Contents lists available at ScienceDirect
Aerospace Science and Technology
www.elsevier.com/locate/aescte

Effect of arbitrary yaw/pitch angle in bird strike numerical simulation using SPH method

Zhuo Zhang, Liang Li *, Dingguo Zhang
School of Science, Nanjing University of Science and Technology, Nanjing 210094, PR China

A R T I C L E I N F O

Article history:
Received 14 June 2018
Accepted 9 August 2018
Available online xxxx

Keywords:
Bird strike
Bird model
Attitude angle
Rotating engine blades
SPH

A B S T R A C T

The influences of arbitrary attitude angles on bird strike on a fixed rigid flat plate and a rotary jet-engine fan are studied. A verified real bird model and a hemispherical-ended cylinder substitute bird model are modeled by using the smoothed particle hydrodynamics (SPH) method. Since birds can strike aircraft engine from any orientations, simulations of bird models striking a rigid flat plate at random attitude angles are first done as a validation test. Results show that different attitude angles of bird model have distinct effect on the response of bird strike. As the attitude angle increases, the peak impact force becomes larger and the bird model loses more energy. By considering the rotation of the jet-engine fan ignored before, the impact behavior of real bird models striking on rotating engine blades from arbitrary attitude angles is investigated. Effects of the attitude angle on the most concerned impact force, kinetic energy and von Mises stress of blade roots are discussed. It is concluded that considering attitude angles of real bird and rotation of the jet-engine fan in bird strike simulation has practical significance on structural tolerant design.

1. Introduction

Bird strike has threatened aircraft's safety all the time since aeroplane was invented in 1903. About 90% of aircraft accidents were reported to be caused by bird strike, although aircraft faced the risk of many foreign object damage (FOD) [1]. Furthermore, according to the Federal Aviation Administration (FAA) statistics, aircraft engines were most frequently impacted component in bird strike accident [2]. When flying birds impact an aircraft engine in the sky and hit compressor blades, it will cause large plastic deformation or local bulging, and even lead to the rupture of blades which will result in an imbalance of the rotor or deteriorating the aerodynamic performance of the engine.

It is estimated that bird strike costs the aviation industry more than 600 million dollars every year [3]. To manage the risk of bird strike accidents, researchers have done a lot of relevant experiments and theoretical studies.

In the study of early bird collisions, Barber et al. [4,5] and Wilbeck [4–6] advocated that a hemispherical-ended cylinder with approximate mass could be used as the bird substitute model. They compared birds with different species, weights, and initial velocities striking on a rigid panel, and noted that in case of high speed, bird material behaved like fluid material. They provided references and made important contributions for future research work. Lavoie et al. [7] impacted gelatin birds on rigid targets and confirmed that the deformation of bird model did behavior like fluid and numerical simulation results correlated well with experiment data. Moreover, they listed the modeling procedure of the gelatin birds. Frederik et al. [8] set bird impact experiments on a rigid plate, wedge and splitter target respectively, and proved that the rigid target could still be valuable in bird strike research. However, the experimental verifications are not only time consuming, but also expensive and hard to control related influencing factors.

In recent decades, with the rapid development of numerical methods and computer technology, numerical simulation has been a time-saving and precise method to study bird strike problems widely since 1980s. Meguid et al. [1] compared namely, bird shape and length to diameter aspect ratio by using the finite element (FE) method, found that the initial contact area between the bird and the target had significance effects on peak force while aspect ratio of bird had little influence on impact force. Nishikawa et al. [9] used a contact algorithm based on Lagrange multiplier method to predict appropriate impact force, this method solved the severe contact-induced deformation due to a large contact force and highly deformable projectile. Previous studies usually adopted the lagrangian formulation to model bird strike. Due to element instability, refining mesh elements and narrowing the time step method had to be used to alleviate the problem [10]. To solve this problem,

* Corresponding author.
E-mail address: liangli@njust.edu.cn (L. Li).

https://doi.org/10.1016/j.ast.2018.08.010
1270-9638/

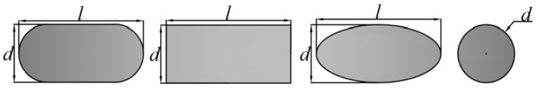

Fig. 1. Substitute bird models: (a) Hemispherical-ended cylinder; (b) Straight-ended cylinder; (c) Ellipsoid and (d) Circular.

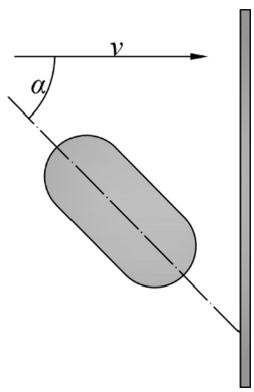

Fig. 2. Schematic of the pitch/yaw angle.

nowadays more researchers use arbitrary Lagrange–Euler (ALE) [3,7,11,12] and smoothed particle hydrodynamics (SPH) [7,8,13–18] method in bird strike problems [13]. Jenq et al. [19] simulated the soft model bird projectile striking a flat rigid panel according to Wilbeck's report in ALE methods, results corresponded well with experiment data. Many researchers investigated the impact responses of composite materials sandwich panels in recent years [20–24].

To date, researchers have made a lot of efforts to discuss appropriate bird model shape [13]. McCarthy et al. [25] used a hemispherical-ended cylinder with a length-to- diameter ratio of two as bird substitute model, which was also adopted by many other researchers frequently. Liu and Li [15] modeled the straight-ended cylinder, which has quite fewer applications than the hemispherical-ended cylinder. Besides, ellipsoid geometry also appeared in some literatures such as Meguid et al. [1] and Reza and Ziaei-Rad [14]. Liu et al. [26] compared the circular model with experiment data. In general, there are four commonly used models: hemispherical-ended cylinder, straight-ended cylinder, ellipsoid and circular, as shown in Fig. 1. In addition, Hedayati and Ziaei-Rad [27] constructed a real geometry bird model with more consistent simulation results with experiments. McCallum et al. [28] established a new model including eight body parts and accounts for variations in density and material strength, which had a longer impact duration and higher peak impact force. Zhang and Fei [17] considered the bird may impact from any orientation: head side, tail side, bottom side and wing side and they proved that bird geometry and impact orientation had important influence on bird strike accidents.

In the period of a bird strike accident, it is possible that the bird impacts the engine from any orientation and any part of the bird may strike on the aircraft firstly [17]. As for impact orientation angles, several studies have revealed that the peak pressure produced by a bird model hitting the rigid plate from the bottom is about three times that from the head. It should be noticed that in many accidents, the energy of bird impact released was lower than that standard currently requires, however, it did cause serious damage continuously in reality [29]. In other words, only considering bird mass and impact speed is not enough to ensure flight safety, further studies are still necessary to consider more factors. Therefore, here we define the pitch/yaw angle between the bird's axis direction and the speed direction as the attitude angle α in Fig. 2.

In this paper, we establish Zhang and Fei's substitute bird model [17] considering geometric characteristics of a flying canvasback in numerical simulations. Note that the rotation of the jet-engine fan in the above-mentioned literatures was ignored, and only limited attitude angles were studied, those results may not reflect the actual situation. To this end, this work will make up such deficiency. This paper is organized as follows: Hugoniot pressure and stagnation pressure are introduced in section 2; material parameters and geometric parameters of a SPH real bird model are given in section 3.1 and section 3.2, respectively; a rigid plat round plate target is constructed in section 3.3; a jet engine fan is modeled and meshed in section 3.4, material parameters as well as equation of state (EOS) parameters of the jet engine fan are given in section 3.5; the traditional cylinder substituted bird model and SPH real bird model with arbitrary attitude angle impacting on the rigid plate are simulated and discussed in section 4.1; simulations of the traditional cylinder substituted bird model and SPH real bird model with arbitrary attitude angles impacting on rotating blades are performed in section 4.2; some conclusions are drawn in section 5.

2. Theoretical background

According to Wilbeck's [6] theory, in case of a cylinder impact on a rigid plate, the flow across a shock can be considered one-dimensional and adiabatic, irreversible. In this situation, the equation of conservation of mass (continuity) and momentum may be written as:

$$\rho_1 V_{sh} = \rho_2 (V_{sh} - V_p) \tag{1}$$

$$P_1 + \rho_1 V_{sh}^2 = P_2 + \rho_2 (V_{sh} - V_p)^2 \tag{2}$$

where ρ_1 and ρ_2 are the particles densities of material before and after impact, respectively; P_1 and P_2 are the pressures of material before and after impact, respectively; V_{sh} is the shock velocity in the fluid; V_p is the velocity of the particles behind the shock and is equal to the initial velocity. Combine Eq. (1) and Eq. (2), the pressure is found to be:

$$P_2 - P_1 = \rho_1 V_{sh} V_p \tag{3}$$

Hugoniot pressure is given by Eq. (3), which is also the pressure in shock region. Thus, Eq. (3) becomes:

$$P_H = \rho_1 V_{sh} V_p \tag{4}$$

As for how to obtain the shock velocity, Hedayati et al. [13] had explained in detail. In the steady-state condition, since the bird material flows in streamlines, the stagnation pressure is given by Eq. (5) according to Bernoulli's equation:

$$P_{stag} = \frac{1}{2} \rho V_p^2 \tag{5}$$

3. Simulation model

3.1. SPH bird material model

When a bird strikes the engine at high speed, the bird material behaves like fluid, and its nonuniformity and inhomogeneity become increasingly negligible, which is practically a homogeneous fluid impinging the target [7]. In order to accurately model the hydrodynamic response, hydrodynamics fluidic material is used in this paper and a linear Mie–Grüneisen equation of state (EOS) that describes the relationship between shock velocity and pressure [30] for the bird model is adopted.