Prediction of Bird Impact behavior through Different bird models using Altair Radioss

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Abstract
Bird Strike simulations are increasingly being used for the design of leading edges of civil aircraft, since conducting bird strike tests is expensive and time-consuming. Major issues in bird impact simulation are the modeling of the bird, the development of material models for the target and models for capturing rivet failures at different fastener locations. This paper discusses various approaches for bird modeling available in ALTAIR RADIOSS: Lagrangian, Arbitrary Lagrangian Eulerian (ALE), and Smooth Particle Hydrodynamics (SPH) techniques. Bird impact studies on a rigid flat plate found in literature were used for the comparative study on the bird modeling techniques. Based on this study, the SPH model was chosen for the prediction of bird impact behavior on a typical aircraft wing leading-edge. The SPH model predicted the impact behavior of a leading-edge for 115 m/s bird strike accurately. The leading-edge deformation characteristics predicted by the model agreed well with test data.

Keywords: Bird Strike, Lagrangian, SPH, Radioss/Explicit

Nomenclature
A: Yield stress
B: Hardening modulus
n: Hardening exponent
C: Strain Rate Coefficient
\( \varepsilon_0 \): Reference Strain Rate
m: Temperature exponent
\( T_{melt} \): Melting Temperature
\( C_0, C_1, C_2, C_3, C_4, C_5 \): Hydrodynamic constants
\( E_n \): Energy per unit of initial volume
\( S_{ij} \): Deviatoric Stress Tensor
\( \theta \): Kinematic Viscosity
\( \dot{e}_{ij} \): Deviatoric Strain Rate Tensor

Introduction
Bird Strike is a major threat to aircraft safety and cause significant economic loss which is estimated to be more than $1 billion per year to the aviation industry worldwide. Many external airframe components are susceptible to collision with birds, particularly during takeoff and landing phases. Though, the engine is usually the most
Bird Modeling Approaches

Bird behavior is similar to a soft projectile. If stresses in the projectile exceed the strength of the material, the material generally starts to flow like a fluid. Hence for high velocities, the behavior of the bird will be more like fluid wherein hydrodynamic theory is valid. However, for low and medium velocity, the bird material doesn’t flow like fluid and in such cases elasto-plastic material characteristics will be dominant during such deformation. Hence, modeling the bird and bird material property inputs are crucial for accurate simulation of bird strike problems. Different modeling approaches have been attempted by various researchers to model the bird impact behavior. Some of the modeling approaches are discussed below.

a) Lagrangian method is the most commonly used method and can be used for low and medium velocity impact where bird mesh encounters only small level of element distortion. In this method, the bird–structure interaction is modeled using contact algorithms defined in the Radioss explicit FE code. However, for high velocity impact, large scale distortion of the bird translates to large distortion of the finite element mesh. Despite many proposed attempts to address the deficiencies of this method, it remains an impractical way to model bird strike.

b) Smooth Particle Hydrodynamics (SPH) is a more recent approach for modeling bird strike, which is essentially a mesh free method based on Lagrangian formulation in which the finite elements have been replaced by a set of discrete, mutually interacting particles. Due to the fact that this approach is a grid-less method, it is well suited for impact problems where large elemental distortions are expected. The main drawback is the larger computational time compared to Lagrangian method. This method is ideally suited for impact problems such as bird strike analysis, as the particles are topologically independent from each other.

c) Arbitrary Lagrangian-Eulerian (ALE) approach models the bird as a slug of fluid moving through an Eulerian mesh, the material being free to move relative to the mesh. The applied load to the Lagrangian mesh of the structure due to bird impact is realized through an ALE coupling interface.

Bird Material Characteristics Modeling from Radioss/Explicit

Johnson–Cook’s model for Elasto-plastic Materials (Law 2)

In this law, the material behaves as linear elastic when the equivalent stress is lower than the yield stress. For higher value of stress, the material behavior is plastic. The relationship between stress and strain during plastic deformation is assumed as follows:

$$
\sigma(\varepsilon_p, \dot{\varepsilon}_p, T) = (A + B\varepsilon_p^n)(1 + C\ln(\dot{\varepsilon}_p)) (1 - (\frac{T - T_0}{T_{melt} - T_0})^m)
$$

where, $$T^* = \frac{T - T_0}{T_{melt} - T_0}$$

When the maximum stress is reached during computation, the stress remains constant and material undergoes deformation until the maximum plastic strain. Element rupture occurs if the plastic strain is larger than $$\varepsilon_{max}$$. If...
the element is a shell, the ruptured element is deleted. If the element is a solid element, the ruptured element has its deviatoric stress tensor permanently set to zero, but the element is not deleted. Therefore, the material rupture is modeled without any damage effect.

**Elasto-Plastic Hydrodynamic material (Law 3)**

This models the elastic and plastic regions, similar to Johnson-Cook’s model defined earlier, with a non-linear variation of pressure and without strain rate effects. This law is used for simulating material behavior in compression. The stress-strain relationship for the material under tension is

\[ \sigma = A + B\varepsilon^n_p \]

The compression relationship is given in terms of pressure, \( p \):

\[ p = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu)E_n \]

where, \( \mu = \rho / \rho_0 - 1 \)

**Elasto-Plastic Hydrodynamic model with strain rate and thermal characteristics parameters (Law 4)**

This is similar to Law 3, however has the additional option of defining the strain rate characteristics and thermal characteristics in the material model

\[ \sigma = (A + B\varepsilon^n_p)\left(1 + Cb\frac{\dot{\varepsilon}}{\varepsilon_0}\right)(1 - T^m) \]

\[ p = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu)E_n \]

Where, \( T^* = \frac{T - T_0}{T_{melt} - T_0} \)

**Hydrodynamic Viscous Fluid Law (Law 6)**

This law is specifically used to model behaviour of fluids. The equations used to define the materials are

\[ S_{ij} = \rho\dot{\varepsilon}_{ij} \]

\[ p = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu)E_n \]

**Bird Impact: Validation and Comparisons of bird model**

Bird strike at high velocities results in highly complex non-linear behavior and hence prediction of impact forces and the behavior of the target is very complex. A seminal study on the estimation of impact forces and the pressure distribution for bird strike on a rigid plate was carried out by Wilbeck [6]. Bird impact at high velocities can be considered to be of 4 phases wherein the first phase consists of very high shock pressures generated at the projectile target interface. As shock pressure propagates into the projectile, a radial release of the shocked material results in a decaying pressure which is the second phase. The pressure decay continues till a steady flow state which constitutes the third phase and finally the termination phase wherein the pressure decays to zero as the end of the projectile approaches the target. In this paper, bird strike analysis of Wilbeck’s experiment [6] is carried out to understand and validate various bird models. The maximum pressure developed based on experiments for different bird mass is shown in Figure 1. A rigid steel plate of 500mm X 500mm size, struck by bird at a velocity of 116m/s was considered in this study. Simulations were carried out for different bird models.
Lagrangian Approach

A 3D solid model was used for the bird. The bird material was modeled with its characteristic behavior defined based on Johnson-Cook model (Law 2), Hydrodynamic viscous model (Law 6), and Elasto-plastic hydrodynamic model (Law 3). Law 4 wasn’t studied as it is an extension of Law 3 with strain rate definitions incorporated. Type 7 interface was used for defining contact. The target was modeled with 2D shell elements with rigid steel plate material characteristics. The model showed large element distortion as can be seen from Figure 2. Constant time step option by introducing nodal mass was evaluated to address the issue of element distortion. However, it was found to increase the mass and contact pressure significantly. Another option to address the element distortion issue was the deletion of the respective element for which time step has gone below the defined minimum time step. Here, the contact pressure dropped below the reference value and impact behavior prediction can be significantly different from the actual behavior due to this decrease in contact pressure.

Figure 1. Maximum Pressure vs Velocity for different mass bird [6]
ALE Approach

This approach was followed to address the element distortion issues observed in the Lagrangian approach. Here, the bird is modeled as a fluid flowing through an Eulerian mesh (Figure 3). The interaction between the bird and the target was modeled using Type 18 interface for contact definition. Material law 51 was used to define the material characteristics.

Figure 2. Lagrangian bird model showing mesh distortion for impact on rigid plate

Figure 3. Cut Section of the ALE bird model for impact on rigid plate
**SPH Model**

The advantage of SPH is that it is a meshless Lagrangian technique and hence the issue of element distortion present in standard Lagrangian approach is absent here. Since it is still a Lagrangian technique, the issues of coupling between the Lagrangian body and Eulerian material does not arise. Law 6 was used to define the material characteristics. Type 7 interface as used for the Lagrangian approach was used to define the contact between the bird and the target. The impact of a SPH bird on the rigid steel plate is shown in Figure 4. The normalized pressure distribution predicted by the SPH model matched quite well with the experimental study of Wilbeck [6] and hence it was decided to use SPH model for further bird impact studies. Detailed results from this approach will be presented in the conference.

![Simulation of SPH bird impact on steel plate](image)

**Figure 4**  
Impact of a SPH bird on the rigid steel plate at 0.4 ms.
Figure 4. Impact of SPH Bird on a rigid steel plate
Bird impact on typical wing leading-edges

The design methodology followed in the development of this typical wing leading-edge is to have skin, rib and baffle plate, which will prevent the bird from impacting the front spar incase of penetration of the skin. A typical wing leading-edge profile of a transport aircraft consisting of nose box skin, baffle and two side ribs is selected for this purpose (Figure 5). Aluminium-2024 alloy was used for skin and baffles and ribs were designed using Carbon-epoxy composites. The selection of the skin thickness was done based on RAE formula and bird strike testing. The role of baffle and selection of its thickness were based on bird strike analysis. The selection of fasteners was done based on a rivet pull-through study on a typical Aluminum plate. The selection of rib stiffness was based on a parametric study through bird strike analysis.

The design, analysis and fabrication of leading-edge specimens were carried out at NAL and bird impact tests were conducted at the Gas Turbine Research Establishment, Bangalore. The specimen dimensions and their profile were based on the leading-edge section of wing of a typical small transport aircraft. The leading-edge was attached to a C-fixture which was subsequently attached to a hub assembly. Altair HyperMesh is used for pre-processing, Radioss/Explicit is used as solver and HyperView is used for post-processing.

Figure 5. Leading Edge test specimen with skin, baffle and two side ribs

SPH technique was used to model the bird. Type 7 interface was used to model the contact between the bird and the leading-edge skin. Self contact options were employed to prevent the skin penetration on itself because of the buckling of the skin due to impact. Typical deformation of the leading-edge component subjected to bird strike is shown in Figure 6. This study showed that the a leading-edge based on Aluminum skin, Aluminum baffle and CFRP ribs is found to successfully withstand a 4 lb bird strike at 115 m/s.

Figure 6. Deformation of leading-edge due to 4 lb bird strike at 115m/s: Experiment and RADIOSS simulation
Conclusion

The available finite element formulations and material laws for bird strike modeling have been assessed. The Lagrangian technique approach for bird strike modeling was tried, however resulted in large element distortion. Several options for time step controls were assessed; however it altered the bird impact characteristics. The pressure distribution characteristics predicted through SPH model showed closer correlations with the experimental data reported in literature. The simulation of impact behavior of a leading-edge for 115 m/s bird strike predicted deformation characteristics accurately using a SPH bird model.

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