FE-TO-SPH APPROACH APPLIED TO THE ANALYSIS OF SOFT BODY IMPACT: BIRD STRIKE AND HAIL IMPACT

Prato*, Anghileri*, Milanese*, Castelletti*
***Politecnico di Milano, Dipartimento di Scienze e Tecnologie Aerospaziali, Milano, Italy**

Abstract

The soft body impact might be considered as one of the greatest problems for aeronautical structure.

To numerically investigate this kind of events both Lagrangian and Smoothed Particles Hydrodynamics (SPH) approaches are generally adopted, but both of them suffer some problems concerning distortion, in Lagrangian elements, and the treatment of essential boundary condition, for SPH approach. The possibility to apply a finite element to SPH transition (FEtoSPH) is here considered.

A numerical investigation on hail impact and bird strike phenomenon was performed at the Laboratory for the Safety in Transports (LaST) of Politecnico di Milano. Each of these three approaches was considered for different mesh definitions and impact velocities. A case study concerning the hail impact against an engine inlet was investigated to evaluate the effect of the use of this innovative approach on possible real impact events.

1 General Introduction

Bird strike and hail impacts onto aircraft structures are classified as soft body impacts. Soft bodies are highly deformable and flow over the structure spreading the impact load

Bird strike has been a threat to flight safety since the early days of aviation. Predicting or even analysing the consequences of a bird strike is still a challenge and the analyses of events involving bird impact are in many cases still out of reach [1-2]. Same goes for the analyses of hail impact especially referred to the barely visible damage especially in composite structure [3-5].

These kinds of events were numerically reproduced using an explicit finite element code which adopts Lagrangian approach. Also the Smoothed Particle Hydrodynamics (SPH) technique is generally used, but both of them present some limits. Nowadays some explicit codes (e.g. Pamcrash and LS-DYNA) implement a rather sophisticated approach that aims at combining the benefit of these two techniques. This approach consists of switching from the finite element (FE) to the SPH approach when a failure criterion for the FE material model is imposed.

Only few research works were performed using this method. Beal et al. in [6] presented some possible industrial problems analysed with this approach using the explicit FE code LS-DYNA. The comparisons with older modelling demonstrate the benefits of the use of this method. Kulak and Bojanowski in [7] used this approach to describe soil behaviour under cone penetration tests. They compared experimental test results with numerical models performed using both the Arbitrary Lagrangian-Eulerian (ALE) method and the new FE to SPH approach. The Hypervelocity impact of an aluminium sphere against a plate of the same material was presented by Plassard et al. in [8]. The debris clouds generated after the impact were numerically studied using SPH, hybrid SPH/solid elements and MM-ALE approach in LS-DYNA and their results compared with the experimental ones. Zahedi et al. [9] used FE to SPH approach to model in ABAQUS/Explicit the effect of crystallographic anisotropy on a response of face centred cubic metals to machining.

In this paper an attempt is made to assess effectiveness and accuracy of this new approach using the explicit code LS-DYNA [10-12], compared to simply Lagrangian and simply SPH method, when applied to the analysis of bird strike and hail impact. As a result of this investigation, benefits and drawbacks of this quite recent approach have been highlighted.

2 Numerical approaches: an overview on FE and SPH methods

Many different approaches can be used to numerically model a soft body impact. In this section a general overview is presented on the three approaches (Lagrangian, Smoothed Particle Hydrodynamics (SPH) and finite element to SPH (FEtoSPH) method) that were used in this research work.

2.1 Lagrangian FE approach

In the Lagrangian approach a continuous medium is divided into a well-defined number of simple elements (2D or 3D) and the solution of a system of equation is necessary to describe the dynamic of this body. This approach is useful to study nonlinear problems with small deformation of elements. As a matter of fact this approach can lose accuracy at very large distortion of elements causing the inaccuracy in problem solution, the increase of the computational cost till the premature termination of the analyses.

2.2 SPH approach

Smoothed Particle Hydrodynamics (SPH) [10-12] technique was introduced in 1977 to overcome these limits of the Lagrangian approach. The main difference between classical FE method and SPH is the absence of a grid. Therefore, the particles are the computational framework on which the problem is solved using an interpolatory solution of the balance equations. The SPH approach comes with a number of drawbacks, for examples tensile instability, difficult essential boundary condition treatment. For all these reasons for many applications the traditional Lagrangian FE approach is still preferred.

2.3 FE to SPH approach

The new FEtoSPH approach was created to overcome all these problems combining the benefits of these two techniques. It is used to define solid parts whose elements are transformed into SPH particles when the solid elements failed.

For example this new technique can be used in transition areas between solid and SPH elements (Figure 1a) or in solid elements subjected to high distortion or failure of the elements (Figure 1b).

Solid elements contain SPH particles initial location and the number of these SPH particles is user defined. For example for a hexahedral element there are 1, 8 or 27 SPH particles. Properties, materials and contacts can be defined both for solid elements and SPH particles.

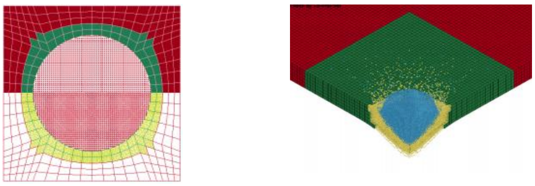

Figure 1: FEtoSPH: transition area (1a); failure of solid elements (1b) [6]

3 Hail Impact

The impact of hailstones (even if small in size) against an aircraft can have serious consequences. Even when it is not likely to cause the collapse of the aircraft structures, a hailstone impact is a menace for what is known as invisible damage. For all these reasons an investigation of this kind of event is necessary.

The analysis of a simple spherical hail stone impacting on a plate with an initial velocity of about 60.6 m/s was developed using all the three methods previously presented. After the presentation of the results of the single approaches, a comparison between them is shown.

3.1 Hail Impact: Lagrangian Approach

A hail stone with a diameter of 50.8 mm was modelled using solid elements with different mesh discretization (Figure 2) in order to evaluate the effects on pressure, stress, strain and contact behaviour during the impact.

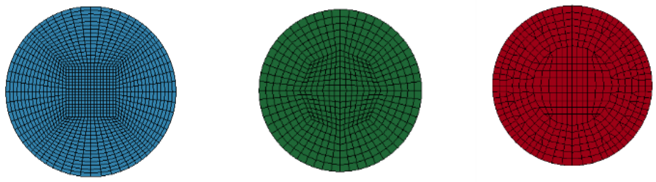

Figure 2: Lagrangian model of the hail stone: Mesh1 (blue), Mesh2 (green), Mesh3 (red).

The material used for the model was the one used by Kim in his research work [4]. A contact between the hail stone and the plate was defined as a node to surface one.

Table 1: Ice material property

Property	Value
Mass density - kg/m^3	846
Shear modulus - MPa	3460
Yield stress - MPa	10.3
Plastic Hardening Modulus - MPa	6890
Bulk modulus – MPa	8990
Plastic failure strain- %	0.35
Ultimate Tensile Stress - MPa	-4

A comparison between the contact forces of the three models shows that there are only low differences between them (Figure 3).

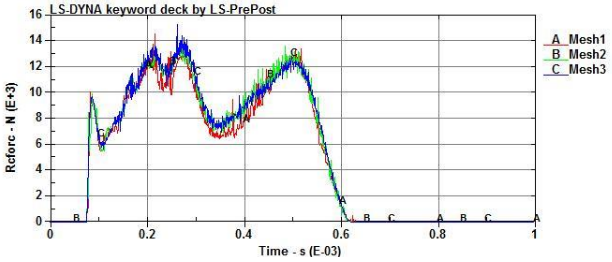

Figure 3: Lagrangian models: contact force.

Small differences occur also for the effective plastic strain, (Figure 4).

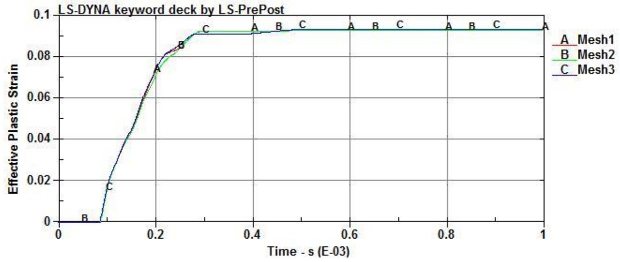

Figure 4: Lagrangian models: effective plastic strain.

There are instead some differences from the comparison of the pressure and the Von Mises stress curve (Figure 5 and Figure 6). This depends mainly on the fact that for mesh1 there were some parts of the hail in which the element dimension was lower than the nominal dimension. This fact implied a high distortion after the first impact of the hail. Mesh2 and mesh3 were instead more homogenous and presented a lower element distortion.

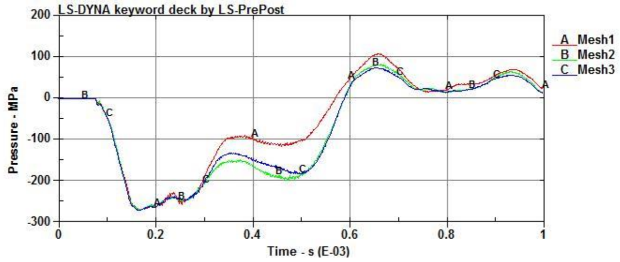

Figure 5: Lagrangian models: pressure.

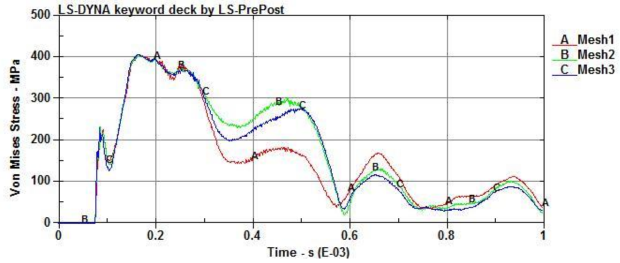

Figure 6: Lagrangian models: Von Mises stress.

Meshes with tetra elements were also created but the excessive distortion of the elements produced instability problem of the model with the subsequent “error termination” of the model.

3.2 Hail Impact: SPH Approach

The SPH approach was also adopted to reproduce the impact dynamics of the same hail stone against the plate, with an initial velocity of 60.6 m/s. Particles were created both from the previous three Lagrangian discretizations (one point for element) and using a uniform particles distribution (Figure 8).

The material model adopted and the contact type were the same previously used for the Lagrangian simulations.

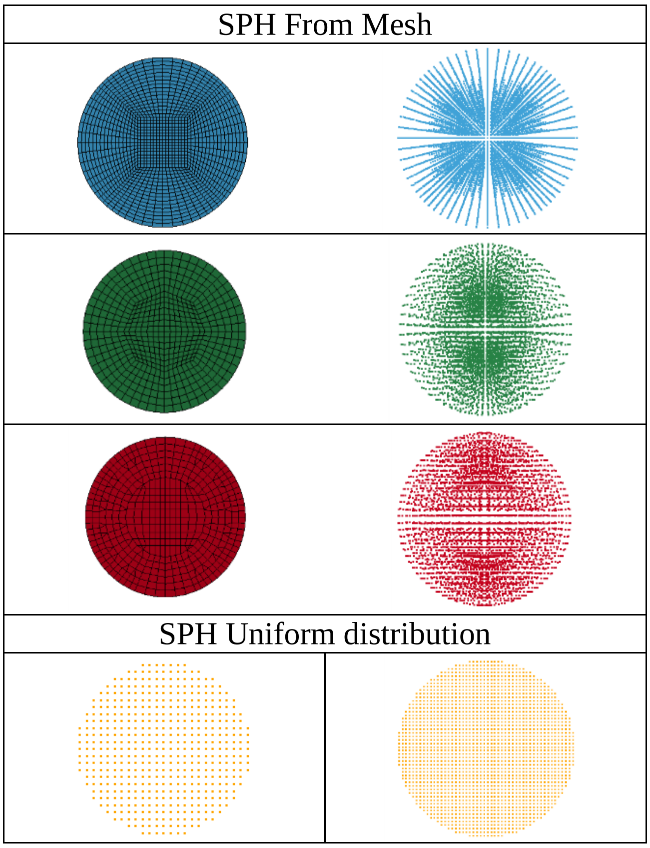

Figure 7: SPH models: particles distribution SPH1 (blue), SPH2 (green), SPH3 (red), SPH4 (yellow-sx), SPH5 (yellow-dx).

A comparison between the different SPH models was performed in term of contact force (Figure 8), effective plastic strain (Figure 9), pressure (Figure 10) and Von Mises stress distribution (Figure 11).

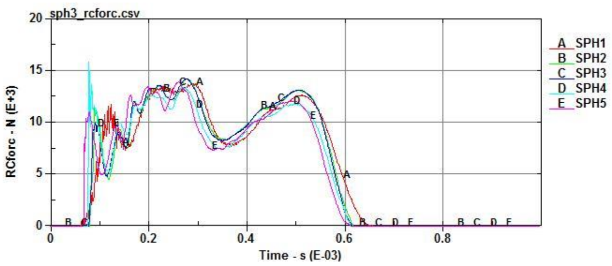

Figure 8: SPH method: contact force.

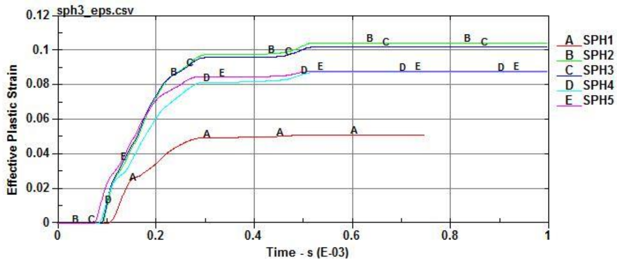

Figure 9: SPH method: effective plastic strain.

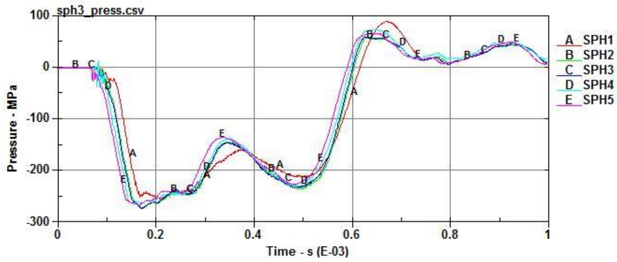

Figure 10: SPH method: pressure.

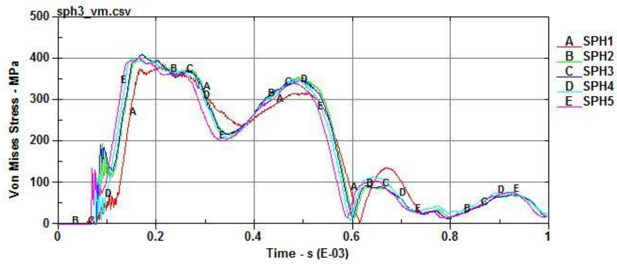

Figure 11: SPH method: Von Mises stress.

From results it can be seen that a non-homogeneous distribution of the particles produce different results respect of a homogeneous one. This observation confirmed what previously saw for the Lagrangian approach.

3.3 Hail Impact: FE-to-SPH Approach

The new hybrid FEtoSPH approach was tested using the same impact dynamic of the hailstone.

For the Lagrangian model Mesh2 and Mesh3, the ones with a more homogeneous distribution of the mesh, were used. The SPH were generated using one integration point for each solid element, like in SPH2 and SPH3. A control card `*ADAPTIVE_SOLID_TO_SPH` was created to switch from Lagrangian model to SPH one if the distortion of the elements was too high.

The material used was the same previously described and the same was also the contact definition.

A comparison between Lagrangian, SPH and FEtoSPH approach was performed in order to evaluate how the new formulation behaves.

3.3.1 FEtoSPH2

Referring to Mesh2 the model behave as a Lagrangian one. All results (Figure 12, 13, 14 and 15) show this evidence.

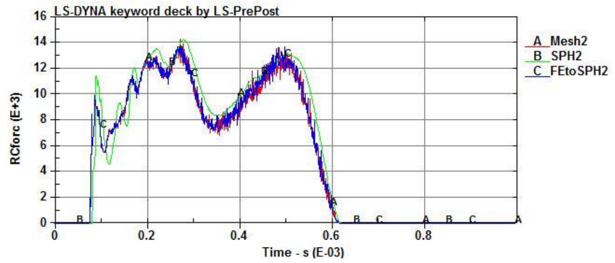

Figure 12: FEtoSPH2: contact force.

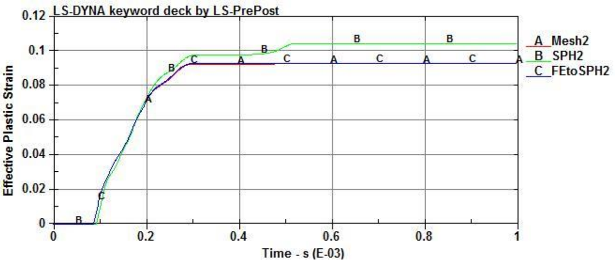

Figure 13: FEtoSPH2: effective plastic strain.

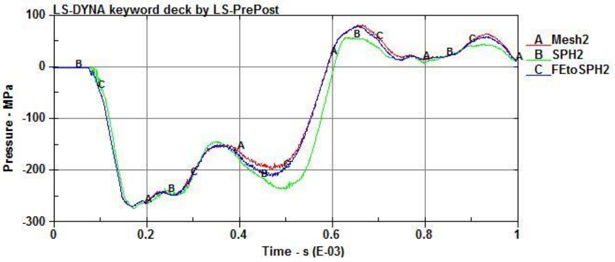

Figure 14: FEtoSPH2: pressure.

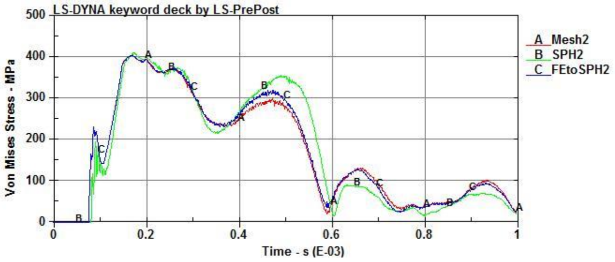

Figure 15: FEtoSPH2: Von Mises stress.

It can be seen that just small differences occur between Lagrangian and FEtoSPH approach. This fact can be related to the distortion of the element.

3.3.2 FEtoSPH3

The same considerations can be done analysing the results of Mesh3 simulation (Figure 16, 17, 18 and 19).

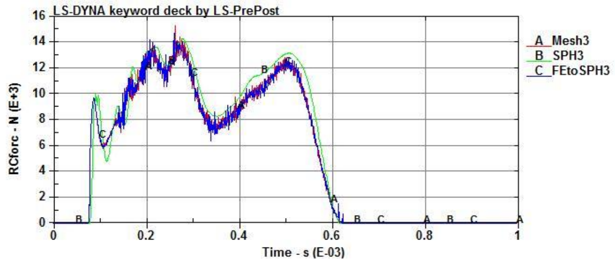

Figure 16: FEtoSPH3: contact force.

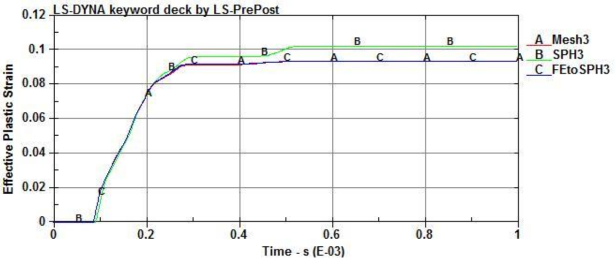

Figure 17: FEtoSPH3: effective plastic strain.

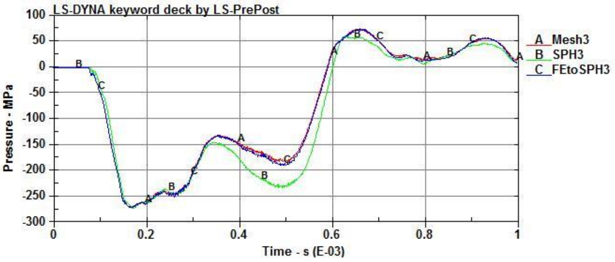

Figure 18: FEtoSPH3: pressure.

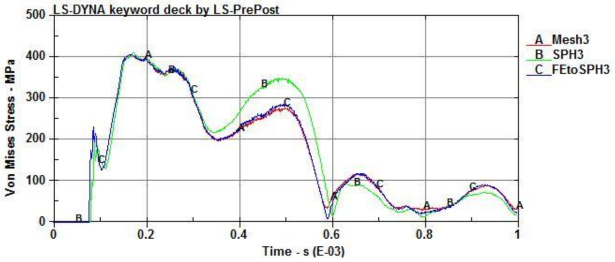

Figure 19: FEtoSPH3: Von Mises stress.

3.3 Hail Impact: Conclusions

Hail impact is one of the most interesting phenomena for aeronautical structures. In this work an investigation on a new approach to represent this kind of phenomena, the FEtoSPH approach, was adopted.

The impact of a hail stone against a plate was modelled using Lagrangian, SPH and FEtoSPH approach.

From results it was demonstrated that if the distortion of the element was not so high, the *ADAPTIVE_SOLID_TO_SPH card was not used and the model behaved as the Lagrangian ones. Only small differences were shown and they were probably related to the effect of the element distortion.

4 Bird strike

The impact of a bird against a structure is another great problem in aeronautical field, especially during the take-off and landing. The rules prescribed the use of real bird during the certification tests, but recently bird surrogates in ballistic jelly are sometimes accepted. Many works were done on this argument but no one on the possibility of using the new FEtoSPH approach to this problem.

A 1.25 kg bird was impacted against a thick plate in steel at different impact velocities. Different approaches were considered: Lagrangian, SPH and FEtoSPH. A comparison between them was performed considering a constant impact velocity.

4.1 Bird strike: Lagrangian approach

The bird was reproduced as a cylinder with a ratio between length and diameter equal to 2. It was modelled using solid elements with a nominal dimension of 3 mm. The material adopted for it was the *MAT_NULL with equation of state and hourglass definition [1].

The plate was modelled using solid elements with a nominal dimension of 4 mm and for the steel the *MAT_PLASTIC_KINEMATIC was adopted.

Contact between the bird and the plate was described using a soft constrained formulation. The plate was also constrained throughout four springs at the corner of the plate.

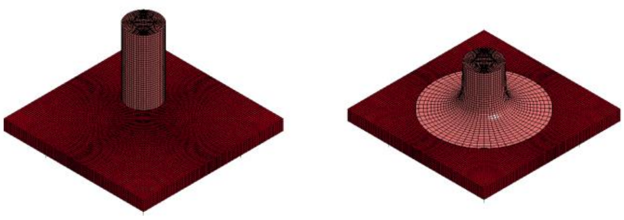

Figure 20: Bird impact: Lagrangian model.

Impact velocities from 100 m/s to 175 m/s were considered. From the comparison of the contact forces at different velocities it can be shown that the characteristics of the curves are similar, with a pick of force at the first impact of the bird against the plate. After a quit constant force region, there is a decrease of it when the bird flew away from the plate.

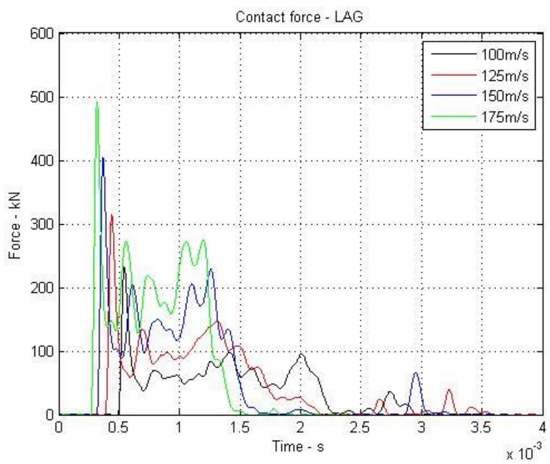

Figure 21: Bird impact: Lagrangian model – contact forces at different impact velocities.

4.2 Bird strike: SPH approach

The SPH approach was also adopted to model the bird. The particles were generated starting from the Lagrangian model and considering one SPH particle for each Lagrangian solid element. The material models used for the bird and for the plate were the same adopted in the previous approach. The same were also the discretization of the thick plate, the contact definition and the boundary conditions.

Figure 22: Bird strike: SPH model.

In figure 23 a comparison of the contact force in the SPH model considering a range of impact velocity between 100 m/s and 175 m/s is shown.
Similar considerations on what previously said for the Lagrangian approach can be done for the SPH one.

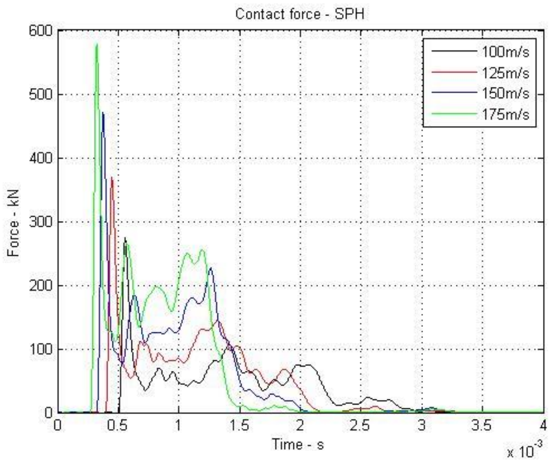

Figure 23: Bird strike: SPH model – contact forces at different impact velocities.

4.3 Bird strike: FEtoSPH approach

Starting from the Lagrangian approach, a FEtoSPH model was realized using the `*ADAPTIVE_SOLID_TO_SPH` card. One SPH particle for each Lagrangian solid element was defined. The SPH and the Lagrangian characteristics of the model were always the same.

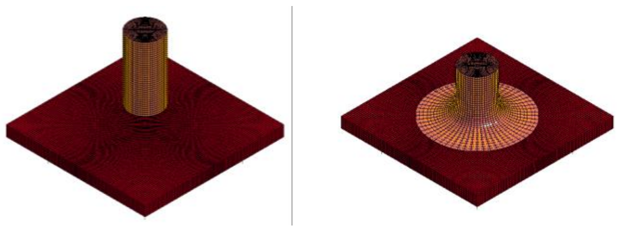

Figure 24: Bird strike: FEtoSPH model.

Comparing the results from the tests it can be clear that the curves are similar to the ones presented for the previous approaches.

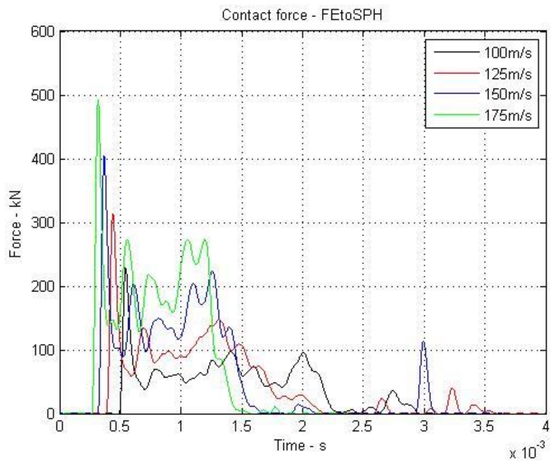

Figure 25: Bird strike: FEtoSPH model – contact forces at different impact velocities.

4.4 Bird strike: Conclusions

Some additional consideration can be done for the bird strike. Considering a constant impact velocity and comparing the contact force of different approaches can be shown that there are only small differences between the Lagrangian and the FEtoSPH approach. Some differences can be shown if the Lagrangian and the SPH model are compared because of the absence of problems concerned with the distortion of the elements. Similar considerations were previously presented for hail impact models.

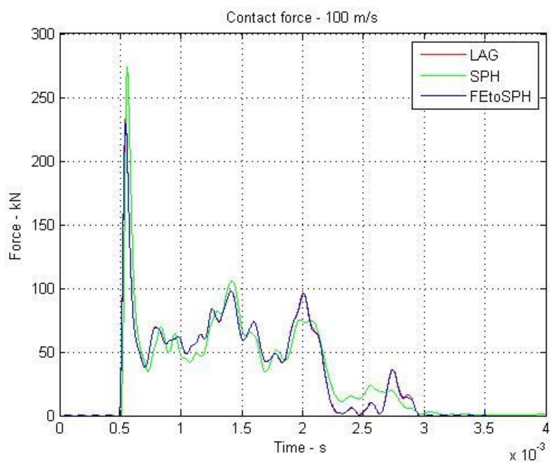

Figure 26: Bird strike: contact forces at 100 m/s.

Considering instead a comparison of the maximum value of the forces as the impact velocity change it can be shown that no great differences between Lagrangian and FEtoSPH occurre as the velocity increase.

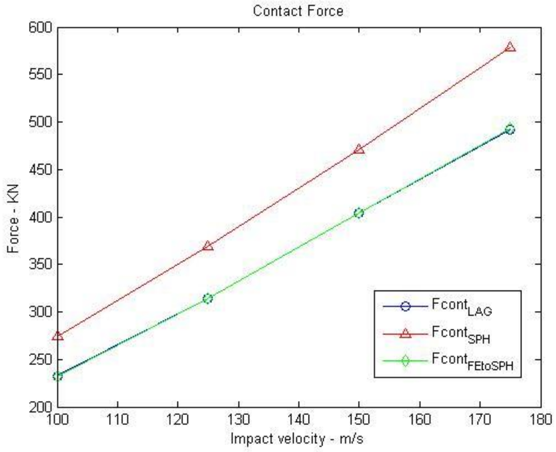

Figure 27: Birdstrike: main value of the contact force.

5 Case study: hail impact against an aeronautical structure

An aircraft, during its life cycle, can occur in hail impact and bird strike. The parts that most of all undergo these events are the leading edges of wings and tail surfaces, the rudders, the engines, and some parts of the fuselage.

In this case study a hail impact against an engine inlet is considered. Lagrangian, SPH and FE to SPH approaches were used to model the hail. Results considering both failure and non-failure material definition were compared for FE to SPH approach. Some final considerations are here presented.

5.1 Case Study: Lagrangian approach

The hail Lagrangian model was a 50.8 mm FE solid model, (Mesh2 previously used). The initial impact velocity was of 180 m/s. The target structure was a part of an engine inlet (Figure 28)

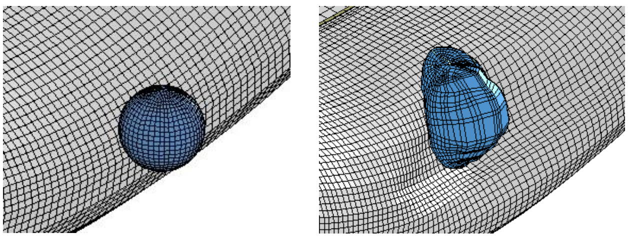

Figure 28: Case study: Lagrangian hail model.

The material adopted for the hail was a *MAT_ISOTROPIC_ELASTIC_FAILURE, whose mechanical characteristics are shown in Table 1. The target structure material was an Aluminium alloy which was numerically modelled using a *MAT_PIECEWISE_LINEAR_PLASTICITY material card. A contact was defined between the hail and the engine inlet. The engine inlet was bounded imposing no rotation and translation to the points in the back part of it.

From results it can be shown that the contact force curve presents a main force value as the hail impacted against the structure ($0.2 \cdot 10^{-3}$ ms) and as started its deformation ($0.4 \cdot 10^{-3}$ ms); than it seems to reach a quite constant value (figure 29).

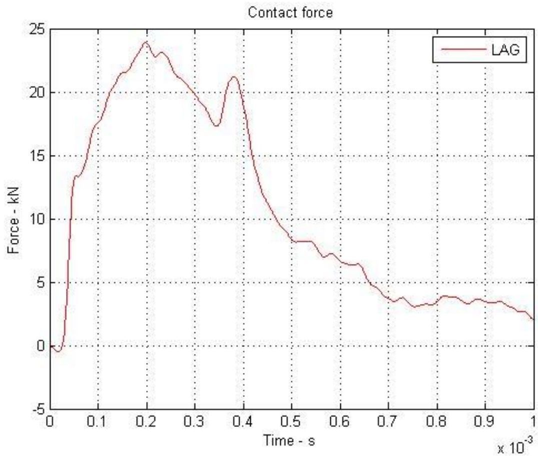

Figure 29: Case study: Lagrangian hail model results.

5.2 Case Study: SPH approach

The SPH model of the hail was obtained considering one SPH particles for each Lagrangian element (Figure 30).

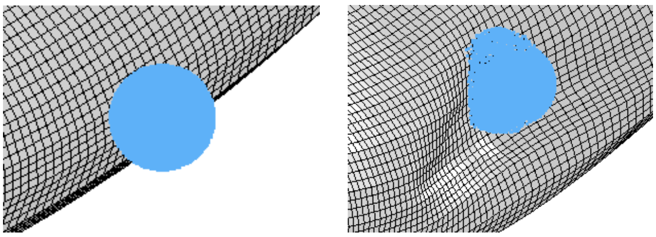

Figure 30: Case study: SPH hail model.

The definitions of contact and of boundary conditions were the same used for the Lagrangian approach.

For the hail material model the `*MAT_ELASTIC_PLASTIC_HYDRO_SPALL` was adopted.

From results it's possible to see that the contact force curve was similar to the one presented for the Lagrangian approach. Some differences occur because of the effect of the mesh-less method related to the non-distortion of the elements (Figure 31). The first relative main value it is close to the Lagrangian model but there is an higher value (about 30 kN) related to the particle flow upon the target structure.

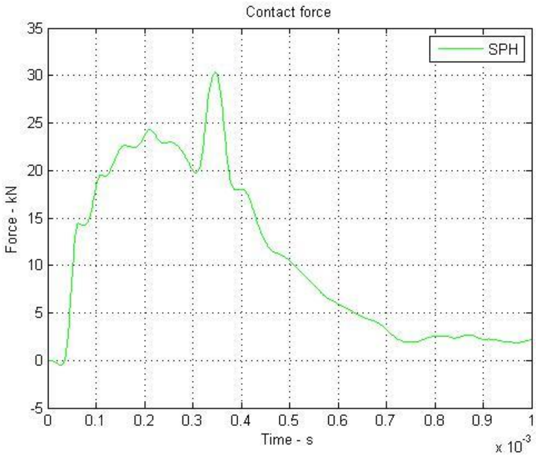

Figure 31: Case study: SPH hail model results

5.3 Case Study: FE to SPH approach

The FEtoSPH model was realised considering the characteristics of the Lagrangian and of the SPH models, both in material, contact and boundary conditions definition. Two different cases were analysed: the presence or not of the Lagrangian material failure.

If the failure mode was not considered, the model seams to behave as the simple Lagrangian one, both in deformation and contact force behaviour (Figure 32)

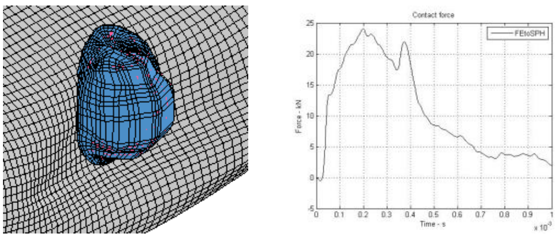

Figure 31: Case study: FEtoSPH hail model results (no failure)

Considering instead the possibility of defining a failure mode, the result seems to be different. From a qualitative point of view the switch between Lagrangian and SPH became evident (Figure 32). The contact force curve presented a higher peak of force at $0.32 \cdot 10^{-3}$ ms.

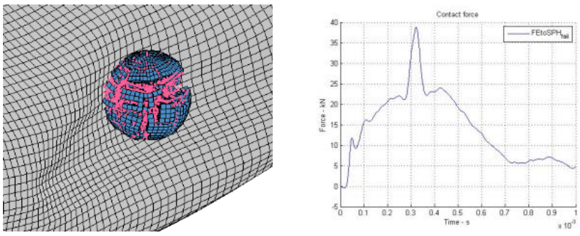

Figure 32: Case study: FEtoSPH hail model results (with failure)

Plotting the Lagrangian part, SPH part and FEtoSPH contact curves it is clear that, approaching the switch from Lagrangian to SPH, the major part of the contact force is related to the SPH part (Figure 33).

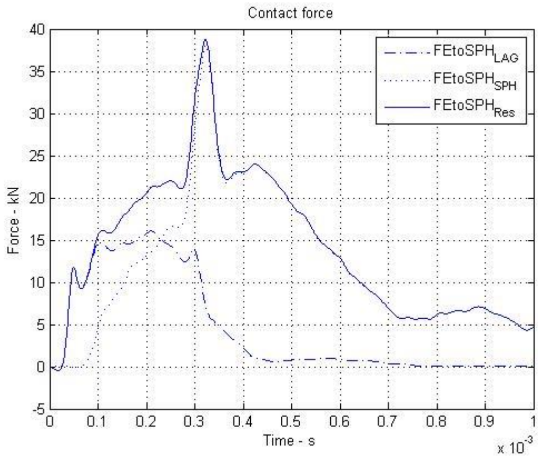

Figure 33: Case study: FEtoSPH hail model comparison of contact force (with failure)

5.4 Case Study: Conclusions

From a comparison of all results it's possible to see that considering the FEtoSPH contact force without the failure mode the curve it's similar to the one of the Lagrangian approach. Some differences occur if it's compared to the SPH force curve. This fact depends on the distribution of SPH particle onto the surface during the contact.

Referring to the FEtoSPH results with the use of a failure criterion more differences are visible because of the switching from

Lagrangian to SPH. The main value of the force is higher than expected because of the higher value of the SPH contact force part (Figure 34).

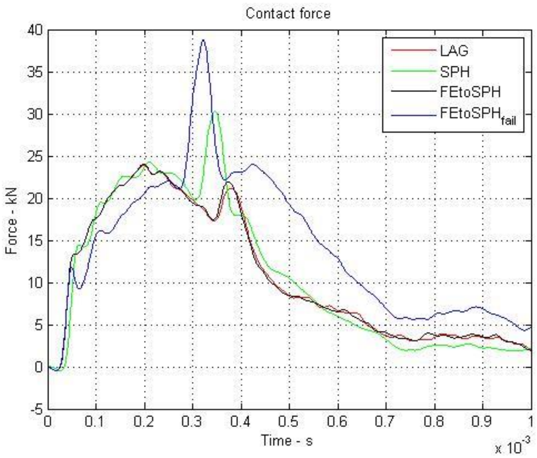

Figure 34: Case study: FEtoSPH hail model comparison of contact force (with failure)

6 Conclusions

In the last years lots of research works have been done on hail impact and bird strike both experimentally and numerically, especially using SPH approach.

In this study the possibility of using the hybrid FEtoSPH approach was investigated.

From the first hail impact analysis a comparison of different mesh discretization and SPH particles distribution was done to evaluate differences and similarities between them in terms of pressure, stress, strain and contact force. The better model for each approach was then applied to the case study.

A bird impact against a steal thick plate was also considered in order to evaluate the effect of impact velocity for each approach: as the velocity increased there was a quite linear increase of the contact force. Considering instead a constant velocity, no great differences were found between the Lagrangian approach and the FEtoSPH one.

As an applicative case of this research work a hail impact against an engine inlet was also studied. From results it was clear that without the use of failure no great differences occurred between Lagrangian and FEtoSPH approach. Instead considering a failure mode, a pick of contact force was evident during the first instants of impact. That's probably because during the switch from Lagrangian to SPH the SPH contact force produced by the particles appeared higher than the one produced by the simple SPH model.

This difference will be investigated in future research work.

References

[1] M. Anghileri, A. Milanese, G. Moretti, L.M. Castelletti, *Preliminary Investigation on the Feasibility of a Bird Surrogate for Full scale Bird Impact Test*, Proceedings of 28th Congress of the International Council of the Aeronautical Sciences (ICAS 2012), Brisbane, Australia, 23-28 Sept. 2012, p. 1-8

[2] M. Anghileri, L.-M.Castelletti, F. Invernizzi, M. Mascheroni, *Birdstrike onto the Composite Intake of a Turbofan Engine*, 5th European Ls-DYNA Users' Conference 2005, Birmingham, UK, 25-26 May 2005, p. 1-10, Paper_5c-21

[3] M.Anghileri, L.-M. Castelletti, A. Milanese, L. Sironi, *Preliminary Investigation on the Residual Strength of Glass-Fibre Panels Subjected to Hail Impact*, Atti del XX Congresso Nazionale AIDAA, Milano, Italia, 29 Giu.-3 Lug. 2009, p. 1-8

[4] H. Kim and K.T. Kedward, *Modeling hail ice impacts and predicting impact damage initiation in composite structures*, AIAA Journal, Vol. 38, No. 7, July 2000

[5] J. D. Tippmann, H. Kim, J. D. Rhymer: *Experimentally Validated Strain Rate Dependent Material Model for Spherical Ice Impact Simulation*, International Journal of Impact Engineering, 57 (2013), p. 43-54

[6] T. Beal, N. Van Dorsselaer, V. Lapoujade, *A contribution to validation of SPH new features*, 9th European LS-DYNA conference, Manchester, UK, June 2013, p. 1-11

[7] R. F. Kulak; C. Bojanowski, *Modeling of Cone Penetration Test Using SPH and MM-ALE Approach*, 8th European LS-DYNA conference, Strasbourg, May 2011, p. 1-10

[8] F. Plassard, J. Mespoulet, P. Hereil, *Hypervelocity impact of aluminium sphere against aluminium plate: experiment and LS-DYNA correlation*, 8th European LS-DYNA conference, Strasbourg, May 2011, p. 1-11

[9] S.A. Zahedi, M. Demiral, A. Roy, V. V. Silberschmidt, *FE/SPH modelling of orthogonal micro-machining of f.c.c. single crystal*, Computational Materials Science, Vol 78, October 2013, p. 104-109

[10] Livermore Software Technology Corporation, *LS-DYNA Keyword User's Manual Vol 1*, Version 971 R6.1.0, August 2012
[11] Livermore Software Technology Corporation, *LS-DYNA Keyword User's Manual Vol 2*, Version 971 R6.1.0, August 2012
[12] Livermore Software Technology Corporation, *LS-DYNA Theory Manual*, March 2006

Contact Author Email Address

mailto: alessia.prato@polimi.it

Copyright Statement