BIRDSTRIKE ONTO STRUCTURES IN ROTATIONAL MOTION

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ABSTRACT

A birdstrike is likely to have serious consequences and, therefore, modern aircraft have to be certified for a proven level of bird impact resistance before being put into operational service.

In this work, the consequences of a bird impact onto structures in rotational motion are investigated from a numerical standpoint.

Referring to a bird surrogate, the jelly projectile used to develop bird-proof structures, a robust SPH model of the bird is initially developed and validated.

Subsequently, the difficulties in modeling the impact of a bird against structures in rotational motion are highlighted and a feasible approach to model the event is proposed.

Two different impact scenarios are then considered: the impact of a bird against low-pressure compressor blades and the impact of a bird against a small dimension propeller spinner. Findings and guidelines for modeling the event are eventually provided.

INTRODUCTION

Since the early beginning of aviation history, birdstrike has been one of the most dangerous threats for aircraft [1].

A bird strike is characterized by loads with high intensity and short duration [2]. The materials undergo high strain rates, large deformations and inelastic strains. In addition, a deep interaction exists between the impact loads and the response of the structure.

Despite the efforts provided to avoid collisions between birds and aircraft (*active safety*) and to produce bird-proof aircraft (*passive safety*), birdstrike causes every year damages for millions of US-dollars and unacceptable losses in human lives.

In view of this, before being introduced into operational work, the aircraft components must be certified for a certain level of bird impact resistance. The *fly-home capability* must be guarantee: after a birdstrike, the aircraft must be able to safely land.

Full-scale tests with real flesh-and-bones birds are mandatory for the homologation of new structures. Birdstrike tests are expensive, difficult to perform and little repeatable. Thus, in the years, analytical and numerical schemes have been implemented to support the development of new structures and hence to reduce production times and costs. In particular, since the end of the eighties [6], nonlinear explicit codes based on Finite Element Method (FEM) have been successfully used to analyze bird strikes and to develop high efficiency (i.e. low-weight and high-resistance) bird-proof structures [6]-[13].

In this work, bird strikes onto structure in rotational motion are investigated from a numerical standpoint using LSTC/LS-Dyna 971-R4 [16].

Various approaches have been adopted to model the bird so far [10]-[12]. A numerical model based on the Smoothed Particle Hydrodynamic (SPH) Method is initially developed and validated referring to both the data collected in tests carried out in seventies [2] and the theory worked out moving from test data for the creation of a valid bird surrogate, the *jelly bird* [3], [4].

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Subsequently, the difficulties in modeling the impact of a bird against structures in rotational motion are described and a feasible approach to model the event is proposed.

Two different impact scenarios are then considered: the impact of a bird against a low-pressure compressor (*fan*) blades and the impact of a bird against a small dimension propeller spinner. With regard to compressor blades, multiple-birds impact is considered, whilst, with regard to the propeller spinner, the differences between considering a motionless spinner and a spinner in rotational motion and between a spinner made with composite materials and a spinner made with metallic materials are investigated.

1 BIRD MODELING

In over fifty years of analyses and researches on birdstrike, a large number of papers have been published. Most of these papers deal with the analysis of specific problems. Others, more specific, investigate the modeling of the bird or the development of artificial birds. With regard to the latter, in particular, various aspects of modeling have been considered and investigated so far. The features of the models proposed reflect the characteristic of the event considered and the code used for the simulations.

In what follow, the bird is modeled adopting the SPH approach. The shape, the material model as well as other important aspects of the modeling such as the analysis setup and the choice of the contact algorithm are considered.

1.1 Birds and bird surrogates

The impact of a real bird is representative of that impact itself [2] and, therefore, it is not surprising that tests with real birds are little repeatable. Considering the impact of a flesh-and-bones bird, not only the weight and the physical properties of the bird, but also parameters such as the species, the age, and the size are relevant because of the influence on the impact loads.

Bird surrogates (such as the jelly projectile currently used in the development of bird-proof structures) guarantee repeatability of the tests and are simple to model.

The jelly projectile model [2] is generally accepted as a substitute of the real bird. At high impact velocity a bird impacting a rigid or deformable structure behaves like a fluid and hence a hydrodynamic material model is a reasonable approximation. Of course, if the impact velocity is not particularly high, such an approximation is not acceptable.

Bird surrogates have been under development for years. In particular, several research works were carried out to find the ideal reference shape and mechanical properties of the artificial bird. Nevertheless, despite the efforts provided to develop an effective artificial bird, the use of flesh-and-bones birds (freshly *euthanized*) is still required in certification tests: the use of artificial birds is not recognized.

In view of this, since the impact behaviors of a flesh-and-bones bird and a jelly projectile are in some aspects different, a number of research works aimed at developing a reliable numerical model of real birds. In particular, research works have shown that the use of the *inverse approach* to find the parameters of the numerical model that better approximate the impact behavior of a real bird is a feasible approach to achieve results close to test data [10].

In what follows, simulations were carried out using jelly bird because analytical results and a vast bibliography on the topic exists.

Shape, material model and equation of state (EOS) of the jelly bird were considered. The results of the simulations carried out to develop a reliable SPH bird model were evaluated referring to impact force and pressure measured in experimental tests [2] and those obtained from the theory developed moving from the tests [3].

1.2 Bird shape

The shape of the bird is particularly important when not only the impact forces but also the pressure are of interests.

In addition, the shape of the bird becomes important when it is necessary to obtain specific load conditions [2]: the blunt-cylinder shape is used for birdstrike onto fan blade whilst the rugby-ball shape is recommendable to reproduce the impact loads of a real bird [10].

1.3 Discretization

Several, different approaches to bird modeling have been proposed so far [10], [12], [13]: the customary Lagrangian FE approach, the Eulerian/ALE approach and, more recently, the approaches based on mesh-less method such as the SPH and EFG methods.

The Lagrangian FE approach is simple to use and it is rather accurate – at least, until the bird undergoes severe deformations.

Explicit FE codes such as MSC/Dytran and LSTC/LS-Dyna implement an Eulerian/ALE solver for coupled Lagrangian/Eulerian or Lagrangian/ALE analysis. This approach is effective when the materials undergo severe deformations, but has a number of drawbacks – first of which, it is not simple to adopt and requires expert users.

Mesh-less or mesh-free methods and, in particular, the SPH method, have shown to be a feasible alternative to the traditional approaches to bird modeling [9]-[15].

The SPH method is based on an interpolatory scheme based on *pseudo*-particles [16] used to discretize the continuum. Explicit FE codes such as Mecalog/RADIOSS, ESI/PamCrash and LSTC/LS-Dyna implement a SPH solver. All the mentioned solvers are rather reliable. In particular, it should be mention that ESI/PamCrash implements a feature that allows FE automatically switching to SPH when the element is too distorted. A feature that is particularly useful when analyzing soft-body impacts.

As long as the bird can be regarded as a fluid, the SPH method is a rather convenient approach to model the bird [15]. However, before adopting this approach, it is recommendable that the user is familiar with the underlying theory and implementation of the method to avoid trivial (newbie's) errors.

1.4 Equation of state

Various equations of state have been proposed so far for the jelly bird.

Several research works focus on the EOS of the bird.

Initially, a polynomial equation of state with the parameters of the water at room temperature was used. Subsequently, these parameters were modified to keep into account the porosity of the jelly used in the tests. It was experimentally noticed that varying the porosity of the jelly projectile it is possible to obtain impact forces and pressure close to those of real birds [3], [4].

However, which of the EOS proposed so far better reproduces the behavior of a flesh-and-bone bird is still an open question. Indeed, when dealing with uncertainty such as those that characterize bird modeling, the recommendable approach is to keep the model simple and evaluate the results obtained in view of the approximations made.

1.5 Fluid-structure interaction

A bird strike is classified as a *soft-body impact*. In particular, since the bird behaves like a fluid during the impact, the interaction between the bird and the structure can be regarded as a problem of *fluid-structure interaction*.

When considering the impact of a bird onto a deformable structure, the impact loads depend on the response of the structure and, in turn, the response of the structure depends on the impact load. In order to accurately model the event is therefore important to model accurately the interaction between the bird and the structure.

The bird/structure interaction is defined in different ways depending on the approach adopted to discretize the bird. Adopting the Lagrangian approach the *contact algorithm* is used. The contact constraint is usually imposed using the penalty method that allows to keep into account the difference in mechanical properties of the bodies in contact. Adopting an Eulerian approach *coupling algorithms* based on penalty methods are used to evaluate the interaction forces between the bird and the structure.

2 IMPACT PRESSURES

Considering birdstrike onto complaint structures such as the composite laminates, the impact forces are less significant than the impact pressure [12], [13].

In view of this, the SPH bird model was to developed and validated focusing in particular on impact pressures measured in experimental tests [2].

2.1 Theoretical aspects

In seventies, a intense test campaign was carried out to gain relevant knowledge, insights and finding on bird strike [2].

With regard to the pressure on a rigid target, it was observed that the birdstrike is characterized by four phases (Fig. 1-LHS): the *initial* shock phase, the release phase, the steady-flow phase, and the final phase.

The time history of the pressure is characterized by an initial peak followed by a constant value. Analytically, the initial peak of pressure can be evaluated as the Hugoniot pressure whilst the steady flow pressure can be evaluated using potential flow theory [2].

When for the first time it was attempt to analyze a bird strike using a numerical scheme based on FEM, it was observed that if the initial peak pressure is not such to cause the failure of the structure, it can be neglected. Accordingly, the impact pressure was modeled as a square wave.

Modern nonlinear explicit FE codes do not need such an approximation because allow *introducing* the bird into the numerical model. As a consequence, impact loads (forces and pressures) and hence the accuracy of the results depends on the model of the bird. In view of this, it is straightforward to understand the paramount importance of a reliable model of the bird to correctly simulate a birdstrike.

A bird model that allow reproducing with a degree of accuracy the time history of the impact pressure is *fundamental* especially when considering birdstrike onto compliant structures such as the composite laminates that are characterized by an elastic-brittle failure.

2.2 SPH bird model

A bird model with the classical cylinder shape (being two the ratio between the length and the diameter) was created.

Three different distributions of the SPH particles were initially considered.

1. **Uniform distribution.**
   The particles were equally spaced to form a uniform grid.
2. **Scattered distribution.**
   Smaller particles were placed among the particles that constitute an equally spaced grid to fill the empty cavities among the particles.
3. **FE-derived distribution.**
   The particles were created from a FE mesh replacing the element with a particle of same mass placed in the center of gravity of the element.

It was observed that, when the number of particles is large *enough*, the uniform grid is a convenient trade-off among accuracy, required CPU-time and stability of the model. In view of this, the bird model eventually consisted of 7040 equally spaced particles. The distance among the particles was 6.8 mm.

With regard to the constitutive law, even if various material models and EOS are available, the most simple ones were adopted.

The customary hydrodynamic elastic-plastic material model was replaced by a *null* material that allows only the isotropic components of the stress tensor whilst a numerical pseudo-viscosity based on the strain rate activates deviatoric components of the stresses [8].

The customary polynomial EOS was replaced by the Grüneisen's EOS that better than the polynomial EOS gives account of the effects of compressibility in the material. Effects that are relevant in events like birdstrike that involve fluids and fluid-like materials and are characterized by high velocities.

The mechanical properties of the bird were the same used in birdstrike analyses since seventies [6]. The Grüneisen's EOS parameters are those of the water [7].

2.3 Results

The results obtained were evaluated in terms of impact force and pressures.

2.3.1 Impact forces

Two values of the impact forces were considered: the peak and the mean forces.

Both the peak value and the mean value of the impact force in the steady flow phase were eventually close to the analytical one.

However, in order to achieve this results, it was necessary to modify the contact interface definition: the method to enforce the contact was changed (the distributed parameters was replaced by the penalty method), the contact forces on the bird were scaled and a contact viscous damping coefficient was introduce to damp spurious oscillations.

Considering a birdstrike onto rigid target, it is in general simple to obtain values of the impact forces close to those in theory and tests – even when adopting approaches different from the one adopted here [12].

On one side, this shows the reliability of the models. On the other side, since the impact forces are a *global parameter*, this does not imply accuracy in the evaluation of local effects and hence in the analysis of the consequences of birdstrike onto compliant structures. In view of this, the impact pressures that are a *local parameter* are more relevant than the forces to evaluate the reliability of the bird model.

2.3.2 Impact pressures

Two values of the impact pressures were considered: the peak and the steady flow state pressure.

The impact pressure was evaluated in terms of ratio between the contact force and the impact surface [16].

Both the peak value and the mean value of the impact pressure in the steady flow phase were eventually close to the analytical one.

However, in order to further investigate the reliability of the numerical model, the internal pressure distribution in shock release phase was considered.

Adopting the SPH approach it is rather complicate to plot fringes. Nevertheless, it is apparent that the pressure wave in the bird shown in Fig. 1-RHS is in accordance with the one inferred from the tests [2].

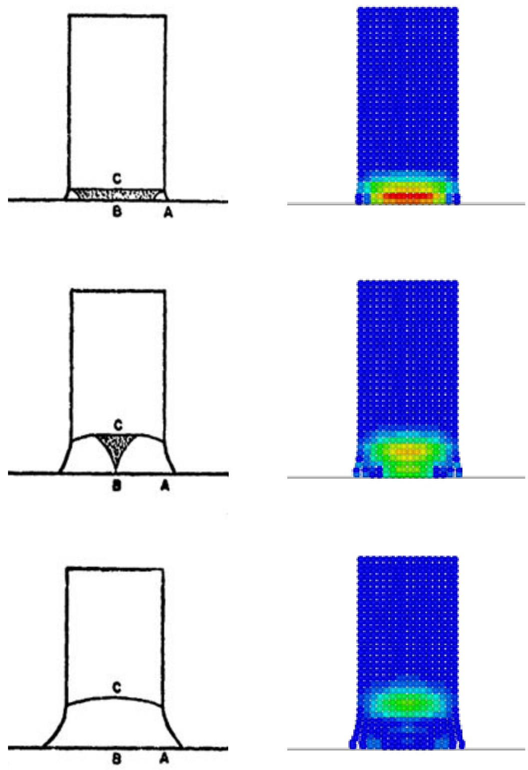

Fig. 1. Shock and release in a bird impact [2].

2.3.3 Required CPU time

With regard to a simple test like the one considered here, it is possible to appreciate how a SPH model allows obtaining accurate results without requiring excessive computational resources.

Differently from a Lagrangian FE model, the SPH bird is indifferent to mesh distortion (because it has not mesh) and differently from an Eulerian/ALE model, large computational resources are not required.

CPU time is important when dealing with birdstrike analyses because for the development of bird-proof structures it is necessary to run several simulations and consider various impact scenarios. Follows that, since the SPH bird is *inexpensive* in terms of required computational resources and CPU time, it is recommendable for *design-by-analysis* procedures.

3 CENTRIFUGAL LOADS

Modeling of structures in rotational motion using explicit FE codes presents a number of difficulties. On one side, it is fundamental to reproduce with a degree of accuracy the centrifugal loads and motion of the elements. On the other side, a *not-too-small* time-step is necessary to maintain the required CPU time within acceptable limits.

3.1 Centrifugal loads modeling

Several different approaches to model the centrifugal loads are available.

If the structure is not particularly complex, it is possible to impose the centrifugal loads directly to the nodes of the structure. A rather elaborate approach that, in general, does not bring to accurate results.

Another approach consists in dividing the simulation into two phases. In the first phase, the body, initially motionless, is accelerated to the actual rotation velocity. In the second phase, the event of interest is simulated. An intuitive approach rather costly in terms of CPU time – also because it requires to impose a slow acceleration pulse curve in the first phase and then wait until the response is settled.

In an effort to reduce the required CPU time, an implicit pre-analysis could be an alternative. Implicit analyses allow larger time-step. However, it should be mention that, with regard to structure in rotational motion, for the accuracy and the convergence of the analysis the time-step can not be too large. Adopting this approach, the state of stress obtained can be either used as pre-stress in an explicit analysis or the simulation can be simply *switched* to explicit [16].

Finally, dynamic relaxation is another feasible approach to calculate pre-stresses in a structure in rotational motion.

3.2 Assessment

Assets and drawbacks of the approaches described were evaluated referring a simple benchmark test.

3.2.1 Benchmark test

The benchmark test considered (Fig. 2) is from an example file meant to show the benefit of using the SPH method in birdstrike analysis [13]. It consisted of the collision of a blade made in Titanium and a 2.2-lb bird. The blade in rotational motion with an angular velocity of 5,200 rpm impacts a bird travelling with a velocity of 100 m/s in a direction parallel to the rotating axis of the blade.

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

In order to evaluate the accuracy of the solution two parameters were considered: the radial position of the node on the tip of the blade and the state of stress. If no round-off errors occur, the node on the tip of blade should describe a circle in a plane normal to the axis of rotation. The state of stress in the blade was evaluated with regard to the analytical solution and a numerical solution obtained with a standard FE analysis carried out with MSC Nastran.

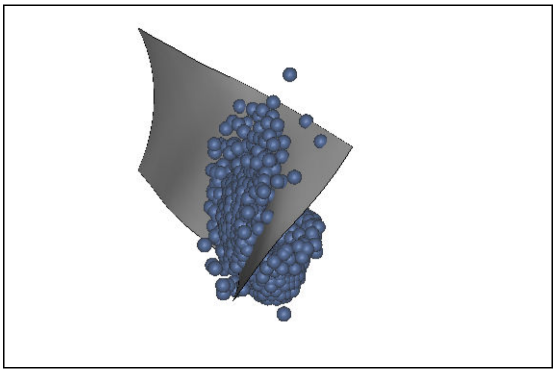

Fig. 2. Birdstrike onto a blade.

3.2.2 Discussion

Dividing the simulation into two phases is rather costly in terms of CPU time.

On the other hand, it was observed that, an implicit pre-analysis requires a time-step smaller than those of the explicit analyses. Larger time-steps led to inaccuracy in the solution or, in the worst cases, prevent the simulation to convergence. In addition, not all the features available using the explicit solver are available using the implicit solver [16].

Dynamic relaxation is rather convenient in terms of CPU time, but the accuracy deeply depends on the choice of the tolerance on convergence.

In view of the remarks so far, the approach adopted in what follows utilized the dynamic relaxation to evaluate the state of pre-stress in the structure. Then the simulations were divided into two phases to leave a period of settling before simulating the event of interest.

4 APPLICATIONS

One of the most distinguish characteristic of structures in rotational motion is the presence of the centrifugal loads that determines in the structure a state of pre-stress and at the same time increase the stiffness of the structure.

The influence of the rotational motion on the bird strike impact dynamics and the differences between the impact onto a motionless structure and a structure in rotational motion were investigated.

4.1 Birdstrike onto a compressor blade

The impact of two 2.2-lb birds onto the same blade of a low-pressure compressor (*fan*) was initially considered.

The impact scenario comes from a benchmark test (available on internet) meant to show the benefits of using an Eulerian approach to model multiple birdstrikes [13].

The low-pressure compressor consists of seventeen blades made of Titanium in rotational motion with a rotation velocity of 5,200 rpm. The birds travel along a direction parallel to the axis of the fan with a velocity of 100 m/s.

4.1.1 Numerical model

The FE mesh of the low-pressure compressor consisted of almost thirty thousands four-node shell elements (1188 elements for each blade). The blades had a variable thickness.

The hub (modeled as a rigid body) imposed the rotational motion to the blades. A damping on the relative motion was defined to avoid stress concentrations at the root of the blades.

The model of bird previously described was used. The size was reduced to that of a 2.2-lb bird and the two-sphere-and-cylinder shape was replaced by the rugby-ball shape that allows more accurate results in terms of impact pressure distribution [10], [12].

With regard to the centrifugal loads, the approach described before was adopted. Accordingly, the simulations consisted of three phases: pre-stress analysis, settling, and impact phase.

1. **Pre-stress analysis.**
   A pre-stress analysis is carried out using dynamic relaxation. The structure reaches the initial state of equilibrium under the centrifugal loads.
2. **Settling.**
   After the pre-stress analysis, the low-pressure compressor is put into rotational motion. The fan completes one round before the impact.
3. **Impact.**
   The birds impact the fan blade with the prescribed velocity and incidence.
   A delay in time between the first and the second bird is provided so that both the birds impact the *same blade*.

4.1.2 Results

The simulation reached a normal termination and the description of the impact dynamics (Fig. 3) was accurate and in accordance with test evidences.

The SPH bird did not affect the time-step neither after the second bird impact (Fig. 4). Furthermore it was not necessary to *invent* a failure criteria to avoid premature terminations of the simulations due to the excessive deformation of the element.

4.1.3 Remarks

Considering normal impacts, tension instability provide a convenient failure criterion for the bird. However, this circumstance is not readily verifiable to the present case because of the *slicing effect* [13].

Since, no data were available for the test considered, simulations were carried out using ALE approach to model the bird [10], [12]. The bird/blade interaction forces obtained with the SPH and the ALE birds were compared and the differences were negligible.

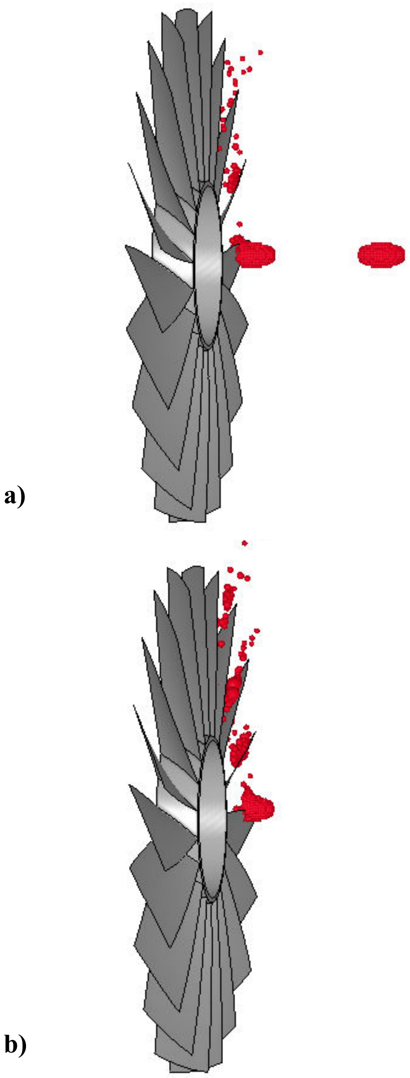

Fig. 3. Bird impact onto a low-pressure fan blade.

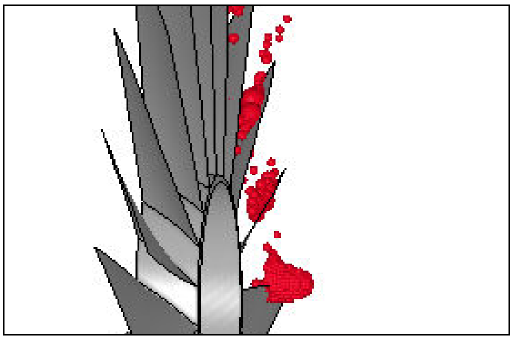

Fig. 4. A detail of the second bird impact.

4.2 Birdstrike onto a propeller spinner

The impact of a 2.2-lb birds onto a spinner made with composite materials was then considered. The spinner is the aerodynamic cone at the hub of an aircraft. In particular, the spinner considered here is characterized by a very simple geometry.

The spinner is in rotational motion with a rotation velocity of 7,800 rpm. The bird impact the spinner with an initial velocity of 100 m/s and an impact angle of 60 deg.

An impact scenario in several aspects rather different from the previous one. An impact scenario introduced here for the first time as a benchmark test for birdstrike onto structure in rotational motion. Indeed, despite the many points of interest, few research works deal with this event.

The difference between the impact onto a motionless spinner and a spinner in rotational motion and the impact onto a spinner made with composite materials and with metallic materials were investigated.

4.2.1 Numerical model

The FE mesh of the spinner consisted of about six thousands (6,080) four-node shell elements. The spinner has a constant thickness of 1.38 mm, but the thickness of the collar (where the spinner is joined to the hub) is double.

The hub, modeled as a rigid body, imposed the rotational motion to the spinner.

The SPH model of bird and the approach to keep in count the centrifugal loads previously described were used.

Impact forces on the hub and the bulkhead behind the spinner were evaluated to investigate damages due to the bird strike and penetration.

4.2.2 Composite material modeling

Composite materials are characterized by high resistance-to-weight and strength-to-weights ratios.

The failure mechanism of a composite structure under dynamic loads is critical. It depends on several factors such as the mechanical properties, orientation and the staking sequences of the plies.

The material model used for the composite spinner is an *elastic-damage model* developed around the idea that damages introduce micro-cracks and cavities into materials and that these defects cause a stiffness degradation with small permanent deformation. A non-smooth failure surface is assumed and the failure criteria are taken to be independent from each other [16].

4.2.3 Birdstrike onto a motionless spinner.

The impact sequence of a birdstrike onto a motionless spinner made with composite materials (Vicotex CFRP woven) is shown in Fig. 5.

4.2.4 Birdstrike onto a composite spinner

The impact sequence of a birdstrike onto a composite (Vicotex CFRP woven) spinner in rotational motion is shown in Fig. 6.

4.2.5 Birdstrike onto a metallic spinner

The impact sequence of a birdstrike onto a metallic (AA 2024-T6) spinner in rotational motion is shown in Fig. 7.

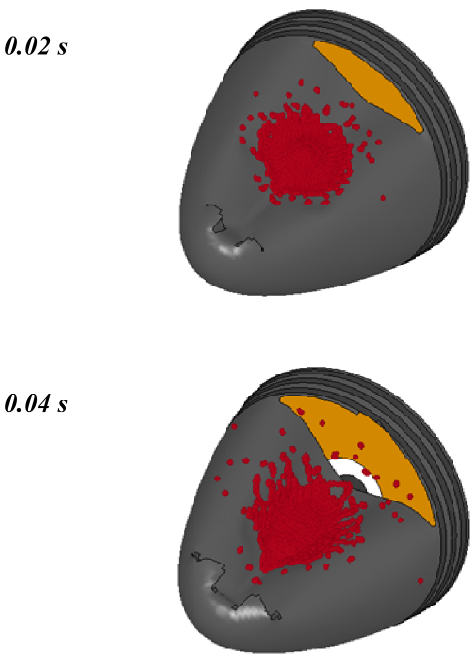

Fig. 5. Birdstrike onto a motionless spinner.

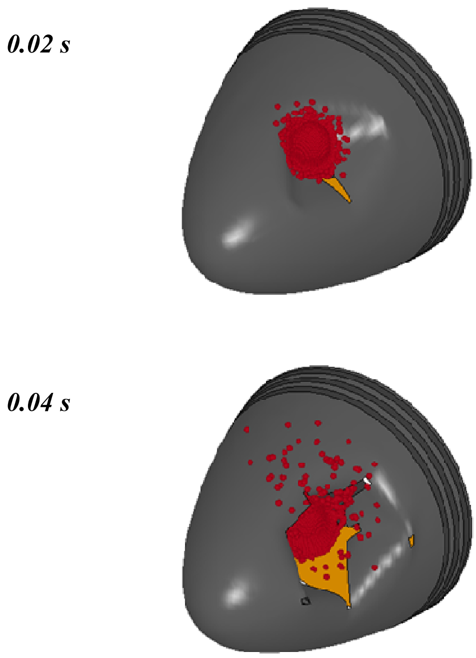

Fig. 6. Birdstrike onto a composite spinner.

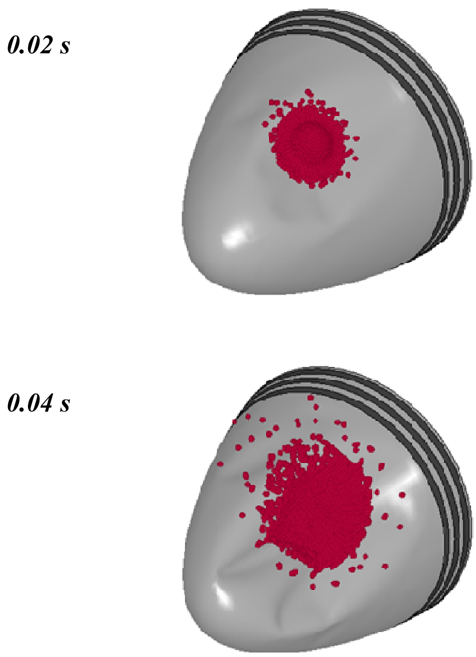

Fig. 7. Birdstrike onto a metallic spinner.

4.2.6 Discussion

With regard to all the three impact scenarios considered, the simulations reached a normal termination.

The description of the impact dynamics and the failure mechanism of the composite structure are accurate and in accordance with the evidences of tests on similar structures.

The rotational motion of the spinner has a remarkable influence on the impact dynamics. The spinner itself is not able to deflect the bird. However, after the collapse of the spinner, the rotational motion pushes away and *deflect the bird* (Fig. 6). As a result, the damages of the structures behind the spinner are negligible if the spinner is in rotational motion, whilst, the damages are relevant if the spinner is motionless. The failure mechanism of the composite structure itself is rather different in the two impact scenarios (as apparent in Fig. 5 and Fig. 6).

The metallic spinner (unlikely the composite laminate spinner) *bags the bird* after the impact (Fig. 7). As a results, the most part of the initial impact energy of the bird is transferred to the structures behind the spinner causing remarkable damages. Only a small amount of the impact energy is dissipated by friction or by the deformation of the spinner (Fig. 7).

In view of the remark so far, a composite laminate spinner seems to be preferable to a metallic one. Of course, this is only a benchmark test and further investigations are necessary to confirm the results obtained here.

CONCLUSIONS

The impact of a bird onto aircraft structures is characterized by high impact loads transferred in a short time to small areas of structures designed to carry distributed loads. It is not surprising, then, that a birdstrike could be cause of serious air accidents.

In this work, the consequence of a bird impact onto structures in rotational motion were investigated from a numerical standpoint using LSTC/LS-Dyna 971-R4.

A robust SPH model of a bird surrogate, the jelly projectile, was initially developed and validate referring to impact forces and pressures measured in experimental tests.

Subsequently, the difficulties in modeling the impact of a bird against structures in rotational motion are highlighted and a convenient approach to model the event consisting of dividing the simulations into three parts (pre-stress analysis, settling, and impact phase) was introduced.

Two different impact scenarios were then considered: the impact of a bird against low-pressure compressor fan blades and the impact of a bird against a small dimension propeller spinner. Two scenarios rather different and particularly significant for the event under investigations. With regard to compressor blades, two-birds impact was considered, whilst, with regard to the propeller spinner, the difference between considering a motionless structure and a structure in rotational motion and between a composite laminated structure and metallic structure were investigated. Findings and guidelines for modeling the event were provided.

Eventually, the reliability of SPH bird model was further shown. Simulations carried out using this model are cost-effective in terms of required computational resources and CPU time. The SPH method is a feasible approach to investigate single and multiple birds impacts onto composite and metallic structures, motionless and in rotational motion.

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