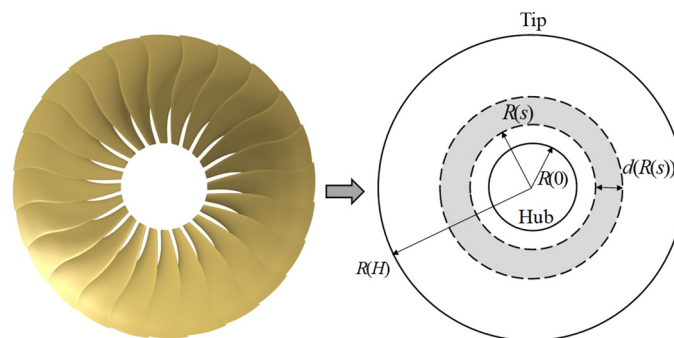


Figure 2. Windward side of engine fan.

Finally, the probability of multiple impacts on the blade caused by the flock of birds can be expressed as

$$P_n = \begin{cases} 1 - \frac{(N_b - nN + n - 1)!}{N_b^{n-1} (N_b - nN)!} & \text{for } nN < N_b \\ 1 & \text{for } nN \geq N_b \end{cases} \quad (8)$$

where the “!” symbol represents the factorial operation.

The procedure for estimating the probability of multiple blade strikes by integrating the above methods is detailed as follows:

1. Initiate a survey focusing on the prevalent bird species responsible for bird strikes in the designated area. Evaluate the flock size and geometric characteristics of these birds.
2. According to the type of engine to be studied, determine the basic parameters of the engine fan N_b , S , $R(\frac{H}{2})$. According to the typical working conditions of the engine, determine the fan speed ω and the flight speed of the airplane V_a .
3. Estimate the number of birds n that hit the fan blades as the airplane passes through the flock according to Equation (3).
4. Substitute the parameters obtained in the first and second steps into Equation (7) to obtain the parameter N . N is the number of leaves cutting any one bird.
5. Determine the relationship between the magnitudes of nN and N_b . If $nN \geq N_b$, there must be blades that can be hit by more than one bird; if $nN < N_b$, the probability of a blade being repeatedly struck by more than one bird is P_n . P_n can be derived from Equation (8).

A flow chart of the above operations is shown in Figure 3.

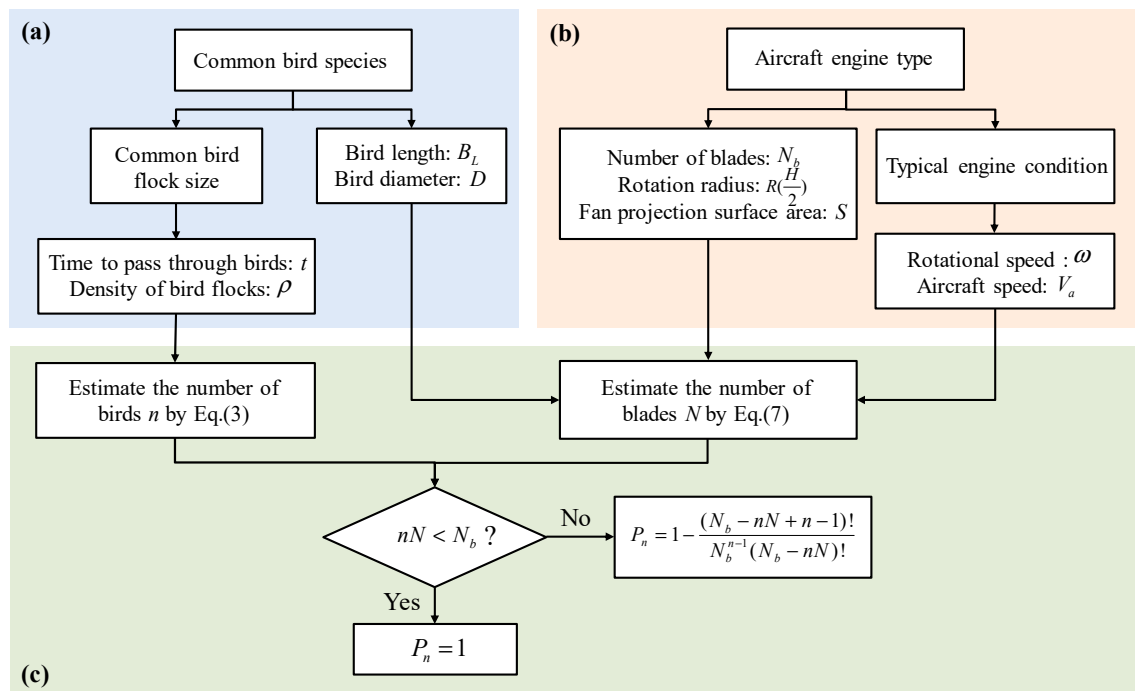


Figure 3. Flow chart of the probability model. (a) Parameters of birds and flocks; (b) fan blade parameters and working conditions; (c) probability model.

2.2. Numerical Simulation Model

2.2.1. SPH Model of Birds

When simulating the modeling of birds, several methods are available, including the Lagrangian method, Arbitrary Lagrangian–Euler (ALE) method, Eulerian method, and Smoothed Particle Hydrodynamic (SPH) method. A comparative analysis of these modeling methods in the papers [23–25] indicates that the SPH method outperforms the others in terms of computational stability, efficiency, and result accuracy. The core concept of the SPH method is to discretize the object into a collection of interacting particles, with no mesh connecting the individual particles. This feature makes it particularly well suited to handling problems with large deformations. As a result, the simulations in this paper are conducted using the SPH method.

In the context of bird modeling parameters, the International Bird Strike Research Group (IBRG) compiled information on the top thirty bird species most commonly associated with bird strike incidents. They gathered data pertaining to the density, mass, shape, and size of ten individuals from each of these species. Utilizing these data, the IBRG established a correlation between a bird's mass and its density and diameter [26]:

$$\rho = -0.063 \times \log_{10} m + 1.148 \quad (9)$$

$$\log_{10} D = 0.335 \times \log_{10} m + 0.9 \quad (10)$$

where m , P , and D are bird mass, density, and diameter, respectively.

The response behavior of birds during high-speed impacts has been observed to resemble that of a homogeneous fluid, as indicated by previous studies. Consequently, any inhomogeneities resulting from other components, such as feathers and bones, can be disregarded. Therefore, employing a single-material model can effectively predict the impact behavior of birds under varying conditions [27]. The null material model is frequently employed for fluids and can more accurately capture the material properties exhibited by birds during high-speed impacts. The model relates the stress and strain of the bird as follows:

$$\sigma_{ij} = -P\delta_{ij} + 2\rho\gamma\dot{e}_{ij} \quad (11)$$

where σ_{ij} and $\dot{e}_{ij}$ are the identity and the rate-of-deformation tensors, respectively, P is the fluid pressure, and γ is the dynamic viscosity coefficient. The relevant parameters of the bird model are shown in Table 1. Figure 4 shows the hemispherical-ended cylinder (HEC) bird model used in this paper, which is divided into 12,640 SPH particles. The SPH particles are equally spaced in all directions, and the total weight of the bird is uniformly distributed in each particle.

Table 1. Parameters related to bird [27].

Parameter	Symbol	Value
Density	ρ	970 kg/m ³
Mass	m	0.680 kg
Diameter	D	0.0706 m
Length	B_L	0.179 m
Relative volumetric for erosion in tension	TEROD	1.1
Relative volume for erosion in compression	CEROD	0.8

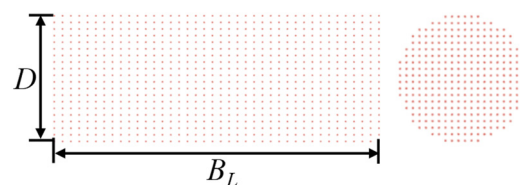


Figure 4. The hemispherical-ended cylinder bird model.

Equations of state (EOS) are instrumental in describing the physical state variables of materials and are frequently employed to elucidate the properties of both fluids and solids. Modeling the material behavior of birds typically involves the use of equations of state. Reference [9] indicates that the Gruneisen EOS is applicable to the bird model in this paper. The Gruneisen EOS for a compressed material can be expressed as follows [28]:

$$p = \frac{\rho_0 C^2 \eta \left(1 + \left(1 - \frac{\gamma_0}{2}\right)\eta - \frac{a}{2}\eta^2\right)}{\left(1 - (S_1 - 1)\eta - S_2 \frac{\eta^2}{1+\eta} - S_3 \frac{\eta^3}{(1+\eta)^2}\right)^2} + (\gamma_0 + a\eta)E \quad (12)$$

The Gruneisen EOS for an expanding material can be described as

$$p = \rho_0 C^2 \eta + (\gamma_0 + a\eta)E \quad (13)$$

$$\eta = \frac{\rho}{\rho_0} - 1 \quad (14)$$

where C is the intercept coefficient between the particle velocity and the cubic excitation velocity curve; S_1 , S_2 , and S_3 are the slope coefficients of the curve; γ_0 is Gruneisen's constant; a is the first-order volume correction coefficient of γ_0 ; ρ_0 is the initial density and ρ is the current density; and E is the internal energy. The corresponding values are provided in Table 2:

Table 2. Parameters used in Gruneisen EOS for birds [27].

Parameter	Value
C	1480 m/s
S_1	1.92
S_2	0
S_3	0
γ_0	0.1
a	0

2.2.2. FE Model of Fan Blades

This paper primarily focuses on the dynamic response of the blades when subjected to impact. For the sake of model simplification, a fixed constraint at the root of the blade is employed to simulate a scenario where the blade is attached to the hub. Figure 5a shows a geometrical model of the fan studied in this paper, which contains 24 equally spaced blades. The height of the blades in the paper is 484.1 mm and the width is 274.1 mm. We take its typical working conditions, $\omega = 500 \text{ rad/s}$ and $V_a = 100 \text{ m/s}$, for the numerical simulations. According to Equation (6), a bird under this condition will undergo slicing by four blades. For computational efficiency, only the four blades cutting the bird were modeled. In Figure 5b, the finite element model of quadruple blades is depicted, employing the Lagrangian method for the fan blades. While shell elements can expedite computations, the blades investigated in this paper exhibit non-uniform thickness and noticeable vibration characteristics in the thickness direction. Hence, solid elements were used for blade discretization. The finite element model of quadruple blades comprises a total of 336,000 elements, with each blade containing 19,680 elements. It consists of 4 elements in the thickness direction, 123 elements in the length direction, and 40 elements in the width direction.

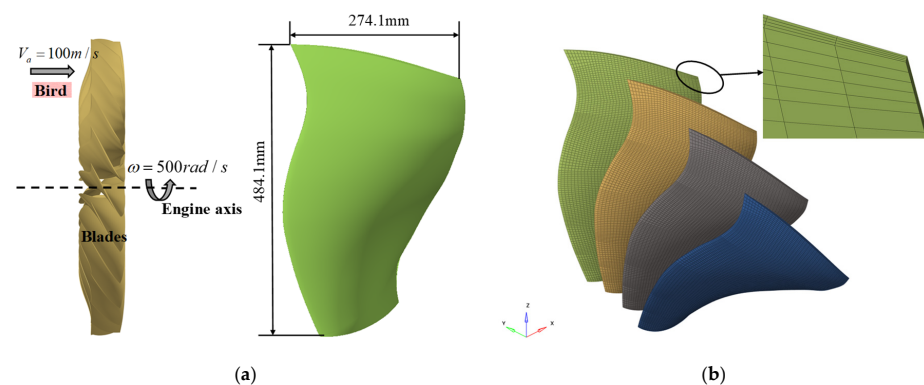


Figure 5. The fan blade model. (a) Geometrical model; (b) FE model of quadruple blades.

In the event of a bird strike on an engine, the fan blades can experience deformation or even failure due to the high-speed impact. To address this, the Johnson–Cook material model is employed, which comprehensively considers the interplay between flow stress,

strain, strain rate, and temperature. This material model effectively captures the relationship between impact load and structural response and is a commonly utilized approach in numerical simulations of bird strike scenarios. In the Johnson–Cook material model, the flow stress can be expressed as [29]

$$\sigma_y = (A + B\bar{\epsilon}^n)(1 + c \ln \dot{\epsilon}^*)(1 - T^{*m}) \quad (15)$$

where A , B , n , c , and m are the constants of the material; $\bar{\epsilon}^p$ is the effective plastic strain; $\dot{\epsilon}^*$ is a unitless rate which can be obtained by dividing the effective plastic strain rate by the quasi-static threshold rate; and $T^* = \frac{T - T_r}{T_m - T_r}$ is the homologous temperature, where T is the current temperature, T_m is the melt temperature of the material, and T_r is the room temperature. In the Johnson–Cook material model, the strain at fracture is given by [29]

$$\epsilon^f = (D_1 + D_2 \exp D_3 \sigma^*)(1 + D_4 \ln \dot{\epsilon}^*)(1 + D_5 T^*) \quad (16)$$

where ϵ^f is the strain at fracture; D_1 , D_2 , D_3 , D_4 , and D_5 are the failure parameters depending on the material; and σ^* is the stress triaxiality.

Considering the dynamic changes in stress rate, strain rate, and temperature during impact, material failure is determined by the following equation:

$$D = \sum \frac{\Delta \bar{\epsilon}^p}{\epsilon^f} \quad (17)$$

where D is the damage parameter; $\Delta \bar{\epsilon}^p$ represents changes in the effective plastic strain; and $\sum$ is the summation symbol. When the value of D reaches 1, the material can be considered to have failed. Table 3 shows the material parameters of the Ti6Al4V titanium alloy fan blade reference in the paper.

Table 3. Johnson–Cook material parameters for Ti6Al4V [30].

Parameter	Symbol	Value
Density	ρ	4420 kg/m ³
Shear modulus	G	41.9 GPa
Yield stress	A	1098 MPa
Strain hardening modulus	B	1092 MPa
Strain hardening exponent	n	0.93
Strain rate dependence coefficient	c	0.014
Softening exponent	m	1.1
Melting temperature	T_M	1878 K
Room temperature	T_R	293 K
Specific heat	C_p	612 J/kg·K
Failure parameters	D_1	0.112
	D_2	0.123
	D_3	0.48
	D_4	0.014
	D_5	3.87

In the case of simulating fan blades using solid elements, the Johnson–Cook material model is employed in conjunction with an EOS [10]. In this study, we choose the Gruneisen EOS to complement the Johnson–Cook material model. The values are shown in Table 4.

Table 4. Parameters used in Gruneisen EOS for Ti-6Al-4V [31].

Parameter	Value
C	5130 m/s
S_1	1.028
S_2	0
S_3	0
γ_0	1.23
α	0.17

2.2.3. Simulation Cases

The problem of multiple bird strikes involves a variety of scenarios. To simplify the problem, we conduct simulations focusing on scenarios where the blades are impacted by a single bird and separately by two birds. To more accurately simulate the response of the blades to impact loads under rotational prestress, this paper uniformly employs the implicit–explicit method in the bird impact simulations. Within the simulation calculations, the implicit method is initially utilized to solve for the rotational prestress within the blades, followed by the application of the explicit dynamics method to simulate the impact process, which involves substantial deformations. In this paper, the cases in Table 5 are used to simulate various scenarios. Cases A, B, and C show a single bird striking the blades. They consider the effect of the strike position s on the blade response; Cases D to N are the cases of two birds impacting the blades. They consider the effects of impact position s and impact time interval Δt on the blade response.

Table 5. Parameters in different bird strike simulations.

Case	n	Δt (ms)	s
A	1	/	$0.2H$
B	1	/	$0.5H$
C	1	/	$0.8H$
D	2	6.28	$0.2H, 0.2H$
E	2	6.28	$0.2H, 0.5H$
F	2	6.28	$0.2H, 0.8H$
G	2	6.28	$0.5H, 0.2H$
H	2	3.14	$0.5H, 0.5H$
I	2	6.28	$0.5H, 0.5H$
J	2	9.42	$0.5H, 0.5H$
K	2	6.28	$0.5H, 0.8H$
L	2	6.28	$0.8H, 0.2H$
M	2	6.28	$0.8H, 0.5H$
N	2	6.28	$0.8H, 0.8H$

As illustrated in Figure 6a, we selected three positions, $0.2H$, $0.5H$, and $0.8H$, to investigate the effect of impact position s on the blade response. In addition, this study also referred to the key impact parameters outlined in the Federal Aviation Regulations Section 33 (FAR-33) [14], and identified blade root stress, blade tip displacement, blade plastic deformation, and the energy of the blade as the principal indicators for assessing the transient response to bird strikes. For subsequent analyses in this paper, individual fan blades are designated numbers. As shown in Figure 6b, eight nodes (B1 to B8) at the blades' tips and four elements (E1 to E4) at the blades' roots were selected.

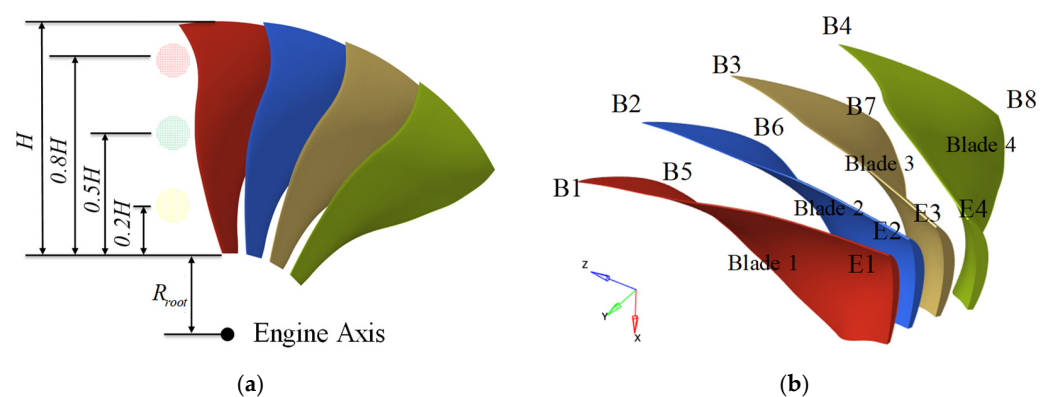


Figure 6. Different strike positions and blade numbers. (a) Different bird strike positions; (b) numbering of nodes, elements, and blades.

3. Simulation Model Validation

3.1. Bird Strike on Flat Plate

Wilbeck et al. [32] systematically investigated the collision mechanism of soft-body impactors by conducting an extensive series of bird strike experiments utilizing rigid flat plates. Their approach incorporated the application of hydrodynamic collision theory. Wilbeck's study divided the bird impact process into four distinct phases:

1. Initial impact phase at contact: This first phase commences when the initial compression wave is formed and propagates back into the bird material;
2. Collisional impact decay phase: The second phase initiates when the peripheral part of the bird is released in a radial pattern;
3. Constant flow phase: The third phase begins when the bird material starts to flow through space in a fixed streamline;
4. End of the impact phase: The impact concludes when all the bird material has reached the target flat plate surface, and the pressure drops to zero.

Appropriate numerical simulations for bird strike analysis should precisely replicate the Hugoniot pressure, steady flow pressure, and the complete pressure-time history. In order to assess the accuracy of the SPH bird model in Figure 4, we built a simulation model of a bird impacting a rigid flat plate at 100 m/s. As illustrated in Figure 7, the deformation of the SPH particles and the pressure change at the center of the rigid plate are well aligned with the bird strike process proposed by Wilbeck.

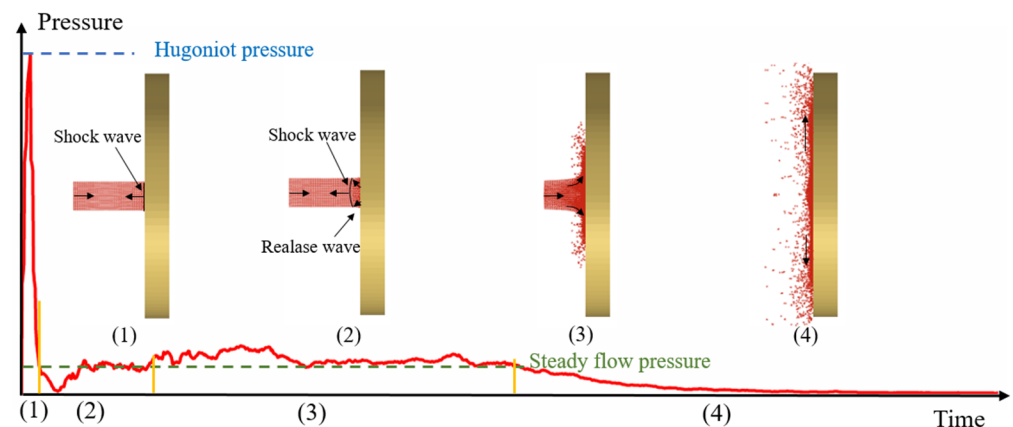


Figure 7. Variation in SPH particle and rigid plate center pressure.

Figure 8 presents the transfer of stress waves during the impact of a bird on a rigid flat plate. The “mushroom-shaped” interface of the impact stress wave in the figure aligns well with the findings from Wilbeck's study. Our numerical simulations confirm that the SPH bird model developed in this paper effectively replicates the actual impact process.

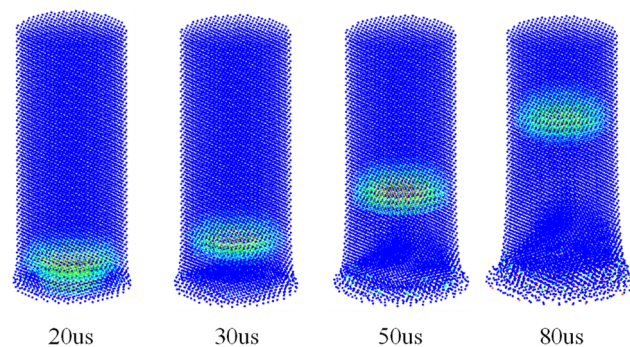


Figure 8. Transmission of stress waves during impact.

3.2. Prestress of Fan Blades

To comprehensively analyze the results of bird strikes blades, it is imperative to conduct prestress simulations on the fan blades prior to the impact simulations [12]. Prestress simulations of the fan blades serve to establish the stress distribution and deformation of the blades under centrifugal forces. This step is instrumental in enhancing the precision of bird strike simulation results. The rotational speed of the fan blades in this paper is 500 rad/s. The prestress of the blades at this speed is implicitly analyzed in LS-DYNA using the dynamic relaxation method. As illustrated in Figure 9, the maximum stress within the blades is concentrated in the middle section, with a peak stress value of approximately 368 MPa. It is noteworthy that this stress level is below the yield strength of TC4 material. Consequently, the blades did not exhibit significant plastic deformation. The blades were able to operate under normal conditions at 500 rad/s prior to the bird strike.

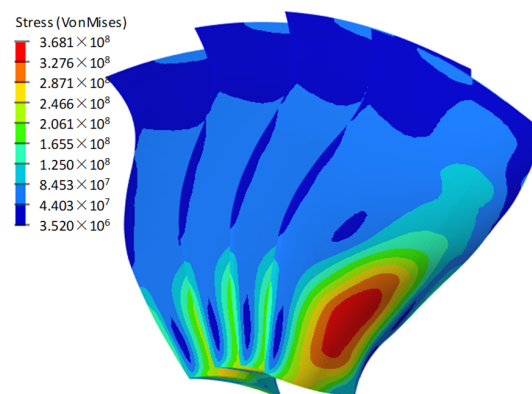


Figure 9. Blade prestress distribution.

4. Results and Discussion

4.1. Single Bird Strike

This section delves into the blade response to bird strikes at the root, middle, and tip. Bird strikes can induce substantial blade deformation, potentially altering the aerodynamic performance and potentially causing issues like unstable engine rotor motion. Hence, the analysis of blade plastic deformation is imperative. Blades of TC4 material exhibit notable crimping of the edges when struck by birds. Figure 10 illustrates the distribution of plastic deformation in various cases, with the maximum effective plastic strains in Cases A, B, and C measuring 0.273, 0.215, and 0.227, respectively.

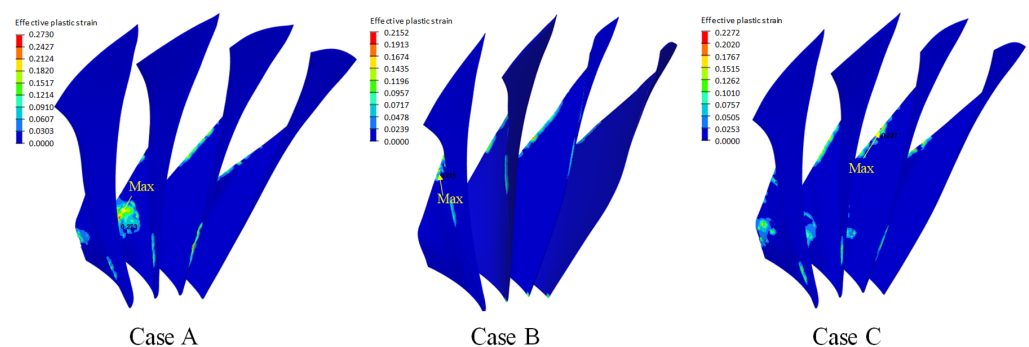


Figure 10. Effective plastic strain of blades.

The magnitude of the maximum effective plastic strain in the different cases is primarily influenced by two key factors: the blades' torsion angle and the tangential velocity at the strike positions. To account for the aerodynamic characteristics of blades, blade design typically adheres to the principle that the torsion angle increases proportionally with the blade height. As depicted in Figure 11, variations in the direction of SPH particle motion

primarily arise from differences in blade torsion angles. Notably, at a $0.2H$ blade height, the blade exhibits a relatively small torsion angle, leading to significant alterations in the motion direction of SPH particles as they slide along the concave surface of the blades after impact. This suggests that birds impose substantial impact loads on the blades during this sliding phase, resulting in extensive plastic deformation. In contrast, at the $0.8H$ blade height, the blades' torsion angles are relatively large, leading to less significant changes in the motion direction of the SPH particles. However, considering the higher rotational tangential velocity at the blade's tip compared to the other locations, the substantial impact velocity of the bird still induces significant plastic deformation on the leading edge of the blade. In the middle of the blades, the combined effects of both factors, blade torsion angle and blade rotational tangential velocity, are less pronounced. When the middle of the blade is struck, plastic deformation is observed at both the leading and trailing edges, but the maximum plastic strain is relatively small.

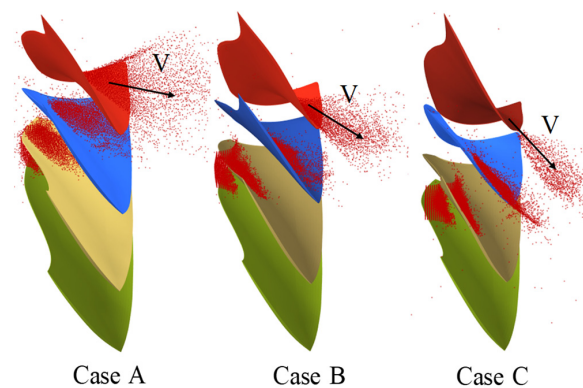


Figure 11. Direction of SPH particle motion at 1.75 ms.

4.2. Multiple Bird Strikes

4.2.1. Multiple-Strike Probabilities for Different Conditions

Table 6 gives the multiple-impact probabilities of the engine fan blades studied in this paper for different cases. Figure 12 illustrates the variation in the probability of a blade experiencing multiple impacts with the number of birds striking the engine under diverse cases. The probability of the blade undergoing multiple impacts escalates rapidly with an increase in the number of birds colliding with the engine. This underscores the significance of delving into research on the issue of blade impact by multiple birds. Additionally, an elevation in the angular velocity of the blades leads to each bird colliding with more blades, consequently heightening the likelihood of multiple bird impacts on the blades. Conversely, as the aircraft speed increases, birds traverse the engine fan area more swiftly, resulting in a reduced probability of multiple bird strikes on the blades.

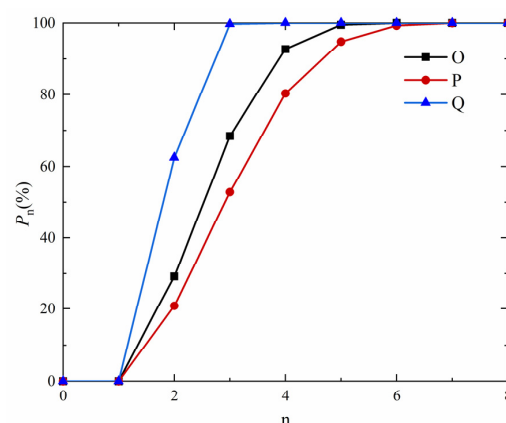


Figure 12. Variation in P_n with n for different cases.

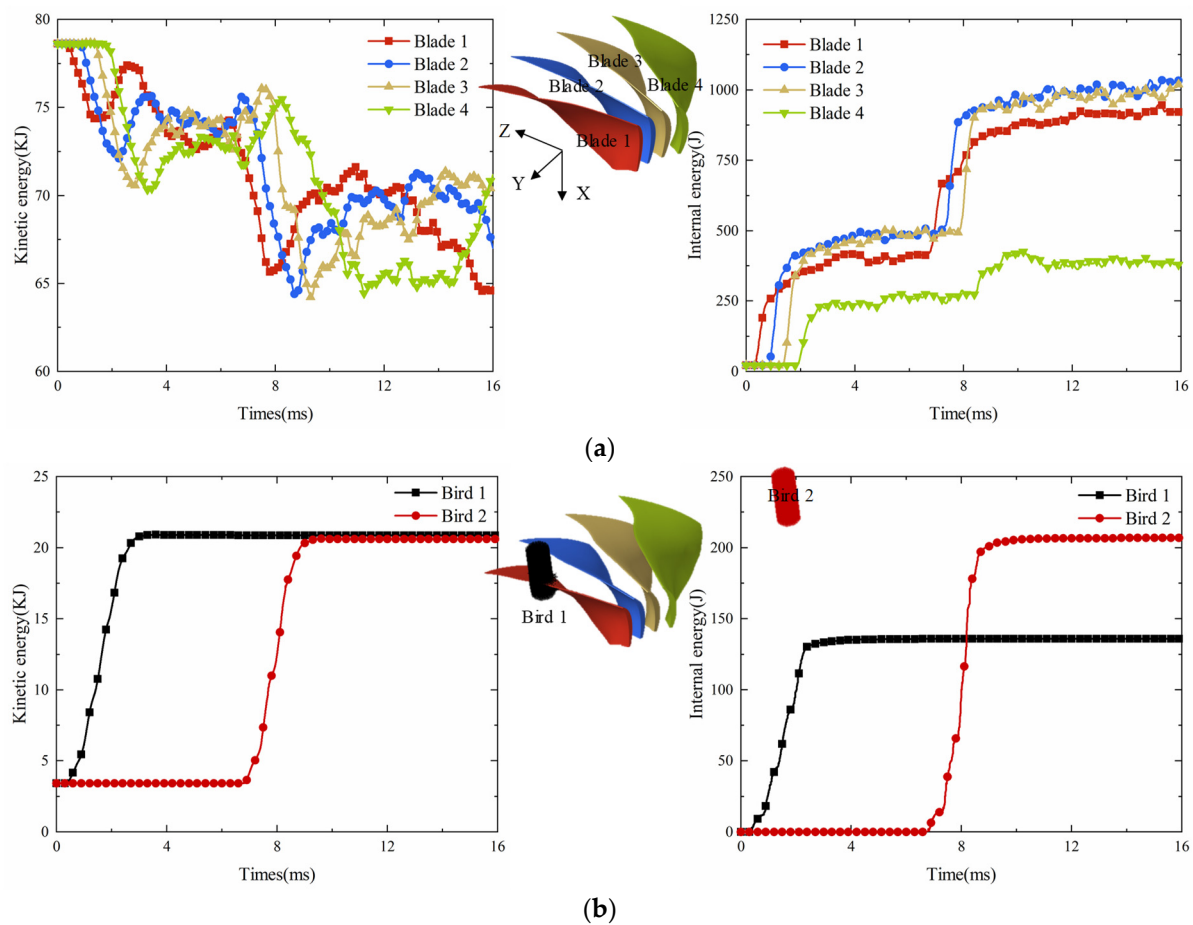
Table 6. Different predicted cases.

Case	ω (rad/s)	V_a (m/s)	N
O	500	100	4
P	500	200	3
Q	1000	100	8

4.2.2. Effects of Impact Time Interval

In this section, based on Cases H, I, J, and B, we investigate how the impact time interval affects the response of the blades. In each of these cases, the first bird strike occurred at approximately 0.5 ms. The second bird strike then occurred at different intervals, around 3.6 ms, 6.8 ms, and 10.0 ms in Cases H, I, and J, respectively.

The bird strike process involves complex energy transformations. Figure 13a,b illustrate the changes in energy for both the blades and the birds in Case I. Here, Bird 1 and Bird 2 denote the birds that struck the blade for the first and second time, respectively. During this impact, the blades lose approximately 40 KJ of kinetic energy, while the birds gain around 34.6 KJ of kinetic energy. The kinetic energy of the blades is primarily converted into the kinetic energy of the birds, with some energy being transformed into the internal energy of both the birds and the blades. The change in the internal energy of the blades is a significant indicator of blade damage [33]. Figure 14b depicts the relationship between the total internal energy of the blades and time in various cases. The internal energies of the blades in Cases H, I, and J show substantial increases after the two bird impacts and become quite similar. This suggests that the time interval between bird impacts has little effect on blade damage.

**Figure 13.** Energy of blades and birds in case I vs. time. (a) Energy of blades; (b) energy of birds.

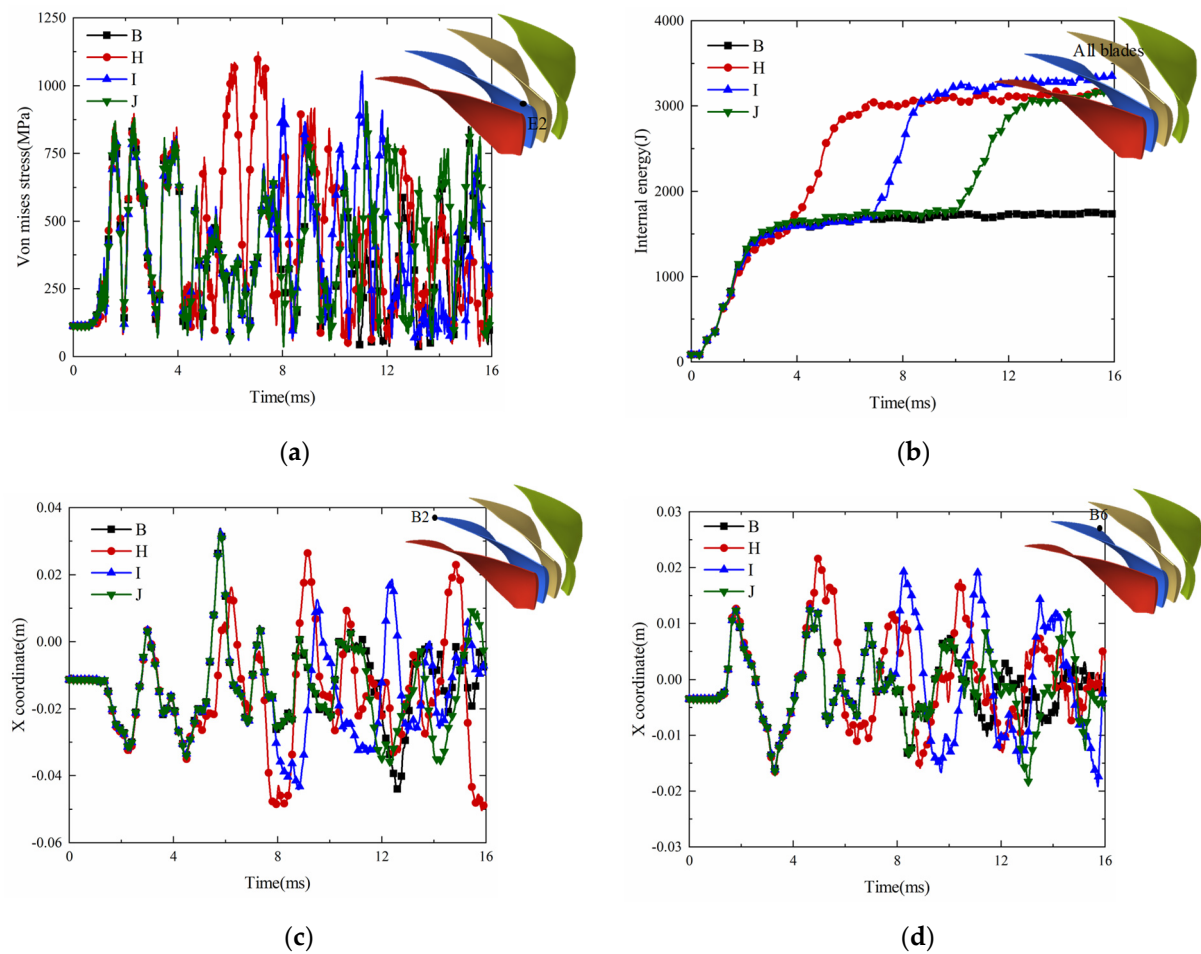


Figure 14. Dynamic response of blades in Cases B, H, I, and J. (a) Stress in blade root E2; (b) blade's internal energy; (c) x coordinate of blade tip B2; (d) x coordinate of blade tip B6.

Figure 15 illustrates the distribution of effective plastic strains in various cases. Although the distribution of plastic strains showed similarities across different impact intervals, variations were observed in the maximum effective plastic strains. The maximum plastic strains were 0.243, 0.236, and 0.231 for Cases H, I, and J, respectively.

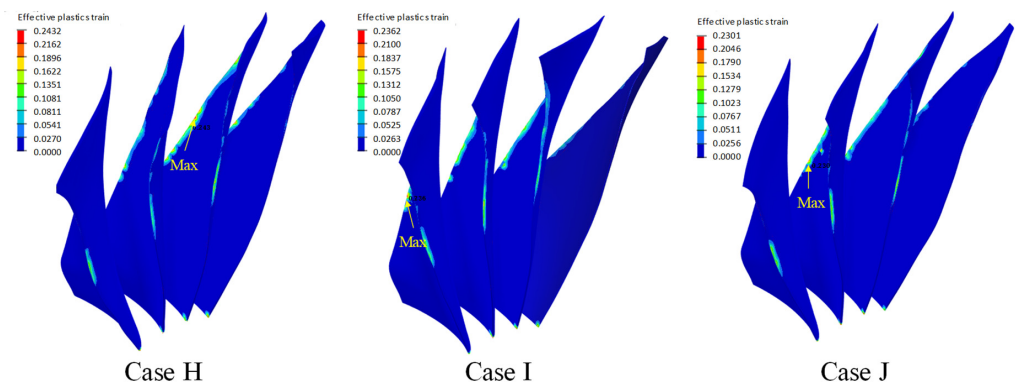


Figure 15. Effective plastic strain of the blades.

Based on the maximum distortion energy theory, excessive von Mises stresses can lead to blade damage. Stress at the root of the blades is a critical parameter to investigate. Since bird strike incidents typically involve multiple blades, this paper focuses on Blade 2 when analyzing data for a single blade. Figure 14a presents the variation in Von Mises stress at

the root (E2) of the blade over time for different cases. Before being impacted by the bird, the stress in the blade root was at 113.41 MPa. After the impact, the stress in the blade root significantly increased and exhibited rapid fluctuations. The maximum blade root stress during bird impact was 1142.38 MPa in Case H, 1053.18 MPa in Case I, 940.55 MPa in Case J, and only 849.82 MPa in Case B. These findings indicate that multiple impacts considerably elevate blade root stresses. There is a trend that suggests the shorter the time interval between multiple impacts, the higher the stresses in the blade root.

Blade tip displacement data are a crucial indicator for assessing bird strike hazards. Following a bird strike, the blades exhibit sustained vibrations, and there is a possibility of the blade tips experiencing a secondary impact with either the engine cases or neighboring blades [12]. Figure 14c,d depict the variation in x coordinate values for blade tips B2 and B6 over time. If there is significant displacement in the positive x direction, blade tip B2 might collide with Blade 1. On the other hand, if there is substantial displacement in the negative x direction, blade tip B6 could collide with Blade 3. These potential impacts need to be considered separately.

The blade tip displacements exhibited a noticeable trend of attenuation after 8 ms in Case B, while the attenuation was not as prominent in the other cases. This suggests that multiple impacts contribute to the continued oscillation of the blades. For blade tip B2, the maximum x coordinate value is lower in Cases H, I, and J than in Case B. In the case of blade tip B6, the minimum x coordinate values in Case I and Case J are -0.0192 m and -0.0183 m, respectively, slightly smaller than the minimum value of -0.0167 m in Case B. However, in Case H, the x coordinate values of the blade tip consistently exceed -0.0167 m after the second impact. Overall, it can be observed that multiple impacts do not significantly increase the maximum displacement of the blade tip and may even have a dampening effect.

4.2.3. Effects of Strike Position

Cases D to N illustrate the effect of different strike positions of birds on blade response. Figure 16 illustrates the maximum stresses and maximum plastic strains of the blades across different scenarios and extrapolates the outcomes for additional blade heights experiencing multiple impacts. In Case D, the blades experience impacts from both birds at the root, leading to the highest strain observed in the blades. In Case N, where both birds strike the blades at the tip, the recorded strain values are only lower than those witnessed in Case D. Cases D, I, and N involve two birds striking at the same location, and the deformation of the blades mainly occurs in the region of the strike, and significant strain superposition occurs in the region of the impact. Additionally, if birds strike the middle of the blade, the strain in the blade will be smaller, consistent with the findings in Section 4.1 that the strain in Case B is less than in Cases A and C.

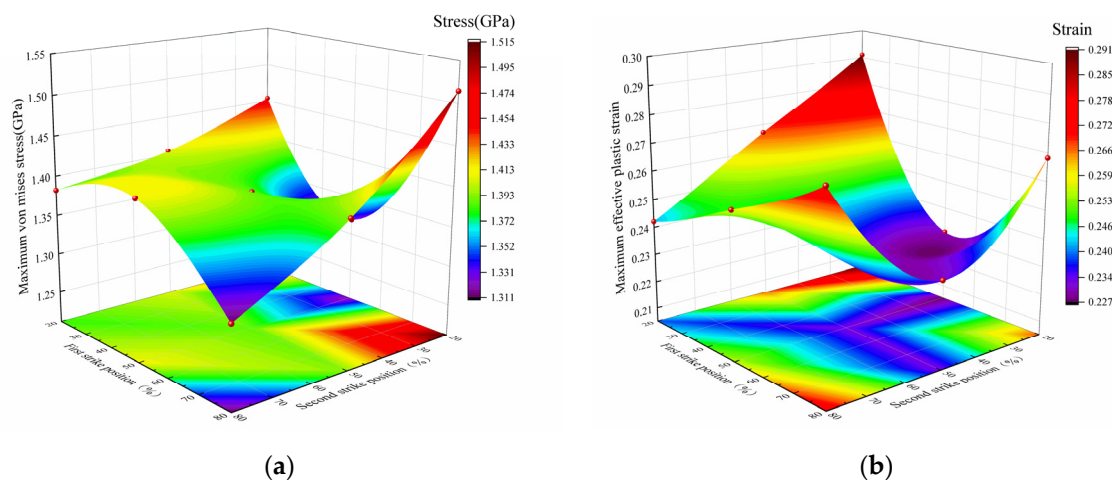


Figure 16. Maximum stress and strain vs. strike position. (a) Maximum stress; (b) maximum strain.

Figure 17 depicts the temporal variation in stress in blade root E2, with t_{strike} indicating the moment when the bird commenced striking Blade 2. In Figure 17a, after the first impact in Cases D, E, and F, the stress at the blade root is minimal. However, after the second bird strike, the stress at the blade root shows a clear upward trend. In Figure 17b, subsequent to the initial bird strike in the middle of the blade, the stress in the blade root swiftly reaches its maximum value, followed by a period of oscillation and gradual decay. Upon the occurrence of the second bird impact, the stress at the leaf root experiences a rapid increase. The maximum blade root stress in Cases L, M, and N is observed around 6 ms, and the blade root stress following the second impact does not surpass the maximum value recorded after the first impact. Figure 18 displays the relationship between the maximum blade root stress and the location of the bird strikes. The highest blade root stress is observed in Case K, while the maximum stress in Cases D, E, and G is significantly lower than in the other cases. This indicates that the stress in the blade root is higher when birds strike the middle of the blade and above. If the birds mainly strike the root of the blade, the stress is lower.

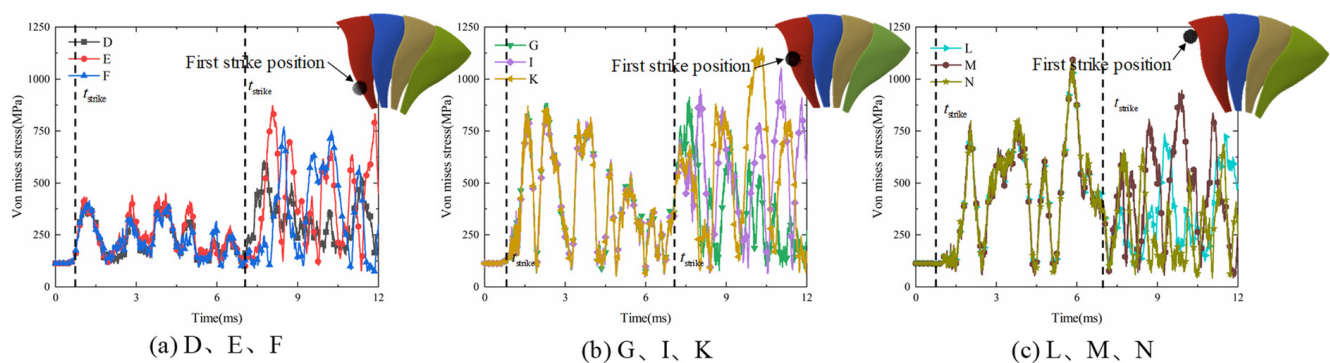


Figure 17. Von Mises stress in blade root E2 vs. time.

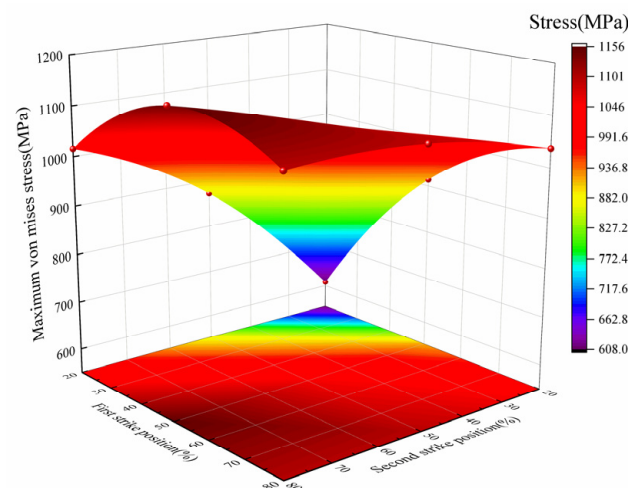


Figure 18. Maximum blade root stress vs. strike position.

Figure 19 illustrates the trend of the total internal energy of the four blades over time in different cases. The significant impact of bird strike position on blade damage is evident. Specifically, the internal energy of the blades in Case D notably surpasses that of the other cases, indicating that multiple bird strikes on the blade root result in the most severe damage. Moreover, Cases E, F, G, and L, each with only one bird impacting the blade root, also exhibit higher internal energies compared to the other cases, suggesting that impacts on the roots of blades would lead to greater damage.

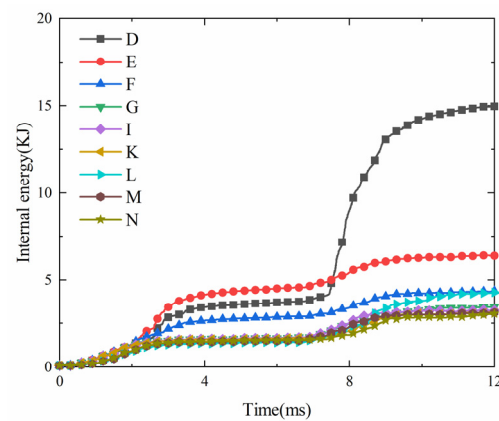


Figure 19. Blades internal energy vs. time.

Figure 20 displays the x coordinates of the tips of Blade 2, revealing significant differences in displacement between different cases. When Bird 1 strikes the root of the blade, the positive x displacement of B2 remains relatively small, regardless of where Bird 2 strikes the blade. The displacement of B2 is greatest when Bird 1 strikes the tip of the blade and Bird 2 strikes the middle of the blade. For B6, the negative x displacement of B6 is greatest when Bird 1 impacts above the middle of the blade and Bird 2 strikes the tip of the blade.

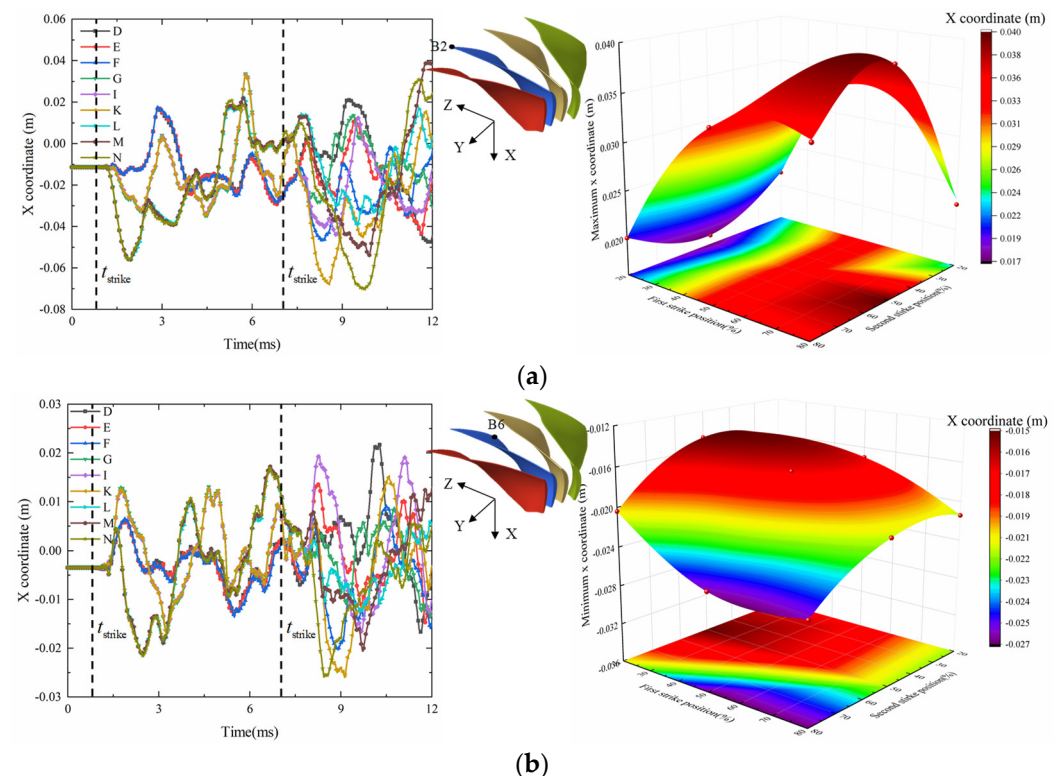


Figure 20. Blade tips x coordinate vs. strike position. (a) X coordinate of blade tip B6; (b) X coordinate of blade tip B2.

5. Conclusions

In this paper, the impact process of birds on rotating fan blades is analyzed, and a probability model for blades subjected to multiple impacts is presented. Based on a typical engine fan, the response of the blades to one and two bird strikes is investigated separately. This study primarily investigates the impact of strike location and the strike time intervals of multiple strikes. The findings can provide valuable references for further research on the

multiple-bird-strike problem and the airworthiness verification of engines. For instance, the effects of multiple bird strikes can be considered at the blade structure design phase, and simulations of the most hazardous impact scenarios can be conducted during the airworthiness verification stage. This paper draws the following conclusions:

1. The probability of multiple impacts on the blades is contingent upon factors such as flock density, bird size, the rotational speed of the fan blades, and the speed of the airplane. An augmentation in the angular velocity of the blades corresponds to an increased probability of multiple impacts on the blades. Conversely, a higher airplane speed is associated with a diminished probability of multiple impacts on the blades.
2. The analysis of the internal energy of the blades showed that in scenarios involving multiple bird strikes, the time interval between bird strikes has a minor effect on blade damage, whereas the strike position exerts a substantial influence.
3. The impact time interval's effect on all analyzed bird strike response indices in this paper is small. However, there is a tendency that with a smaller time interval between multiple impacts, the stress in the blade root tends to increase. Furthermore, in contrast to a single-bird-strike scenario, multiple bird strikes may not substantially augment the maximum displacement of the blade tip. In fact, they could even mitigate the displacement of the blade tip to some extent.
4. The strike position significantly influences the blades' response, with minimal plastic strain observed when the bird strikes the middle of the blades. Notably, the most substantial blade damage occurs when birds strike the root of the blade, and this damage is predominantly influenced by the strike position of the first bird. When birds strike the blades above the center of the blades, they are more prone to being involved in accidents where the blades collide with each other.

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