Copyright © 2007 ICCES ICCES, vol.2, no.4, pp.111-118, 2007

Review of existing numerical methods and validation procedure available for bird strike modelling

M-A Lavoie[1], A. Gakwaya[1], M. Nejad Ensan[2] and D.G. Zimcik[2]

Summary

This paper reviews numerical methods that are currently available to simulate bird strike as well as the theory of the event. It also summarizes important parameters and provides guidelines as to how to set up the analysis and how to evaluate a model. The information provided is based on physical properties and available results regarding a bird and its behaviour upon impact. The simulations have been performed with LS-DYNA 970 but can be done in similar dynamic finite elements analysis codes.

keywords: Non-linear finite element analysis, Impact simulation, Bird modeling, ALE method, SPH method.

1. Introduction

Ever since man put airplanes in the air, they have had the most unfortunate tendency to prematurely come down for various reasons, some of them more life threatening than others. Therefore, during the certification process, an aircraft must demonstrate its ability to land safely after being struck by a bird anywhere on the structure, at normal operating speeds [1]. The performance of the key components, including the wing and engines, must be demonstrated and they must maintain their structural integrity.

Considerable amounts of time and cost are involved. Therefore there is a need to improve modelling capabilities and to enable verification by numerical methods. To accurately predict the response of an aircraft structure under impact loading, it is essential to have an accurate bird model. Because of lack of availability, bird models are generally developed based on tests data that are nearly 30 years old [6]. The models are then used in the simulation of impacts on aeronautical structures and the required adjustments are made to the bird models after experimental testing of the structures. The different models used are the Lagrangian bird model [2],[3],[7],[8], the arbitrary Lagrangian Euler bird model [2],[3], and the smooth particles hydrodynamics model [4],[5].

This paper aims at summarizing the steps involved in creating the bird model. Section 2 covers the theory of bird strikes and provides an analytical evaluation of the phenomenon. Section 3 gives a sample of experimental data that are currently available. Section 4 describes the available modelling methods and an analysis of

[1]Department of Mechanical Engineering, Laval University, Cité Universitaire, Quebec, Qc, Canada G1K 7P4

[2]Institute for Aerospace Research, National Research Council, Ottawa, Ont. Canada.

the results is given in Section 5. Finally, recommendations are made regarding the best suitable method.

2. Theory of bird impact

The bird strike event is often considered as a jet of water hitting a target. It can be divided into two stages: the initial shock and the steady flow. The pressure of the initial shock (Hugoniot pressure) is given by equation (1); the pressure of the steady flow (stagnation pressure) is calculated according to Bernoulli and is given by equation (2):

$$\text{Hugoniot pressure:} \quad P_{shock} = \rho_0 v_{shock} v_{impact} \tag{1}$$

$$\text{Stagnation pressure} \quad P_{stagnation} = \frac{1}{2}\rho_0 v_{impact}^2 \tag{2}$$

Analytically, those two pressures are important since the Hugoniot pressure gives the maximum possible value for the impact and the stagnation pressure gives the expected reading when the flow stabilizes. It is also important to realize that the pressure is independent of the size of the projectile since the mass is not a variable in the pressure equation. So while the force and energy of a larger projectile will cause more damage, the pressure results are the same for a bird of different weight.

The values of the variables needed to calculate the stagnation pressure are easily available. On the other hand, the Hugoniot pressure depends on the impact velocity and the shock velocity, which itself also depends on the impact velocity. The information required to calculate the pressures are found in Wilbeck [6].

The other useful information resulting from associating the bird with water is the equation of state (EOS) used to describe the pressure-density relationship in the bird medium. A few equations are available, and the one most commonly used for bird impacts is a polynomial of degree 3 [6] defined as follow:

$$P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3; \qquad \mu = \rho/\rho_o - 1 \tag{3}$$

The coefficients are given by expressions based on the initial density ρ_0, the speed of sound in water and an experimental constant k [6].

3. Wilbeck's test results

Dr. James Wilbeck [5]was one of the first researchers to investigate the experimental behaviour of a bird under impact. His conclusions and results are very important to this day since they provide the shape and characteristics used for numerical bird models. By publishing his results he also provided useful information to validate the numerical models.

Substitutes such as gelatine, beef, RTV rubber, and neoprene were compared against data from a chicken projectile. Experiments showed that the most suitable substitute material is gelatine with a 10% porosity and a density of 950 kg/m^3. The tests also showed that the geometry of the projectile is of importance. The most suitable shape for the projectile is then a cylinder with hemispherical ends with a length to diameter ratio equal to 2, as illustrated b Figure 1A.

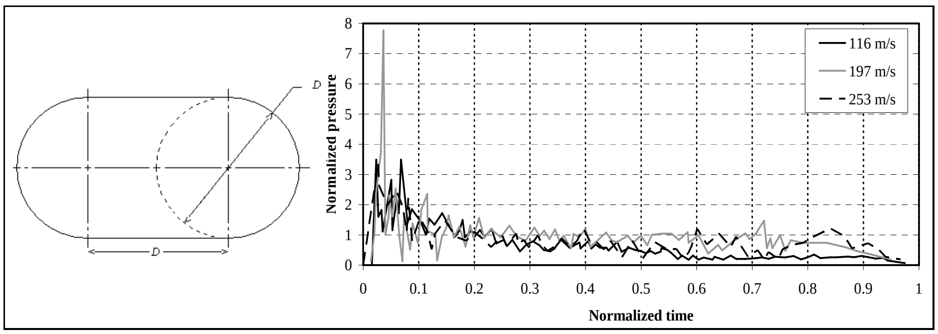

Figure 1: A: Bird model geometry, B: Wilbeck's results for the bird projectile

In the impact tests that Wilbeck conducted, the birds and substitutes were fired on a rigid plate at velocities ranging from 100-300 m/s. The results presented are normalized where the pressure is divided by the stagnation pressure and the time by the duration of the impact.

The results obtained for a bird projectile fired at three different velocities are presented in Figure 1B. The results are good in the sense that there is a rise of pressure at the initial impact and then the pressure stabilizes around its stagnation value. However, the normalized Hugoniot pressures should be significantly higher and decrease with an increase of the velocity of impact. Part of the explanation resides in the fact that the Hugoniot pressure is punctual and the duration of the impact is very short. It is possible that the maximums were not properly captured by the acquisition system available at the time.

Most authors studying bird impact use the results given by Wilbeck to develop their numerical bird model [7],[8]. McCarthy does refer to more recent data, but these are not available to the public [5]. Nevertheless, for the time being, it is possible to create a respectably valid numerical bird model. The available methods are described in the next section.

4. Numerical bird models

Three main modelling methods are currently available. These are: the Lagrangian mesh, the arbitrary Lagrangian-Euler (ALE) mesh, and the smooth particle hydrodynamics (SPH) method. The validity of a bird model is established by comparing the pressure impulse applied to a flat rigid plate to the analytical and experimental values discussed earlier.

In the present paper, a 1 kg bird impacts a 0.5×0.5 m square plate. The material properties of steel have been used for the plate. The pressure is measured at an element located at the center of the plate. As stated previously, the bird has a density of 950 kg/m^3 and according to Figure 1. A, it has a diameter of 93 mm. The simulations with the different bird models have been run using LS-DYNA 970 but could equally be done with most explicit finite element software packages.

Regardless of the modeling method, the material usually employed to model the bird is elastic-plastic-hydrodynamic [3],[5] with the polynomial equation of state (EOS) of equation (3). It is well suited for bird strike because it behaves as an elastic-plastic material, until the impact, and then it is governed by the pressure-volume relationship of the equation of state. This way, a low shear strength value can be given to the bird allowing it to retain its shape until the impact.

The parameters for the ALE simulation are a shear modulus of 2.0 GPa, a yield stress of 0.02 MPa and a plastic hardening modulus of 0.001 MPa. These three parameters are more or less arbitrary and help the analysis to run smoothly [3],[9].

4.1 Lagrangian bird model

The Lagrangian modeling method discretizes a volume with a large number of small geometries called elements. However, when the deformations are large, it becomes increasingly difficult to calculate the state and stresses in the elements because the timestep, based on the aspect ratio, keeps on decreasing. Moreover, the accuracy of the results obtained decreases. The bird modeled with solid Lagrangian elements uses approximately 500 solid hexagonal elements. The interaction with the target is controlled by a contact algorithm between the bird and the target.

4.2 ALE bird model

The second modeling method used is the ALE method. At the beginning of the analysis, the denser material is concentrated in one part of the mesh, but as the analysis progresses, the fluid is allowed to flow everywhere in the mesh. The coupling with a solid structure is done by tracking the relative displacements between the coupled Lagrangian nodes and the bird. However, mesh distortion can become an issue with the ALE method if the volume of the elements becomes negative.

In LS-DYNA, the ALE bird uses the multi-material option, allowing materials (air and bird) to coexist in an element prior to the start of the simulation. A total of approximately 19,000 solid elements of equal length, width, and depth are used to mesh the bird and its surrounding. This number is much higher than that required for the Lagrangian bird which slows down the analysis, but yields better results. The interaction between the bird and the structure is controlled by the *constrained_Lagrange _in_solid card. It is important to refer to the analytical and experimental data to evaluate the pressure results and to adjust the numerous interaction parameters.

4.3 SPH bird model

As an alternative, the smooth particle hydrodynamics method can be used. The SPH was developed by Monaghan in the late 1970's for astrophysics problems with application to hypervelocity impacts ($\sim$10 km/s) [10] where the material shatters upon impact. Because of the large deformation of a bird, this theory is also applicable to bird strike analysis in spite of the much lower velocity. Johnson and McCarthy [4],[5] have recently used this technique in their bird impact simulation with success, confirming its applicability.

The SPH method uses the Lagrangian formulation for the equations of motion but instead of a grid, kernel functions are used to calculate an estimation of the field variables at each particle. The kernel function is active only over a given volume around each node. Each node has a given mass and constitutes an element in the sense that the state variables are evaluated at its location. The method is said to be mesh free because there is no predefined grid restraining which nodes can interact together. In practice, the SPH method uses fewer elements than the ALE method, it avoids the material interface problems associated with it, and it has a shorter solution time.

The SPH bird model includes 4460 evenly distributed nodes, each having a lumped mass of 0.224 gram. The distance between the nodes is of about 6 mm and for larger birds, it is preferable to keep the distance constant and increase the number of particles. The interaction with the structure is realized by defining a contact between the SPH nodes and the Lagrangian elements of the target.

5. Results & Analysis

The results shown are based on an impact velocity of 116 m/s in order to compare with the available experimental data [6]. Thus, the Hugoniot pressure is expected to have a maximal value of about 93.6 MPa and the stagnation pressure, 6.3 MPa, giving normalized values of 14.9 and 1.0, respectively. Similar results were obtained for the two other velocities for which experimental results are available but they are not shown since they lead to the same conclusions.

5.1 Lagrangian bird model

The distortions sequence of the bird model impacting the rigid plate, are shown in Figure 2A. As expected, the distortions of the bird meshed with the Lagrangian method are very important. As the impact progresses, the flow is less and less consistent with the reality and the bird penetrates the wall (ex.: see time 1.28 ms).

The effect of the large distortions observed is reflected in pressure results in Figure 2B. The first pressure rise coincides with the experimental results and the duration of the initial shock is similar. However, the normalized pressure should stabilize at its stagnation value, but instead undergoes a second increase due to the high distortion and penetration of the bird. As for the Hugoniot pressure, it is higher than the experimental value, but the maximum reached is still 50% lower than the analytical value.

A similar simulation using 2000 hexahedral elements was also performed to evaluate the effect of the mesh refinement on the results. Overall, the normalized Hugoniot pressure decreased to 6.5 and the same inconsistent behaviour of the pressure was observed after the initial shock.

5.2 ALE bird model

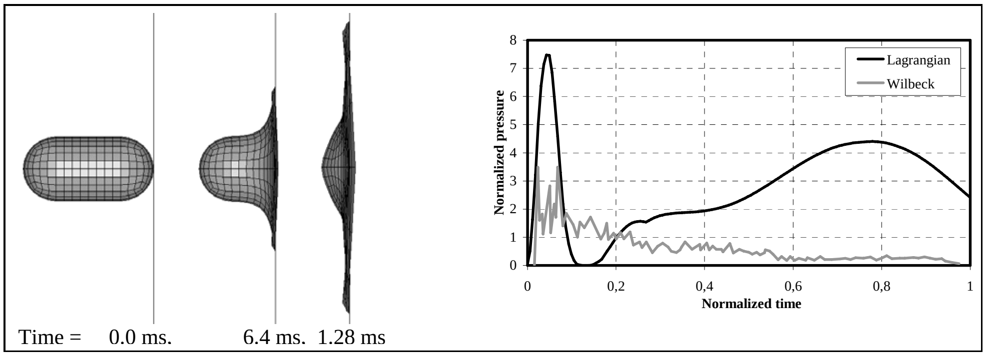

Figure 2: Lagrangian bird A: Deformations, B: Normalized pressure's results

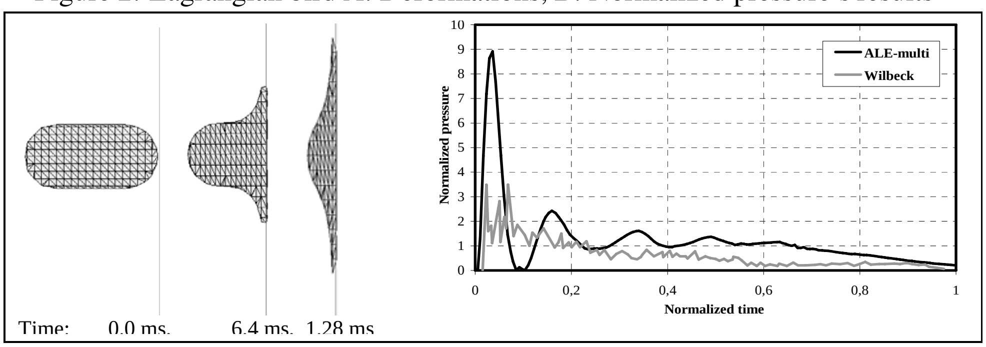

Figure 3: ALE bird A: Deformations, B: Normalized pressure's results

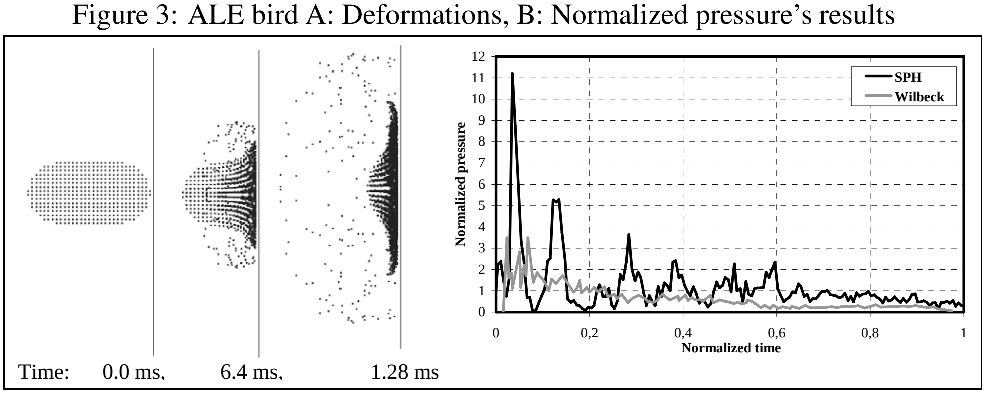

Figure 4: SPH bird A: Deformations, B: Normalized pressure's results

The second modeling method employed is the Arbitrary-Lagrangian-Eulerian formulation. In this instance, the flow of the bird over the target is much smoother, as illustrated in Figure 3A, where only the dense fluid counterpart of the mesh is shown.

Thus, the ALE method improves the flow of the bird with respect to the Lagrangian bird model. The pressure results improved as well. The normalized Hugoniot pressure is now 40% lower than the analytical one. The duration of the initial shock is respected, and the pressure stabilizes around 1.0. The oscillations of the pressure are due to the stiffness of the fluid-structure interaction. The phenomenon can be damped out more by increasing the damping factor, but this will affect the value of the Hugoniot pressure.

5.3 SPH bird model

The last modeling method is the smooth particle hydrodynamics. The results are very satisfactory given the recent development of this method. The deformations shown in Figure 4A are consistent with that of the ALE bird model shown in Figure 3A. The SPH method also has the advantage that it is easier to follow the matter flow of the bird, especially for the bird fragments that fly away and are lost with the ALE visualization.

The normalized pressure results are also in good agreement with the experimental results. Figure 4B shows that the Hugoniot pressure reached is of 11.2, further reducing the gap with the analytical value to 25%. After the initial shock, the pressure stabilizes at 1.0 and the duration of the initial shock remains consistent with the experimental data. The pressure is, however, spurious in nature, which is due to the lack of viscosity in the SPH formulation.

6. Conclusions

The numerical bird models have been compared against analytical and experimental values. The ALE and SPH models compared well with the analytical predictions, but the comparison with the experimental data highlights the need for future bird calibration testing and publication of the results obtained.

When comparing the bird models, it becomes obvious that the Lagrangian method is no longer suitable. The ALE method is a standard approach to bird impact modelling. Moreover, improvements to the SPH method formulation and its implementation into commercial finite element software should give better results in term of the stability of the pressure which will make it even more appealing for further use.

Acknowledgement

We would like to thank the Consortium for Research and Innovation in Aerospace in Quebec for financial support of this project as well as Laval University and the

National Research Council of Canada for their close collaboration and the industrial partners who provided practical application to the project.

References

1. Policy Statement Number ANE-2001-35.13-R0, *Policy for Bird Strike*, Federal Aviation Administration, U.S. Department of Transportation, April 2002
2. Alan Dobyns, Frank Frederici, Rober Young, *Bird Strike Analysis and Test of a Spinning S-92 Tail Rotor*, American Helicopter Society 57th Annual Forum, Washington, DC, May 9-11 2001
3. Hörmann, U. Stelzmann, M.A. McCarthy, J.R. Xiao, *Horizontal Tailplane Subjected to Impact Loading*, 8th International LS-DYNA Users Conference, May 2-4 2004
4. Alastair F. Johnson, Martin Holzapfel, *Modelling Soft Body Impact on Composite Structures*, Composite Structures, **61**, 2003, 103-113
5. M.A. McCarthy, J.R. Xiao, C.T. McCarthy, A. Kamoulakos, J. Ramos, J.P. Gallard, V. Melito, *Modelling of Bird Strike on an Aircraft Wing Leading Edge Made from Fibre Metal Laminates – Part 2: Modelling of Impact with SPH Bird Model*, Applied Composite Materials, **11**, 2004, 317-340
6. James S. Wilbeck, *Impact Behavior of Low Strength Projectiles*, Air Force Materials Laboratory, Technical Report AFML-TR-77-134, 1977
7. L. Iannucci, *Bird-strike impact modelling*, Seminar Foreign Object Impact and Energy Absorbing Structure, London, England, 1998
8. E. Niering, *Simulation of Bird Strikes on Turbine Engines*, Journal of engineering for gas Turbine and Power, **112**, 1990, 572-578
9. Frederick Stoll, Robert A. Brockman, *Finite Element Simulation of High-Speed Soft-Body Impacts*, American Institute of Aeronautics and Astronautics, 1997, 334-344
10. J.J. Monaghan, *Smoothed Particle Hydrodynamics*, Annu. Rev. Astron. Astrophys., **30**, 1992, 543-574