Numerical research on the effect of aircraft leading-edge curvature on bird strike resistance

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Abstract. With development of aviation industry, bird strike becomes great threat to flight safety. Numerical study has attracted widely attention due to high-cost experimental test. In this paper, Smooth Particle Hydrodynamic (SPH) couple with Lagrangian method is taken to study on the effect of both material and aircraft leading-edge curvature on bird strike resistance. Simulation result shows that fiber-metal material structure can offer greater impacting stiffness than aviation aluminum alloy materials. Besides, appropriate reduction of the curvature radius on the top of skin of leading-edge is beneficial to improve the structural stiffness, however, when curvature radius is too small, the impact resistance of the structure becomes worse due to matrix damage of material. The work in this paper may provide reference for the design of leading-edge structure.

1. Introduction
With rapidly developing of world’s aviation industry and expanding of space shared by birds and human, the threat of bird collision to flight safety is increasing. According to Federal Aviation Administration (FAA), over 156000 animal attack incidents has been reported during 1900-2014, 97% of which were aircraft bird strike accidents [1]. The data from Civil Aviation Administration of China (CAAC) also showed 3816 bird strike accidents had taken place with civil aircrafts during 2015, which causes about 119.632 million-yuan economic loss [2]. Thus, FAA, EASA and CAAC put forward specific requirement for bird strike resistance of civil aircraft in airworthiness certificate. Under CCAR part 25, subpart 25.631, A requirement is that aircraft tail leading edge structure must make sure safe flight and landing after impacted with a 3.6 kg bird. However, the cost of bird strike test is extremely high, reasonable and effective finite element simulation makes great significance in anti-bird strike design of aircraft.

First bird strike accident took place was 1900s when the Wright brothers sent humans to the sky, their plane hit a bird in 1905 according to the record. But research on bird strike was systematically taken until 1970s. Wilbeck [3] firstly applied hydrodynamic theory to study the impact of a soft body against a flat target. Combining with a Hopkinson bar, a serials of experimental tests on the high-speed impact behavior of different materials were carried out, the result showed that for the normal impact of a cylinder on a rigid plate, the impact consists of four main regimes: (a) shock regime, (b) release regime, (c) steady flow regime, (d) termination of impact, which was widely accepted and referenced by later researchers. As for numerical simulation, the early finite element approach was restricted by coupling between impact load and structure deformation, bird large deformation and material constitution under high strain rate. With update of mathematical algorithm and nonlinear finite element method, a couple of numerical approaches to cope with these problems has been developed. Among them, Lagrangian algorithm, Eulerian algorithm, Arbitrary Lagrangian-Eulerian algorithm (ALE) and meshless Smooth...
Particle Hydrodynamic algorithm were main approaches to characterize bird impact model. Lawson and Tuley [4], Schuette [5] and Niering [6] adopted Lagrangian elements for the impactor in DYNA3D to simulate bird strike on engine fan blades, the results indicated that internal friction in the bird material take big position in formulation of peak pressure of impact center. Doyyns [7] compared the Lagrangian bird model with Eulerian model in DYTRAN, simulation indicated Eulerian result provide a better approximate to the experimental result while Lagrangian produce a twice higher impact load. In contrast to classical Eulerian mesh, Jeng [8] adopted ALE formulation to make simulation more efficient. Although the Eulerian algorithm can solve the mesh distortion problem in the finite element simulation, it is difficult to capture the material boundary in the calculation process, and the structure after deformation need to be meshed repeatedly, so analysis efficiency is relatively low. Meshless method fundamentally solves the problem of large deformation or repeatedly re-mesh in traditional finite element simulation. Therefore, meshless SPH method attract more attention in modern high-speed bird strike simulation. In [9-10], a comparison study of Lagrangian, ALE and SPH bird impacting a rigid plate was carried out. The Lagrangian bird was concluded to be worst due to element distortion while ALE and SPH satisfying, and SPH had a lower CPU cost among them. Liu [11] study bird strike under different velocities, results show that SPH algorithm combined with equation of state is best suited for bird strike simulation at high impact velocities. Besides, various bird strike resistant structures have been designed and tested by researchers. In [12-14], leading edge structure under impact velocities various from 116-147 m/s have been studied with LS-DYNA. In [15-17], Leading edge structure was modified from material and structure aspects.

In this paper, the effect of aircraft leading edge curvature on bird strike resistance is analyzed. Firstly, a verification simulation of SPH method is implemented in section 2. In section 3, leading-Edge skin with different curvature on the top impact area subjected to bird strike are compared. Simulation result shows that, in appropriate range, the smaller the radius of curvature, higher performance the bird impact resistance.

2. Verification of SPH bird model
Before bird strike analysis on leading-edge structure, A verification simulation of SPH method and bird model is implemented. Although there are many studies on bird strike, the relevant experimental data are limited. In this paper, SPH model is compared with Wilbeck’s experiment. The target plate is 152.5mm in diameter and 50.8mm thick made of steel to approximately rigid body according to hypothesis by theoretical analysis. The bird model in Wilbeck’s report was right circular cylinder with length-to diameter ratios of approximately 2. In this paper, model size keeps in coincident with Wilbeck’s report except bird geometry which is cylinder with hemispherical end instead. The verification model is shown in figure 1. The pressure time curve of impact center is extracted as shown in figure. 2. In Pressure-Time curve, to eliminate the influence of geometry size and impact velocity, the data of time and pressure absorbed are plotted in nondimensionalized form, by dividing the pressure by \( P = \frac{1}{2} \rho v^2 \) and the time by \( t_p = \frac{L}{u_0} \), which \( \rho \), \( v \), \( L \) refer to bird mass density, impact velocity and bird length respectively. The dimensionless impact duration is about “1” which match well with hydrodynamic theory, the figure 2 shows four states of entire impact process. A dimensionless peak pressure of “8.26” is obtained in initial shock regime and pressure during steady flow regime is “1” which indicates bird model in this paper is reliable and can be used in later analysis.
3. Bird strike numerical simulation

A typical configuration of the leading-edge structure of an aircraft tail is shown in the figure 3 consist of leading-edge skin (in short skin, shown in blue) and inner box structure (consist of front and back beam, ribs and cornual plates for connecting). The main part in contact with high-speed bird is outer skin. To protect inner flight control system, thus, the outer skin should keep sufficient impact stiffness. In [18], a triangular reinforcement is introduced between box structure and skin to cut bird body so that less impact energy transferred to skin. In most cases, the box geometry size is fixed. To improve bird strike resistance, different skins have been designed and simulated. The configuration is shown in figure 4, in which chord length W is fixed to 280 mm according to box structure size. Skin height H various from 260mm to 290mm. A bird mass of 3.7 kg is selected in current simulation which meets airworthiness requirement of CCAR. Impacting velocity is taken as 120 m/s considering most bird strike incidence taken place during take-off or climbing.

A comparative analysis of bird impacting leading-edge skin made of high strength aviation aluminum alloy and fiber-metal composite is made as a first step. As shown in fig 3, the angle between bird axil and front beam is set as 45° to restore the actual condition as much as possible. Maximum deformation during impact of leading-edge skin is shown in figure 5. As shown in figure 5(a), for skin of aluminum...
alloy, deformation near the impact area is more severe than others, maximum resultant displacement is about 21.44 mm while some elastic deformation recovers as the impact lasts. Skin with fiber-metal material has a different deformation, however, area below the top impact section has larger displacement. For energy analysis, the energy absorbed by metal skin and fiber-metal skin are $5.94 \times 10^5$ mJ and $3.19 \times 10^5$ mJ respectively. Simulation result shows that skin of fiber-metal material has greater structure stiffness due to material anisotropy.

![Resultant Displacement](image)

(a) Skin of aluminum alloy

![Resultant Displacement](image)

(b) Fiber-metal material

**Figure 5.** Structure deformations of skin with different material. (a) aluminum alloy, (b) fiber-metal material

Basing on previous discussion, simulations of skin with different curvature on top contacting surface are implemented. The approach is changing the height of skin (refer to figure. 4). A list of different models is shown in table 1.

| Material  | H (mm) | Curvature radius (mm) | Energy absorbed (10^5 mJ) |
|-----------|--------|------------------------|---------------------------|
| #0        | M      | 280                    | 35                        | 5.94                     |
| #1        | F-M    | 260                    | 37.7                      | 26.6                     |
| #2        | F-M    | 270                    | 36.3                      | 18.2                     |
| #3        | F-M    | 280                    | 35                        | 3.19                      |
| #4        | F-M    | 290                    | 33.8                      | 6.31                      |

**Table 1.** Parameter and result of different configurations
In table 1, M and F-M refer to aluminum alloy (metal) and fiber-metal material. The model of fiber-metal material has same type and plies. As shown in table 1, with the decrease of curvature radius, less energy is absorbed except configuration four (#4) of fiber-metal skin. To figure out this case, tensile matrix damage mode of different configurations is extracted and shown in figure 6. In first three configurations, third configuration (#3) remains complete after impacting while other two configurations can’t withstand the impact of birds and be penetrated. It can be explained by bending stiffness of the structure decreases with the increase of curvature radius. When curvature radius less than 35 mm in this model, as shown in figure 6(d), the damage area of material increases. For most fiber reinforced composites, strength along the longitudinal direction is much greater than that in the other two directions, but when curvature radius is as small as 33.8mm in this model, and matrix damage is the main failure mode. It can be seen from table 1 that when H exceed 280 mm, energy absorbed by skin is more than that of the smaller curvature radius structure.

4. Conclusion
A verification simulation of SPH approach on bird strike is implement at first. The pressure-time curve of impact center matches well with hydrodynamic theory and experimental data which indicate that SPH method in bird strike study is reliable. A study on the effect of aircraft leading-edge curvature on bird strike resistance is implemented basing on this method. Simulation results show that leading-edge skin with fiber-metal material has better bird strike resistant performance than with pure aluminum alloy. Besides, appropriate reduction of the curvature radius on the top of skin is beneficial to improve the structural stiffness. But when curvature radius is too small, the impact resistance of the structure becomes worse due to matrix damage of large area. The work of this paper may provide reference for the design of leading-edge structure.

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