Application of the SPH Method for Simulation of Aerospace Structures under Impact Loading

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Abstract

The SPH method is applied in industrial level problems as encountered for example in studies related to bird impact on composite aircraft structures. This paper first demonstrates the accuracy of the method for bird impact on rigid target modeling and then applies the developed model to a more complex problem, namely the secondary bird impact.

Keywords: bird impact, SPH accuracy, fluid-structure interaction

Introduction

Because of its low computational cost, its reasonable precision and stability compared with classical methods FEM and, more importantly, because of its ability to handle large distortions by avoiding the need for intensive FEM remeshing, SPH is a competitive approach compared to finite elements (FE) and is increasingly being used in some fast-transient dynamics problems. Several authors have proposed to couple FE and SPH which seems a reasonable approach in order to benefit from the advantages of both formulations.

The method was initially developed in the late 70's and early 80's by Lucy and Monaghan [1,2] and applied to hypervelocity impacts occurring in outer space. In addition to its original application, it has been used to solve a variety of problems such as fluid flows [3,4], underwater explosions [5], metal forming [6], impact on metallic targets [7,8], concrete fragmentation [9], debris flow and avalanches [10].

Such versatility has been useful to study bird strike modeling as part of a university/industry Consortium for Research and Innovation in Aerospace Quebec (CRIAQ) project entitled *Impact Modeling of Composite Aircraft Structures*. The purpose of the project was to develop reliable design tool for passengers' protection when an aircraft undergoes soft body impact, such as a bird, or high velocity debris impact while decreasing the time and costs involved in the certification process. It has led to the use of SPH in LS-DYNA and the development of an in-house program.

The current paper presents how the accuracy of the SPH method is assessed when using it to model a numerical bird. Afterwards, the numerical bird model is used to demonstrate the proof of concept of a complex simulation, namely the secondary bird impact.

Accuracy – Bird Impact on Rigid Target

In recent years, efforts were increased to model the bird impact event and predict the viability of aircraft structures prior to the mandatory expensive destructive certification procedures. This is within the scope of the CRIAQ impact modeling project and different modeling techniques were studied [11] as well as ways to evaluate the reliability of the obtained numerical results. Moreover, because the available experimental data were collected several year ago with the then available instrumentation [12], new tests were conducted and results were published in Lavoie [13]. Here the numerical SPH bird model is briefly described and compared against some of those new experimental data. Especially with respect to the deformation of the bird, it was found that SPH was the best performing numerical method when compared to the ALE approach.

During the experimental set up, a 1 kg gelatine bird substitute impacted a rigid 0.0127 m (½ in) thick steel plate at a velocity of 95 m/s (185 knots). The plate was of 0.3048 by 0.3048 m (12 by 12 in) side dimension with an edge of 0.0127 m (½ in) wide by 0.00635 m (¼ in) thick. A high-speed video camera was used to capture the behavior of the projectile during the impact and frames were taken at a frequency of 3000 frames/sec.

The numerical model includes a steel target modeled with solid elements and the bird, modeled with about 4500 SPH particles. An automatic nodes to surface contact control the interaction between the projectile and the target. Figure 1 presents the numerical model generated.

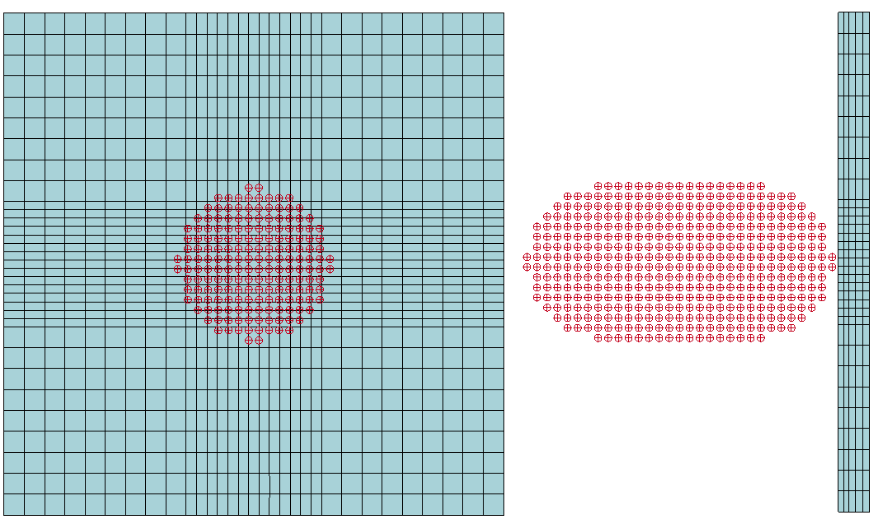

Figure 1 Numerical model for the SPH impact on a rigid flat plate

An elastic material model is used for the plate and an elastic-plastic-hydrodynamic material model with a polynomial equation of state is used to model the bird. The physical properties are given below using the international system of units and the simulation ran for 0.005 s.

```
*MAT_ELASTIC
$      MID        RO         E        PR        DA        DB
         3 7830.00002.0700E+11  0.300000

*MAT_ELASTIC_PLASTIC_HYDRO
$      MID        RO         G      SIGY        EH        PC        FS
         1 950.00000 2.0000E+9 20000.000 1000.0000
```

```
$      EPS1      EPS2      EPS3      EPS4      EPS5      EPS6      EPS7      EPS8
      0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
$      EPS9     EPS10     EPS11     EPS12     EPS13     EPS14     EPS15     EPS16
      0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
$       ES1       ES2       ES3       ES4       ES5       ES6       ES7       ES8
      0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
$       ES9      ES10      ES11      ES12      ES13      ES14      ES15      ES16
      0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000

*EOS_LINEAR_POLYNOMIAL
$     EOSID        C0        C1        C2        C3        C4        C5        C6
          1     0.000 2.0600E+9 6.1900E+91.0300E+10
$        E0        V0
      0.000     0.000
```

Snap-shots are compared for the experimental and numerical deformations from the beginning of the impact at time intervals of 0.0066 s in figure 2. A very good correlation can be observed between the two sets of data. Moreover, the increase of the diameter of the projectile and the deceleration of the end of the projectile were measured to provide a more quantitative approach. Those are illustrated in figure 3 where an experimental curve is given for each of the three valid tests conducted. Although the time intervals are relatively large for the experimental data, the trend of both numerical and experimental is very similar.

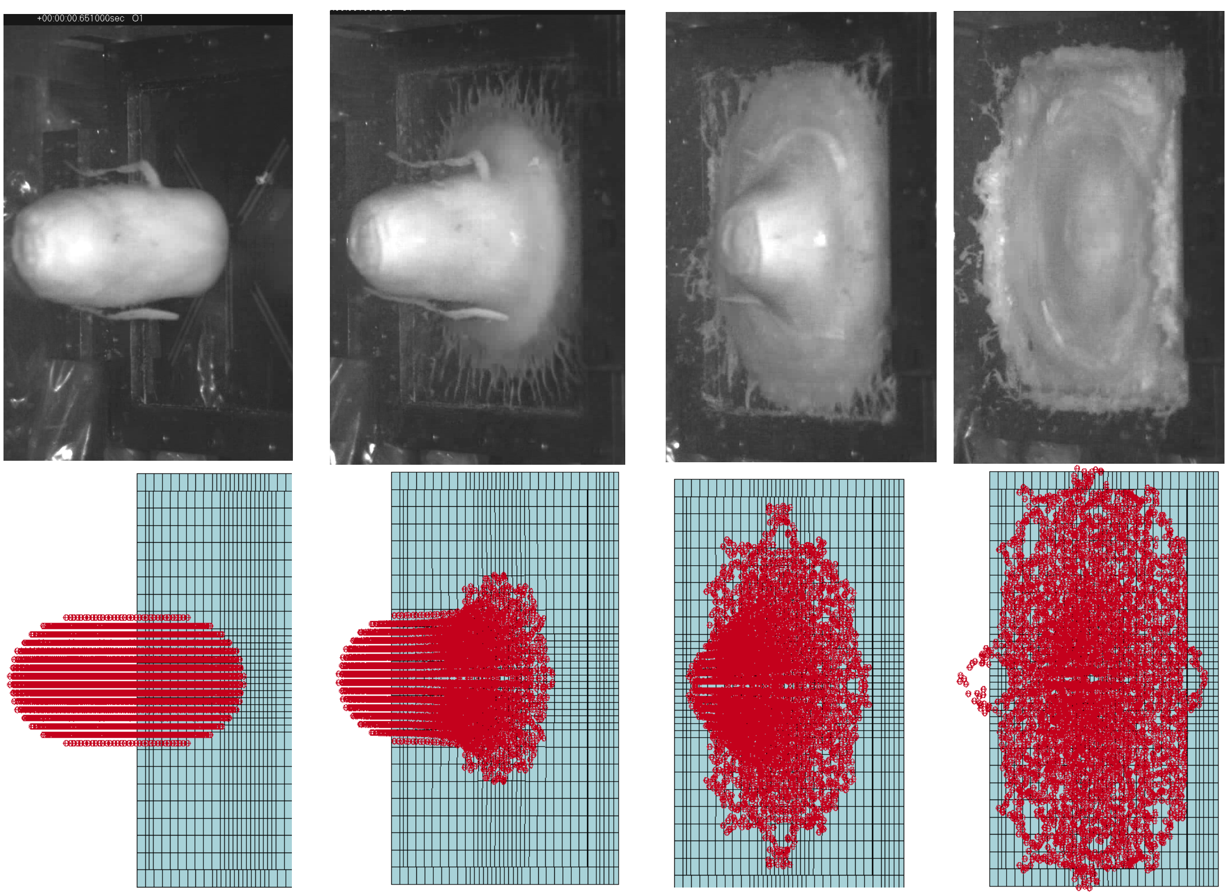

Figure 2 Impact at 0° at time intervals of 0.66 ms, video camera and SPH method

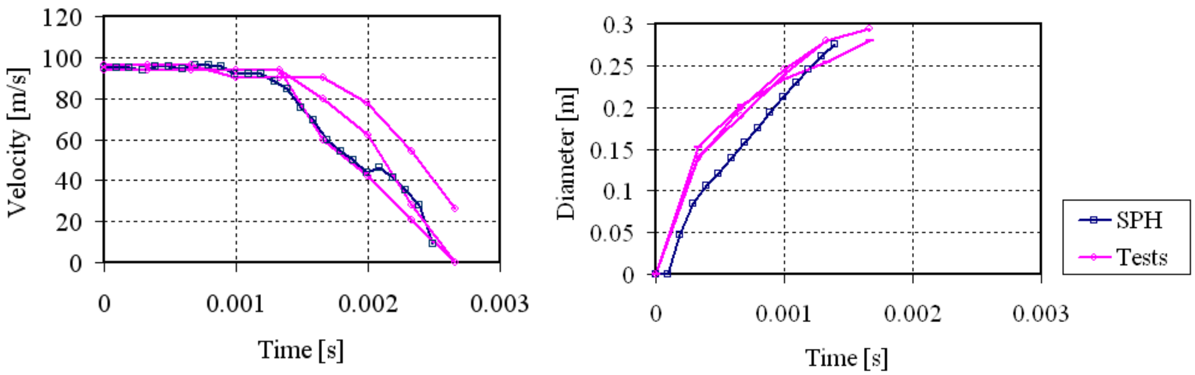

Figure 3 Variation of velocity (left) and diameter of the projectile (right) at 0° angle

The accuracy of the SPH bird model can be assessed in other ways. For instance, it is possible to incline the target and observe what happens then. It is also quite current to compare the pressure reading at the center of impact and the radial pressure distribution with the analytical and experimental values. For more information, the reader is referred to Lavoie [11] for an analytical approach and Lavoie [13] for an experimental approach.

The general conclusion drawn from the results presented here is that the SPH method yields results that are sufficiently reliable for it to be used in a more complex numerical simulation where the unknown are related to the structure and not the projectile.

Proof of concept – Secondary Bird impact

Once the accuracy of SPH is demonstrated for bird impact, it becomes interesting to apply it to a large scale simulation and examine the type of complex problems that can be solved with SPH. In collaboration with one of the partner of the CRIAQ project, the secondary bird impact was studied. Following tests, it came to attention that most of the bird mass hitting the engine pylon component was deflected and hit the engine cowling. Figure 4 below illustrate where the impact would typically occur.

Figure 4 Point of impact on a typical aircraft

Thus, SPH particles were used to perform the post-tests analysis since it incurs no mass loss after the initial impact. The numerical analysis was performed in LS-DYNA to study the impact of a bird on a wing leading edge with a swept angle and to evaluate the potential harmfulness of secondary debris on surrounding structures. The objective of the numerical simulations was to provide simulation data that could be compared against tests results. The data is given in terms of energy, velocity of the projectile debris after the initial impact and the mass percentage of deflected debris that can reach a nearby structure.

A 1.81 kg (4 lbs) bird travelling at a velocity of 180 m/s (350 knots) impacts the pylon leading edge at a swept angle. The bird is modelled with about 9000 SPH particles using the same elastic plastic material model and equation of state as given above. The structure is made of aluminum where the thickness is sufficient so that the leading edge remains intact in order for most of the debris to be deflected toward the engine cowling, which represents a worse case scenario. The leading edge and engine cowling, represented by the wall, are constrained so as not to move in space. Forces imparted on the wall are measured with the contact and the simulation last 0.01 s. Figure 5 below gives a schematic of the problem studied.

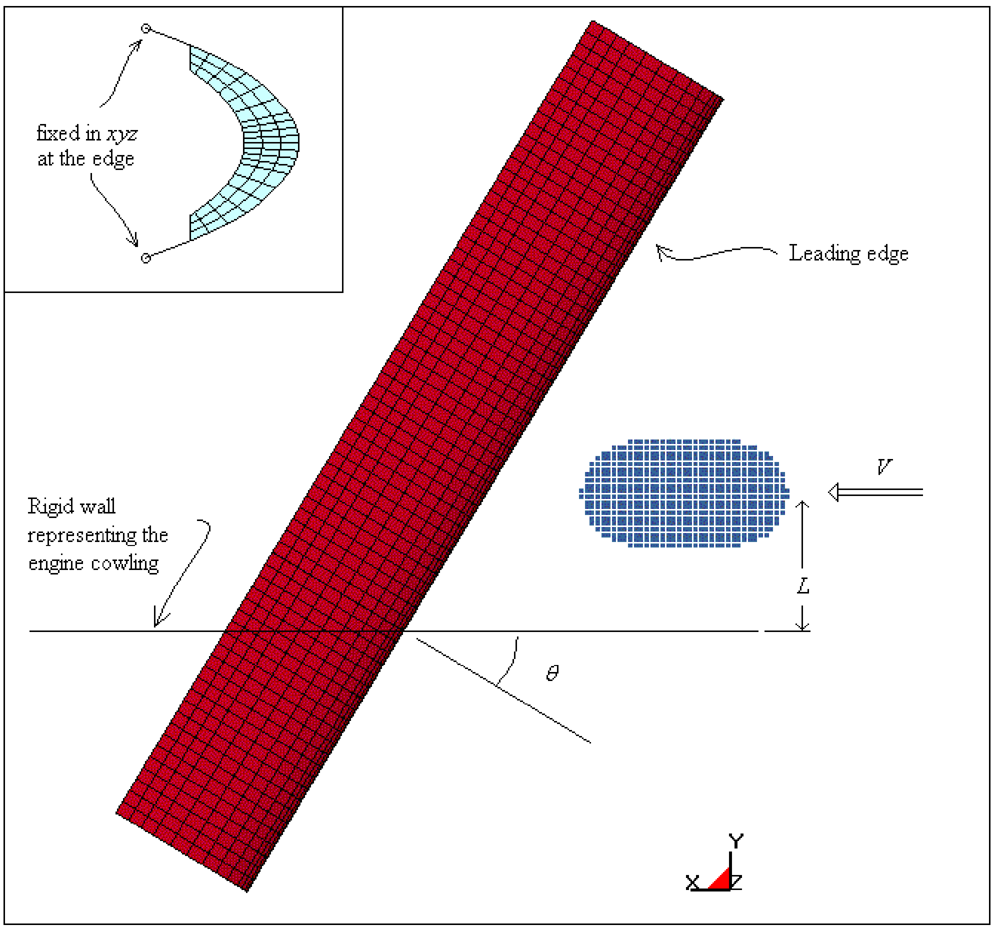

Figure 5 Numerical model for the secondary bird impact

The first data retrieved is to visually observe what happens to the bird after the first impact, which is given in Figure 6 below. As expected, a significant portion of the bird is deflected towards the rigid wall.

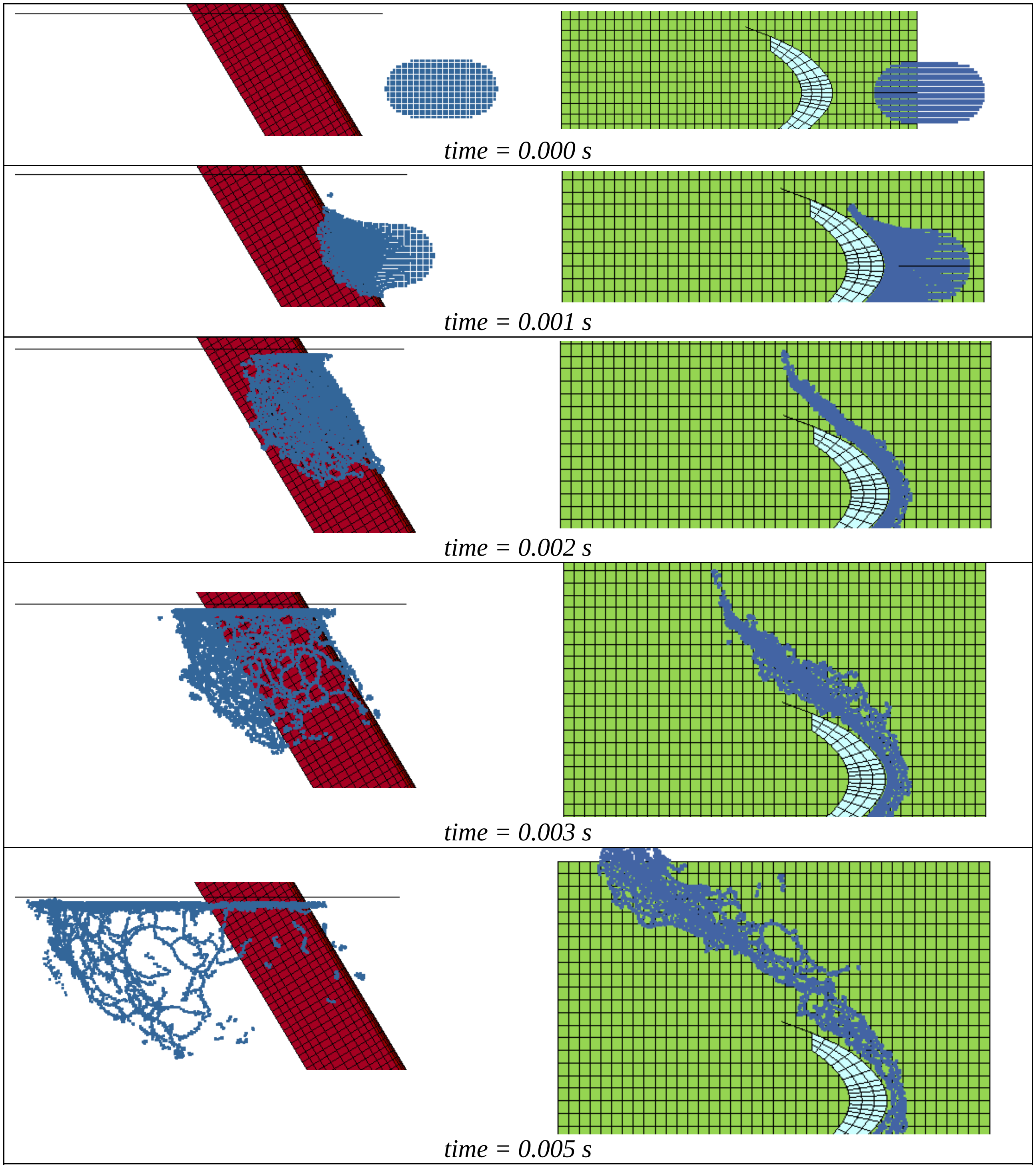

Figure 6 Progression of the secondary bird impact

Secondly, the residual velocity and mass, that is the velocity at which the debris hit the wall, was qualitatively measured using the post-processor in LS-DYNA. The core of the impact occurs 0.0025 sec after the initial impact on the leading edge.

The velocity is perpendicular to the engine cowling and ranges form 100 to 150 m/s. The mass deflected towards the engine cowling represents about 45% of the initial mass of the bird and was calculated by averaging the number of particles within 10 mm of the rigid wall. It is note worthy that the peak force transmitted to the wall is not coincident with the maximum mass impacting it.

Finally, it is also of interest to know how much energy can be imparted by the bird to the engine cowling. A very approximate value can be obtained by integrating over time the resulting force on the rigid wall representing the engine cowling. The value was compared against the energy absorbed by the leading edge and amounted to about half of that value.

This summarizes up the initial steps of solving the secondary bird impact and shows that SPH can be effectively used to solve the problem. Further development and increase in accuracy can be achieved by up-dating the radius and geometry of the leading edge and engine cowling to that of the real structure, making sure that the boundary conditions are representative of reality, using the appropriate material properties for the leading edge and engine cowling, and using the actual distances between the point of impact and engine cowling.

Conclusion

We have shown in this paper how the SPH method can be used to obtain accurate results for bird impact simulations and how it is suitable for complex problems that cannot be successfully solved using other numerical methods. Given the success of SPH method in the current project, it should be used in subsequent work involving more complex fluid-solid interaction as in aircraft ditching simulation.

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References

1 L. B. Lucy, *A Numerical Approach to the Testing of the Fission Hypothesis*, The Astronomical Journal, **82**, 1977, 1013-1024

2 J. J. Monaghan & R. A. Gingold, *Shock Simulation by the Particle Method SPH*, Journal of Computational Physics, **52**, 1983, 374-389

3 Chad E. Sparks, Ronald L. Hinrichsen, David Friedmann, Co*mparison and validation of smooth particle hydrodynamic (SPH) and coupled Euler Lagrange (CEL) techniques for modeling hydrodynamic ram*, 13th AIAA/ASME/AHS Adaptive Structures Conference, April 18-21, 2005, Austin, Texas

4 Liang Xue, Breaking *dam flood using smooth particle hydrodynamics method*, 10th International Symposium on Interaction of the Effects of Munitions with Structures, May 7-11, 2001, San Diego, California

5 M. B. Liu, G. R. Liu, K. Y. Lam, Z. Zong, *Smoothed particle hydrodynamics for numerical simulation of underwater explosion*, Computational Mechanics, **30**, 2003, 106-118

6 J. Bonet & S. Kulasegaram, *Correction and stabilization of smooth particle hydrodynamics methods with applications in metal forming simulations*, International Journal for Numerical Methods in Engineering, **47**,2000, 1189-1214

7 James Campbell, Rade Vignjevic, Séverine Lepage, *Numerical simulation of high velocity impacts on thin metallic targets II*, Dynamics & Control of Systems & Structures in Space (DCSSS), 6th Conference, July 2004, Riomaggiore, Italy

8 Rade Vignjevic, James Campbell, Séverine Lepage, *Numerical simulation of high velocity impacts on thin metallic targets I*, Dynamics & Control of Systems & Structures in Space (DCSSS), 6th Conference, July 2004, Riomaggiore, Italy

9 T. Rabczud & J. Eibl, *Simulation of high velocity concrete fragmentation using SPH/MLSPH*, International Journal for Numerical Methods in Engineering, **56**, 2003, 1421-1444

10 M. X. Rodriguez-Paz, J. Bonet, *A corrected smooth particle hydrodynamics method for the simulations of debris flows*, Numerical Method for Partial Differential Equations, **20**, 2004, 140-163

11 M-A Lavoie, A. Gakwaya, M. Nejad Ensan, D.G. Zimcik, *Validation of Available Approaches for Numerical Bird Strike Modeling Tools*, International Review of Mechanical Engineering, **1**, 2007, 380-389

12 James S. Wilbeck, *Impact Behavior of Low Strength Projectiles*, Air Force Materials Laboratory, 1977

13 M-A Lavoie, A. Gakwaya, M. Nejad Ensan, D.G. Zimcik, D. Nandall, *Bird's substitute tests results and evaluation of the available numerical methods*, in preparation for publication