

BIRDSTRIKE: THE INFLUENCE OF THE BIRD MODELLING ON THE SLICING FORCES

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ABSTRACT

Birdstrike is one of the most dangerous threats for flight safety. The consequences of a birdstrike can be dramatic and, therefore, the aircraft structure have to be certified for a proven level of bird impact resistance before being put into operational service. Since the experimental tests are expensive and troublesome, numerical techniques are usually used to develop high-efficiency bird-proof structures. In that, explicit nonlinear finite element codes have shown to be a rather convenient design tool. In this research, the influence of the bird modelling on slicing forces has been investigated with regard to different numerical bird models developed and validated referring to straight impact birdstrike tests. Two benchmark tests were eventually considered. Initially, a simple test case, the impact of a bird with a single fan blade, was considered in order to focus on the advantage and disadvantages of the different bird models. Hence, a test case consisting of the impact of two birds onto a complete rotating fan was considered. Event insights and guidelines for further investigation were eventually drawn.

KEYWORDS

Birdstrike, Fan blade, Slicing forces, Nonlinear Explicit FE Analysis, SPH, ALE approach

ACRONYMS

ALE Arbitrary Lagrangian Eulerian
DEM Discrete Element Method
FEM Finite Element Method
SPH Smoothed Particle Hydrodynamic

INTRODUCTION

Since the early beginning of aviation history, birdstrike has been one of the most dangerous threats for the aircraft (Ref. 1).

Birdstrike causes every year damages for more than eighty millions US-dollars – though most of times it has not tragic consequences (Ref. 1, 2).

A birdstrike is characterised by loads with high intensity and short duration (Ref. 3). The materials undergo high strain rates, large deformations and inelastic strains. Moreover, a deep interaction exists between the impact loads and the response of the structure. These features of the event make the analysis of a bird strike extremely troublesome.

In the early seventies, when birdstrike became an actual problem, the (first) approach adopted to develop bird-proof structure consisted of *trial-and-error procedures* based on massive full-scale bird-strike tests – which resulted in being extremely expensive and not particularly effective neither when successful.

Afterwards, specific test programmes were carried out to acquire relevant knowledge about the event (Ref. 3).

The data collected were organised in database and used to develop and validate *analytical* (Figure 1, Ref. 3) and *numerical* (Ref. 4, 5) tools which significantly reduced the number of tests.

One of the mentioned numerical tools named MAGNA, in particular, was actually used for over a decade to improve the design of existing aircraft and to develop new bird-proof structures (Ref. 4, 5) – though strongly reliant on experimental evidences and not particularly accurate.

Indeed, only at the end of eighties, when the nonlinear explicit FE codes were applied to the study of the event (Figure 2), it became possible to analyse the event with a degree of accuracy (Ref. 6).

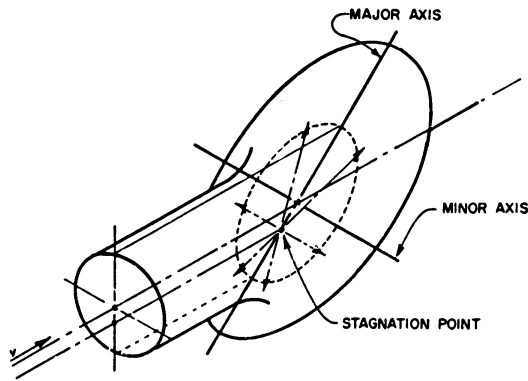


Figure 1. Analytical model for birdstrike (Ref. 3).

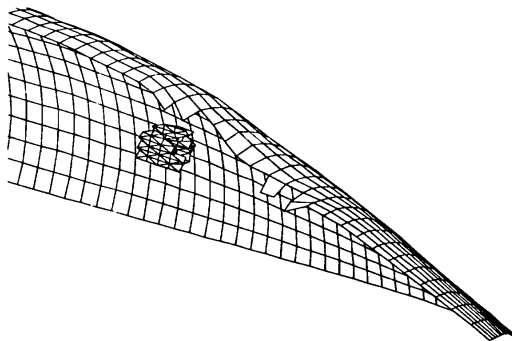


Figure 2. Bird-strike analysis using a nonlinear explicit FE code named X3D (Ref. 6).

Nowadays, computer modelling is extensively and successfully used to develop high efficiency (i.e. lightweight high-resistance) bird-proof structures (Ref. 6, 9-14, 16-18).

Full-scale bird-strike tests are still carried out (mostly) for the validation of the numerical model and for the certification of the subcomponents of the aircraft.

One of the most controversial themes when considering a bird-strike test is the meaningfulness of the test itself (Ref. 7).

For the certification tests, the use of real birds is mandatory. Nevertheless, the use of real birds in aircraft component testing is not ideal as the tests are not uniform.

Indeed, when developing new structures is customary the use of artificial bird/bullets.

Advantages coming from the use of artificial bird include: convenience, cost, reproducible results and a reduced need to suppress birds for the tests.

A number of different shapes were suggested for the artificial bird (Ref. 7) – which permit the most appropriate values of mass, density, diameter and length to be used together in the same projectile.

It has been long recognised that, depending on the testing situations, it is recommendable to use an accurate value for the *length* and for the *diameter* of the artificial bird.

When the impact loads in time are important (as in a high velocity straight impact against a panel) the *length* of the bird/projectile is crucial.

When investigating the slicing effect of rotating airfoils, the *diameter* of the bird/projectile is crucial. In that, the length is irrelevant so long as a slice of the required mass is achieved and therefore an accurate diameter is most important.

The toughness (i.e. the resistance to *splitting*) and the internal density variation, as well, have an influence when the slicing effect of an engine fan blade of sharp leading edge.

Remarks on (advantages and disadvantages of) an artificial bird are here propounded because readily extendible to the numerical model of the bird.

The bird in FE analyses, in fact, is most of times closer to the artificial bird than to the real bird (Ref. 10).

As well as bird strike, bird ingestion is potentially a catastrophic event as it can lead to the loss of the engine, to the loss of the *fly-home capability*, to the loss of the aircraft and, in the worse of the cases, to loss of human lives.

Therefore, it is easy to understand the importance of developing numerical techniques to analyse the event with a degree of confidence.

With regard to the low-pressure fan of a turbofan engine, a bird strike is likely to damage the fan blades rather seriously (Figure 3).

The *physical features* of the fan blades (the geometry and the material) and the *loads* the fan blades undergo (centrifugal loads, aerodynamic loads, thermal loads) make the analysis of this event particularly troublesome (Ref. 16-18).

Indeed, in this research, using LSTC/LS-Dyna (Ref. 15), the influence of the numerical model of the bird on the *impact loads* has been investigated – with particular regard to the *slicing forces* arising when the bird and the fan blade collide.

Two benchmark tests were considered – featuring: the first, the impact of a 4-lb bird with a single fan blade and, the second, the impact of two 4-lb birds with a complete 17-blade fan.

Four different bird models were considered.

1. Lagrangian *Finite Element* (FE) model.
2. *Arbitrary Lagrangian Eulerian* (ALE) model.
3. *Smoothed Particle Hydrodynamic* (SPH) model.
4. *Nodal Masses* (NM) model.

These bird models were originally developed and validated (Ref. 10) referring to the data collected during full-scale straight impact tests (Ref. 8).

The tests, indeed, were carried out to develop reliable numerical model for the analysis of a (real) 4-lb bird impact onto the intake of a turbofan engine (Ref. 9-14).

Numerical models developed referring to those data have been proficiently used to investigate the consequences of a bird strike onto a intake made using composite materials (Ref. 10) and to study *subsequent* (Ref. 11) or *multiple* bird strikes (Ref. 9).

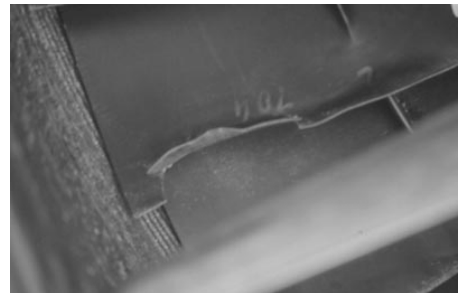
Using these four bird models, at the beginning, a simple benchmark test was considered in order to set up the numerical model: the collision of a fan blade rotating around its axis with a standard 4 lb-bird. Hence, a more evolved benchmark test was considered: the impact of two birds (one after the other) onto a complete fan rotating around its own axis (Ref. 17).

Since no experimental data were available, the attention was focused, in particular, on the advantage and the disadvantages in the use of the different bird models.

As a result, event insights and guidelines for further investigations were eventually drawn.



(A)



(B)

Figure 3. Damages caused by a birdstrike onto a fan: (A) an overall view and (B) a detail.

NUMERICAL MODEL OF THE BIRD

The numerical model of the bird (*geometry* and *material*) is central in a birdstrike analysis when using explicit FE codes. On the features of the model, in fact, the impact loads rely.

Customarily, the bird is modelled like a *cylindrical water bullet* (Ref. 6). Since a bird is primarily water and the impact velocities are rather high, this model is commonly accepted – though not free from criticisms (Ref. 10).

Four different bird models were considered: Finite Element (FE), Arbitrary Lagrangian Eulerian (ALE), Smoothed Particle Hydrodynamic (SPH) and Nodal Masses (NM) model.

Experimental test

The data collected during experimental tests are fundamental for the development and the validation of a numerical model.

In 1996, an intense test programme has been carried out to characterise the numerical model of the bird (Ref. 8).

Using an air-gun, 4-lb chickens were launched with an initial velocity of 265 kts toward a massive (solid) target inclined of 30 deg with respect to the direction of the birds. The target was accurately instrumented in order to acquire the profile in time of the impact forces.

Birdstrike tests are rather difficult to perform. Nevertheless, the tests were repeatable (as shown by the close agreement among the data obtained) and the data acquired reliable – also when compared with the ones of the tests previously carried out (Ref. 3).

Features of the model

A part from the different approach adopted, the bird models have the same features: the same *geometry* and the same *material*.

The bird was modelled as a water projectile with the shape of a rugby ball: length 20 cm, diameter 10 cm. Constitutive law, material model and equation of state were decided after preliminary simulations carried out using the FE bird model and hence implemented and verified with the other models. No failure criterion was defined.

The impact scenario (impact velocity and bird incidence) was the same of the experimental tests. The event duration considered was 4 ms real-time.

Model optimisation

The *optimisation* of a numerical model is a rather common practise – though not exactly free from criticisms.

Nevertheless, an *improvement* of the parameters that characterise the model of the bird was deemed, with regard to the problem considered, not only reasonable but also recommendable.

After a sensitivity analysis, those parameters (related to both *geometry* and *material* of the bird) which have the deepest influence on the correlation between numerical results and experimental data were chosen as *optimisation variables*.

It has been recognised that in order to correctly reproduce the mutual interaction between fluid and structure during a birdstrike, it is important to fit not only the maximum and the mean value but also the profile in time of the impact force.

In view of that, the *object function* was defined as the square root of the sum of the square of the distance between experimental data and numerical results.

The resulting object function was neither particularly smooth nor defined everywhere in the optimisation domain (Ref. 10).

Moving from these observation, it was developed and implemented (in a MATLAB-like environment) a robust zeroth-order algorithm based on *Bracketing Method* meant to be insensitive to *singularity* errors due to premature termination of the simulations.

The scheme adopted is not particularly efficient (i.e. fast-converging).

Nevertheless, the optimisation domain was limited in size, the simulations were not particularly time consuming, and the initial (*guess*) solution was close to an *admissible* optimum.

As a result, independently from the bird model, the optimisation process had a prompt convergence.

The values of the parameters obtained after the optimisation process are reported in Table 1.

Remarks

With regard to the results of the optimisation process (in Table 1) some remarks are needed.

It is not surprising that different values of the characteristic parameters have been obtained for different models: different models require different parameters.

The rugby-ball was eventually found to be the optimal shape for the bird: in that, the actual shape of the birds used in the tests had an influence.

Since the dimensions of the bird were fixed, it is reasonable that the obtained bird density was eventually higher than the one of the water.

	Bird model			
	FE	ALE	SPH	NM
Reference length of the model [mm]	9.7	9.7	10.0	10.0
Number of elements or particles	1800	70091	1445	1445
Mass of the particles [grams]			1.255	0.632
Density of the material [kg/m ³]	1115.9	1115.9	1201.5	
Speed of sound in the material [m/s]	1836.0	1836.0	1820.5	
CPU-time referred to the FE one		x 3.18	x 0.33	x 0.29
Error on the convergence [%]	2.58	7.05	1.19	3.30

Table 1. Features of different bird models.

Eventually, it is important to underline that the validity of the bird models developed basically relies on the reference test case considered.

Nevertheless, since the relative errors are the same order of the deviation from the mean of the data collected during the tests, the developed models were deemed definitively feasible to be used with a certain confidence in analyses concerning similar events and impact scenarios.

2. BENCHMARK TEST #1

The first benchmark test here considered (also available on internet) is from an example test meant to show the benefit of using a SPH bird model.

Features of the benchmark test

The impact scenario in the benchmark test vaguely recalls the actual bird-strike tests carried out when the impact behaviour of a fan blade is under investigation.

A fan blade (actually a constant thickness airfoil, Figure 4) rotating round its own axis with an angular velocity of 5220 rpm impacts a 2.5-lb bird travelling with a velocity of 100 m/s in a direction parallel to the rotating axis of the blade.

The bird is not fixed and this is a rather distinctive difference with the actual experimental test: in the full-scale tests, in fact, the bird is usually suspended and motionless. Another difference is the weight of the bird: in what follows, the weight of the bird is 4-lb – that is the *standard weight* prescribed for the homologation of the turbofan nacelles.

The benchmark test, despite the apparent simplicity, embodies all the features that make troublesome the analysis of the event and therefore was here considered.

Numerical model

The numerical model was eventually rather different from the original benchmark test.

Of the original model, only the geometry of the blade and the impact scenario (the fan blade rotating velocity and the bird velocity) were saved.

FE model of the fan blade. The mesh of the fan blade consisted of 2840 four-node shell elements.

The shell element formulation and the characteristic length were chosen to improve the accuracy.

Furthermore, a control on the accuracy (Ref. 15) was defined and the double precision version of the FE code was used.

The thickness of the blade was slightly increased – because it was observed that the centrifugal loads were such to plastically deform the blade.

The mechanical properties of the fan blade were explicitly specified to reproduce in detail the stress/strain curve of the material (i.e. Titanium Ti-6Al-4V). The dependence on the strain-rate was modelled by means of Cowper-Symond coefficients.

The rotation velocity was imposed to the blade through a rigid body.

A number of simulations were carried out to set those analysis parameters important for the accuracy of the solution.

After these simulations, in particular, it was recognised the importance of carefully modelling the centrifugal loads to correctly reproduce the dynamics of the fan blade.

Accordingly, the simulations were made consist of three phases: *pre-stress analysis*, *settling*, and *impact* phase.

- *Pre-stress analysis phase.* Before the analysis starts, a pre-stress analysis is carried out so that the blade may achieve an initial equilibrium configuration under the centrifugal loads.

Using LSTC LS-Dyna, instead of a pre-stress analysis, a preliminary *implicit* simulation can be carried out to bring the structure to an equilibrium configuration (Ref. 16). With regard to the problem considered, no actual benefits were found out in that. On the contrary, the implicit solver poses severe limitations on the choice of the materials and of the element formulation. Accordingly, it was concluded that the pre-stress analysis is, in general, to be preferred.

- *Settling phase.* After the pre-stress analysis, the simulation starts: the fan blade and the bird are put into motion.

The bird is placed at a distance from the fan blade: the magnitude of this distance is chosen so that the bird impacts the blade only after the blade has completed one complete turn around its own rotation axis. That is to avoid oscillations in the response of the fan blade due to *overshooting*.

- *Impact phase.* Eventually, the bird impacts the fan blade – both with their own prescribed velocity and incidence.

Bird model. The four numerical bird models previously developed and validated were used.

In that, the main difference with the original benchmark test was the weight of the bird. Another relevant difference was the shape of the bird.

Using to the FE bird model, the influence of a number of characteristic parameters of the bird were considered: the motion, the shape, the consistency, and the toughness.

Furthermore, as an explorative study was carried out to investigate the influence of the *airflow* on the blade and of the *thermal loads*.

Results obtained

The results obtained using the four different bird models were evaluated (*qualitatively*) referring to the description of the impact dynamics (Figure 4), and (*quantitatively*) referring to parameters related to the impact loads and maximum stress and strain in the fan blade (Table 2). The overall CPU-time required for the simulation was also considered.

	Bird model			
	FE	ALE	SPH	NM
F_{MAX} [kN]	34.96	NA	0.15	21.99
F_{avg} [kN]	12.48	NA	0.02	7.24
$\sigma_{VM, MAX}$ [N/mm ²]	249.9	322.1	209.1	266.7
ϵ_{pl}	34%	40%	4%	11%
Relative CPU-Time		x 3.83	x 1.14	x 0.88

Table 2. Results obtained with different bird models.

FE model of the bird (Figure 4-A). The simulations carried out with the FE bird model, at the beginning, had a normal termination.

As the *end time* was doubled (it was increased from 0.002 s to 0.004 s), the simulation had a premature termination due to the huge distortion in the bird mesh.

The premature termination of the simulation can be avoided defining an erosion criterion. The erosion criterion has a deep influence on the *mass* conservation and on the *momentum* transferred to the structure. Indeed, it is an awkward problem to set up the erosion criterion as it could eventually result in being a rather arbitrary option.

Regardless, before the error termination, the FE model provided a rather verisimilar representation of the dynamics of the event (Figure 4-A). In that, it was recognised the importance of defining a *symmetric* contact interaction – here, obtained by defining two (*inverted-role*) contacts.

ALE model of the bird (Figure 4-B). Using the ALE bird model, the simulation reached a normal termination and the description of the impact dynamics was accurate and verisimilar.

When adopting ALE approach, it was not necessary to define an erosion criterion.

The *diffusivity* (that most of the time is a drawback) provided an intrinsic erosion criterion: in that, the mass was not conserved – though the loss in the bird mass evaluated at the end of the simulation was practically negligible.

The time-step was constant during the simulation: unfortunately, the overall required CPU-time was negatively affected by the high time-per-cycle typical of the ALE approach (Table 2).

SPH model of the bird (Figure 4-C). Using the SPH bird model, the simulation reached a normal termination and the description of the impact dynamics was accurate and verisimilar – though different from the one obtained with the ALE bird model.

A proper value of the *viscous damping coefficient* (Ref. 10, 15) increased the stability of the analysis as it reduced the spurious spikes in the contact force due to the FE/SPH coupling.

Doubts remain about the influence on the results of the *tension instability* (i.e. numerical erosion in tension due to the loss of neighbourhood).

NM model of the bird (Figure 4-D). Using the NM bird model, the simulation reached a normal termination, but the behaviour of the bird was rather unrealistic: the *nodal masses* were swept away without interact one with the other.

A complete *Discrete Element* model (made not only with nodal mass-elements but also with spring- and damp- elements) could probably provide the necessary internal interaction mechanisms the model lacks (Ref. 10).

Nevertheless, the well-known drawbacks arising when implementing a complete DE model in a FE framework make this option not recommendable (Ref. 10).

Discussion

The benchmark test considered represented the occasion to have a deeper insight in the event and, at the same time, allowed to recognise the importance of the numerical model of the bird with particular regard to the approach to the modelling.

The FE model showed to be proficient for the analysis of the first instants of the impact and hence to be a powerful analysis tool when the mesh distortions are not considerable.

Nevertheless, when the objective is to analyse the slicing of the bird, the FE model is not exactly recommendable for the analysis of the event.

With regard to the ALE and the SPH bird models, the description of the impact dynamics obtained was verisimilar – though different.

In that, it is worthy the observation that the SPH models are appropriate for the analysis of *high velocity impacts*, as well as, the ALE models are appropriate for low velocity impact analysis – featuring high mesh distortions.

The *momentum transferred* to the fan blade has the same time profile: same values, same timings.

Unfortunately, nothing can be said about the impact force (Table 2) since the interaction between the ALE bird and the FE mesh of the fan blade structure is defined via a coupling constraint rather different from the contact algorithm.

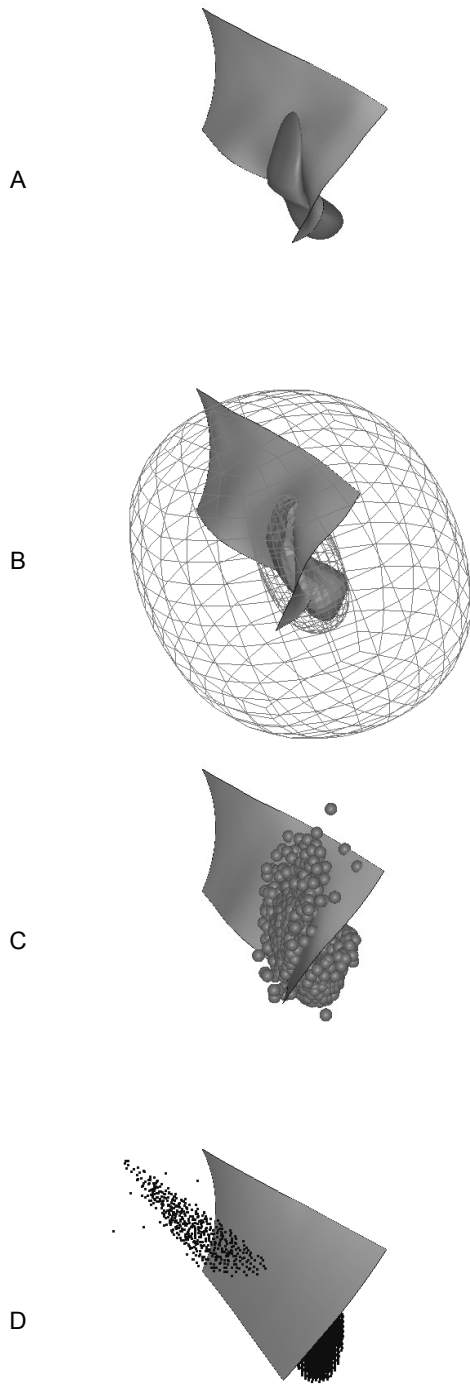


Figure 4. Bird strike impact onto a fan blade using different bird models: (A) FE, (B) ALE, (C) SPH, and (D) NM bird model.

The relevant difference between these two models is in the overall CPU-time required for the analysis: (both) the two approaches are insensitive to the bird distortion but the time-per-cycle of the SPH is definitively much smaller.

The NM bird model was eventually the less proficient among the models here considered. The substantial incorrectness of the results obtained with this model is basically due to the lack of internal interactions among the nodal masses. The lack of internal interactions is not so detrimental when considering high velocity straight impact (Ref. 10), but for sure it makes the NM model definitively not appropriate for the analysis of the event here considered (and it is rather evident in Figure 4-D).

BENCHMARK TEST #2

The second benchmark test considered (also available on internet) is originally meant to show the benefits of using an Eulerian approach to model multiple bird strikes (Ref. 17).

Features of the benchmark test

In the original benchmark two 2.5-lb birds impact a rotating fan (Figure 5).

The fan consists of seventeen blades: the rotation velocity is 5220 rpm.

The birds travel along a direction parallel to the fan axis with a velocity of 100 m/s. A small delay in time between the first and the second is provided. As briefly mentioned before, the two birds are modelled adopting the Eulerian approach: the mesh is fixed in the space and the material flows inside of it.

Regardless to the details of the model, it is worthy recalling that the Eulerian approach is known to have more drawbacks than benefits (that is why the Eulerian approach was not considered). Among the drawbacks, in particular, the most evident (evident also in Figure 5) is that the Eulerian approach requires a remarkable large number of elements to guarantee an acceptable degree of accuracy.

Numerical model

Of the original benchmark test (Figure 5) only the geometry of the blades was saved.

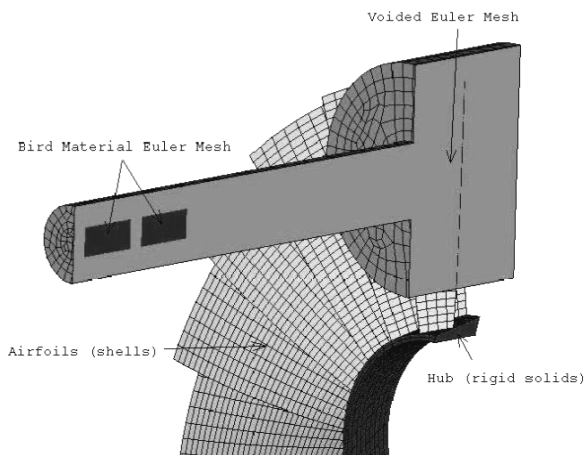


Figure 5. Original numerical model provided for the benchmark test #2 (Ref. 17).

FE model of the fan. The FE mesh of the fan consisted of almost thirty thousands four-node shell elements (1188 elements for each blade).

The blades had a variable thickness like in the original model, but the thickness was slightly increased to avoid plastic deformation at the root of the blades due to the centrifugal loads. Indeed, differently from the original benchmark test, where the deformation of the blades was under investigation, the attention was focused on the *slicing* and therefore the overall stiffness of the fan blades to avoid excessive deformations.

For each blade was defined a part: that eventually simplified the definition of the contact interactions as well as the understanding of the contact forces obtained from the simulations.

The hub (modelled as a rigid body) imposed the rotatory motion to the blades: in that, a damping on the relative motion was also defined to avoid stress concentrations at the root of the blades (Ref. 15).

The same approach to the *analysis initialisation* described before was adopted. Accordingly, the simulations consisted of three phases: pre-stress analysis, settling, and impact phase.

Bird model. Four different bird models were considered: the FE model, the ALE model, the SPH model and the NM model.

Differently from the original benchmark test, the two birds that impacted the fan weighted 4 lb.

Results obtained

The results obtained were evaluated with regard to the description of the *impact dynamics* and to the *feasibility* of the different bird models as a tool for the analysis of the event.

The results obtained eventually confirmed what already observed when considering the benchmark test #1.

FE model of the bird (Figure 6-A). As predictable, the simulation carried out with the FE bird model had a premature termination due to the huge distortion in the mesh of the (first) bird.

Indeed, the simulation crashed just after the first bird impacted the fan and long before the second bird reached the fan (Figure 6-A).

Accordingly, (unless defining an *appropriate* erosion criterion) it is not feasible to analyse the event adopting the Lagrangian FE approach.

ALE model of the bird (Figure 6-B). When adopting the ALE approach, the simulation reached a normal termination and the description of the impact dynamics was accurate and verisimilar.

The time-step remained practically constant during the simulation, but doubts about the accuracy of the results arise when considering the significant distortion of the ALE mesh (Figure 6-B).

SPH model of the bird (Figure 6-C). Using the SPH bird model, the simulation reached a normal termination and the description of the impact dynamics was accurate and verisimilar.

Considering a high velocity straight impact, it was observed that the tension instability provide a *reasonable* failure criterion for the bird (Ref. 10). Unfortunately, this observation is not readily applicable to the present case because of the *slicing effect*.

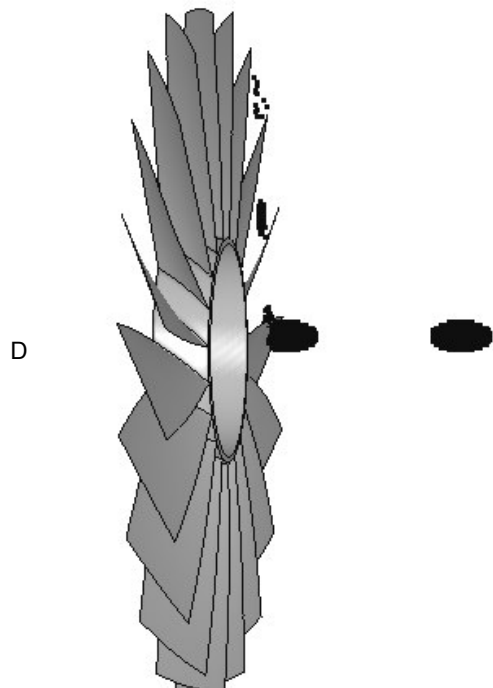
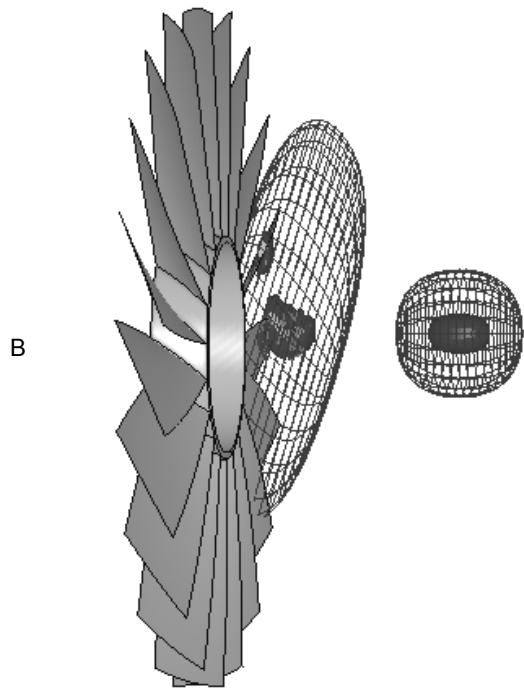
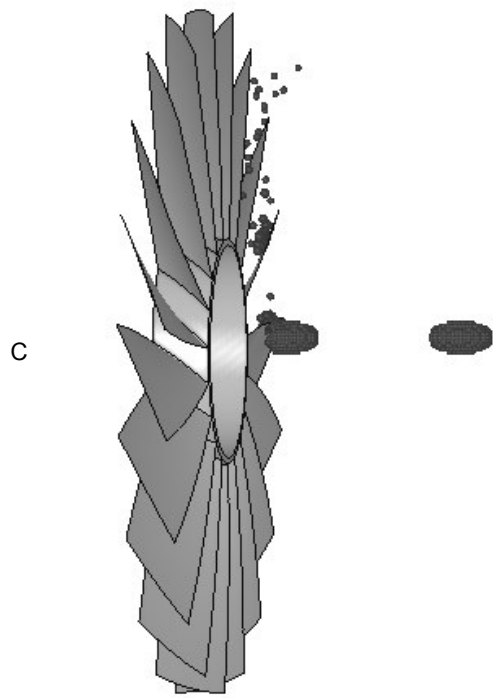
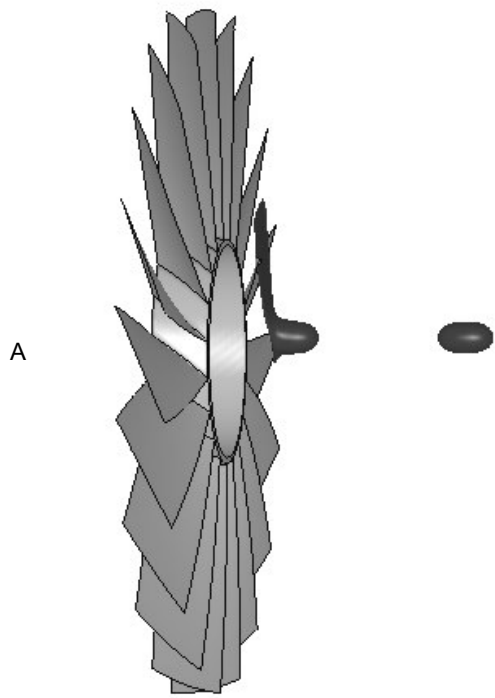


Figure 6. Bird strike impact onto a fan using different bird models: (A) Lagrangian FE, (B) ALE, (C) SPH, and (D) NM bird model.

Figure 6 (cont'ed). Bird strike impact onto a fan using different bird models: (A) Lagrangian FE, (B) ALE, (C) SPH, and (D) NM bird model.

When the fan blade passes through two particles and the distance between these particles is greater than the (contact) thickness of the blade no contact interaction is detected. That is the case of the impact of subsequent blades with the bird (Figure 6-C and Figure 7-LHS).

The influence of the slicing effect (evaluated also referring to the results obtained with the ALE model) is not relevant and, therefore, a part from the doubts about the influence of the *tension instability*, the SPH model proved to be a feasible tool for the analysis of the event.

NM model of the bird (Figure 6-D). When using the NM model, the simulation reached a normal termination, but the impact behaviour of the bird was definitively unrealistic (Figure 6-D) and that is evident when considering the impact of the second bird (Figure 7).

In Figure 7, in particular, the SPH and the NM bird models are directly compared. The difference, rather evident in the graphical comparison, is even more obvious when considering the impact loads.

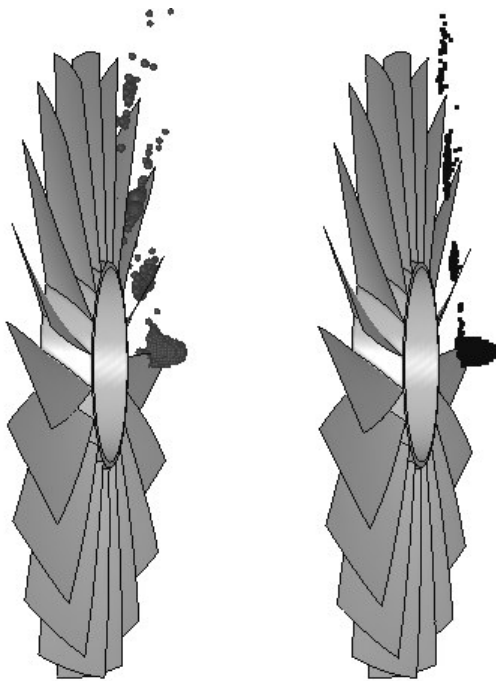


Figure 7. Second bird strike using the SPH (LHS) and the NM (RHS) bird model.

Discussion

The results obtained showed the difficulties due to the mesh distortion arising when adopting both the Lagrangian FE and ALE approaches, confirmed the doubts about the influence on impact loads of the *tension instability* intrinsic of the SPH Method, and stigmatised the irremediable lack of internal interactions of the NM model.

In view of these findings, it was concluded that the SPH model is, at the moment, the most feasible bird model for the analysis of the event.

CONCLUSIONS

Birdstrike is a serious threat for modern aircraft. The consequences of a birdstrike can be dramatic and, therefore, numerical techniques to develop high-efficient bird-proof structures are essential.

In this research, the feasibility of four different bird models as a tool to analyse a birdstrike onto a fan blade was investigated – focusing on the influence of the bird modelling on the *slicing forces*.

Two different benchmark tests featuring, the first, the impact of a bird onto a fan blade and, the second, the impact of two birds with a seventeen-blade fan were considered.

In view of the results obtained, advantages and disadvantages of the four different bird models were recognised.

Contextually, it was observed: the weakness of the Lagrangian approach with regard to the distortion of the FE mesh, the proficiency (among a number of known drawbacks) of the ALE approach, the uncertain regarding the tension instability intrinsic in the SPH Method, and the severe limitations to the applicability of the NM model.

It was eventually concluded that the SPH bird model is, at the moment, the most feasible model for the analysis of the event considered. Regardless to the *tension instability* (the influence of which can be easily evaluated), the SPH model demonstrated to be reliable when considering the description of the *impact dynamics* and the impact loads and convenient with regard to the overall CPU-time required of the simulations.

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