A Review of Research on Bird Impacting on Jet Engines

Yuecheng Jin¹,*

¹The Sino-British College, University of Shanghai for Science and Technology, Shanghai, 200093

*SBC-15-1058@sbc-usst.edu.cn

Abstract. Bird strikes can lead to permanent deformations, sudden decrease of thrust, even engine failure during the flight. Bird strikes on rotating blades can also cause slices of birds hitting other parts which may lead to greater damages. Bird strikes cannot be completely avoided. However, reduction of bird impacting on jet engines can be achieved by suitable design and manufacturing, through the mathematical modelling, simulation analysis and practical experiment of jet engines.

1. Introduction

With Wright brothers operating the first fixed-wing aircraft off the ground in 1903, humans can fly like birds in the sky. According to Boeing's reports, three-quarters of bird strikes were related to aero-engines. Civil Aviation Authority (CAA) and International Civil Aviation Organization (ICAO) have similar conclusions. Bird strikes can lead to permanent deformations, sudden decrease of thrust, even engine failure during flight. Bird strikes on rotating blades can also cause slices of birds hitting other parts which may lead to greater damage. Bird strike cannot be completely avoided. However, reduction of bird impacting on jet engines can be achieved by suitable design and manufacturing, through the mathematical modelling, simulation analysis and practical experiment of jet engines.

The rest of the paper is organized as follows: numerical simulation analysis is illustrated in Section 2, contents related to bird strike tests is carried out in Section 3, anti-bird strike design of jet engines is given in Section 4. Conclusions are given in Section 5.

2. Numerical simulation analysis

Numerical simulation analysis relies on mathematics or computer-based methods, greatly reducing the cost and destruction of the experiments.

2.1 Method of numerical simulation analysis

According to physical properties of the blades and bird during the impact, several transient states may exist, thus several possible methods as follows [1].

(1). Structure-structure coupling computation

The bird is considered as rigid body and the blade is considered as deformable target.

(2). Fluid-structure decoupled algorithm

The bird is considered as fluid during the impact and the blade is considered as deformed target. The bird and the blade response is modelled separately by building the bird impact model first then calculate the blade response.

(3). Fluid-structure coupling computation
The bird is considered as fluid during the impact and the blade is considered as deformed target. The bird and the engine is considered as the whole system during the impact.

(4). Contact-impact finite element method
The border of the bird and the blades is determined and the force during the impact is calculated by changing of momentum. This method can reduce the errors caused by the coupling computation and has higher precision.

2.2 Probability of bird impacting on different area of the engine blade

2.2.1 Probabilities of impacting regions on the blades. Ma Li et al. [2] defined the engine into three parts: blade apex, blade body and blade root. The probability of impact region that the bird will hit is dependent on the area of the three parts and it is defined as:

\[ P_a = \frac{S_a}{S_T}, P_b = \frac{S_b}{S_T}, P_r = \frac{S_r}{S_T} \]  

Where \( P_a \) is the probability of the bird impacting on the blade apex, \( P_b \) is the probability of the bird impacting on the blade body; \( P_r \) is the bird impacting on the blade root. \( S_a, S_b, S_r \) and \( S_T \) are the area of the blade apex, body, root and the total area, respectively [2].

2.2.2 Probabilities of bird passing the air inlet. According to Ref.[2], the passing probabilities is the ratio of the diameter of the bird model \( D \) and the width of air inlet interval \( L \).

\[ P_2 = \frac{L-D}{L} \times 100\% \]  

The relationship between the width of the inlet and the radius of the bird model \( R \) is:

\[ L = \alpha R - \delta \]  

Where \( \alpha \) is the angle between the two holder support, \( \delta \) is the thickness of the holder support, \( R \) is the radius of the impacting point. The analysis only consider that the whole bird passing through the air inlet, in real situations that part of the birds tissues may pass through and increase the possibilities.

2.2.3 Probabilities of impacting regions on the blades. Considering all the probabilities, the equations can be get as \( P = P_1 \times P_2 \), and the probability that the bird will most likely to be hit is the apex blade part and the root is less likely to be hit. This conclusion is applicable to almost all jet engines.

2.3 Bird modeling

2.3.1 Smoothed Particle Hydrodynamics method (SPH method). Barber et al.[3] firstly demonstrated that the material constitution birds can be modelled as fluid during high velocity impact with rigid body because the birds’ tissue strength is significantly lower than the impacting stress. The SPH method[4] is used to simulate bird model is based on normalized corrected Kernel interpolation which is first order consistent and conservative.

2.3.2 Bird geometry. Budgey [5] proposed the relationship between bird mass and density, bird diameter and mass. Budgey also proposed relationship between the mass of the bird model and slicing effect in his report.

\[ \rho = -0.063 \times \log_{10} m + 1.148, \log_{10} D = 0.335 \times \log_{10} m + 0.900 \]  

Where \( \rho \) denotes density, \( m \) is the mass, \( D \) represents the bird diameter.
Currently, three main shapes of the bird model are used in the strike tests and simulations which are
the hemispherical-ended cylinder, ellipsoidal and flat-ended cylinder. The hemispherical-ended cylinder is the most commonly used shape in the test and stimulation which is adapted by McCarthy et al.[6], Langrand et al.[7] and Airoldi and Cacchione[8][9]. The ellipsoidal is important because it is recommended by IBRG.

2.3.3 Bird material. As mentioned above, the strength of birds is significantly lower than the strength of the blades, birds are considered as continuous fluid. The most commonly used bird material model is the Isotropic-Elastic-Plastic-Hydrodynamic (IEPH) material proposed by Anghileri et al.[10], which takes the slicing effect of the artificial bird into consideration. The forces acting on the blade can be calculated using the impulse which is the change of momentum. The equation of state (EOS) with the IEPH material model is applied to accurately model the hydrodynamic response [6].

\[
P = P_0 + B \left( \frac{\rho}{\rho_0} \right)^\gamma - 1
\]  

(5)

Where \( P_0 \) is the reference pressure, \( B \) and \( \gamma \) are experimental parameters which are dependent on the bird model.

2.4 Fan blade modeling

Since each engine has different geometry and material model. Three different engines are taken as the examples in this section.

2.4.1 Engine 1[11]. As shown in Figure 1, the engine consists of 22 equally distributed engine blades attached to the disks with 16.36 degrees between the two following blades. This disk part is considered as rigid body, neglecting the impacting effect. Corresponding radiuses are measured from the axis of rotation of the rotor. The external radius is 570mm measured from the center of rotation to the tip of the blade. The impacting radius is the radius of the impacting point which is 514mm. The internal radius is the radius from the axis to the root of the blades which is 175mm.

The blade and its support were meshed using TrueGrid software. The blade was meshed with 21,400 elements: 107 elements along lengthwise, 50 elements width wise and 4 elements through the thickness.

![Figure 1](image)

2.4.2 Engine 2[12]. As shown in Figure 2, a typical modern jet engine fan blade was modeled. The fan blade assemble consists of 18 equally distributed blade sector and a hub section. Only two blades is collected in the simulation in order to increase the efficiency of calculation. The mesh has 69,470 elements and 127,972 nodes. The engine blades are typically made of titanium alloy Ti-6Al-4V and the material model used in the simulation is Johnson-Cook viscoelasticity material model.
2.4.3 Engine 3[13]. As shown in Figure 3, the hub is assumed be rigid body compared with the blade. The inner and outer radius of the blades is 0.51m and 1.47m, respectively. Shell-163 elements in LS-DYNA were used to simulate the blade with 31 nodes in the axial direction and 61 nodes in the radial direction. The thickness of the blades can be presented as:

\[ \Delta = 0.026 - 0.00463y^2 - (z + 0.1)^2 \]  

(6)

**Figure 2.** Geometrical model and finite element model [2]

![Geometrical model and finite element model](image)

2.5 Simulation process and results

2.5.1 Simulation process. According to the simulations, there are also common points that the bird impacts the engine blades in the analysis. The bird impacting the engine blade can be divided into three stages.

In the first stage, the bird model strikes the front edge of the bird with large relative velocity. In this stage, the blade cutting the bird model and under the great impacting force, the blade bend to the other side and the front edges shows evident plastic deformation. There is concave edges occurs at the impacting point and cracks and off-falling emerges. This can cause further damage when the engine continues working with cracks propagation and metallic failure which is called the secondary damage.

**Figure 3.** Distributed 3D fan blade finite-element model[13]

![Distributed 3D fan blade finite-element model](image)
In the second stage, the bird slices cutting by the blade hitting the blade causing the whole blade to bend over. Plastic deformations can occur at the shrouds and the roots and the damage is smaller compared to the first stage. In the third stage, the blade oscillate and recover because its own elasticity. This can cause further crack propagation, off-fall and fatigue.

2.5.2 Bird shape influence. The impact location was set at the radius of 514mm (86% of the blade span) from the rotation axis. Two different bird model, hemispherical bird model and ellipsoidal bird were selected in the simulation to show the difference of the impact. All the other parameter was controlled to show the direct comparison [11].

(1) Hemispherical bird model

For the hemispherical bird model, the stress generated by the impact distributed over a larger area than the ellipsoidal bird model. For the hemispherical bird, deformation of the blade was more widely spread, and the plastic deformations were observed at the trailing edge of the impacted blade and the root of the leading edge of the leading blade.

(2) Ellipsoidal bird model

The ellipsoidal bird model has the highest plastic strain observed closing to the impacting point. The ellipsoidal bird impact the leading blade suffered only local deformation (deformation around the impact point). The ellipsoidal bird model has the highest plastic strain observed closing to the impacting point.

2.5.3 Bird incidence angle. According to the simulation, the normal incidence can lead to the maximum impacting force and plastic strains causing great damage when the other parameters are controlled. When the incidence angle is greater or equal to 60 degrees, the impacting force is distinctly reduced and the blade will only suffer from elastic strain [13].

2.5.4 Bird impact location. The response of the blades was strongly dependent on the bird impact locations. The impact location moves towards the rotational axis the contact forces were reduced. The contact force magnitude was related to the blade pitch angle which increases with the distance from the rotation axis. Consequently, this influenced the bird slice size and its change of momentum during the impact [2], as shown in Table 1.

| Bird strike location | Blade damage degree |
|---------------------|---------------------|
| Fan blade root      | Plastic deformation in the edges of the root, little deformations in the fan blade body and apex, no cracks and off-falling. |
| Fan blade body      | Big plastic deformation at the front edge of the blade body, deformations found at the root and apex of the fan blade with off-falling and relatively big deformation at the fan blade body. |
| Fan blade apex      | Great deformations at the front edges of the blade apex with off-falling, plastic deformation at the body and root of the fan blade with cracks. Big plastic deformation at the fan blade body. |

3. Bird impacting experiment

3.1 Experiment process

The bird model is prepared according to simulation and the velocity of the bird and rotational speed is according to the international military standard. The impact location is chosen at the apex of the blade since it can cause the greatest damage in the simulation. The experiment is mainly to find real impacting stress and force and the whole experiment is recorded by high-speed camera.

In all the experiments, the bird model hit disintegrates into slices and there is distinct bending to the
other side of the blade at the striking point. The bird model continues hitting the following blade with the similar phenomenon but smaller concave edges at the impacting point until the bird model is consumed totally [14].

3.2 Damage classification and standard
According to the American aviation turbine bird injecting statistical report [15], the damage is classified into 6 sorts. According to the Rolls-Royce bird injecting standard [16], the damage is classified into 5 sorts, as shown in Table 2.

Table 2. Damage Classification of Fan Blade Bird Strike by R.R.

| Category                  | Description                                                                 |
|---------------------------|-----------------------------------------------------------------------------|
| Tip bending               | Caused by the strike of the blade tip, resulting in loss of thrust          |
| Front chord dent          | The degree in loss of thrust depends on the dent depth                      |
| Axial tearing             | Crack propagation might result in chipping                                  |
| Radial tear at the boss root | Chipping due to crack propagation at the boss root of the blade with shrouds |
| Breakage at the blade root | The whole blade flies out                                                   |

The Rolls-Royce also divided the damage into 6 levels [16], as shown in Table 3.

Table 3. Blade Damage Grade of Bird Ingestion Test by R.R.

| Damage Grade | Damage condition                                      |
|--------------|-------------------------------------------------------|
| 2            | Front, rear chord bending or warping                   |
| 2            | Boss bumping and chipping                             |
| 4            | Slight blade blending                                  |
| 4            | Several local warping                                 |
| 6            | Bending of severe plastic deformation on the impact   |
| 6            | radius                                                |
| 8            | Deformed boss, but still abutted                      |
| 8            | Bending of severe plastic deformation at the blade root|
| 8            | The boss is not abutted after the test                 |
| 10           | Scarping with other blades, or being cut off          |
| 15           | Tip fracture                                          |
|              | Blade fracture from the blade root                     |

3.3. The definition of damage parameter and evaluation method

3.3.1 The equivalent plastic strain damage parameter. The blade failure modes such as the overall deformation, curling, dent, tear and breakage are caused by the plastic strain of the local or root material of the blade. According to the uniaxial tension curve in the blade material property, the plastic strain of the blade fracture and failure can be determined. The maximum equivalent plastic strain when the blade is struck by the bird can be obtained through the numerical calculation or test of the impact response. η, the plastic strain damage parameter can be defined as [17][18]:

$$\eta = \frac{\varepsilon_{p,\text{max}}}{\varepsilon^*}$$  \hspace{1cm} (7)

3.3.2 Blade deformation parameter. Due to the lateral vibration and torsional movement after the blade is struck by the bird, the tip may be exposed to the adjacent blades, or collide with the casing, which will lead to mechanical failures of the engine. According to the actual blade design, the blade tip displacement can be determined when the blade fails, and the actual maximum displacement of the
blade tip can be obtained through the numerical calculation or test of the impact response. \( \lambda \), the blade deformation damage parameter can be defined as[18]:

\[
\dot{\lambda} = \frac{U_{\text{tip}, \text{max}}}{U_{\text{tip}}}
\]

After calculation, if \( \eta \geq 1 \) or \( \lambda \geq 1 \), then the blade is considered to be metallic failure. If the damage parameter is \( 0 \leq \eta < 1 \) or \( 0 \leq \lambda < 1 \), then the level of destruction and the corresponding risks can be evaluated.

3.4 Experimental results and comparison

The experiment shows the similar phenomenon to the simulation results. The bird impacting can be divided into three stages. The bird impacts the front edges of the blades in the first stages with the biggest impacting force causing plastic deformation at the front edges and shrouds. This is the most dangerous periods. The second part is the slices of birds hitting the blades with relatively small impacting force and causing little damage. The third period is the blades recovering under its own elasticity and vibrating which does not cause new damage but has the possibility to aggravate the formal damage.

The experimental result and the simulation show the similar trend of bird impacting on the blades and the same damage sort at each stage. The difference is the specific value calculated at the instant time which may cause by systemic and random errors.

4. Designs for reducing damage of bird impacting

To reduce the damage of the bird strike to the engine blades, several designs are proposed. After searching, the designs can be divided into two sorts: one is using technical method to lower the possibilities of bird from attacking the engine blades as results reducing the damage indirectly; the other method is applying new designs to reduce the impact damage directly.

4.1 Indirect design

4.1.1 Changing inlet area. According to some research, several Russia jet fighters will close the major inlet and use vice inlet during the landing process. This method is to reduce windward area of the engine blade thus reducing the possibilities of the bird impact.

4.1.2 White flash lines on engine cowling. Researchers have also presented other methods. For example, people now paint a white spiral of a gradually varied width on the conic engine cowling which rotates at a high speed with the rotor of the fan. When the engine is running, these spirals appear as a white flash circle which discourages birds from flying into the engine. Although these measures work to some extent, they are far from perfect.

4.2 Direct design

4.2.1 Wide-chord hollow fan blades. Wide-chord hollow fan blades first launched by Rolls-Royce features strong intensity and their weight is much less than that of narrow-chord solid fan blades which not only increases efficiency of engines but also reduces vibratory fatigue of engines and improves anti-bird-strike performance. A number of achievements with regard to bird-resistant fan blades have been made based on many of the above theories. Pratt & Whitney Group has developed a kind of milling groove wide-chord hollow fan blades, improving its anti-strike performance. Fan blades of such structure are not only applied to PW4084 engines of Boeing777 but also to F119 of F22, fourth-generation fighters [19].

4.2.2 Prevent bird strike with blast wave. The idea of preventing bird strike with blast waves presented
is based on military helicopter using reactive oriented explosive attaching on the propeller to destroy the inevitable barrier and protect the blades. The specific design involves attaching a certain amount of linear oriented explosive to inlet fan blades of jet engines. When a bird hits the blade, the explosive explodes, shattering bird carcass into pieces. As only a small amount of oriented explosive is applied to shatter bird carcass, it will not cause damage to fan blades and can ensure that blast waves are controlled within the designing limits of jet engines. The article herein is going to calculate the impact of such blast waves on the stability margin of jet engines and make sure the blast waves are within the designing range of the engine while managing to smash bird carcass [19].

4.2.3 Protection cables. The specific designing idea of a bird strike protection device is to attach a certain number of protection cables to the front inlet fan hub of jet engines. When the inlet fans are working, protection cables rotate at an angular velocity, creating a protective shield in front of the engine which is able to smash bird carcass before it hits the engine so as to reduce damage to engines by bird strikes. It is primarily decided to make protection cables from composite materials which feature robust impact strength to ensure the cables will not break when smashing bird carcass [20].

5. Conclusions
In this article, the research status of the bird impacting on the jet engine blades was stated. Firstly, the bird impacting research should include the establish of the standardized bird models which can give comparable experiment results and numerical simulations. Secondly, the development numerical simulation method and model like the SPH method and using finite element method is the top priority in the bird impacting research to visualize the complex process and reduce the experimental expense. Then the damage level is determined according to the experiment. Finally, several possible anti-bird strike devices is introduced.

The future anti-bird strike method can be concentrated on the bird incidence angle since the change of the impact can greatly reduce the impact damage. Considering the backswept wings can dramatically reduce the air friction at high speed, a conjecture of backswept wide-chord hollow fan blades jet engine blade may be designed to promote the air inflow efficiency and reduce frictional energy loss as well as changing the bird impact angle thus greatly promote the anti-bird strike ability.

References
[1] Chen Wei, Guan Yupu, Gao Deping. Numerical simulation of the transient response of blade due to bird impact [J]. Chinese Journal of Aeronautics, 2003, 24(6):531-533.
[2] Ma Li, Jiang Jiayu, Xue Qinzheng. Research on bird impact of aeroengine first stage fan[J]. Aeroengine, 2014, 40(2):65-69.
[3] Barber J P, Fry P F, Klyce J M, et al. Impact of Soft Bodies on Jet Engine Fan Blades[J]. Impact of Soft Bodies on Jet Engine Fan Blades, 1977.
[4] Chevrolet D, Audic S, Bonini J. Bird Impact Analysis on a Bladed Disk[J]. Bird Impact Analysis on A Bladed Disk, 2003.
[5] Budgey R. The development of a substitute artificial bird by the international Bird strike Research Group for use in aircraft component testing. International Bird Strike Committee ISBC25/WP-IE3, Amsterdam[C]// International Bird Strike Committee. 2000.
[6] M A McCarthy, J R Xiao, C T McCarthy, et al. Modelling bird impacts on an aircraft wing – Part 2: Modelling the impact with an SPH bird model[J]. International Journal of Crashworthiness, 2005, 10(1):51-59.
[7] B Langrand, AS Bayart, Y Chauveau, et al. Assessment of multi-physics FE methods for bird strike modelling-Application to a metallic riveted airframe[J]. International Journal of Crashworthiness, 2002, 7(4):415-428.
[8] Airoldi A, Cacchione B. Numerical analysis of bird impact on aircraft structures undergoing large deformations and localised failure. Impact Loading of Lightweight Structures 2005;49.
[9] D.H. Zhang, Q.G. Fei, H. Liu, Effects of bird’s striking orientation on bird impact analysis
based on a realistic bird model, J. Vib. Shock 34(22) (2015) 103–108.

[10] Anghileri M, Sala G. Theoretical assessment, numerical simulation and comparison with tests of birdstrike on deformable structures. Proceedings of the 20th ICAS congress, Sorrento, Italy; September 8-13, 1996. p. 665-674.

[11] Vignjevic R, Orlowski M, Vuyst T D, et al. A parametric study of bird strike on engine blades[J]. International Journal of Impact Engineering, 2013, 60(60):44-57.

[12] Zhang D, Fei Q. Effect of bird geometry and impact orientation in bird striking on a rotary jet-engine fan analysis using SPH method[J]. Aerospace Science & Technology, 2016, 54:320-329.

[13] R. H. Mao, S. A. Meguid, T. Y. Ng. Effects of incidence angle in bird strike on integrity of aero-engine fan blade [J]. International Journal of Crashworthiness, 2009, 14(4):295-308.

[14] Zhang Haiyang, Yu Duokui, Wang Xiangping. Numerical and experimental investigation of damage of bird impact on fan blades [J]. Journal of propulsion technology, 2015, 36(9):1382-1388.

[15] Engine, aircraft, turbojet and turbofan, general specification for, MIL-E5007D.

[16] Horsley. J. The rolls-royce way of validating fan integrity. AIAA 93-2602.

[17] Huang Zhiyong, Chen Wei, Zhao Haiou. Parameters and methods for evaluating bird impact damage of fan/compressor blade[J]. Aeroengine, 2005, 31(1):28-30.

[18] Zhiyong Huang, Wei Chen, Haiou Zhao, et al. Evaluation of bird impact parameter and method [J]. Aviation engine, 2005, 31(1):28-30.

[19] Peifeng Wen, Shuanqin Cao. Problem of aviation engine and its solution[J]. International Aviation, 1996(10):50-51.

[20] Hou Bingduo. Turbofan engine bird collision protection device design and simulation research[D]. Nanchang Hangkong University, 2012.