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Design of aircraft structures against threat of bird strikes

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Abstract In this paper, a method to design bird-strike-resistant aircraft structures is presented and illustrated through examples. The focus is on bird strike experiments and simulations. The explicit finite element software PAM-CRASH is employed to conduct bird strike simulations, and a coupled Smooth Particles Hydrodynamic (SPH) and Finite Element (FE) method is used to simulate the interaction between a bird and a target structure. The SPH method is explained, and an SPH bird model is established. Constitutive models for various structural materials, such as aluminum alloys, composite materials, honeycomb, and foam materials that are used in aircraft structures, are presented, and model parameters are identified by conducting various material tests. Good agreements between simulation results and experimental data suggest that the numerical model is capable of predicting the dynamic responses of various aircraft structures under a bird strike, and numerical simulation can be used as a tool to design bird-strike-resistant aircraft structures.

1. Introduction

Bird strikes have long been a significant threat to aviation safety. The first bird strike dated back to September 7, 1905, recorded by the Wright brothers.[1] The United States Air Force reported 13427 bird/wildlife strikes to aircraft worldwide between 1989 and 1993, and estimated the damage to civilian and military aircraft to cost hundreds of millions of dollars every year. Most bird strikes occurred when an aircraft was at a low altitude during the take-off and landing phases of a flight.[2] The most vulnerable components to bird strikes are aircraft engines, nose, and wings/empennages,[3,4] as shown in Fig. 1. To ensure flight safety, aviation regulations require a certain level of bird strike resistance for critical components. As specified in Part 25 of Federal Aviation Regulations, an airplane must be capable of successfully completing a flight during which likely a structural damage occurs as a result of impact with a 4 lb (1 lb = 0.4536 kg) bird (8 lb for an empennage structure) when the velocity of the airplane relative to the bird along the airplane's flight path is equal to V_c (design cruise speed) at the sea level or $0.85V_c$ at 8000 ft (1 ft = 0.3048 m), whichever is more critical. Similar requirements

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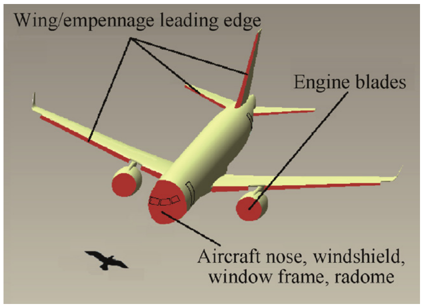

Fig. 1 Illustration of aircraft components vulnerable to bird strikes.

have also been included in the China Civil Aviation Regulations (CCAR) and the certification specifications CS-25 (Large Airplanes) by the European Aviation Safety Agency.[5–7] This calls for continuous efforts to design bird-strike-resistant aircraft components through a combination of tests and simulations.

Most early researches on bird strikes were experimental studies. Barber et al.[8] were among the pioneers to conduct bird strike experiments. They performed bird impact tests on a rigid plate, and found that the peak pressure generated during the impact was proportional to the square of the impact velocity, independent of the bird geometry. While a bird impact experiment provides a direct method to examine a component's bird-strike resistance, with rapid development of the computer technology and the finite element method, numerical simulation is proven as a viable alternative method to design and certify a bird-strike-resistant component more economically. Airoldi and Cacchione[9] investigated the performance of Lagrangian bird models, considering different bird material characteristics and focusing on numerical modeling of the pressure distributions on a target. Vijay et al.[10,11] developed various bird models, and compared Lagrangian, arbitrary Lagrangian Eulerian (ALE), and Smooth Particle Hydrodynamic (SPH) methods to simulate a bird-strike event. Lakshmi and Walter[12] studied the effect of the equation of state models of a bird material on the predicted impact load. Lavoie et al.[13] performed bird impact tests using gelatin as a bird substitute to validate numerical models, and promoted the use of numerical tools in the aircraft design and certification process. Hanssen et al.[14] performed bird-strike tests on a double-sandwich panel, and developed a numerical model to simulate the test process. Their result showed that the Finite Element (FE) method was able to represent failure of both aluminum cover plates and aluminum foam cores. McCarthy et al.[3,15] studied bird strikes on an aircraft wing's leading edge made from two kinds of fiber metal laminates with different lay-ups, using SPH bird and various material models. More recently, Georgiadis et al.[16] established a simulation methodology to support the bird-strike certification of a moveable trailing edge of the Boeing 787 Dreamliner, made of a carbon fiber epoxy composite. In their work, the explicit finite element software PAM-CRASH was selected to perform simulations where the bird was modeled with the SPH method and the joints were represented by different advanced fastener elements.

The current research on bird-strike simulation is mainly focused on the following three aspects:

(1) Constitutive models for a bird. The bird body is not a homogeneous medium. It includes bones, meat, feathers, etc., and thus an equivalent model must be established. Moreover, the bird shows different mechanical behaviors under different impact velocities: under low-speed impact, the bird can be considered as an elastic–plastic body, while under high-speed impact, its behavior is similar to that of a fluid.[17]
(2) Mechanical behaviors of aeronautical materials under high strain rates. A bird strike is a rapid process, which often occurs in a few mini seconds, and as a result, the material under a bird strike may experience intermediate to high strain rates. For many materials, the strain rate can significantly affect their mechanical behaviors, which in turn will influence the dynamic response of the structure.
(3) Numerical techniques to simulate the bird strike process. Three methods have been used to simulate the dynamic response of aircraft structures under a bird strike: the uncoupled method, the coupled method, and the SPH method. The uncoupled method disregards the bird and treats the impact load as a known quantity to analyze the structural response. The coupled method models both the bird and the structure, and simulates the bird-structure interaction by applying a contact-impact coupling algorithm or a fluid–structure coupling algorithm. The SPH method is a meshless method and capable of solving large-deformation and nonlinear dynamic problems. Technically speaking, the SPH method is a special case of the coupled method.[18]

Three basic design principles can be employed to protect aircraft structures against bird strikes:

(1) To improve the energy absorption ability of a structure. When the target structure is almost perpendicular to the bird strike direction, such as the aircraft nose or engine, all the impact energy would be applied to the structure. In such cases, the energy absorption ability of the structure determines its anti-bird strike performance. Energy absorbing materials, such as honey comb and foam, are usually adopted to improve the structure's energy absorption ability.
(2) To improve the energy dissipation ability of a structure. When the target structure is thin or not perpendicular to the bird strike direction, such as the horizontal tail and the windshield, much of the impact energy can be dissipated if the impact direction can be changed to some extent. This requires novel structural design and matching structural stiffness.
(3) To adopt the multi-layer protection design. Some components, such as the nose and the vertical tail, contain important pipelines and flight control systems, so bird-strike damage can lead to extremely dangerous consequences. These components are usually designed as multi-layer structures to improve the bird-strike resistance.

In this paper, a method to design bird-strike-resistant aircraft structures is presented and illustrated through examples. The structure of the paper is as follows. In Section 2, methods to conduct bird strike simulations and experiments are pre-

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