THE INFLUENCE OF BIRD MODELS PARAMETERS ON THE RESULTS OF NUMERICAL ANALYSES OF BIRD STRIKES

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ABSTRACT

One of the factors that significantly exert a negative influence on flight safety is bird strikes. Various parts of an aircraft are subjected to damage. Apart from the mandatory physical tests, there are various numerical methods for bird strike modelling. In order to conduct an analysis of a bird strike into an aircraft windshield, the solver FE code LS_DYNA was used. Moreover, in this paper, the Smooth Particle Hydrodynamics (SPH) is being used and developed for bird modelling. For comparison three bird models were elaborated upon, one in a shape of a cylinder with hemispherical ends (homogeneous model) and two others as multi-material models, one in a shape of a simplified white stork and the other one close to the real-life white stork. Multi-material bird models had various parameters. As a result of the research, various simulations of bird impact parameters were conducted, including kinetic energy, internal energy, impact forces, pressure, impact angle, and others. It can be noted that the character and the grade of the windshield damage and other impact parameters depends on a shape bird model. This concerns in particular large birds with mass exceeding 1.8 kg.

Keywords: aircraft, bird strikes, multi-material bird models, numerical simulations, SPH method.

INTRODUCTION

The majority of numerical simulations of bird strikes is related to aircraft certification in aspect of meeting EASA or FAA safety requirements (Heimbs, 2011). Nonetheless, the problem is interesting in a broader context since the studies in the certification aspect are limited to standardized bird models regarding shape, size, mass, density etc. An analysis of the bird strikes literature suggests that events involving birds of higher mass and size then stipulated by EASA or FAA frequently result in damage considerably exceeding the approvable standards (Dennis and Lyle, 2009). The case study of the bird strike described in the paper (N109TK, 2012) has contributed to choice of a helicopter windshield for the research.

In order to perform the modelling of bird strikes, it is necessary to select a proper bird model. Investigations exploit various geometrical figures in order to model the bird shape, the most common one being a cylinder, an ellipsoid and a cylinder with hemispherical endings (Heimbs, 2011; Koh, 2006). Few authors present research findings which employ an approximate shape of certain bird species on the basis of biometrical data (McCallum and Constantinou, 2005; Nizampatnam, 2007; Hedayati and Ziaei-Rad, 2012). The analyses focused mainly on the impact of the model with a flat steel or an aluminium plate. Therefore, it seems reasonable to conduct scans of a selected aircraft element, e.g. a helicopter windshield. Within the conducted
analyses, the impact loaded object was a helicopter windshield. The legal regulations concerning the strength requirements for the helicopter glazing include the specification CS 29.631, FAR Part 29. According to these specifications, the windshield in the category of a heavy helicopter should withstand a bird strike whose mass equals 1 kg at a speed of 180, and an altitude of 2438 m (Certification Specifications for Large Rotorcraft, CS-29, Amdt 2, 2011). There are no requirements regarding the categories of light helicopters and airplanes. Taking into account events, in which the bird mass exceeded 1 kg, the windshield was damaged and the bird remains were in the cockpit, the author decided to examine similar cases in a numerical environment.

Moreover, it is worth noticing that an analysis of the studies and the author’s experience (Cwiklak, 2016; Dennis and Lyle, 2009) shows that the relevance of a bird model shape increases significantly with its increasing mass, particularly for birds exceeding 1.8 kg. For that reason 3.6 kg was chosen as representative mass for large birds, such as white stork (https://en.wikipedia.org/wiki/White_stork). In order to conduct an analysis of a bird strike into an aircraft windshield, the author used the LS_DYNA software package (LS-DYNA® Keyword User’s Manual, 2007). This is a computational code designed to analyse the fast changing phenomena by means of the finite-element method.

METHODS

Bird strike, as a collision of an aircraft, or its components with a bird may be numerically modelled by means of the following methods (Heimbs, 2006; Lavoie et al., 2007):

- classic approach, where the bird is modelled according to the Langrangian method;
- ALE coupling (Arbitrary Lagrangian Eulerian);
- SPH method (Smoothed Particle Hydrodynamics).

In the carried out analyses the Smoothed Particle Hydrodynamics method was used. The method was coupled with finite elements method with the scope to overcome the FE limitations related to finite element mesh deformation occurring when dealing with large deformations (Vogt et al., 2015). The main difference between the Lagrangian and SPH method is the fact that the latter is a meshless method. The particles themselves create objects and the equations are solved for them. The main principle of SPH is an approximation of field variables based on their values in chosen points in space. Hydrodynamics forces satisfying Navies-Stokes equations are calculated in those points and the system solves the equations of motion [206] on that basis. Approximation in SPH uses a kernel function, which value approaches zero in infinity, while its integral over its domain equals unity. The kernel causes smoothing of the particles in the surrounding of a point. This method is commonly used for fluid flows simulations. Since during high-velocity collision birds behave like a fluid, the SPH is successfully used for bird strikes modelling (Heimbs, 2006; Grimaldi et al., 2013; Grimaldi, 2011).

Numerical bird models

For comparison, three bird models were elaborated (Figure 1) upon, one in a shape of a cylinder with hemispherical ends (homogenic model no. 4) and two others as multi-material models, one in a shape of a simplified white stork (no. 1) and the other one close to the real-life white stork (no. 2). Multi-material bird models had various parameters. The dimensions of the bird models were set on the basis of an assumed bird mass (3.6 kg) and density of the material. For a cylinder with hemispherical ends, the author assumed the ratio of the model length and the
diameter equal to 2:1. \( D = 142.52 \text{ mm and } L = 285.04 \text{ mm} \), whereas the number of the SPH particles equaled 28,784.

![model no. 4](image1)

![model no. 1](image2)

![model no. 2](image3)

Fig. 1 - Bird models used in FE analyses: cylinder-shaped model with spherical endings (model no. 4), bird model with a simplified shape (model no. 1) and real-life white stork bird model (model no. 2)

For the stork model of a simplified shape, the following parameters were assumed:
- mass = 3.6 kg;
- 70% of the mass is the bird torso;
- the densities of the material for the head, neck and torso were assumed on the basis of paper (McCallum and Constantinou, 2005), in which the authors considered a goose, disregarding, however, the bird’s beak. The densities of these components should not deviate from one other too much; the densities equaled 900 kg/m\(^3\) – head, 1,500 kg/m\(^3\) – neck, 1,150 kg/m\(^3\) – torso;
- the density of the wings was selected so as the total width of the bird dummy should not exceed the width of the windshield, since this would require significant modifications of the existing model. Moreover, the density of the wings was determined by the total mass of the bird model and was finally equal to 590 kg/m\(^3\). When generating the bird model, the following simplifications were assumed:
- the bird’s beak, legs, feet and the tail were disregarded;
- the shape of the torso and the head were assumed to be cylindrical;
- the shape of the neck was assumed to be cylindrical;
- the shape of the wings was assumed to be rectangular with hemispherical ends. 757.58 mm

Taking into consideration the above data and the used simplifications, it was possible to obtain a bird model, whose weight of 3.604 kg was composed of 29,972 SPH particles. It was 455.51 mm long. Its wing span measured 757.58 mm. When developing the shape of particular parts of the simplified stork model, the work was taken into consideration. Next, the author produced a stork model whose parameters were similar to the shape of a natural bird. Thus, a solid stork model, which served as a basis for the SPH model, was used. Its parameters were as follows:
- mass = 3.6 kg
- 68% - bird’s torso, legs and feet;
- 22% - wings;
- 10% - neck, head and beak.

The developed model consists of 37,638 SPH elements. The bird’s length, from beak to tail, equals 991.83 mm and the wing span is 1,534.15 mm. The biometric parameters correspond to an average stork size (https://en.wikipedia.org/wiki/White_stork). In general, the dimensions of a natural stork (length and wingspan) were two times bigger than the model of simplified
shape. While generating the SPH particles, attempts were made to make similar distances between them in each of the three models. The distances equalled on average 6 mm.

An initial velocity of the bird model was 285 km/h (79.16 m/s), using the option *INITIAL_VELOCITY. The vectors of velocity were applied to all particles of the model (SPH), grouping the above-mentioned components in the so-called sets (*SET). The bird model used a “zero” material model (*MAT_NULL), where the author declared the Grüneisen equation of state (*EOS_GRUNEISEN). The equation defines the pressure in the shock-compressed material, as Hedayati et al., 2014).

\[
p = \rho_0 C^2 \mu \left[ 1 + \left( 1 - \frac{\gamma_0}{2} \right) \mu - \frac{\mu^2}{2} \right] \left[ 1 - (S_1 - 1) \mu - S_2 \frac{\mu^2}{\mu + 1} - S_3 \frac{\mu^3}{(\mu + 1)^2} \right] + (\gamma_0 + a \mu) E, \tag{1}
\]

whereas for the expanded material, as:

\[
p = \rho_0 C^2 \mu + (\gamma_0 + a \mu) E, \tag{2}
\]

where:

- \( C \) - bulk speed of sound;
- \( \gamma_0 \) - Grüneisen gamma;
- \( S_1 \) - linear coefficient;
- \( S_2 \) - quadratic coefficient;
- \( S_3 \) - cubic coefficient;
- \( a \) - first order volume correction to \( \gamma_0 \);
- \( \mu \) - volume parameter, expressed as \( \mu = (\rho/\rho_0) - 1 \);
- \( \rho \) - actual density;
- \( \rho_0 \) - initial density;
- \( E \) - internal energy per unit of mass.

The material data of a dummy bird have been listed in Table 1.

<table>
<thead>
<tr>
<th>Density ( \text{RO [kg/m}^3 )</th>
<th>Cut-off pressure ( \text{PC [Pa]} )</th>
<th>Viscosity coefficient ( \text{MU [Pa-s]} )</th>
<th>Bulk speed of sound ( \text{C [m/s]} )</th>
<th>Linear coefficient ( \text{S1 [-]} )</th>
<th>Grüneisen gamma ( \gamma_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>950</td>
<td>(-10^6)</td>
<td>0.001</td>
<td>1.480</td>
<td>1.92</td>
<td>0.1</td>
</tr>
</tbody>
</table>

**Windshield model**

The FEM analyses were conducted using the windshield model, built of 8-node solid elements. For this purpose, a generator of solid components in the pre-processor LS-PrePost was used. It created a mesh of solid elements by adding thickness to the existing shell elements. Thus, the number of elements was not changed (9,339), yet the number of nodes doubled. In the properties, the default type of elements - ELFORM = 1 was declared.

In order to lock the window, which corresponds to fixing it to the helicopter structure, all nodes on the glass edge were grouped in a set of nodes (*SET_NODE). Therefore, it was possible to
receive all the degrees of freedom – translational in directions $x$, $y$ and $z$ and rotational against all the three axes of the global coordinate system.

Table 2 - Material data used in windshield model

<table>
<thead>
<tr>
<th>Density (RO) [kg/m$^3$]</th>
<th>Young’s modulus (E) [Pa]</th>
<th>Poisson’s ratio (PR) [-]</th>
<th>Yield stress (SIGY) [Pa]</th>
<th>Failure strain (FS) [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1190</td>
<td>3.13·10$^9$</td>
<td>0.426</td>
<td>6.8·10$^7$</td>
<td>0.067</td>
</tr>
</tbody>
</table>

The windshield of the helicopter Agusta A-109 is made from acrylic glass (http://www.agustawestland.com/product/helicopters/aw109-power-2). This material is available under different trade names, depending on the manufacturer, e.g.: Plexiglas™, Perspex™. Its main ingredient is poly(methyl methacrylate) – PMMA. The material parameters of the types of glass which are given in study (Wang et al., 2011), are presented in Table 2. The model used is ideal elastic plastic (*MAT_PLASTIC_KINEMATIC), with the reinforcement modulus equal to 0. The used model material took into account destruction, thus the components of the windshield model, in which the ultimate stresses were exceeded (FS = 0.067, Table 2), underwent erosion, i.e. they were removed from the model during the simulation.

As a contact between the windshield (master) and the bird model (slave) *CONTACT_AUTOMATIC_NODES_TO_SURFACE card was used. The boundary of the windshield is set by constraining the node’s rotational and translational degree of freedoms at the edge of the windshield.

In order to perform a preliminary validation of the developed models, numerical analyses were made by making assumptions from Willbeck’s work (Willbeck, 1978). The obtained courses of pressure are represented in Figure 2.

![Fig. 2 - Distribution of Hugoniot pressure and steady flow during a bird impact](image)

It should be noted that mass of analyzed models was three times over the Willbeck’s reference model mass (1 kg) thus the resulting values of Hugoniot pressure were respectively higher. Nonetheless, the analysis of the obtained curves shows that their shape is similar to those obtained in the above-mentioned investigation. It is possible to distinguish Hugoniot peak pressure and steady flow.
RESULTS
As a result of the research, various simulations using the LS_DYNA software package were conducted, including kinetic energy, internal energy, displacement, impact forces, pressure. The effect of a bird model shape on collision parameters was studied for three models at different impact angles (Figure 3). In the first scenario, the bird model velocity vector coincides with the x-axis and the longitudinal axis of the helicopter. The impact is not perpendicular to the surface, as the helicopter windshield is set at 40° angle with its longitudinal axis. Next, the effect of impacts at 30° (almost perpendicular to windshield) and -15° was investigated.
Figure 4 depicts a comparison of the windshield deformation resulting from impacts with the analyzed bird models depending on impact angle. The analysis of the first scenario shows that in case of cylinder-shaped model cracking of the windshield begins in the top right corner, in the vicinity of the point of its connection with the frame. With regard to bird model of simplified shape the damage to the windshield starts in a certain distance from the frame. The size of the crack is similar in both cases. By contrast the damage caused by the real-life white stork bird model occurred near to the center of the windshield with a tendency to the right. Moreover, a vertical crack can be observed. The most damaging to the windshield is an impact normal to its surface, destroying its central part in the vicinity of the theoretical piercing point [Figures 3, 4, middle column] and is comparable for all of the bird models. It can be concluded that bird model shape has a considerable impact on the numerical bird strike analysis output.

![Image](a) ![Image](b)

Fig. 5 - Kinetic energy (a) and internal energy (b) distribution depending on bird model

Figure 5 presents distribution of kinetic energy and internal energy during the impact process. It should be noticed that the character of the kinetic energy distribution is different in each scenario. It can be noted that in case of model no. 4 the kinetic energy is lost significantly faster, both at 0° and 30° impact angle – this is a result of a shorter length of the model and mass concentration in a smaller volume. By contrast, due to the complexity of model no. 1 and 2, the loss of energy is less steep and occurs at a later stage, when the bird’s torso hits the surface. Taking into account the angle of impact, it is noticeable that the energy loss is slower for smaller impact angles, because the velocity loss is slower. In some cases a decrease of windshield deflection can be observed, which is evidence for an elastic response of the system. When the bird model impacts the windshield at an angle normal to the surface it is practically pierced. Furthermore, a characteristic short-term curve collapse takes place in time of windshield perforation during each simulation. This is particularly explicit for the impact at normal angle. The curves illustrating internal energy distribution (Figure 4b) are similar in shape, however, for model number 4 the maximum value of internal energy amounts to 1.4 kJ, while it is approximately only 0.85 kJ for model number 1 and 2.

One of the analyzed parameters was a resultant force (Figure 6). The analysis of the parameter depending on bird model and impact angle shows that for 0° impact angle the highest maximum force value was reached by model number 2 at 38 kN, followed by model number 1 (27 kN) and model number 4 (20 kN). The situation was different at 30° impact angle, for which the maximum force values varied from the previous situation and amounted for model no. 2 to 35 kN, for model number 1 to 39 kN and for model number 4 to 47 kN, which was the highest value in this scenario. Whereas the maximum values of the parameter for -15° impact amounted for model number 2 to 50 kN, for model number 1 to 45 kN and for model number 4 to 18 kN.
Based on the obtained results, it can be concluded that the differences in the forces values and their distribution results from the bird model shape, including its length and various mass concentration. Examining model number 4 in aspect of the impact angle one can easily spot differences in the resultant force distribution. At the angle almost normal to the windshield surface (30°) the maximum resultant force value is the highest compared to the other models and is reached in relatively short time, circa 4ms. The curve shape results from the fact that the mass is concentrated in smaller volume compared to the longer models. Much less steep resultant force distribution occurs in simulations at 0° and -15° because the relatively small angle in relation to the windshield causes the model to virtually slide off its surface. Investigating model number 1 and no. 2 it can be noticed that in contrast to model number 4 the force reached its maximum value in, respectively to its length, longer time (model number 1 - 6.5 ms, model number 2 - 11.5 ms) and reached higher value caused by the bird`s torso impact. The process of windshield piercing was much more violent as well (sudden drop of the force value in the perforation moment).

CONCLUSIONS

The paper presents the results of numerical analyses of three dummy birds, which differ in shape and parameters like mass and dimensions, during the impact process with the helicopter windshield. Taking into account an analysis of the available subject literature as well as the previous research conducted by the author, the SPH method was selected for bird modelling. Also Grüneisen equation of state was applied for this purpose. An influence of the bird shape and its dimensions on such analysis parameters as pressure, kinetic energy, impact angle, windshield deflection was analyzed. The impact of the bird model at an angle normal to the windshield surface occurs in a shorter time causing its destruction in the central part and has a similar character for all models. In impacts other than in the normal direction to the windshield, the windshield is destroyed at the point of its connection with its frame. The effects of the collision depend on the impact angle. At small angles in relation to the glass surface, the bird slides off it without causing it damage. Differences in the values of kinetic energy, impact force and their distribution in time depend on the shape of the model, including its length and...
weight distribution. Summing up the obtained results, it can be concluded that the adopted shape of the bird significantly affects the behavior of the windshield during the collision process. Taking into consideration the results of the conducted analysis, the real white stork bird model seems to be the most representative one for the bird strike process. Analyzing the bird strike described in (N109TK, 2012) it can be seen some similarities to the nature of the damage caused in the numerical simulation to the real accident.

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REFERENCES


