

BIRDSTRIKE: AN INVESTIGATION ON FEASIBLE BIRD MODELS FOR NONLINEAR EXPLICIT FINITE ELEMENT ANALYSES

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KEYWORDS

Birdstrike, Nonlinear Finite Element Analyses, Smoothed Particle Hydrodynamics, Element Free Galerkin

LIST OF ACRONYMS

FE	Finite Element
ALE	Arbitrary Lagrangian Eulerian
SPH	Smoothed Particle Hydrodynamics
DE	Discrete Element
EFG	Element Free Galerkin

ABSTRACT

Regardless to the efforts provided and the progresses achieved, birdstrike still represents a serious menace for flight safety. A birdstrike is characterised by large nonlinear elastic and inelastic deformations, high strain rate and high impact loads transferred in a very short time. The mutual dependency of impact loads and structure response calls for the use of advanced numerical techniques. In particular, nonlinear explicit finite element codes have shown to be a reliable tool to design bird-proof structures. In finite element analyses, the bird model is central. In view of that, various approaches to model the bird are considered referring to normal and oblique impacts onto a rigid target. Differently from other similar works focused only on flesh-and-bones birds, here, also artificial (jelly) birds are considered. The customary Lagrangian, Eulerian and Arbitrary Lagrangian Eulerian approaches are compared with the Smoothed Particle Hydrodynamics, the Discrete Element and the Element Free Galerkin ones. Eventually, findings and guidelines for using of these models are obtained.

1. INTRODUCTION

Regardless to the efforts provided and the progresses achieved, birdstrike still represents a serious menace for flight safety (Ref. 1).

A birdstrike is characterised by large nonlinear elastic and inelastic deformations, high strain rate and high impact loads transferred in a very short time. Indeed, the mutual dependency of impact loads and structure response requires the use of advanced analysis techniques. In view of that, experimental tests are the only way to investigate the event.

Experimental tests are difficult to perform, time-consuming and expensive. Therefore, numerical approaches are usually recommendable.

In particular, nonlinear explicit codes based on Finite Element Method (FEM) are widely diffused to develop high efficiency (i.e. high-strength and low-weight) bird-proof structures. As shown by a number of researches (Ref. 2-6), these codes represent a useful and reliable design tool when validated referring to specific experimental tests. Indeed, due to the complexity of the event, it is difficult to extend the use of a numerical model to impact scenarios different from the one used to validate the model.

When simulating birdstrike, the bird model is central and modern explicit codes commercially available offer several approaches to model a bird. In this work the feasibility of different bird models is investigated referring to normal and oblique bird impacts onto a rigid target. Differently from previous works focused on flesh-and-bones bird (Ref. 3), here, also artificial birds (i.e. cylindrical jelly projectiles) are considered.

The analysis of the results obtained from simulations of birdstrike tests carried out with flesh-and-bones birds is rather complicated.

As pointed out in various works (Ref. 7-9), a birdstrike test carried out with a flesh-and-bones bird is representative only for bird used in the test. Indeed, even small differences among *specimens* (birds) of the same species or family are likely to cause scattering in the acquired data and eventually make complicate the analysis of the results of different shots.

In contrast, the use of artificial bird allows the repeatability of the event. For that and other more practical reasons (Ref. 7), artificial birds are usually preferred to flesh-and-bones bird especially when carrying out birdstrike tests to develop new structures.

Artificial birds allow focusing on the structure response. Furthermore, for artificial (jelly) birds theoretical and semi-empirical formulas exist.

The feasibility of different numerical models of the bird was investigated: Lagrangian FE, Eulerian and Arbitrary Lagrangian Eulerian (ALE), Smoothed Particle Hydrodynamics (SPH), Discrete Element (DE) and Element Free Galerkin (EFG) models.

Initially, the research focused on the *normal* and *oblique* impacts of a jelly bird onto a flat rigid target: numerical results were compared with experimental tests data and analytical formulas (Ref. 9) in terms of impact loads and pressures.

Subsequently, the impact of a flesh-and-bones bird onto a inclined flat rigid target was investigated (Ref. 11).

Eventually, findings and guidelines for further analyses has been obtained.

2. FRAMEWORK

In the framework provided by LSTC LS-Dyna 970 (Ref. 12), six different bird models were investigated.

In effort to compare numerical results with analytical and experimental data, two different impact scenarios were considered.

2.1. Bird modelling

The numerical model of the bird is central in birdstrike analyses when using explicit FE codes. Impact loads and hence the accuracy of the results depend on that.

Indeed, other aspects of the problem should be considered when deciding the model to be used in the analyses.

In effort to highlight advantages and disadvantages of different approaches, six bird models were investigated.

1. Lagrangian Finite Element (FE) model.
2. Eulerian and Arbitrary Lagrangian Eulerian (ALE) model.
3. Smoothed Particle Hydrodynamics (SPH) model.
4. Element Free Galerkin (EFG) model.
5. Discrete Element (DE) model consisting of lumped masses (M), dampers (C), springs (K).
6. Discrete Element (DE) model consisting of independent elements tied together with rigid connectors – *spot-weld* (SW).

2.1.1. Lagrangian FE model

Lagrangian FE bird models are widely used for birdstrike analyses.

When bird deformations are small, this model provides accurate results without requiring excessive computational resources.

Nevertheless, as the simulation proceeds, distortions in the bird mesh cause an error termination of the simulation.

2.1.2. Eulerian and ALE models

Adopting the Eulerian approach, the material flows across a mesh fixed in the space.

Adopting the ALE approach, the material flows across a mesh which, in turn, moves arbitrarily in the space.

In both the cases, in order to capture the full motion of a body, it is necessary to discretise a region in the three-dimensional space larger than the actual dimensions of the body.

In addition, adopting the ALE approach, it is mandatory to carefully manage arbitrary *motion* and *dilatation* of the ALE mesh to avoid material flowing out the mesh.

2.1.3. SPH model

The SPH method was firstly introduced to investigate astrophysical problems. Nevertheless, it was soon found suiting birdstrike features and applied to the development of bird-proof structures (Ref. 5).

SPH is a genuine meshless method and, therefore, is indifferent to the body distortions.

The *tensile instability* (numerical failure due to the lost of neighbourhood among the particles) seems not to be a drawback when considering birdstrike, but, on the contrary, it provides a *convenient* failure criterion (Ref. 5).

Equally spaced grids of particles are required to build an efficient SPH model. Indeed, the particles are the computational framework on which the governing equations are solved (Ref. 12).

The mass of each particle depends on the density of the material and on a reference initial volume evaluated with regard to the so-called *smoothing length* that is probably the most distinguish parameter of the SPH method.

2.1.4. Discrete element models

Two different Discrete Element (DE) models were considered.

DE bird models, consisting of sole nodal masses (NM), were successfully used for the analysis of birdstrike onto complaint structures (Ref. 5).

The drawback of this model is the lack of dissipation mechanism due to the absence of internal connections among the nodal masses. In effort to overcome this drawback, a full masses springs and dampers model was worked out.

The same procedure used for SPH model particles distribution may be used for the discrete masses positioning. The value of the mass was obtained dividing the bird mass by the number of nodal masses.

The properties of the springs and dampers were fixed referring to simple simulations carried out with a single solid element from the Lagrangian FE bird model under tensile and compressive loads. All the discrete elements have the same properties. More sophisticated models with *variable* properties of the discrete elements are beyond the scope of the present work though they are easily achievable.

In effort to overcome the premature analysis termination due to FE mesh distortions, model consisting of solid elements tied together with *breakable rigid connectors* were developed. Before the mesh distortions become troublesome, the connectors fail avoiding premature analysis termination. Like the models previously described, also these models are usually addressed as Discrete Element.

Moving from the FE model, a bird model was developed following this approach and using breakable spot-weld fittings (Ref. 12). In particular, in order to create the spot-weld inner-connection, it was necessary to shrink the solid elements. Shear and normal stresses failure criteria for the spot-welds were calculated with regard to the ultimate values of the bird material and without neglecting the influence of high-frequency noise on the spot-weld failure.

Unfortunately, the self-contact among the solid elements makes this approach time-consuming. Furthermore, when the spot-welds fail, the elements still undergo deformation leading sometimes to unrealistic behaviours of the continuum.

2.1.5. EFG model

EFG method was introduced as the definitive meshless method – though it is not genuinely meshless. It was firstly applied to crack-growing problems, but it is now successfully used also in soft-body impact analyses.

Differently from the customary FE model, the EFG model needs a regular tetrahedral mesh – used for the spatial integration of the fluid properties. Interaction force between the elements are defined by mobile least square method.

The use of this approach for birdstrike is still pioneering – though rather promising.

2.2. FE model of the target

Two different models were developed for the rigid target.

For jelly bird analyses, the target was a 200x200 mm flat surface. The mesh consisted of 2000 5-mm thickness shell elements. The edge length, 20 mm, was meant to obtain a mesh coarser than the one of the bird. The target was modelled as rigid.

Referring to the *normal impact*, the global z-axis coordinates coincided with the bird direction and the origin was fixed in the target centre. The initial velocity was set to 150 m/s.

With regard to the *oblique impact*, the target was rotated of 30 deg angle around the global y-axis coordinates. The initial velocity was set to 150 m/s.

For flesh-and-bones bird analyses, the actual geometry of the target was used and a detailed mesh was built (Ref. 5). The initial velocity was set to 139 m/s (i.e. the impact velocity measured during the tests).

2.3. Impact scenarios

Two different impact scenarios were considered: *normal impact* and *oblique impact*.

2.3.1. Normal impact

The first scenario considered, was the impact of a bird straight against a rigid target along the main axis of the bird (supposed to be the direction of bird flight).

2.3.2. Oblique impact

The second scenario considered was the impact of a bird against a rigid target inclined of 30 deg angle with respect to the direction of the bird flight.

Experimental data and analytical solutions for jelly birds are documented in literature for the described impact scenarios (Ref. 9).

Furthermore, concerning oblique impacts, data from tests carried out to characterise the impact behaviour of a flesh-and-bones bird were available (Ref. 11).

3. ARTIFICIAL BIRD

In birdstrike numerical simulations, the bird is customarily modelled as a cylindrical projectile with the mechanical properties of the water.

Since a bird is primarily made of water and the impact velocities are rather high, this model is commonly accepted – though not free from criticisms (Ref. 5, 9).

On the other hand, this model provides results close to the ones obtained in tests carried out using artificial birds (i.e. cylindrical jelly projectiles). Furthermore, for this bird model analytical solutions and semi-empirical formulas exist. For all these reasons, initially, the impact of a cylindrical water bullet bird was considered.

3.1. Forces and pressure

Accordingly with the theory (Ref. 10), the impact between a soft body and a rigid target consists of four characteristic phases (shown in Fig. 1): the (initial) shock phase, the release phase, the steady-flow phase and the final phase.

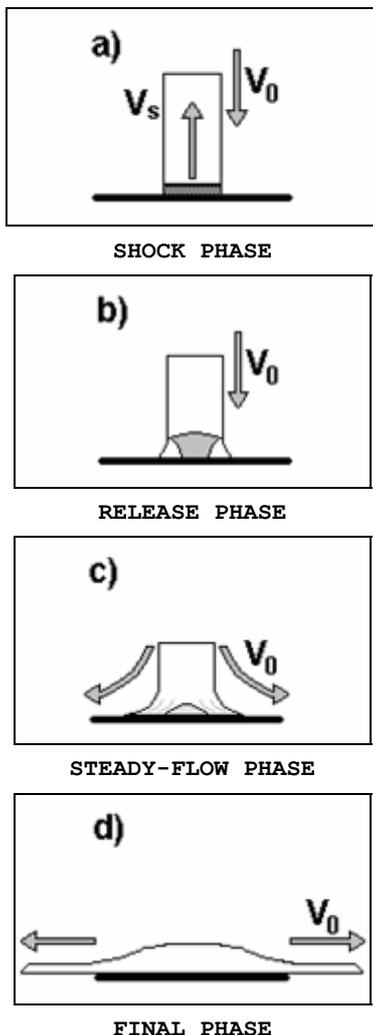


Figure 1: Characteristic phases of a soft-body impact onto a rigid flat target (Ref. 9).

These phases are present in normal impact as well as in oblique impact when considering only the normal component of the momentum to evaluate the force transmitted to the target.

The capability of a numerical model to represent these phases can be evaluated in terms of forces and pressures in agreement with the water jet theory (Ref. 9).

Referring to an impact with an angle ϑ , three force values are usually considered: the impulse transmitted to the rigid target in the first impact phase, F_{imp} , the peak force reached during the impact, F_p , and the mean force, F_m .

Impulse force, F_{imp} . The impulse force is the Hugoniot's pressure multiplied by the projectile base area, A . The initial velocity of the bird U_0 and the sound speed in the material are used as an approximation for the velocity of shocked particles U_p and shock velocity in the material U_s , respectively.

$$F_{imp} = \rho U_0 C A, \quad (1)$$

Peak force, F_p . The peak force is obtained through an empirical formula developed for cylindrical projectiles which depends on the projectile dimensions.

$$F_p = \frac{2mv^2 \sin \vartheta}{L + D \cot \vartheta} \quad (2)$$

Mean force, F_m . The mean force is defined as the ratio between initial momentum and time needed by the projectile to run along its own length:

$$F_m = \frac{mv^2}{l} \quad (3)$$

3.2. Numerical models

As pointed out before, the numerical model of the bird is central in a birdstrike analysis when using explicit FE codes.

3.2.1. Geometry

A number of research works on birdstrike deal with the relationships between dimensions and masses of a *standardised* bird-surrogate (Ref. 5-7). The mass of the bird is prescribed by the requirements for the certification of the structure. Different shapes have been suggested depending on the event under investigation (Ref. 7, 8). For the ratio between length and diameter the value of 2 is usually recommended because it brings results close to the experimental measures and dimensions similar to the ones of actual birds used in the tests.

In this work, in effort to compare numerical, analytical and semi-empirical results the bird is modelled as a jelly cylinder with a length-diameter ratio equals to 2 and mechanical properties of the water (Ref. 10).

3.2.2. Numerical models

Following the guidelines provided before, six different bird models were realised.

In particular, for all the models the characteristic length was fixed as a trade-off between accuracy and CPU-time.

FE model. The FE mesh consisted 7040 of eight-node solid elements.

In order to investigate the influence of the bird shape, two different meshes were built: a smooth one and a faceted one.

Eulerian and ALE model. As mentioned before, adopting Eulerian and ALE approaches, it is necessary to discretise wide regions of the space. For the event under investigation, although the number of elements defined for bird was the same of the Lagrangian model, the overall Eulerian and the ALE models consisted respectively of 282123 and 85176 elements.

SPH model. The SPH bird model consisted of 7040 equally spaced particles. The distance among the particles was set to 6.875 mm. Different SPH particles lay-outs were investigated, but eventually the customary cubic frame was demonstrated to be the most convenient trade-off among accuracy, required CPU-time and model stability.

DE-MCK model. Masses layout was obtained from the SPH model. Springs and dampers were added to form an ordered cubic frame. Eventually, 50385 elements (masses, springs and dampers) were defined.

DE-SW model. The DE-SW model consisted of 7040 solid elements, the same of the Lagrangian model, and 7913 spot-welds. Working out the model is not trivial. A short code was implemented to build the elements and then to define the rigid connector among them.

EFG model. The EFG elements are similar to tetra elements in the geometry but are rather different in the definitions – as they only represent the *shadow* domain for the nodes used to construct the approximation (Ref. 12).

In view of that, the reference dimension of the EFG elements was taken greater than the one of the FE model, but small enough to avoid premature analysis termination due to excessive EFG mesh distortions.

Eventually, 4726 EFG tetra elements, regular in shape, were defined.

3.2.3. Material models

For the bird model, the constitutive law and mechanical properties typical in birdstrike analyses were used (Ref. 10).

Moving from the idea that the bird is an isotropic Newtonian fluid with mechanical properties close to the one of the water, the elastic-plastic hydrodynamic material model was adopted. In that, the deviatoric components of the stresses are directly related with deformations and the isotropic components are obtained by a polynomial equation of state.

As a convenient alternative (Ref. 5), a material model featuring only the isotropic components of the stress tensor was also considered. For this material model a *numerical* viscosity activates deviatoric components of the stresses that depend on the strain rate.

Grüneisen's equation of state (Ref. 12) was associated to this material model.

3.3. Results obtained

The simulations carried out in this part of the research focused, in particular, on the impact forces.

The pressure distribution inside the bird during the shock release phase and the required CPU-time were also considered.

3.3.1. Impact forces (Fig. 2)

Three values of the impact forces were considered: *impulse*, *peak* and *mean* forces.

An approximate time profile for the impact forces was obtained scaling the force by the theoretical value of the impulse force, based on dimensional and mass characteristics of the birds (Ref. 9).

The comparison with the analytical results was meant to be representative of the model accuracy. In view of that, the curves obtained were not filtered.

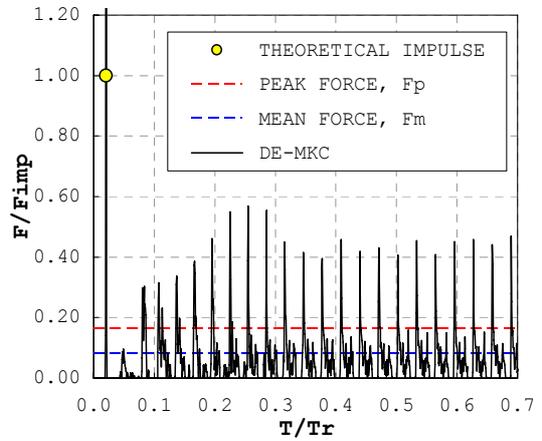
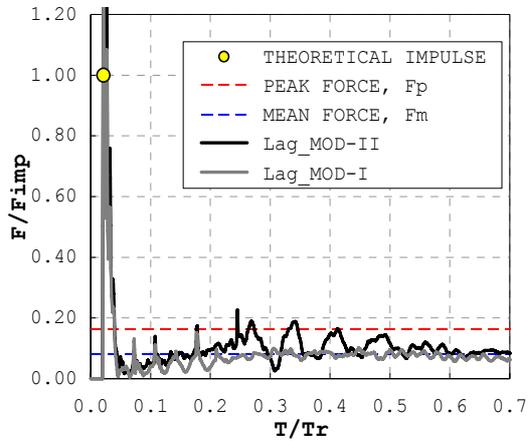
FE model. Regardless to the high frequency noise due to the mesh coarseness and to the explicit time integration scheme, the force profile obtained using the FE model is rather close to the analytical one – especially when adopting the material model without deviatoric stresses and Grüneisen's equation of state.

The peak value is far, but the mean value in steady flow phase is close to the analytical one – and this is important because the first peak can be neglected when it is not such to cause the failure of the structure (Ref. 9).

Furthermore, being affected by numerical noise, the peak value can be easily reduced simply introducing a damping on the contact forces or building a finer mesh.

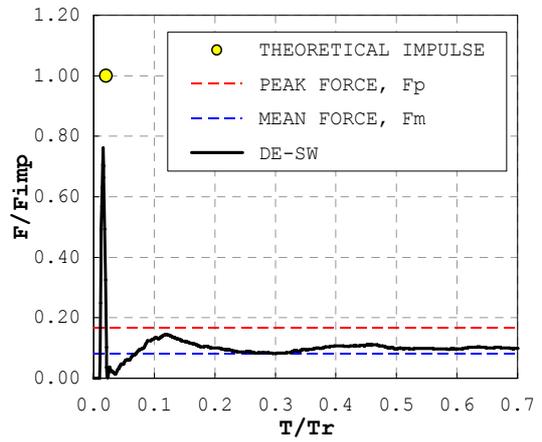
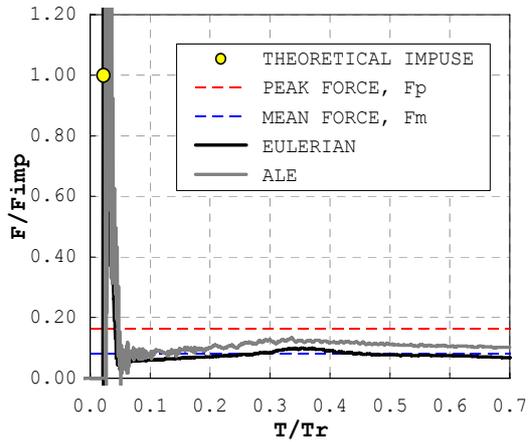
Eulerian and ALE model. When adopting Eulerian or ALE approaches, the peak value of the impact force is higher than the analytical one.

Lagrangian/Eulerian or Lagrangian/ALE coupling is rather troublesome. When considering compliant structures, the interaction forces are usually underestimated.



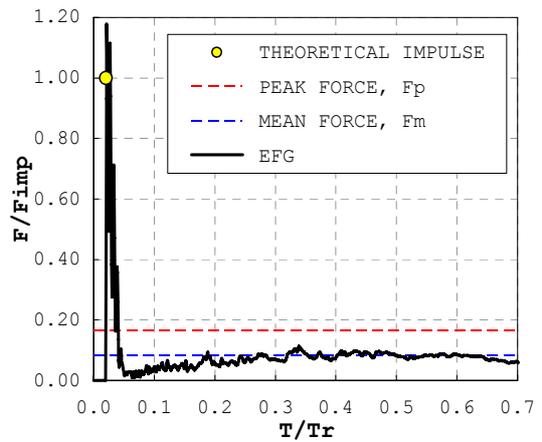
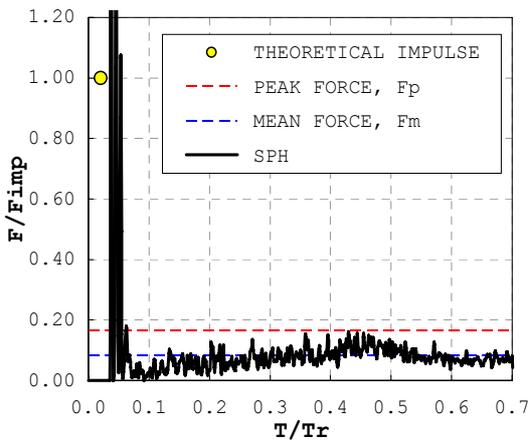
LAGRANGIAN FE MODEL

DE - MASS-DAMPERS-SPRINGS



EULERIAN AND ALE MODEL

DE - RIGID CONNECTORS



SPH MODEL

EFG MODEL

Figure 2 (cont'ed): Numerical results vs. analytical solutions.

Figure 2 (cont'ed): Numerical results vs. analytical solutions.

On the other side, with regard to the event considered, as the target was rigid high frequency noise brought to high peak value of the forces. In that, the absence of hourglass controls had an influence.

The mean value of the impact force was not far from the analytical one.

SPH model. The peak value of the impact force obtained with the SPH model was higher than the analytical one.

Something similar was noticed for Eulerian and ALE models, but the underlying causes are different. Also in this case, the higher value of the peak force is due to coupling problems, but, in this case, the problems can be easily solved acting on the contact interface definition (i.e. changing the method to enforce the contact or defining a nonzero contact viscous damping coefficient).

The mean value of the impact force in the steady flow phase was not far from the analytical one.

DE-MKC model. Among the models considered, DE-MKC model was the one that provided the force profile less close to the theory.

As it was impossible to introduce an effective internal energy dissipation mechanism, eventually a saw-teeth profile was obtained for the impact force. Each one of the peaks corresponds to one layer of nodal masses.

Nevertheless, the results obtained were not deemed totally negative. The behaviour observed can be easily avoided giving *uneven* distributions of *uneven* masses. Furthermore, similar models have shown to be suitable for birdstrike onto compliant structures – as the mean force is not far from the analytical value and it is alien to mesh distortions problems.

DE-SW model. Using the DE-SW model, the peak force is lower than the analytical one, though the mean force is close to the analytical value.

The low value of the peak force is due both to the premature failure of the rigid connectors and the lack of internal interaction.

The only interaction among the elements was a contact interface – that eventually resulted rather ineffective because of the elements distortion.

The efforts provided to increase the value of the peak force were eventually unsuccessful.

EFG model. The EFG model provided encouraging results.

The impact force profile is smooth, the peak value and the mean value are not far from the analytical one.

In Table 1 the relative error on the impulse, peak and mean forces are listed with regard to the models investigated.

BIRD MODEL	F_{IMP}	F_P	F_M
FE model (mat_I)	24 %	-6 %	-4 %
FE model (mat_II)	53 %	12 %	1 %
Eulerian model	137 %	-38 %	0 %
ALE model	179 %	-18 %	40 %
SPH model	132 %	-2 %	40 %
DE-MCK model	178 %	---	---
DE-SW model	-23 %	-26 %	1 %
EFG model	17 %	-29 %	0 %

Table 1: Relative errors on impact forces referring to theoretical values.

As a concluding remark, it should be noted that, for all the models considered, it was possible to obtain a time profile of the impact force close *enough* to the theory. That shows the feasibility of the models with regard to impact forces.

On the other side, when investigating the consequences of birdstrike onto compliant structures, the impact pressure is even more relevant than the forces. Indeed, the first applications of explicit FE codes to the analysis of birdstrike aimed to obtain a more accurate description of the impact pressure during the event (Ref. 10).

The analysis of the impact pressure is among the future works of the present research.

3.3.2. Internal pressure distribution (Fig. 3)

Another aspect of the event, here considered to investigate the feasibility of the numerical bird model, was the internal pressure distribution in shock release phase.

The development of pressure shock and releases waves into the material leads to the growth of strains and to a radial acceleration of the impacted material.

In Fig 3 the pressure fringes plots for the six bird models are shown. Red fringes correspond to a pressure of 250 MPa.

The shock wave is visualised like an uniform pressure variation growing from the bottom of the jelly projectile. The birth of release waves in the material appears like region with a lower pressure.

FE model. The pressure wave time profile obtained with the FE model is qualitatively close to the theory.

It is possible to distinguish the four phases and the value of the pressure in the shock release phase is same order of the analytical one.

Eulerian and ALE model. The Eulerian and the ALE models provide a rather similar description of the pressure evolution: in both the cases, it is possible to distinguish the four phases of the impact. Indeed, adopting the ALE approach, as the mesh *flows* with the bird, the description is more accurate when the mesh is coarse.

SPH model. As a general remark, it is important to mention that, when using SPH models, it is rather complicate to trace the pressure (or the stress) waves in the material. The SPH method is basically founded on an interpolation scheme used to find an approximate solution for quantities of interest. In view of that, it is easy to understand the reason why it is difficult to trace the pressure fringes, at least, graphically.

DE-MKC model. For the DE-MKC, it was impossible to create a fringe of the pressure inside the bird. Nevertheless, in order to give an idea of the features of this model, a frame from the simulation carried out with this model (same instant of the other models) is shown in Fig. 8.

DE-SW model. DE-SW does not present a neat visualisation, even if it is anyway possible to understand the development of pressure waves. Due to the absence of continuum material DE-MKC can not reproduce this behaviour.

EFG model. The EFG like the SPH is a meshless method. Differently from the SPH, the EFG model allows to create a fringe (on the shadow elements) of the pressure.

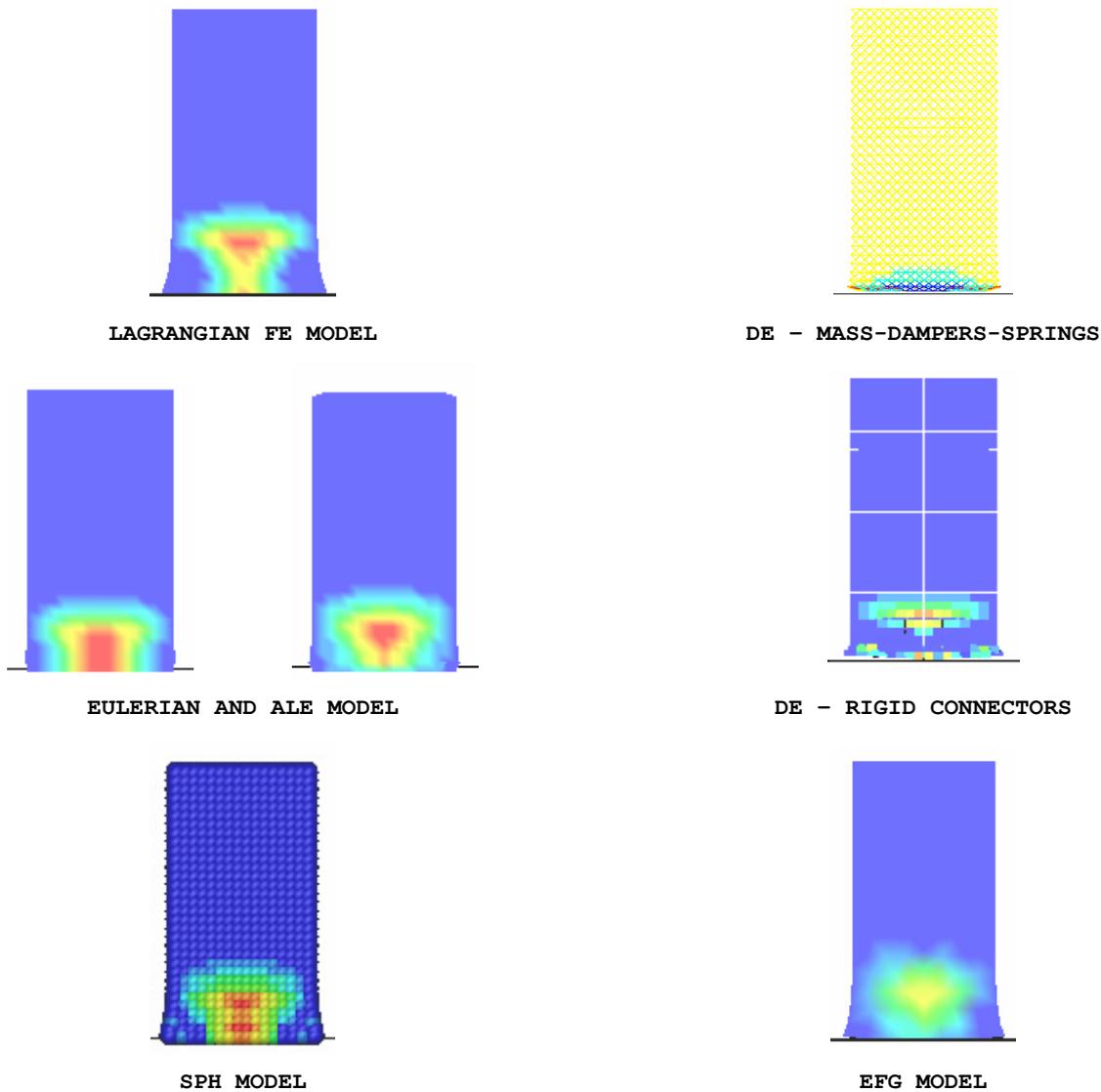


Figure 3 (continued): Pressure fringe during the shock release phase.

Figure 3 (continued): Pressure fringe during the shock release phase.

Using the EFG model, it is possible to distinguish the four phases of the event and the pressure during the shock release phase is close to the value analytically predicted.

3.3.3. Required CPU-time (Table 2)

Required CPU time is an important parameter when considering birdstrike analyses.

In effort to develop new bird-proof structures, it is necessary to carried out several simulations. In view of that, the bird model should not affect the minimum stable time-step – anytime: neither at the beginning nor during the simulation.

The CPU-time required adopting the bird model under investigation is shown in Table 2.

In particular, to make the results independent from the machine used for the simulation, twelve simulations for each model were carried out and the mean CPU-time was scaled on the CPU-time required for the Lagrangian FE model.

In view of the results shown in Fig. 4, without other concerns but the CPU-time, it is immediate to conclude that the use of DE-MKC model is recommendable. Of course, accuracy and mesh distortions suggest otherwise.

In particular, the overall results obtained for the SPH or the EFG model (description of the event, correlation with the theory and required CPU-time) are encouraging and, at the same time, challenging.

BIRD MODEL	<i>Jelly bird</i>	<i>Real bird</i>
FE model (mat_I)	1.0	1.0
FE model (mat_II)	0.8	0.5
Eulerian model	23.2	3.3
ALE model	13.4	2.7
SPH model	0.9	0.6
DE-MCK model	0.8	0.4
DE-SW model	50.7	3.5
EFG model	1.8	0.9

Table 2: CPU-time required for the simulations referred to the Lagrangian FE model.

4. FLESH-AND-BONES BIRD

The bird surrogates are used to develop bird-proof structures, but for the certification flesh-and-bones birds are required.

The analytical results considered before also fit experimental data. Nevertheless, birdstrike carried out to develop reliable numerical model are considered (Ref. 11).

For these tests a time profile of the impact force is available.

4.1. Numerical bird model

In order to obtain a closer correlation with experimental tests data, it was necessary to modify the numerical model considering the bird geometry as well as the target.

4.1.1. Impact scenario

The impact scenario in the tests is the same as the one previously indicated as oblique impact.

The bird impacted a massive flat target rotated of 30 deg angle with regard to the bird direction. Impact velocity is set to 139 m/s.

4.1.2. Bird modelling

In order to obtain numerical results close to experimental data, a rugby-ball shape and specific mechanical properties (Ref. 5) were chosen to represent the bird.

4.1.3. The target

The target model was modified to reproduce the actual test facility. The force transducers used to measure the impact force were modelled in detail.

4.2. Numerical-experimental correlation

The correlation between numerical results and experimental data measures the attitude of the different bird models to reproduce the event.

In particular, the description of the event, the time profile of the impact force and the required CPU time are considered.

4.2.1. Description of the event (Fig. 4)

The numerical results obtained with the different models were qualitatively evaluated referring to the high-speed movie.

FE model. The FE model provided a reasonable description of the first instants of the event.

The representation worsened as the deformations became relevant – though the simulations reached a normal termination.

Eulerian and ALE model. The behaviour of Eulerian and ALE bird models observed during the simulation was close to that of a jelly bird.

When adopting the Eulerian approach, the bird *trembles* while crossing the Eulerian mesh. When adopting the ALE approach, the mesh at the end of the simulation was so stretched that doubts on the accuracy of the solution seem reasonable.

SPH model. The description of the event using the SPH bird model is commonsense.

The scattering of the SPH particles is close to the one filmed during the tests using high-speed camera.

DE model. When using the discrete element models (either the MKC or the SW model), the impact behaviour of the bird was fragmented and unrealistic. Neither a damping at the interface was sufficient to improve it.

EFG model. The impact behaviour of the EFG model is similar to the one of a tetra elements model – though it is not. The behaviour of the EFG bird is closer to the one of a FE model than to the one of a SPH model. Differently from the SPH model, there is not particles scattering. On the other hand, the EFG mesh distortions are smaller than the one of a tetra-elements model and the EFG elements are not involved in the contact interface.

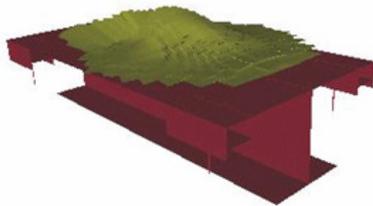
4.2.2. Impact force time profile (Fig. 5)

The impact force time profile obtained in the tests was used to evaluate the reliability of the bird models worked out.

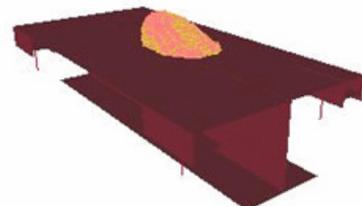
FE model. The FE model provided a good numerical-experimental correlation.

Eulerian and ALE model. Also Eulerian and ALE model eventually provided a satisfactory numerical-experimental correlation. This outcome was the result of an enhancement in the definition of fluid-structure interaction.

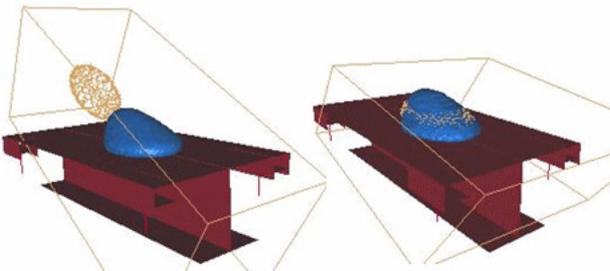
SPH model. The FE model provided a good numerical-experimental correlation. The peak value is slightly higher than the experimental one and occurs earlier, but improvements are easily achievable modifying the contact interface definition.



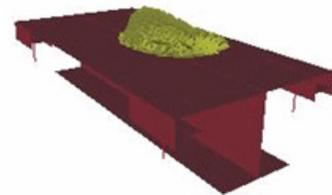
LAGRANGIAN FE MODEL



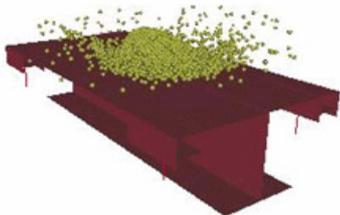
DE - MASS-DAMPERS-SPRINGS



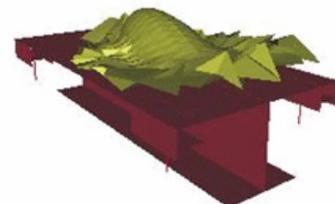
EULERIAN AND ALE MODEL



DE - RIGID CONNECTORS



SPH MODEL



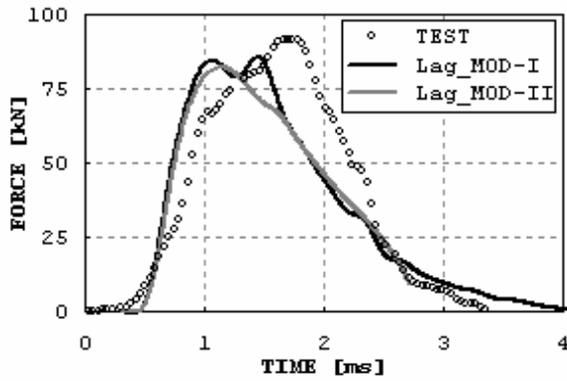
EFG MODEL

Figure 4 (cont'ed): Birdstrike using a flesh-and-bone bird.

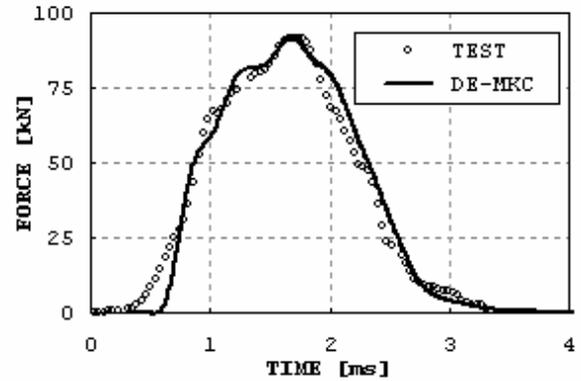
Figure 4 (cont'ed): Birdstrike using a flesh-and-bone bird.

DE model. Surprisingly, the DE models provided good numerical-experimental correlations. In particular, the DE-MCK model guarantees the closest numerical-experimental correlation – despite the lack of dissipation mechanisms and the poor description of the event provided.

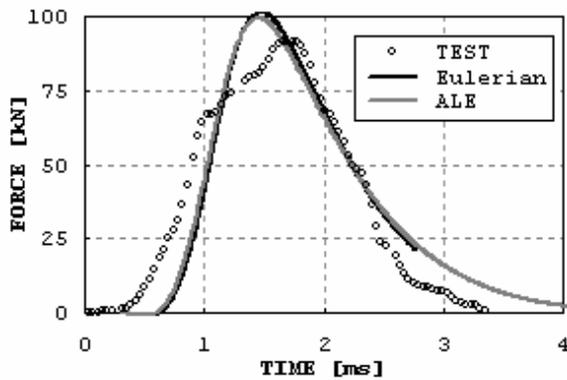
EFG model. Using the EFG model, a close numerical-experimental correlation was obtained. In particular, the shape of the curve is similar to the experimental one – though the peak value is smaller.



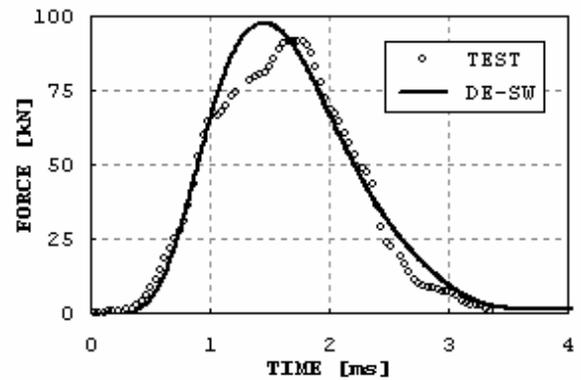
LAGRANGIAN FE MODEL



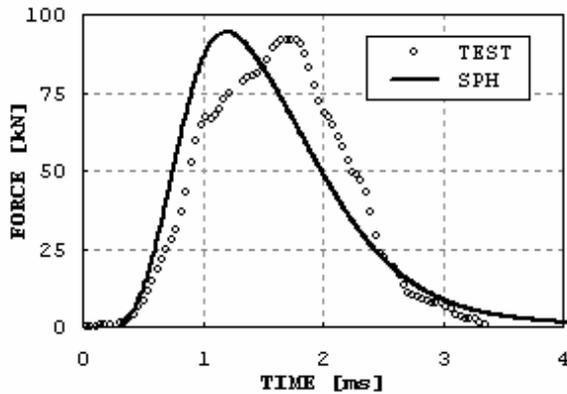
DE - MASS-DAMPERS-SPRINGS



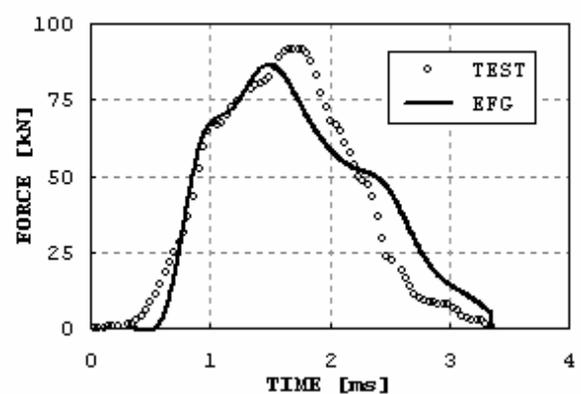
EULERIAN AND ALE MODEL



DE - RIGID CONNECTORS



SPH MODEL



EFG MODEL

Figure 5 (cont'ed): Numerical-experimental correlation for flesh-and-bone birdstrike.

Figure 5 (cont'ed): Numerical-experimental correlation for flesh-and-bone birdstrike.

4.2.3. Required CPU-time (Table 1)

As mentioned before, required CPU time is an important parameter when considering birdstrike analyses.

In Table 2, are also reported CPU-times required when adopting the bird model under investigation is shown to simulate flesh-and-bones birdstrike.

5. REMARKS

Concluding, some general remarks can be drawn in view of the results obtained.

FE model. When the deformations are small, FE models are reliable and required CPU-time are reasonable.

In view of that, Lagrangian FE approach is suitable in the early instants of the impact for the analysis of birdstrike onto brittle structures.

In order to avoid premature termination of the simulations, failure criteria for the bird can be defined (Ref. 5).

Eulerian and ALE model. When the fluid-structure *coupling* is properly set, Eulerian and ALE models lead to rather accurate results. Unfortunately, these models call for massive computational resources.

The high time-per-cycles and the large number of elements necessary to guarantee a satisfactory degree of accuracy make these approaches rather time-consuming.

Furthermore, adopting ALE approach, ALE mesh deformations must keep in count. In effort to avoid loss in accuracy a fine mesh is required.

The bird impact behaviour adopting Eulerian and ALE approaches is, in general, smoother than the ones observed for the other models considered.

SPH model. The SPH model led to accurate results and, at the same time, was also the most efficient among the bird model investigated.

The SPH model realised provided good results for both the jelly and the flesh-and-bones bird. It provided a commonsense descriptions of the event without suffer for large deformations.

Tensile instability that represents a severe limitation to the application of this approach to other continuum mechanic problems, when considering birdstrike becomes a convenient failure criterion (Ref. 5).

DE-MCK model. The masses-dampers-and-springs DE model is computationally rather efficient, but the results obtained for the flesh-and-bones bird oblique impact fit the experimental data.

The first limitation to the use of this approach consists of the use of equivalent elements that provide only forces.

DE-SW model. The DE model consisting of solid elements and breakable spot-welds provided satisfactory results but, differently from the other DE model, it is rather time-consuming.

When the bird impacts the target, also because of the numerical noise at the contact interface, the impact force suddenly reaches the spot-welds ultimate force. The spot-welds fail and that partly explains the low force peak observed for this bird model.

After the spot-welds failure, the solid elements are free to deform. The number of active contacts grow and so does the time-per-cycle.

In addition, the large solid elements deformations cause inaccuracy in contact detection. As a consequence, the internal energy dissipation mechanism is diminished.

EFG model. The EFG model provided a close numerical experimental correlation.

On the other side, application of the EFG method to birdstrike analysis are pioneering and EFG models are still rather difficult to tune.

A number of parameters can be defined in a wide range of values producing a number of unpredictable effects on the simulation.

Nevertheless, the method is promising and the results definitively encouraging.

CONCLUSIONS

A birdstrike is characterised by large nonlinear elastic and inelastic deformations, high strain rate and high impact loads transferred in a very short time.

The mutual dependency of impact loads and structure response calls for the use of advanced numerical techniques. In particular, nonlinear explicit finite element codes have shown to be a reliable tool to design bird-proof structures.

In finite element analyses, the bird model is central. In view of that, various approaches to model the bird are considered referring to normal and oblique bird impacts onto a rigid target.

Differently from other similar works focused only on flesh-and-bones birds, here, also artificial (jelly) birds are considered.

The customary Lagrangian, Eulerian and Arbitrary Lagrangian Eulerian approaches were compared with the Smoothed Particle Hydrodynamics, the Discrete Element and the Element Free Galerkin ones.

The models developed eventually provided satisfactory results with regard to both jelly and flesh-and-bones birds.

Obviously, different models provided different impact behaviours of the bird and different degrees of accuracy. Findings and guidelines for the use of the models investigated are obtained.

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REFERENCES

- 1 J. Thorpe: "*Fatalities and destroyed civil aircraft due to bird strike, 1912-2002*". International Bird Strike Committee, 26th Meeting. Warsaw, Poland. May 2003.
- 2 L.-M.L. Castelletti, and M. Anghileri: "Multiple birdstrike analysis: A survey of feasible techniques". Proc. 30th European Rotorcraft Forum, September 2004. Marseille, France.
- 3 M. Anghileri, L.-M. L. Castelletti, L. Lanzi, and F. Mentuccia: "Composite materials for bird-strike analysis using explicit finite element commercial codes". Structures Under Shock and Impact VII, SUSI 2004, International Conference. Crete, Greece. March 2004.
- 4 L.-M. L. Castelletti, and M. Anghileri: "Multiple birdstrike analysis: a survey of feasible techniques" 30th European Rotorcraft forum. Marseilles, France. Sept 2004.
- 5 M. Anghileri, L.-M. L. Castelletti and V. Mazza: "Birdstrike: approaches to the analysis of impacts with penetration". International Conference on Impact Loading of Lightweight Structures, WIT Transactions on Engineering Sciences, Vol 49. May 2005.
- 6 M. Anghileri, L.-M. L. Castelletti, F. Invernizzi, e M. Mascheroni, "Birdstrike onto the composite intake of a turbofan engine", 5th European LS-Dyna Users Conference, Birmingham, UK, May 2005.
- 7 R. Budgey: "The development of a substitute artificial bird by the international birdstrike research group for use in aircraft component testing". 25th Meeting International Bird Strike Committee. Amsterdam, Nederland, 17-21 April 2000.
- 8 S. C. McCallum and C. Constantinou: "The influence of bird-shape in bird-strike analysis" 5th European LS-Dyna Users Conference, Birmingham, UK, May 2005.
- 9 J. P. Barber, H. R. Taylor and J. S. Wilbeck: "*Bird impact forces and pressures on rigid and compliant targets*". Dayton University, Ohio. Final report. Apr-Dec 1976.
- 10 R. A. Brockman, T. W. Held: "*Explicit finite element method for transparency impact analysis*". University of Dayton Research Institute Report WL-TR-91-3006, 1991.
- 11 M. Anghileri, G. Sala: "*Theoretical assessment, numerical simulation and comparison with tests of birdstrike on deformable structures*". In: Proceedings of the 20th ICAS Congress. vol. 1. 1996. pp. 665-674.
- 12 J. O. Hallquist: "*LS-DYNA Theory Manual*", Livermore Software Technology Corporation, March 2006.