Transient Dynamics of Slicing-Impact Loading on Jet Engine Fan Blades during a Bird-strike Event

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Abstract

Based upon numerous field events involving bird-strikes on aircraft propulsion system components, the engine manufacturers have long recognized the need for better understanding and insight in the physics of slicing action for analytically predicting the damage to the fan blade. A medium or large size bird being ingested in a running engine with aircraft velocity in the range of 100-120 m/second, essentially during the take-off time, is capable of doing a catastrophic damage to multiple blades on the fan rotor. The slicing action during oblique impact at the thin leading edge of the metal airfoil can cause non-linear plastic deformation, which is highly transient in nature with peak magnitude becoming large enough to block the airflow to an extent that can result into engine stall. Precise analytical modeling of an actual bird-strike event on a jet engine fan blade is a very difficult and highly challenging problem in the area of transient nonlinear dynamics. LS-DYNA® offers many different options such as Lagrangian bird, SPH bird as well as ALE approach to simulate the dynamic loading on the fan-blade, which is generally localized at the sharp leading edge and peaks usually within 0.1 milliseconds of initial contact. The present paper provides a historical and current perspective from the modeling considerations of fan blade airfoil during the design and development cycle and its implementations in LS-DYNA simulations for accurately determining its dynamic response under bird-strike.

Introduction

The numerical simulation of a bird impacting a spinning turbofan rotor and determining the dynamic loads on fan blades is an active area of advanced research and numerous papers have been published during the last 30 years. However, majority of groundbreaking original work in the area of bird-strike analysis has been developed by the engine manufacturers independently based upon actual field events and test observations [1] and as such has remained in their respective proprietary domain for a considerable time. The involvement of academic research community in bird-strike analysis has sparked interest as a new topic of attention due to some recent high-profile incidents such as Hudson river accident on US Air flight of 2009. At the same time their knowledge base about the bird-strike loading and the damage to the jet engine components is of rudimentary nature and are built on some fundamentally flawed simplifying assumptions [2]. Due to this reason, their level of physical insight into the complex nonlinear transient dynamics of soft-body impact of highly deformable bird is not consistent with the damage observed and test data that are readily available in multiple public domain sources such as FAA data base, ASME/AIAA conference proceedings and other technical literatures. Most of the research work in the area of bird-strike analysis from academic community has been limited to normal impact on a flat surface only with shock wave type Hugoniot pressure consideration, which has no application in the fan-blade damage prediction. In 2011, Heimbs [3] had presented a comprehensive review of all different aspects of computational methods of bird-strike simulations. In a recent paper Abrate [4] further updated the list of published papers until 2016. After the bird is ingested in a running engine, the following nonlinear dynamic events take place in a very quick succession, usually within fraction of a millisecond.

First, the incoming bird is sliced by the sharp leading edge of the rotating blades resulting into multiple pieces distributed over a sector of the fan-rotor in a sequential manner, and then the bird-slurry flows and spreads like a fluid on the pressure surface of the airfoil. The initiation of slicing process involves oblique impact with incidence angle of about 25° and bird debris travel on the airfoil, which is of highly transient nature that usually lasts for about 2 milliseconds [5]. Recent academic literatures are ignoring the significance of slicing action and focusing on the second-order parameters such as bird-shape and bird material characterization as the key elements of the loading mechanism on the fan blades. Additionally some authors, in their analytical model, have not considered at all an important physics of the loading mechanism of fan blades which is governed by the nonlinearity of the slice-size and the transient dynamic response of the blade during the slicing action by the lead edge of the airfoil, which needs to be emphasized.

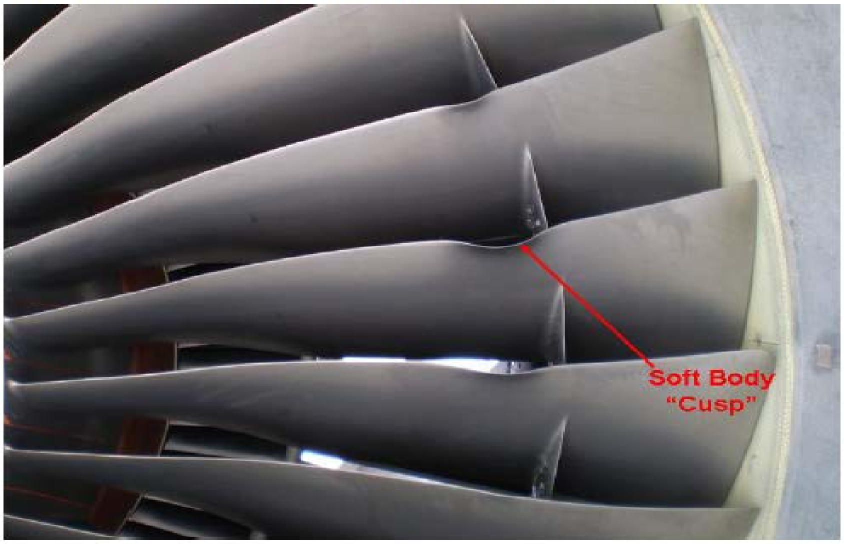

FIG. 1: Picture of typical fan blade damage due to bird-strike [1]

During the last decade, the current methodology of bird-strike numerical simulation on the fan blade airfoil design has become quite sophisticated and LS-DYNA modeling approach has achieved a level of maturity so that analytical predictions are highly reliable as demonstrated through many whirligig rig-tests. The explicit solver like LS-DYNA has become an almost industry standard to carry out a detailed bird-strike analysis and deploy it as a predictive tool during the design phase of a new airfoil. It should be noted that the early fundamental groundbreaking work [6 - 25] of conceptual nature dealing with the slicing action and the loading mechanism of the fan blade listed in this review are readily available in open literature, and do not use any manufacturer's proprietary information. Furthermore for the convenience of the readers, the list of references provided from public domain sources used in this paper also includes the respective hyperlink to each citation.

The physics and the prevailing methodology for accurate modeling of bird-slicing action and the resulting damage to fan blades have been built upon the groundbreaking work of Barber, Fry, Klyce and Taylor [6]. Since the original 1977 publication of their fundamental model of impact of soft bodies on jet engine fan blades, the slicing model has been verified and confirmed by abundant field experiences as well as multiple rig tests conducted by various engine manufacturers and the regulatory agencies. Since mid-1980's, different aspects of bird-strike analysis methodology and solution algorithms have been developed by leading engine manufacturers such as General Electric [7], Pratt and Whitney [8, 9, 10], Rolls-Royce [11], MTU in Germany [12, 13] and Saturn plant in Russia [14, 15], GTRE in India [16], IHI in Japan [17] etc. As such these codes and the related progress in the numerical simulation of bird-strike modeling methodologies are of proprietary nature, and most of the advanced research works have been out of sight of public domain, and essentially out of scrutiny of academic community

[18, 19, 20, 21]. However, all the numerical schemes were anchored in precise capturing of the high-velocity slicing action and the lead edge loading of the blade. In 1977, historically for the first time, a conceptual soft-body loading action during slicing as a fluid model was proposed by Barber [6] and his coworkers from the University of Dayton Research Institute and Wright-Patterson Air Force Base.

Original 1977 conceptual bird slicing model developed at the University of Dayton/WPAFB [6]:

In 1977, Barber and his coworkers [6] were the trailblazers to study the dynamic response of jet engine fan blades during bird-strike, where they emphasized the slicing action by the lead edge of the rotating airfoil shaped blades (see FIG. 2). In their schematic model, they considered bird as a moving projectile, which was sliced by a blade oriented at an oblique angle of 25° with respect to the bird trajectory. In their model, the incidence angle of 25° was empirically derived based upon the typical blade design in 70's. Referring to FIG.2 as the projectile is sliced, the impacting side or the lead edge of the blade is continuously loaded from underneath; thus bending it upwards. This insight was the very first attempt to describe as to how a slicing action can load the blade and will deform it locally by forming a "cusp" at the impacting edge of the blade.

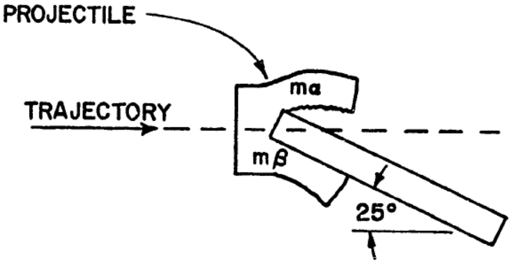

FIG. 2: Schematic for soft body impact onto edge of a rigid plate (approximating lead edge of fan blade) [6].

In the LS-DYNA implementation phase, the bird-slicing model has gone through its own developments, modifications, enhancements and improvements. They have included typical incoming bird being modeled in the geometrical shape of a circular cylinder with L/D = 2, and its axis coinciding with the engine axis. A typical result of LS-DYNA modeling of slicing mechanism of the bird produces following results (see FIG. 3).

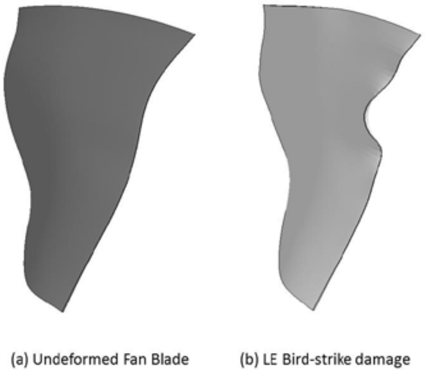

FIG. 3 "Cusp" type of plastically deformed Lead edge damage to metal fan blade during slicing of the incoming bird

The following is a chronological list of improvements and enhancements introduced in the bird-slicing methodology by different engine manufacturers:

(a) In 1984, Storace and his team [7] from the General Electric Company analyzed the bird orientation effect by using the largest slice-mass cut-out of a right circular cylinder model to represent incoming bird.

(c) In 1990, Niering [12] from Turbinen-Union of Munich, Germany analytically investigated the loading time-history applied by a pre-sliced bird as it travelled across the blade chord.

(d) In 1991, Teichman and Tadros [9] from Pratt & Whitney of Canada studied an incoming 1.5 Lbs bird, assumed in the shape of an ellipsoid, and the size of the slice effect in order to determine the blade deformation.

(e) In 1994, Martindale [11] from Rolls-Royce of Derby, England presented the results of a bird slice mass loading on the pressure side of the blade airfoil.

(f) In 2005, Frischbier and Kraus [13] from MTU, Germany analytically modeled the slicing action of a large size bird due to multiple blades being hit in one sector of the spinning rotor.

(g) In 2007, Ryabov and his coworkers [14] from Sarov Engineering Center of NPO Saturn in Russia using LS-DYNA systematically showed as to how a Lagrangian bird will be sliced by a fan blade.

Although, the very first slicing mechanism was proposed in 1977 by Barber and in his coworkers at the Wright-Patterson Airforce Base, the GE Aviation conceptual hypothesis was that it is the slice-size which was important [7], and not the mechanism itself. As such in an attempt to be conservative in their analysis, they assumed the largest possible slice, which happens to be when the bird cylinder axis is oriented along the velocity vector and opening between two consecutive blades. However, this assumption of largest possible impactor but a pre-sliced modeling approach under-predicted the damage to the fan blades. A similar observation was made by the MTU team, which also considered the pre-sliced bird in the shape of a hockey-puck.

Apparently unaware of the importance of slicing action, a recent 2016 paper of Zhanga and Fei [26] starts with the incorrect statement in the introduction section of their paper that, " …… realistic bird models have not been introduced into a specific aircraft structure's bird striking analysis yet". As a rebuttal and a proof of good similarity of field observation in FIG. 1 and analytical simulation in FIG. 3 highlight a typical cusp-shaped plastic deformation to the metal fan blade airfoil at its leading edge caused due to the slicing action of the ingested bird, and its explicit results, respectively.

Key Features of bird slicing model evolution and its simulation in LS-DYNA

In order to keep the historical perspective of our present discussion focused on slicing action of the bird, we will be using the original illustrations adapted from of previously published contributions in the respective journals (items (a) to (g)). This step enables us to bring to attention, as to how engine manufacturers have independently developed and pursued the bird-strike modeling and analytical methodology over many years. It should be noted that their original contributions are now available in many technical publications [6 - 25], which we will be referring and reviewing in the current discussion. The current author formally acknowledges their respective contributions to the body of knowledge with full credit to their work. For the past 10 years, the bird modeling scheme and meshing technique has been an evolving process and now it has achieved a matured robust methodology, which is being followed almost universally by all the major engine manufacturers in their routine design cycles of bird-strike tolerant fan blades. The following sections provide a historical time-line as to how the slicing model was conceptually developed and has progressed during the last 40 years:

Bird slicing model with bird-axis oriented along the Relative Velocity Vector [7]:

Once the effect of slicing action was understood as a transient loading mechanism, the focus shifted to quantify the amount of damage to the impacting edge with respect to the slice-size. As it is obvious from the Newton's second law of motion that larger the slice-mass, bigger will be the force. Keeping this rationale in mind, Storace and his coworkers [7] used the largest possible slice size, which can be cut out of bird-cylinder. Referring to FIG. 4, they determined the magnitude of dynamic force using an in-house computer code called NOSAPM.

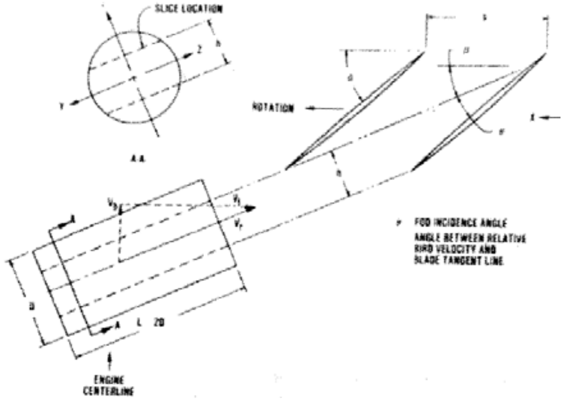

FIG 4: Soft-body impactor definition for full stage analysis. In this simulation, the bird is idealized as a right circular cylinder with a length-to-diameter (L/D) ratio of 2. The orientation of the axis of the bird is chosen to produce a slice having the largest possible mass [7].

Bird slicing model developed at Pratt & Whitney [8, 9, 10]:

Martin's approach [8] for modeling the bird as made up of individual particles was the first one of its kind, what is today is known as SPH bird. Teichman and Tadros [9] from Pratt and Whitney used a transient nonlinear impact analysis computer program, called PW/WHAM to simulate the engine component structural response to soft and hard body impacts (see FIG. 5). Their studies showed that the major factors affecting the structural response of fan blades under a bird strike are bird size (weight), blade size, bird velocity, fan blade rotational speed, fan blade spanwise location of impact, and bird orientation with respect to engine centerline.

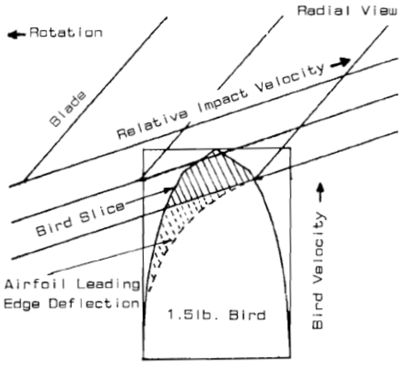

FIG. 5: Fan blade slicing of incoming bird in a 1991 paper by Teichman and Tadros [9].

Bird slicing model developed at Rolls-Royce, England [11]:

In 1994, Martindale [11] of Rolls-Royce analytically determined the deformation of hollow titanium fan blade caused by bird-strike. FIG. 6 shows the basic impact mechanism which is the cause of blade damage. As the bird enters the fan, it is sliced by each blade in turn. The mass of each slice is accelerated very quickly by the blades and exits the rear of the fan with greatly increased velocity. The acceleration imparted to the bird-slice mass produces high pressure loadings on the fan blade surface, typically 15 MPa (2175 psi), producing a dent or cup in the leading edge. This is the same acceleration loading caused by Coriolis forces described by Niering [12] in his earlier 1990 study.

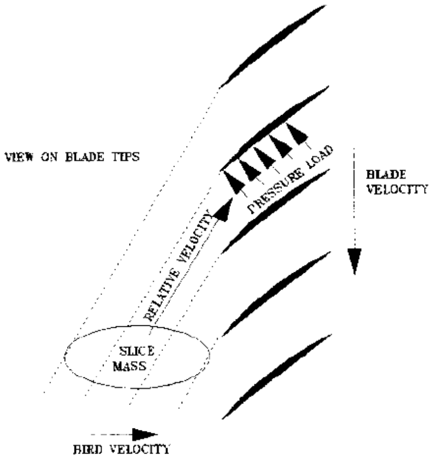

FIG. 6: Bird slice mass loading of rotating fan blades in a by Martindale [11].

Bird slicing model developed at MTU, Germany [12, 13] :

Niering [12] used an explicit finite-element code called DYNA3D (forerunner of LS-DYNA) to determine the dynamic load applied on a fan blade pressure surface by a pre-cut bird-slice in the shape of a hockey puck, as it slides, flows, deforms and travels through the airfoil chord from the lead-edge to the trail-edge side. Their model helped us in understanding as to how the Coriolis forces affect the trajectory of the bird-slice. These forces generate very high von Mises stress in the blade material, which can plastically deform the entire blade. FIG. 7 shows the results of the Niering's model.

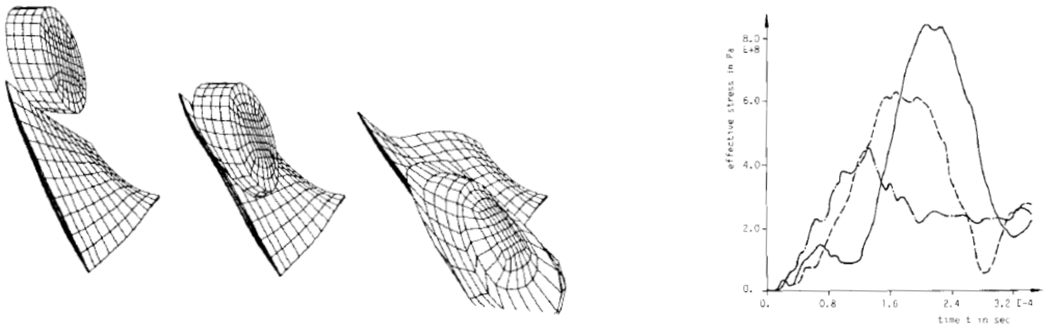

FIG. 7: Calculation of a bird strike on the intake blade of an engine: structural patterns and von Mises effective stresses in three points of the blade impact area by Niering [12].

In 2005 using LS-DYNA as a solver, Frischbier and Kraus of MTU [13] extended the learnings of single blade damage by a typical bird-slice to the slicing action of a full-size bird being impacted and sliced by multiple blades in one sector of the fan rotor. They used smooth particle hydrodynamic (SPH) element as well as ALE method to model the incoming bird. Their bird slicing model is graphically shown in FIG. 8, as the bird comes into contact with fan blades first. In their bird-strike model, they do not only consider the bird entering and being sliced by the fan, rather they also include the dynamic effect of bird slurry entering into the core of the engine. The bird slurry loads the HPC stage-1 rotor as well, which was confirmed in their test on PW6000 engine ingestion test performed in 2004.

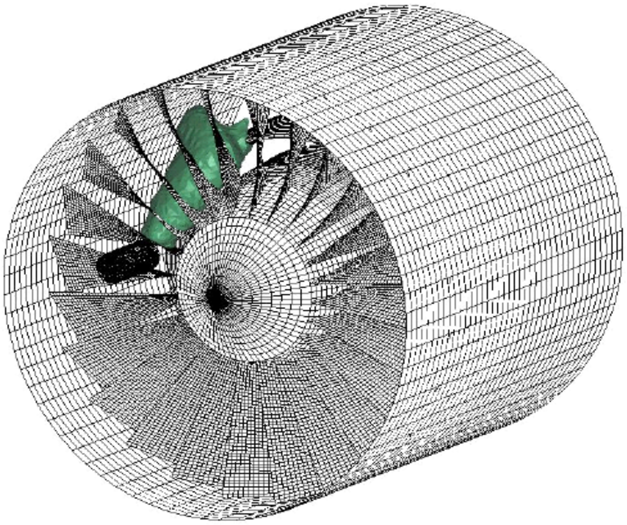

FIG. 8: Bird slicing and acceleration in the fan from a 2005 Paper by Frischbier and Kraus of MTU, Germany [13].

Preference of bird slicing model for Lagrangian FEA mesh developed at Saturn plant, Russia [14, 15]:

The contact dynamic forces produced by the ALE bird have been found to be very contradictory in nature. According to Goyal et al [19] the ALE bird produced much higher load than measured value, whereas Russian researchers like Ryabov and his coworkers' [14] findings were actually just opposite. In 2007 using LS-DYNA as the solver, Ryabov and his colleagues [14] compared the different modeling scheme of the bird as (a) Lagrangian mesh, (b) SPH (**S**mooth **P**article **H**ydrodynamics) and (c) ALE (**A**rbitrary **L**agrangian **E**ulerian) mesh. Their basis of comparison was to which option would be best suited to capture the physics of slicing action in terms of,

(a) Mesh distortion,
(b) Numerical accuracy of the peak contact forces applied by the bird on the blade, and
(c) Computational efficiency in terms of turn-around time.

Shmotin and his colleagues [15] further refined their LS-DYNA bird-strike slicing technique by using friction between the bird and the airfoil. Their paper considered different geometrical shaped idealized 1.5 Lbs bird traveling along the engine axis at 80 m/second, as it is sliced by coming into contact with multiple blades. In their model they also consider effect of friction on the blade surface. They verified their analytical results with the measured experimental data. They performed the Lagrangian bird simulations with five different values of the coefficient of frictions (μ = 0.0, 0.2, 05 0.7 and 1.0). Their finding was that analytical results matched much better with the experimental data with coefficient of friction being zero. Based upon their detailed analysis, ALE was the most inefficient for bird-strike analysis. Their main conclusion was that choosing between Lagrangian and SPH approaches, the first one is more preferable. Both Lagrangian and SPH approaches gave close loads to the blades, but the total CPU time for Lagrangian approach is ~1.5 times lower than for SPH. In the LS-DYNA simulations different researchers have attempted many different ways [16 – 24] to model the slicing action by considering it as a Lagrangian bird, ALE bird and more recently as a SPH bird.

Further advancements in bird-strike analysis [16 -24]

The bird material is best represented as a null hydrodynamic fluid using *MAT_009 made up of 10% air + 90% water. Its volumetric strain vs. compressive pressure is supplied using an equation of state (*EOS). The dynamic contact-impact load $F_{slicing}(t)$ during the slicing action with $B_a(t)$ being the bird-foot-print area on the airfoil leading edge, is computed as,

$$F_{slicing}(t) = B_a(t)\left[\frac{1}{2}\rho_{Bird}(V_n)^2\right] \tag{1}$$

In the above equation, V_n is the normal component of the bird relative velocity vector $V_{\mathrm{Re}lative}$ with respect the leading edge of the airfoil at the radial location of the rotating blade (see FIG. 9). The typical magnitudes of velocities relevant to the bird-strike impact event are:

(a) Normal component of relative velocity vector of the bird with respect to the tangential velocity of the rotating blades is usually 200 m/s.
(b) Axial velocity of incoming bird with respect to the fan blade is usually 100 – 120 m/s.
(c) Peak out-of-plane velocity of the blade airfoil pressure surface during local plastic deformation is about 40 – 60 m/s.

Depending upon the size of the bird as well as running speed of the fan rotor, the peak dynamic load on the blade airfoil can reach anywhere from 100 – 300 Kilo Newtons [5]. In February 2016, Abrate of the Southern Illinois University published a review paper in the Progress in Aerospace Sciences [4] detailing the status of bird-strike analytical methodology with respect to all aerospace structures. Abrate's paper of 2016 gives the best mathematical description to precisely determine the size of the bird-slice, which includes the full nonlinear effect of blade deformation, after a bird gets ingested into the engine (see FIG. 9). The detailed of all the necessary and relevant equations of the slicing model calculations can be found in author's previous ASME paper [5] of 2013.

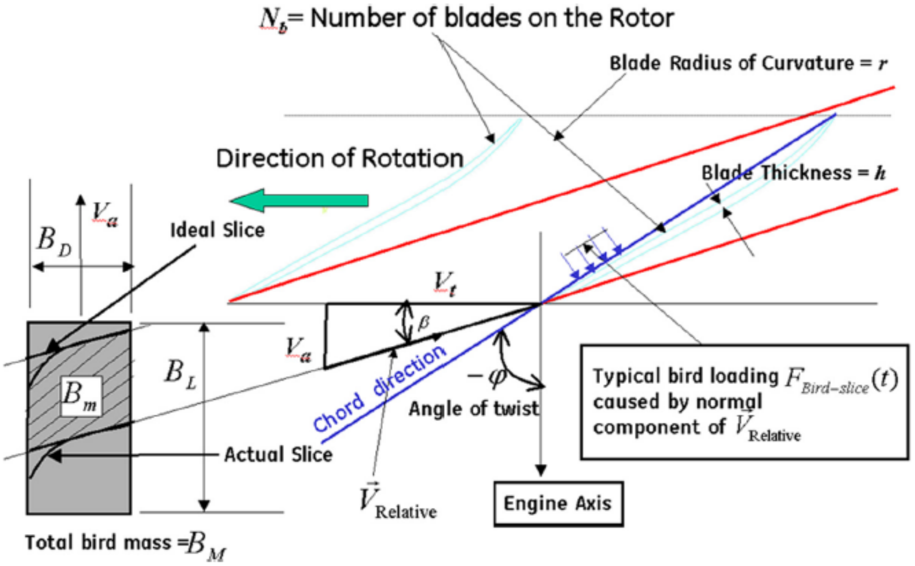

FIG. 9: Effect of relative velocity vector $V_{\mathrm{Re}lative}$ and nonlinear effect of airfoil leading edge deformation during slicing action of the fan blade [5].

Many different parameters such as, (a) Bird size, (b) Incidence Angle, (c) Relative velocity of impact, (d) Blade span height of initial contact, (e) Blade leading edge thickness at the pint of impact, (f) Blade material properties (Composite vs. Metal) , (g) Number of fan blades on the rotor, (h) Rotational speed (RPM) of the fan, (i) Aircraft speed, and (j) Hydrodynamic pressure loading at the leading edge of the airfoil during the slicing-impact play a significant role in affecting the bird-strike damage to a fan blade. In any analytical simulation during the preliminary design of a blade airfoil, the biggest challenge is that how a systematic study can be made, where effect of each of these parameters can be properly evaluated, in a given design space. The LS-DYNA model must be validated for this purpose such that the results remain numerically stable for the entire duration of the analysis and without any significant increase in the hourglass energy. On that note in the recent times a lot of research work has been done to get a better insight into the dynamic response of a fan blade subjected to a bird-strike loading during routine commercial flight.

Improvements in Lagrangian Bird slicing model developed at the Royal Institute of Technology, Stockholm, Sweden [25]:

In 2015, Hampus Larsson [25] of KTH Royal Institute of Technology in Sweden analytically determined the transient loading time-history during the slicing process as the contact area changes. In his thesis, the bird slicing model previously produced by Sinha and his coworkers [5] was further improved by considering the airfoil curvature. Larson’s work showed that camber curvature and changing depth of slice at the leading edge of the airfoil have a significant effect on the dynamic loading of the blade. The curvature also affects the exit trajectory of the bird-slice after it has slid out of the blade pressure surface at the trail-edge of the blade. The dynamic response of a composite fan blade can studied in detail using the results of reference [27].

The detailed slicing action described in the Larsson’s thesis is schematically shown in FIG. 10. In this model he investigated of the time-dependent parameter slicing depth ‘*h*’ and the resulting sliced area $A_c(h)$. It should be noted that the rotating blade is moving from right to left as the slicing action progresses through time using the bird cylinder with the original diameter being ‘*D*’.

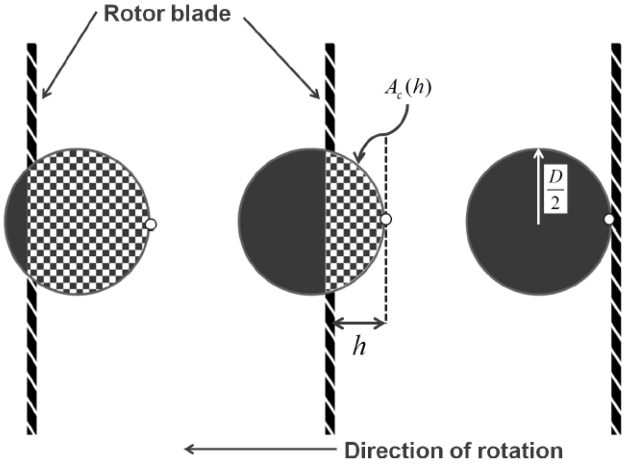

FIG. 10: Sliced area as a function of ‘*h*’ for the time steps, looking into the engine in the axial direction as presented by Larsson of KTH Royal Institute of Technology in Sweden [25].

Currently, a good amount of research work is being done about modeling the bird-strike on composite fan blades [21, 22, 28, 29]. Two review papers first one published by Heimbs [3] in 2011, and the recent one by Abrate [4] in 2016, provide the most comprehensive list of references in the area of bird-strike analysis on composite blades as well.

For instance, in addition to some fundamental work in the area of bird-strike slicing analysis listed here, Siddens and coworkers [21] from Virginia Tech are analyzing the progressive failure of composite blades caused by the slicing action of the bird by the leading edge of the fan blade. Sinha [22] considers the slicing action of the bird by lead-edge of a composite fan blade, which is of current interest in th1e entire aerospace industry. It should be noted that as composites do not have any ductility, and as such do not form local “cusp” as exhibited in the metal blade plastic deformation of the leading edge, it can rupture the fibers into pieces as shown in FIG. 11. In the LS-DYNA formulation the composite blade is modeled as an orthotropic plate or shell with equivalent bulk elastic properties such as E_a ,E_b, E_c, ,ν_{ba},ν_{ca} , and,ν_{cb} etc. Here (a, b, c) represent the local material orthogonal directions, usually span, chord and thickness directions. Thus, similar to the isotropic plate formulation, the corresponding equations of flexural rigidity for an orthotropic rectangular plate with uniform thickness h’ are:

$$D_{11} = \frac{E_a h^3}{12(1-\nu_{ab}\nu_{ba})} \qquad D_{22} = \frac{E_b h^3}{12(1-\nu_{ab}\nu_{ba})} \qquad D_{12} = \frac{\nu_{ba} E_a h^3}{12(1-\nu_{ab}\nu_{ba})} = \frac{\nu_{ab} E_b h^3}{12(1-\nu_{ab}\nu_{ba})}$$

$$\text{and,} \quad D_{66} = \frac{G_{ab} h^3}{12} \qquad D_{16} = \frac{G_{ac} h^3}{12} \qquad D_{26} = \frac{G_{bc} h^3}{12} \quad . \tag{2}$$

Most of the composite failure models are still in the proprietary domain of the engine manufacturers. In LS-DYNA solver, they are usually implemented through UMAT option. Other composite failure models such as MAT_161 and MAT_162 are available on license by MSC Corporation. In the UMAT implementation of fiber-reinforced layered composite, the equivalent bulk modulus K for determining the sound velocity in the bulk material is calculated using dominant Young’s modulus term E_a (EA) which is usually the span direction of the fan blade, the Poisson’s ratio in the in-plane direction ,ν_{ba} (PRBA), and the Poisson’s ratio in the thickness direction ,ν_{ca} (PRCA), as,

$$\begin{aligned} K &= \frac{Hydrostatic\ \ pressure}{Volumetric\ \ strain} = \frac{E_a}{3(1-\nu_{ab}-\nu_{ac})} \\ &= \frac{\text{EA}}{3[1-\text{PRBA}*(\text{EA/EB})-\text{PRCA}*(\text{EA/EC})]} \end{aligned} \tag{3}$$

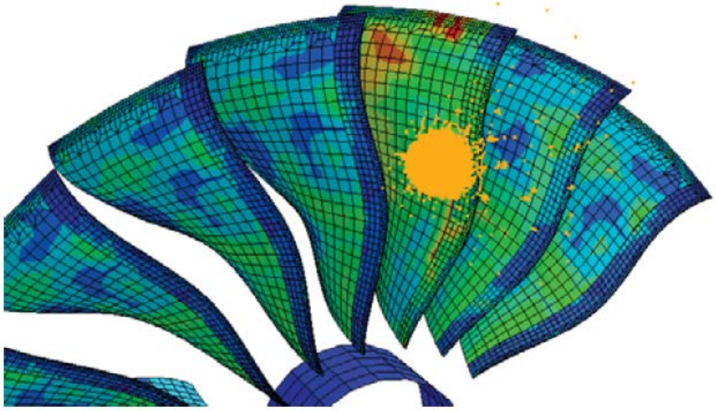

FIG. 11: Progressive damage to a composite Fan blade rotor due to bird-strike [21].

In the composite fan blade bird-strike applications, it is sufficient to use equivalent elastic smeared up bulk material properties such as E_a ,E_b, E_c, ,ν_{ba},ν_{ca} , and,ν_{cb} etc instead of ply-by-ply modeling approach, usually followed in several academic publications. From the practical design consideration, in order to withstand the slicing-impact load at the leading edge, usually wrapped-around metal cladding is required, which is also shown in Figure-11.

Comparison of bird-strike modeling using Lagrangian and SPH Elements

As a field experience and also by their supporting evidence in a rig test, Pratt & Whitney engineers have made significant contributions in this field. In an April 2000 paper by Vasco [10], presented at the LS-DYNA Users conference, showed the picture of a bird-strike damage on a fan rotor, witnessed during a rig test. In his analysis, bird was modeled as a fluid with Lagrangian solid elements. His LS-DYNA results of blade damage showed an excellent comparison between the analytical results and the test observation. The current trend is to model the bird using SPH elements [3]. In a SPH bird representation, the following is a set of cards needed to model the incoming bird in LS-DYNA.

*CONTROL_SPH card allows the all the SPH elements to be encased in a box. This card is used to input the basic information about the SPH elements.
*ELEMENT_SPH card enables the SPH elements to be defined by SPH nodes, Part number along with its nodal masses.
*SECTION_SPH card is used to determine the reaction load on the SPH elements.

The most recommended interface card between the bird and the blade is:
*CONTACT_AUTOMATIC_NODES_TO_SURFACE_TITLE

It should be noted that in all the bird and blade interfaces, only the pressure side of the blade should used in the SURFACE SEGMENT definition. This recommendation applies equally well both for the Lagrangian bird as well as the SPH bird. Similar to Ryabov's study [14], in this sample bird-strike problem, a single blade airfoil mesh is generated. The blade is considered clamped at the airfoil root. The blade is hit in the middle, such that the incoming bird is sliced. Two different models of the bird (a) Lagrangian and (b) SPH mesh have been generated. Both models have same number of bird nodes (57571 nodes). The model has been run for 2 milliseconds from the initial contact. FIG. 12 shows the slicing of a Lagrangian bird mesh, and FIG. 13 illustrates the slicing of a similar SPH bird mesh. Bird material properties are described by Equation of state using the compressibility characteristics of 90% Water + 10% air mixture.

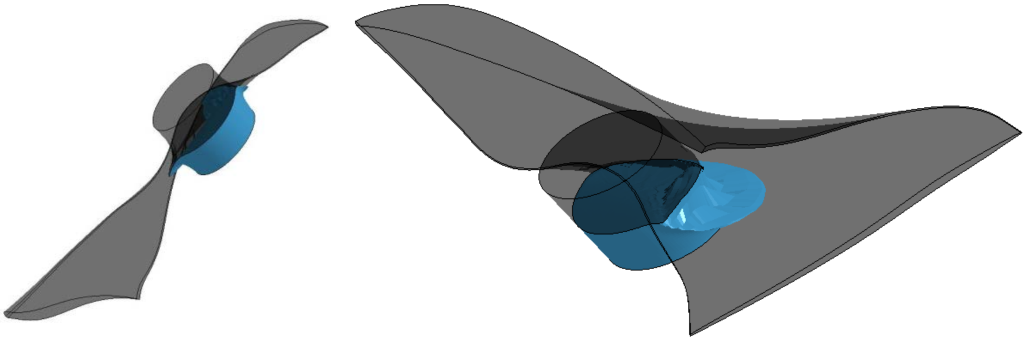

FIG.12: Two different views of a Lagrangian bird being sliced by a metal blade in LS-DYNA simulation and a "cusp" is forming at the leading edge simultaneously

In the sample example problem considered in this paper, the peak dynamic load with the Lagrangian bird reaches up to 150 Kilo Newton. During the slicing phase, the corresponding dynamic normal pressure on the concave surface of the blade airfoil in the vicinity of leading edge elements, applied by the bird material (10% Air + 90% water) gets as high as 350 MPa. These numbers are consistent with Eq. (1) and also agree very well with the semi-analytical solution of reference [5]. Depending upon the bird-size and its weight, the peak magnitude of the transient dynamic slicing-load can reach in the range of 200 – 300 Kilo Newton lasting for about 1-2 milliseconds of time duration. For large size wide-chord fan blades, and the span height at which the bird-strike happens, the total loading duration time could be as high as 3-4 milliseconds. In a fully-blade rotor, the 3rd and 4th blade may have maximum damage than the first two blades. This is usually because the first two blades may not get the full slice due to phase difference in deformation of different blades of the sector being hit by the bird.

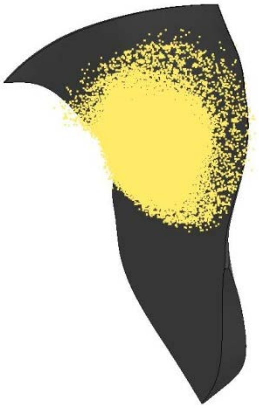

FIG.13: Slicing of SPH bird in LS-DYNA simulation

Figure-14 shows the normalized dynamic load characteristics of a typical bird-slicing model for both Lagrangian and SPH birds. As it is evident, the SPH bird captures the full dynamic characteristics of the load time-history similar to Lagrangian bird, but it underestimates the peak load by almost 20%. Otherwise, the loading pattern is approximately true for the entire duration of the dynamic event, which includes both the slicing time as well as the bird-slice travel time on the concave surface of the airfoil. The second peak of 40% of the peak load during the travel time signifies the effect of Coriolis forces due to sliding motion of the bird slice on a rotating blade. In addition, the computation time with the SPH bird of exactly same size (number of nodes) bird model, is almost 3 times longer than the corresponding Lagrangian bird model.

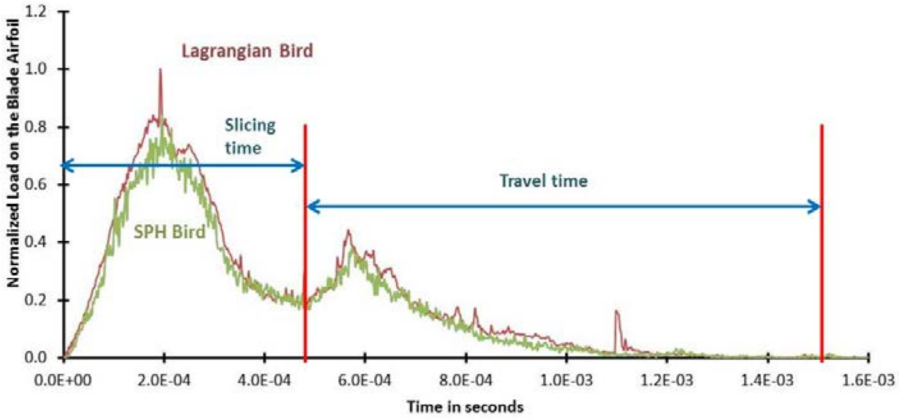

FIG. 14: Comparison of dynamic load applied by the Lagrangian bird vs. SPH Bird on the blade airfoil. SPH bird peak-load is about 80% of the peak-load computed by the corresponding Lagrangian bird.

SPH Bird produces consistent results and can handle slicing action without sever distortion of the mesh. Bird loading wise both Lagrangian and SPH Birds exhibit almost similar dynamic characteristics, but magnitude wise SPH bird peak load is only about 80% of the corresponding Lagrangian bird. However, the SPH bird is very expensive in terms of computational resources.

Conclusions

In this study, an attempt has been made to highlight the physics of bird-slicing action by a running turbofan engine. This review paper provides a historical perspective of the bird-strike analytical methodology, as it has evolved and matured during the 40 years, mainly at various engine manufacturers. The numerical simulations using LS-DYNA as the solver has been at the forefront of technical advancement in this area. LS-DYNA offers many different options such as Lagrangian bird, SPH bird as well as ALE approach to simulate the dynamic loading on the fan-blade. As it has been observed, the ALE bird never produces the right magnitude of dynamic loads, which is anywhere closer to the observed magnitude. Currently, the SPH Bird modeling is being used both for metal as well as composite fan blades. This study focuses on a detailed comparison about the numerical accuracy and computational performance in capturing the transient dynamic loads on the fan blade during bird-slicing event.

In a typical field-event of a single bird being ingested in a running engine, it is common to observe bird-strike damage to multiple blades of the fan rotor. The most damage in the shape of a “Cusp” at the leading edge of the airfoil may happen to the 3rd or 4th blade in the impacting sector of the fan rotor from the point of initial contact. The analytical modeling and numerical simulation of a typical bird-strike event on a fully-bladed fan rotor, is extremely computational intensive, and may take several days of run time even on MPP servers and the fastest computers in the world. SPH Bird has been found to be taking 3 times longer to run than a comparative Lagrangian bird for identical size LS-DYNA model in terms of number of nodes. Numerical accuracy wise, the peak load computed by SPH bird is only 80% of that of corresponding size Langrangian bird. Although Lagrangian bird invariably exhibits severe mesh distortion, this problem can be resolved very easily by refining the mesh. As the computers have become powerful, faster and smaller, the model size with a very refined mesh has become almost a non-issue. It may be of additional concern that a Lagrangian bird may show some additional spurious peaks during the travel time of the slice. However, that should not be of any concern, because most of the damage during the bird-strike is caused at the lead edge during the slicing and during the sweep time.

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