A Strategy to Design Bird-proof Spinners

Prof. Marco Anghileri
Dr. Luigi-Maria L. Castelletti
Ing. Dario Molinelli
Ing. Federico Motta

Politecnico di Milano, Dipartimento di Ingegneria Aerospaziale
Via La Masa 34, 20156 Milano, Italia
Phone: +39 02 2399 8334, Fax: +39 02 2399 8332

* Mail to: marco.anghileri@polimi.it

Summary:

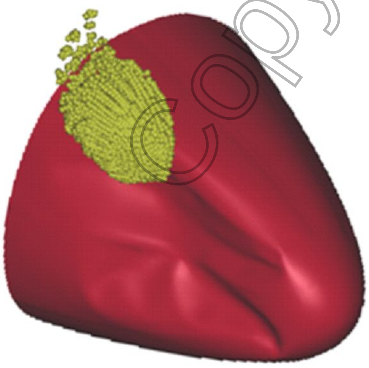
Birdstrike is a serious threat for flight safety which causes every year remarkable losses. Even if modern aircrafts are certified for a level of bird impact resistance, it may happen that structures designed to carry aerodynamic loads, like a propeller spinner, may collapse after a bird strike. In general, the collapse of the spinner is not a concern if the *fly-home capability* is not compromised.

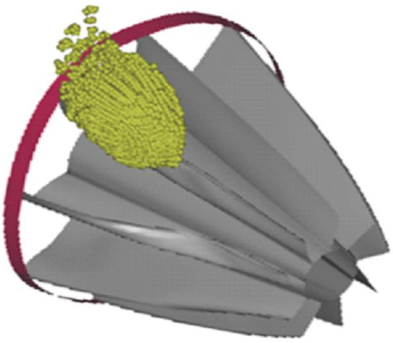
In this paper, a strategy to design bird-proof spinner is introduced and its effectiveness evaluated by means of LS-Dyna.

A SPH model of the bird was initially developed and validated. Then the impact of the bird onto a composite spinners was investigated. In particular, to capture its complex failure mechanism, the dynamic behaviour of the composite material used in the aircraft constructions was validated against specific dynamic tests. The influence of the spinner motion was also investigated and the differences between motionless and revolving spinners were pointed out.

Improvements to the design of the reference spinner based on the idea of *deflecting-the-bird* instead of *bagging-the-bird* were developed and their performances numerically evaluated.

In view of the results obtained, it was concluded that composite material and rotational motion can be exploited to design bird-proof spinner. Furthermore, it was observed that increasing the thickness of a spinner is not only against the weight constraints typical of aircraft constructions, but it is also ineffective.





Keywords:

Birdstrike, Propeller Spinner, SPH Method, Composite material, Rotational motion

1 INTRODUCTION

Statistics [1] show that birdstrike still represents a serious threat for flight safety. Every year, collisions between aircraft and birds cause remarkable losses.

A bird strike is a high-energy impact characterised by loads with high intensity and short duration [3]. The materials undergo high strain rates, large deformations and inelastic strains. In addition, a deep, mutual influence exists between the impact loads and the response of the structure.

Modern aircrafts are certified for a level of bird impact resistance. However, it may happen that structures designed to carry aerodynamic loads, such as a propeller spinner, collapse because of a bird strike. In general, the collapse of a spinner is not a concern – unless behind the spinner are housed equipments that are necessary for the operating service of the aircraft. In this case, the *fly-home capability* has to be guaranteed and, therefore, the spinner has to be designed to protect the equipments.

In this paper, a strategy to design bird-proof spinners is introduced. Using LS-Dyna [7], a numerical model of the bird which allows simulating a complex event such as the birdstrike onto a structure in rotational motion was initially developed and validate. In particular, the Smoothed Particle Hydrodynamics (SPH) approach [8-14] was adopted because better than other approaches [12] allows modelling the large deformations of the bird, strike and penetration inside the spinner and, hence, the impact dynamics and the load transfer mechanism.

Propeller spinners are usually made with aluminium alloy. Nevertheless, recent technologies have made the manufacturing of composite spinners *easy-and-cheap* and, therefore, the diffusion of composite spinners is increasing.

In an effort to capture the complex failure mechanism of a composite spinner, the crash behaviour of a composite material used in the aircraft constructions was investigated and a material model validated against data collected in static and dynamic tests [10].

The influence of the spinner motion was investigated and the difference between a birdstrike onto a motionless spinner and onto a spinner in rotational motion were pointed out.

Improvements to the design of a reference spinner based on the idea of *deflecting-the-bird* instead of *bagging-the-bird* were introduced and their crash performances numerically evaluated.

In view of the results of the simulation carried out, it was concluded that composite material and rotational motion can be exploited to design bird-proof spinner. It was also observed that increasing the thickness of a spinner is not only against the weight constraints typical of aircraft constructions, but it could be ineffective.

2 BIRD MODELLING

In over sixty years of analyses and researches on birdstrike, a large number of papers have been published. Most of these papers deals with the analysis of specific problems, others focused on the development of an artificial bird and a large number investigated the bird modelling.

With regard to the latter, in particular, it should be mentioned that various aspects of the bird modelling were investigated even if the features of the models proposed reflected the characteristic of the event considered and the code used for the simulations.

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

2.1 Problem overview

2.1.1 Real birds and surrogates

The impact of a real bird is representative of that impact itself [2]: tests with real birds are generally little repeatable. When considering the impact of a real *flesh-and-bones* bird, not only weight and physical properties of the bird, but also species, age, and size are relevant because all these parameters affect the impact loads.

Bird surrogates, on the contrary, guarantee the repeatability of the tests and furthermore are simple to model. For these reasons, jelly projectiles [3] are widely used as substitutes of real birds in the development of bird-proof structures.

At high impact velocity a bird impacting a rigid or a deformable structure behaves like a fluid and hence a hydrodynamic material model is a reasonable approximation. If the impact velocity is small, such an approximation is less acceptable even if, in this case, the bird strike is not likely to be a threat.

Bird surrogates have been under development for years. However, despite the efforts provided to develop an effective artificial bird [2], the use of flesh-and-bones birds is still required in certification tests.

However, in what follows, simulations were carried out using jelly bird [4]. Shape, material and equation of state 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 tests carried out in seventies and those obtained from the theory developed moving from the tests [3].

2.1.2 Bird shape

The shape of the bird is particularly important when not only the impact forces but also the pressure are of interests. The shape of the bird is also important when it is necessary to obtain specific load conditions [2]: for example, the blunt-cylinder shape is usually used for birdstrike onto fan blades whilst the rugby-ball shape [8] adopted here is recommended to reproduce the impact loads of a real bird onto compliant structures.

2.1.3 Discretisation

Various approaches to bird modelling have been proposed so far [8-13]: the customary Lagrangian FE approach, the Eulerian/ALE approach and, more recently, approaches based on mesh-less methods such as the SPH and the EFG methods.

The Lagrangian FE approach is simple to use and accurate – unless the bird undergoes large deformations. In presence of large deformations, a *properly defined* failure criterion is needed.

The most sophisticated explicit FE codes such as LS-Dyna implement Eulerian and Arbitrary Lagrangian Eulerian (ALE) solvers for coupled Lagrangian/Eulerian and Lagrangian/ALE analyses. The coupled approach is useful when the materials undergo severe deformations, but has a number of drawbacks – the first of which is that its use is not simple and therefore requires skilled users.

The SPH method is a feasible and convenient alternative to the customary approaches to bird modelling when the material undergoes severe deformations [8-13] and therefore it is adopted here.

As long as the bird can be regarded as a fluid, the SPH method is a reliable approach to bird modelling. However, before adopting this approach, it is recommendable that the user is familiar with theory and implementation of the method to avoid newbie's errors.

2.1.4 Equation of state

Various equations of state (EOS) have been proposed for the bird so far. Historically, a polynomial equation of state with the parameters of the water at room temperature was initially used [3, 5].

These parameters were then modified to keep into account the porosity of the jelly projectiles used in the development tests. It was experimentally shown [4] that using jelly projectile with a 15% porosity it was possible to obtain impact forces and pressure close to those of real birds.

The EOS that better reproduces the behaviour of a real bird is still an open question. In view of this, the approach adopted here was to keep the model simple and evaluate the results obtained in view of the approximations made.

2.1.5 Fluid-structure interaction

A bird strike is classified as a soft-body impact. The bird during an high velocity impact behaves like a fluid and therefore 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 crucial to accurately model the interaction between the bird and the structure.

The bird-structure interaction is defined in different ways depending on the approach adopted to discretise the bird.

When adopting the Lagrangian approach (either FE or SPH), 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.

When adopting the Eulerian (or the ALE) approach, coupling algorithms based on penalty methods are used to evaluate the interaction forces between the bird and the structure.

The accuracy of the results depend on the choice of the parameters used to define either the contact or the coupling algorithm. Therefore, these parameters should be carefully chosen with regard to the features of the problem considered, the properties of the materials and the level of discretisation.

2.2 SPH BIRD MODEL

Considering birdstrike onto complaint structures, the impact forces are less significant than the impact pressures.

A bird model that allows reproducing with a degree of accuracy the time history of the impact pressures is essential especially when considering bird strike onto structures characterised by an elastic-brittle failure such as composite laminates.

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

2.2.1 Theoretical aspects

In seventies, an intense test campaign was carried out to acquire relevant knowledge, insights and finding on birdstrike [3].

With regard to the pressure on a rigid target, it was observed that the birdstrike is characterized by four phases (Fig. 1-LHS): (1) the initial shock phase, (2) the release phase, (3) the steady-flow phase, and (4) the final phase (that, however, is not always presents).

2.2.2 Numerical model

In an effort to validate the SPH model of the bird the impact scenario described in the theory was numerically reproduced. A bird with the customary cylindrical shape was created.

The bird model consisted of 7040 equally spaced particles – the distance among the particles was 6.8 mm. An uniform distribution of the particles was adopted because it was observed that, if the number of particles is large enough (like here), an uniform distribution is a convenient trade-off among accuracy, required CPU-time and stability of the model.

The material model adopted was slightly different from the customary one [5]. In place of the hydrodynamic elastic-plastic material, a material model was used 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 (*MAT_NULL, [7]). In place of the polynomial equation of state, the Grüneisen's EOS (*EOS_GRUNEISEN, [7]) was used which gives account of the effects of compressibility in the material and, besides, suits the features of the SPH solver better than the polynomial one.

The parameter to characterise the mechanical properties of the bird were derived from the customary ones [5]. The Grüneisen's EOS was that of the water [6].

2.2.3 Numerical-experimental correlation

The results obtained were compared with the experimental data [3, 4] in terms of impact forces and pressures.

Two values of the impact forces were considered: the peak and the average forces. Both peak and average values were close to the experimental one.

When considering a birdstrike onto rigid target, it is possible to obtain values of the impact forces close to those of theory and tests even by adopting approaches different from that adopted here [13].

Overall, this shows the reliability of the models. However, the impact force is a global parameter: the accuracy of the impact force does not imply the accuracy of the impact pressure that, on the contrary, is a local parameter.

Since local effects are fundamental to analyse the consequences of a birdstrike onto compliant structures, impact pressures are deemed more relevant than forces to evaluate the reliability of the numerical model.

The impact pressures were evaluated in terms of ratio between the contact force and the impact surface. Two values of the impact pressures were considered: the peak and the steady flow state pressure. Both peak and average values were close to the experimental one.

The pressure distribution inside the bird was also considered. The pressure wave obtained with the SPH approach (shown in Fig. 1-RHS) was in accordance with the one inferred from the tests [3].

2.2.4 Required CPU time

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.
The SPH model allows obtaining accurate results without requiring excessive computational resources and, therefore, it is recommendable for design-by-analysis procedures.

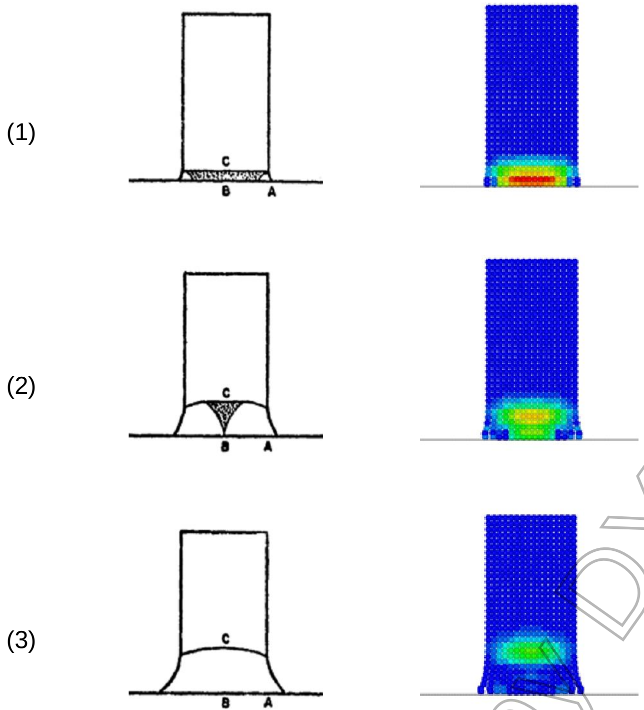


Figure 1. Phases of a birdstrike: in theory [3] and in the numerical simulation.

3 CENTRIFUGAL LOADS

One of the most distinguish characteristic of structures in rotational motion is the presence of the centrifugal loads that determines a state of pre-stress and increase the stiffness of the structure.
The modelling 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, on the other side, a *not-too-small* time-step is necessary to maintain the overall computational time within acceptable limits.

3.1 Centrifugal loads modelling

Various approaches to model the centrifugal loads are available using LS-Dyna.
If the structure is not particularly complex, it is possible to impose the centrifugal loads directly to the nodes of the structure or using the general damping option for a pre-stress analysis. However, these approaches, in general, do not bring accurate results for complex structures.
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. This is an intuitive approach, but costly in terms of CPU time – also because, in the first phase, it is necessary to accelerate the structure *slowly* to avoid instabilities and continue the simulation until the end of the transitory.
In an effort to reduce the required CPU time, an implicit analysis could be an alternative to the first phase described above. Implicit analyses usually allow larger time-step even if, with regard to structures in rotational motion, for the accuracy and the convergence of the analysis the time-step can not be too large. Implicit analysis then can be performed either as a pre-analysis or as a part of the simulation using the *switch-to-explicit* capability of LS-Dyna.
The dynamic relaxation is another option to calculate pre-stresses in a structure in rotational motion.

3.2 Assessment

Assets and drawbacks of the approaches described were evaluated considering the impact of a bird against a fan blade.

3.2.1 Benchmark test

An example file by Dr. Jean Luc Lacome which was thought to show the assets of the SPH method for birdstrike analyses was modified [11, 14] and used as a benchmark (Fig. 2).
A single blade made of Titanium alloy, in rotational motion with an angular velocity of 5,200 rpm, impacts a 2.2 lb bird travelling with a velocity of 100 m/s in a direction parallel to the rotating axis of the blade.
Despite the apparent simplicity, this benchmark has all the features that make troublesome the analysis of the impact of a bird onto structures in rotational motion.
Two parameters were considered to evaluate the accuracy of the solution obtained: 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 accuracy of the state of stress in the blade was evaluated referring to the analytical solution (obtained using a simplified beam model) and to the numerical solution (obtained with NASTRAN).

3.2.2 Discussion

After the simulations, it was observed that dividing the simulations into two phases is rather costly in terms of CPU time and, for simple problems (like that under investigation), the first phase is even more time-consuming than the phase in which the event of interest is simulated.
An implicit pre-stress analysis requires a time-step as small as that of the explicit simulation. Larger time-steps lead to inaccuracy or, in the worst cases, prevented the simulation to convergence. In addition, it should be mentioned that not all the features of the explicit solver are available for the implicit solver.
The use of the dynamic relaxation is 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 utilised the dynamic relaxation to evaluate the state of stress in the structure. Then, the simulations were divided into two phases to leave a period of settling before simulating the event of interest.

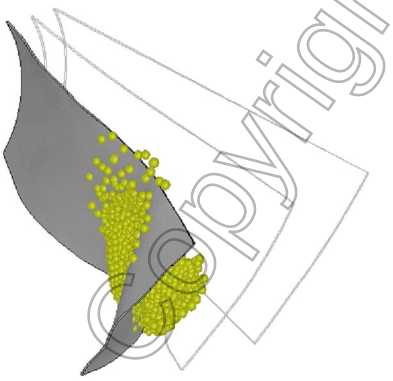


Figure 2. Birdstrike onto a single fan blade.

4 BIRD-PROOF SPINNERS

The impact of a bird onto a spinner made with composite materials was investigated because, even if few research works deal with this event, it presents several points of interest.
Three different impact scenarios were considered: motionless spinner made of composite material, spinner made of composite material in rotational motion and spinner made of metallic material in rotational motion. The differences among these three impact scenarios were investigated.
Subsequently, a strategy to design bird-proof spinner is introduced and its effectiveness numerically evaluated.

4.1 Birdstrike onto a spinner

4.1.1 Impact scenarios

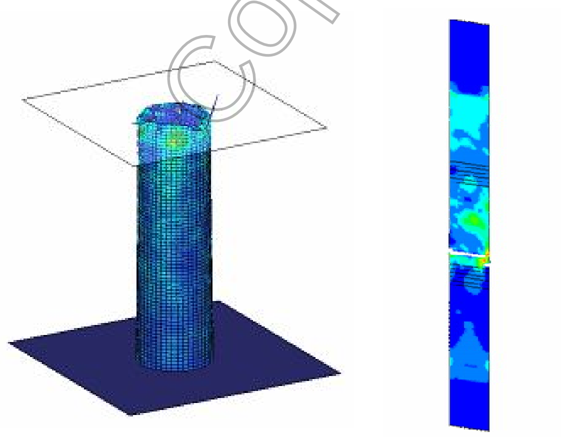
A spinner is the aerodynamic nose cone that fits on the front of the propeller. The spinner considered here, in particular, is characterised by a very simple geometry.
The spinner is rotating with a rotation velocity of 7,800 rpm when a 2.2 lb bird impacts it with an initial velocity of 100 m/s and an angle of 60 deg.
Despite the apparent simplicity, this impact scenario presents all the distinguishing characteristics of the problem and therefore it was used here to assess the potentialities of the code used in the simulations as a means to investigate the consequences of birdstrike onto structures in rotational motion.

4.1.2 Numerical model

The FE mesh of the spinner consisted of over six thousands four-node shell elements. Two shell formulations were initially used: the co-rotational Hughes-Liu and the fully integrated shell element formulation. Since no significant differences were noticed in the results the latter was eventually adopted because *faster* [7].
For the composite laminates one integration point per layer was used. For the metallic structure the same total number of integration points was used.
The spinner has a constant thickness of 1.38 mm. The thickness of the collar (where the spinner is joined to the hub) is doubled. The hub, modelled as a rigid body, imposed the rotational motion to the spinner.
The SPH model of bird and the approach to model centrifugal loads previously described were used.
Impact forces on the hub and the bulkhead behind the spinner were evaluated to investigate the severity of the damages due to the bird strike and penetration.

4.1.3 Composite material modelling

Composite materials are characterised by high resistance-to-weight and strength-to-weights ratios and therefore are widely used in engineering.
The failure mechanism of a composite structure under dynamic loads is critical. It depends on several factors such as mechanical properties, orientation and the staking sequences of the plies.
The material model used here for the composite is based on 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 [7].
The mechanical properties and the parameters that characterise the crash behaviour of the material were from previous research works [9, 10]. Data collected in static and dynamic tests were used to validate the material model (Fig. 3).



Drop test Fastens test

Figure 3. Simulations carried out for composite material characterisation.

4.1.4 Results of the simulations

The impact sequence of a birdstrike onto a *motionless* spinner made with composite materials is shown in Fig. 5.
The impact sequence of a birdstrike onto a composite spinner *in rotational motion* is shown in Fig. 6.
The impact sequence of a birdstrike onto a *metallic* (AA 2024-T6) spinner in rotational motion is shown in Fig. 7.

The description of the impact dynamics and the failure mechanism of the composite structure were accurate and in accordance with the evidences of tests carried out with similar structures.
The SPH model of the bird allowed simulating bird strike and penetration, impacts onto composite and metallic structures, motionless and in rotational motion. With regard to all the three impact scenarios considered, the simulations reached a normal termination.
Furthermore, simulations were effective in terms of required computational resources, memory usage and CPU time.

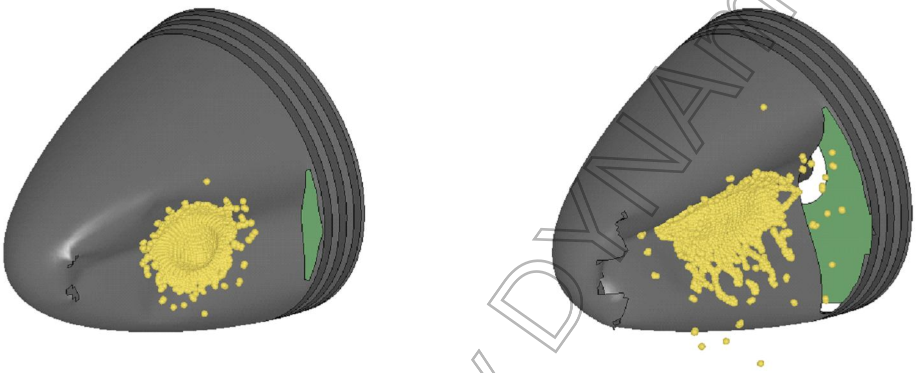


Figure 5. Birdstrike onto a motionless spinner.

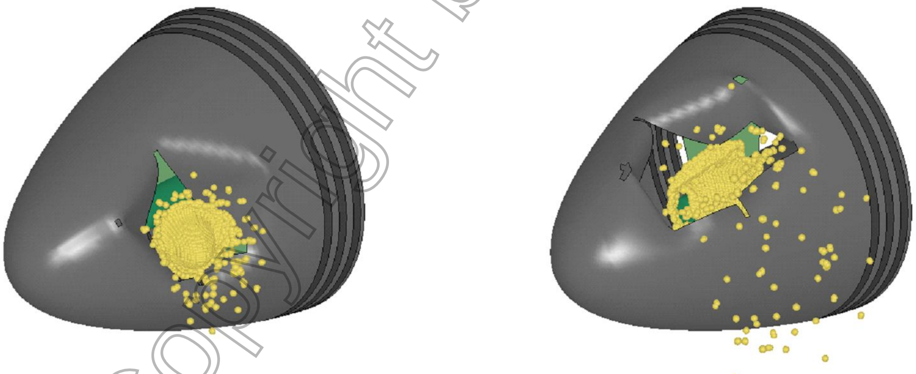


Figure 6. Birdstrike onto a composite spinner in rotational motion.

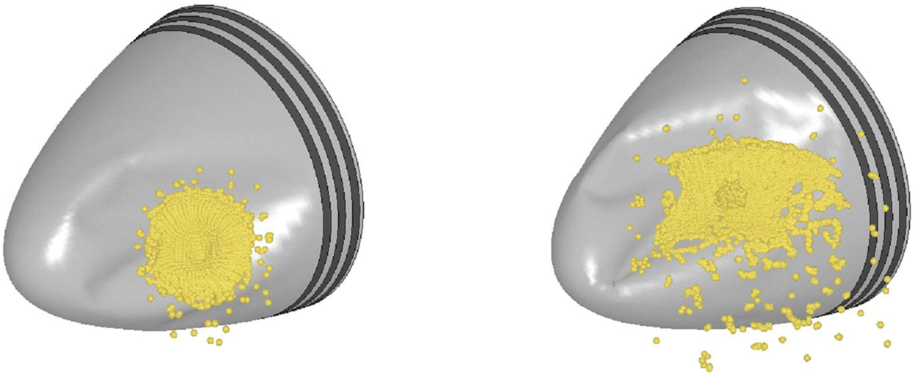


Figure 7. Birdstrike onto a metallic spinner in rotational motion.

4.1.5 Discussion

The rotational motion of the spinner has a remarkable influence on the impact dynamics. The spinner is not able to deflect the bird. However, after collapsing, due to its rotational motion it *deflects* the bird (it literally moves the bird away). As a consequence, if the spinner is in rotational motion, the damages of the structures behind the spinner are less severe. Also, the failure mechanism of the composite structure is different in the two impact scenarios (as evident in Fig. 5 and Fig. 6).

The metallic spinner, differently from the composite spinner, *bags* the bird after the impact (Fig. 7). Therefore, the most part of the initial impact energy of the bird is transferred to the structures behind the spinner causing severe 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. However, further investigations and tests are necessary to confirm the results obtained here.

4.2 A strategy to design a bird-proof spinner

Moving from the results of the simulations described above, a strategy to design bird-proof spinners was developed. In particular, the basic idea was to exploit the rotational motion of the spinner to deflect the bird.

In Fig. 8 is shown a device thought to move the bird away and protect the equipment behind the spinner. This device is made of PVC to be light and resistant, but other materials can be used.

The dimensions of the device were chosen without referring to a specific requirement in terms of clearance which could have a remarkable influence on the design.

Numerical simulations showed the effectiveness of such a device: it improves the crash performances of the spinner and can be also mounted on already operative spinners.

The main drawback of the device introduced here is the weight. Lighter versions based on the same concept are under development.

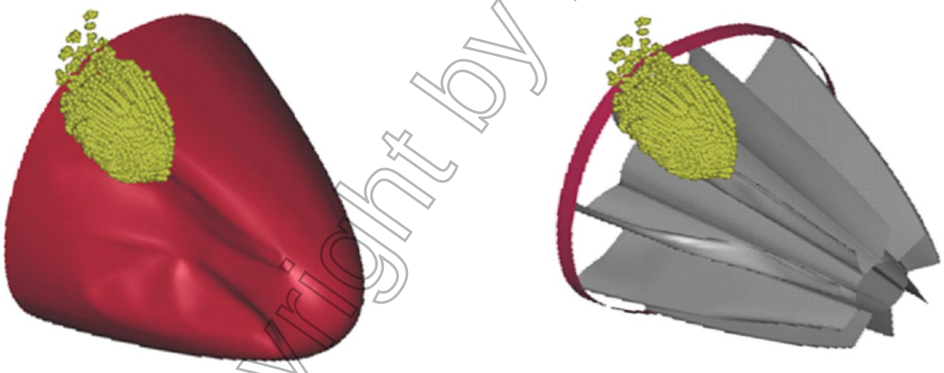


Figure 8. A strategy to design a bird-proof spinner.

5 CONCLUSIONS

A birdstrike is characterised by high impact loads transferred in a short time and concentrated in relatively small areas of structures that are designed to carry only aerodynamic loads. It is not surprising, then, that a birdstrike could be the cause of serious accidents and air tragedy.

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

A robust SPH model of a bird surrogate (i.e. the customary jelly projectile) was initially developed and validated referring to impact forces and pressures measured in experimental tests. Findings and guidelines for the bird modelling were provided.

Subsequently, the difficulties in modelling the impact of a bird against structures in rotational motion were 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.

The impact of a bird against a small dimension propeller spinner was then considered. Three different impact scenarios were considered: the impact of a 2.2 lb bird against a motionless composite spinner, against a composite spinner in rotational motion and against a metallic spinner in rotational motion.

It was observed that the rotational motion of the spinner can be exploited to deflect the bird and on this basis a strategy to design bird-proof propeller was developed.

6 LITERATURE

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. R Budgey: “The development of a substitute artificial bird by the international birdstrike research group for use in aircraft component testing”, Proceedings of the 25th Annual Meeting of the International Bird Strike Committee, IBSC25/WP-IE3. Amsterdam, 17-21 April 2000.
3. 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
4. Wilbeck J S and Rand J L, “The Development of a Substitute Bird Model”, Journal of Engineering for Power, Vol. 103. pp 725-730. 1981.
5. Brockman R A and Held T W, “Explicit Finite element method for transparency impact analysis”, Technical report, University of Dayton Research Institute, Wright Patterson Air Force Base, 1991.
6. Meyers M A, “Dynamic behavior of materials”. John Wiley & Sons, Inc. 1994.
7. J. O. Hallquist: “LS-DYNA Theoretical Manual” Livermore Software Technology Corporation, 2006.
8. 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
9. Anghileri M, Castelletti L-M L, Lanzi L, and Mentuccia F, “Composite materials and bird-strike analysis using explicit finite element commercial codes”, in Jones and Brebbia, Structures Under Shock and Impact 8th Series, Structures and materials, 15, Southampton, UK, WIT, pp 465-474, 2004.
10. M. Anghileri, L.-M. L. Castelletti, F. Invernizzi and M. Mascheroni: “Birdstrike onto the composite intake of a turbofan engine”, 5th European LS-Dyna Users Conference, Birmingham, UK, May 2005.
11. L.-M. L. Castelletti and M. Anghileri: “Birdstrike: the influence of the bird modelling on the Slicing forces”, Proceedings of 31st European Rotorcraft Forum, Florence, Italy, Sept. 2005
12. L.-M. L. Castelletti and M. Anghileri: “Toward a methodology for the design of bird-proof intakes made with composite materials”. 25th Congress of the International Council of the Aeronautical Sciences, ICAS 2006. Hamburg, Germany. Sept. 2006.
13. M. Anghileri, L.-M. L. Castelletti, and F. Motta: “Birdstrike: An investigation on feasible bird models for nonlinear explicit finite element analyses”, Proceedings of 32nd European Rotorcraft Forum, Maastricht, The Netherland, Sept. 2006
14. L.-M. L. Castelletti, M. Anghileri: “Birdstrike onto structures in rotational motion”, 26^{th} International Congress of the Aeronautical Sciences, ICAS 2008. Anchorage, Alaska. September 14-19, 2008., 2008-9.4.4, p. 1-11