Modeling Bird Impact on a Rotating Fan: The Influence of Bird Parameters

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Abstract

The ability to withstand bird impact is one of the major requirements of the modern aircraft jet engine. In fact, rigorous certification procedures are put in place to assess the engine's ability to sustain severe impact loads developed during bird impact. Full scale bird tests are expensive and time consuming, and call for the use of accurate numerical approximations during the design stages of engine development. The main difficulties encountered in achieving accurate finite element (FE) analysis are related to modeling of the bird which undergoes severe deformations, and modeling of the contact between the bird (soft) and blade (stiff) materials. Thus far Smooth Particle Hydrodynamics (SPH) modeling in LS-DYNA®, which is a meshless method, had shown potential in adequately modeling the bird and the bird-blade interactions. Recent publications also show the ability of SPH based models to capture impact strains and forces seen by the rotating fan blades [1, 2]. The current study further investigates the interaction of the SPH bird with the FE blades, and the ability of the model to capture realistic blade deformation. The main emphasis is placed on the effect of the bird related parameters on the damage sustained by the blades.

1 Introduction

As airplanes share the sky with birds, they are vulnerable to bird strikes, which could result in serious structural damage and performance loss. An engine is not exempted from such collisions, and has to comply with strict airworthiness standards which are put in place to ensure its safe operation after a bird strike. In fact, before an engine can be certified for service, it has to pass full scale bird ingestion tests, which are expensive and time consuming to perform. To maximize the probability of passing the test, finite element (FE) computer simulations of the impact event are performed during the design process.

1.1Theory

When it comes to modeling a bird strike, FE representation of the blades is rather straightforward since their mechanical properties and geometries are known. On the contrary, properties related to the bird are complex and largely unknown, and thus far, have been the subject of numerous research efforts [5-9]. Some of the earlier experimental work on quantifying bird properties was done by Wilbeck [3]. He concluded that during soft body impact, the yield stress of the projectile is quickly surpassed due to rapid deceleration [3]. Hence, elastic properties are insignificant, and the bird can be treated as a hydrodynamic body which essentially acts like water during impact. Hydrodynamic pressure-volume relation can be defined by an equation of state (EOS) in the form of a third degree polynomial, refer to Equation 1.

$$P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3$$
$$\mu = {}^{\rho}\!/_{\rho_0} - 1 \qquad [1]$$

In Equation 1 **μ** is the relative density. For a material such as water which exhibits the linear Hugoniot relation between shock velocity and particle velocity, the EOS can be expressed in terms of the following coefficients [4]:

$$\begin{aligned} C_0 &= 0 \\ C_1 &= \rho_0 c_0^2 \\ C_2 &= (2k-1)C_1 \\ C_3 &= (k-1)(3k-1)C_1 \end{aligned} \qquad [2]$$

Where, $\mathbf{C_o}$ is the initial equilibrium pressure and is considered to be negligible, $\boldsymbol{\rho_0}$ is the initial density, $\mathbf{c_o}$ is the speed of sound in the material and **k** is the experimental constant derived by Wilbeck. Based on experimental results, Wilbeck had proposed to use an EOS corresponding to that of water with 10% porosity (air) [3]. Additional studies were performed to investigate the effect of the EOS on shock pressure, steady-state pressure and radial pressure distribution [5-7]. In fact, A. Nizampatnam [5] showed that 30-40% porosity provides better results. Overall, an EOS of the bird is an approximation of its actual properties and serves as a calibration parameter in the model [4].

Given the large shock pressures developed during impact and the significant mismatch between the mechanical properties of the blades and the bird, it is common place to model the bird as a homogeneous body with simplified shape and properties. Previous publications compared the influence of the bird aspect ratios and basic geometries including cylindrical, spherical, ellipsoidal and cylindrical with two hemispherical ends on the resultant impact pressure profile [5-8]. Overall, the most frequently adopted and recommended shapes are a cylinder with two hemispherical ends [3, 5-8] or an ellipsoid [1, 8, 10] with an aspect ratio of 2 [4-8, 12]. Some effort has been placed in creating more detailed models of the bird, which better mimic its actual shape (head, neck, and torso), density distribution and mechanical properties (i.e. softer lighter lungs vs. denser stiffer bones) [5, 9]. These models have the potential of improving accuracy of the simulation, but they significantly complicate the problem by introducing new parameters. Hence, for this study it was decided to refrain from the use of such models and represent the bird by a hemispherical ended cylinder.

1.2 Motivation and Scope

Numerous papers have been found that dealt with modeling of bird impact on flat plates, stationary engine blades, wing leading edges and windshields. In addition, different methods have been applied for bird modeling including Lagrangian, arbitrary Lagrangian-Eulerian and smooth particle hydrodynamics (SPH). The SPH method offers an advantage over other methods, as it is a mesh-less technique that has the potential to properly capture the physics involved in the ingestion of the bird by an engine. However, a limited number of papers have been found that dealt with bird strike analysis of rotating engine fan blades, with even fewer studies employing SPH to model the bird [1, 2, 10]. The main focus of this study was to implement the SPH method for modeling a bird impact on a rotating fan, and to investigate the influence of the bird parameters on the damage sustained by the blades. A comparison was made between the severity of the impact damage and the deformed shape of the blades with respect to different aspect ratios and EOSs of the bird. Also, a sensitivity study was performed regarding the number of SPH particles used.

2 Description of the model

The computer model was setup to mimic the test conditions of the recent engine bird strike test. This engine has an intermediate size fan and was impacted by a 0.7 kg [1.5 lb] bird. During this test, the blades were rotating at 10,000 rpm, the bird speed was measured to be about 75 m/s [3 in/ms] and the impact occurred at approximately 70% of the blade span. The damage sustained by the blades was qualitatively assessed in terms of the shape of the deformed blades and the severity of the overall damage of the fan. Results of these simulations were compared to the damage sustained by the blades during the actual bird strike test.

2.1 The Fan

The fan model was simplified to include only the blades to avoid the complexities associated with detailed modeling of blade-to-hub root attachments. As a result, all boundary conditions and constraints were imposed at the root nodes. To reduce the model size and the computational time, the number of blades included in the model was reduced to 12. This quantity was more than sufficient to fully ingest the bird. The properties of the blades were defined by a comprehensive Johnson-Cook material model which incorporates strain rate sensitivity and temperature effect. Previous studies have shown that Johnson-Cook models are appropriate for capturing blade deformation and failure under conditions prevalent during a bird strike on an engine [11]. The blades were modeled by a fully integrated shell element (ELFORM 16), and in total were made up of 55,000 nodes and 18,000 shell elements. The impact model also took into account the stresses associated with rotation of the blades, and included post-impact damping to minimize blade oscillations. This model was created and imported into LS-DYNA via an in-house software.

2.2 The Bird

The bird geometry (cylinder with hemispherical ends) was generated directly in LS-DYNA Prepost 2.2, by creating the spherical and cylindrical shapes, and merging the overlapping SPH nodes. In this study aspect ratios (AR) of 1.5 and 2 were considered, see Figure 1. The number of particles used was varied from 10,000 to 110,000 to assess the sensitivity of the model. The bird density was set to 950 kg/m^3 [0.034 lb/in^3], a value which corresponds to the density of gelatin and is within the range of commonly used densities for birds (900-950 kg/m^3) [7, 8, 12].

Material properties of the bird were defined as elastic-plastic-hydrodynamic. In the elastic region, the shear modulus and yield stress were set to 2.0 GPa [0.29 Msi] and 0.02 MPa [2.9 psi], respectively. These values were effectively used in previous studies [12]. Overall, these parameters are not expected to have a significant influence on the stresses developed during impact, as the elastic region is quickly exceeded. The hydrodynamic regime was defined by an equation of state corresponding to water with 0%, 10% and 15% porosity; respective coefficients are summarized in Table 1. The coefficients for 0% porosity were calculated based on the Eq. 2 with $k = 2$ and c_o=1480 m/s [12]. Coefficients for 10% porosity are based on the pressure-density relationship derived by Wilbeck [3]. In the case of 15% porosity, coefficients were chosen to slightly offset the curve to the right, hence making the bird more compressible (compliant), see Figure 2. This approximation was acceptable for the current study, since the actual coefficients are hard to determine and the EOS can be treated as a calibration parameter to adjust the model [4].

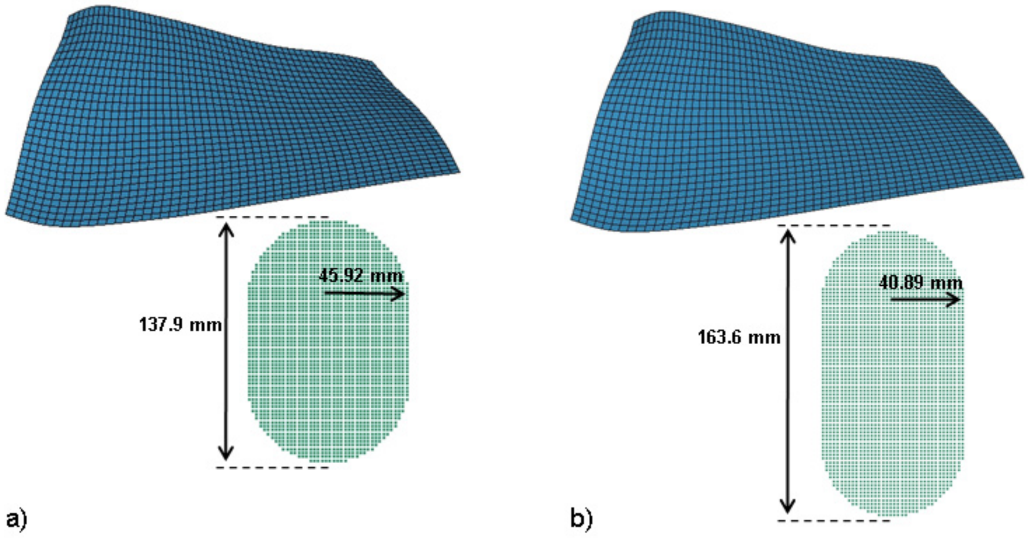

Figure 1, Dimensions and positioning of a bird with an aspect ratio of a) 1.5 and b) 2

Table 1, Equation of state coefficients used in the model to represent water with 0%, 10% and 15% porosity

Coefficients	**0% porosity [MPa/ Ksi]**	**10% porosity [MPa/ Ksi]**	**15% porosity [MPa/ Ksi]**
C_1	2060/ 300	28/ 4.06	6.9/ 1
C_2	6160/ 900	-85/ -12.3	-3180/ -200
C_3	10300/ 1500	35000/ 5076	31000/ 4500

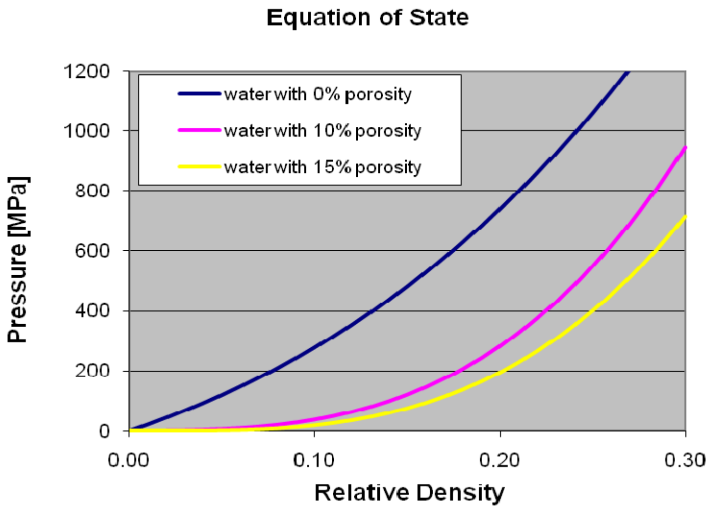

Figure 2, Pressure-density relationships as per EOS coefficients given in Table 1

2.3 Contact

An automatic-nodes-to-surface contact was defined between the blades (master) and the bird (slave). This contact type checked for penetration of the master segment by the slave nodes, which was in fact a desired feature due to the nature of the problem at hand. The viscous damping coefficient (VDC) was set to 40% to eliminate any instability due to the difference in the mechanical properties between the two impacted materials which can develop in SPH based models [13].

3 Discussion of Results

Numerous simulations were run with birds having different EOS, AR, number of particles and locations (with respect to the blade) to achieve a better statistical representation of the observed trends. An example of the bird-blade interaction at different time steps is included in the Appendix. The initial step of this study was aimed at assessing the sensitivity of the model to the number of SPH particles used to represent the bird. The particle count was varied from 10,000 to 110,000. Overall, it was found that the minimum number of particles required to achieve smooth blade deformation was about 36,000.

3.1 Effect of the Equation of State

Equations of state corresponding to the different amounts of porosity were compared in terms of the resultant shapes of the deformed blades and the overall damage to the fan. Implementation of EOS corresponding to 0% porosity [from this point on referred to as EOS 0] led to visibly more damage to the blades than the use of EOS corresponding to 10% or 15% porosity [EOS 10 and EOS 15]. These results were anticipated since EOS 0 represents a ‘stiffer’ bird which would in turn cause more damage than the ‘softer’ more porous bird of the same mass. In fact, previous studies have shown that birds modeled by EOS 0 generated a higher impact pressure on the target structure than those modeled by EOS of porous water [6, 7].

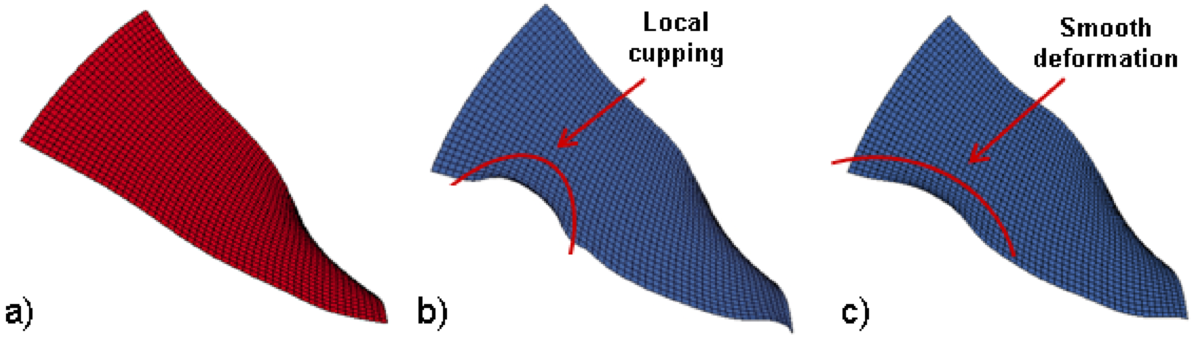

Figure 4, Shape of a) an un-deformed blade and of deformed blades obtained with b) EOS 0 and c) EOS 10

Moreover, interesting observations were made regarding the post-impact blade shapes attained by using different EOS. Overall, the use of EOS 0 resulted in well pronounced cupping (Figure 4b) that could be seen in 4-6 blades. On the contrary, implementation of EOS 10 or 15 led to only 1 or 2 blades being substantially damaged. In addition, these blades showed more global deformation (Figure 4c) instead of the localized cupping as in the case with EOS 0. These differences are further illustrated by Figure 5, which shows blade deformation in terms of leading edge deflection from the original shape for EOS 0 (5a) and EOS 10 (5b).

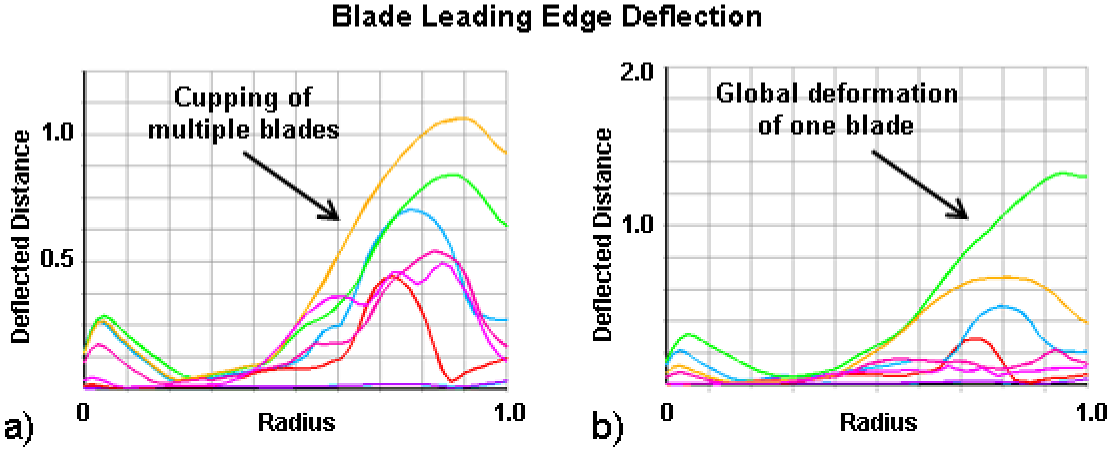

Figure 5, Blade deformation plots for a bird with a) EOS 0 and b) EOS 10 [Values are relatively scaled]

These characteristic differences between the deformed blade shapes can probably be linked to the radial pressure distribution created during impact by a cylindrical projectile. It was shown by R. Jain et al [6] that the contact pressure is the maximum at the center of the projectile and drops quickly towards its sides. Figure 6 shows that pressure at the center is significantly higher for a projectile with no porosity versus that with 10% or 15% porosity. In fact, the cupped shape of a deformed blade resembles the bird shape (hemispherical cylinder) used in the current study. L.-M. L. Castelleti et al [10] also emphasized the influence of the diameter and internal density variations of the projectile on the slicing effect of a rotating blade. Even though these parameters are initially the same for all test cases corresponding to the same AR, they change during impact, and these changes are in part governed by the EOS, which defines the pressure-volume response of a soft projectile. Hence, it can be anticipated that the bird-blade interactions and the resultant pressure distribution profiles are more complex during impact with a rotating structure than during a straight head-on collision. Thus, bird porosity has an intriguing effect on deformation of rotating blades.

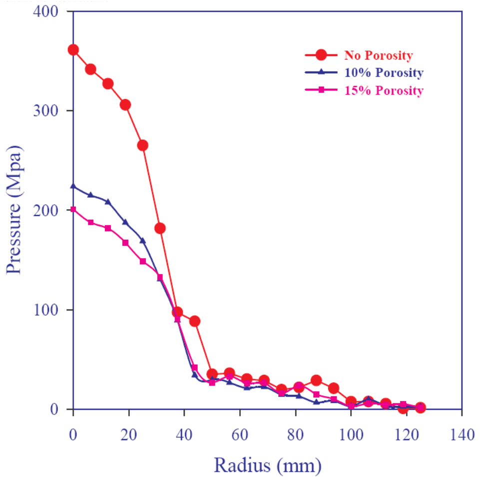

Figure 6, Radial pressure distribution generated during impact of a soft cylindrical projectile [6].

3.2 Effect of the Aspect Ratio

The effect of the bird geometry on the deformed blade shape was investigated by considering birds of different aspect ratios, 1.5 vs. 2 [referred to as AR 1.5 and AR 2]. As it was anticipated, more blades are damaged when a bird is modelled by AR 2 (Figure 7a), simply due to the fact that it is longer. Additionally, the shape of the deformed blades was also strongly influenced by the bird AR. Application of a smaller diameter bird, AR 2, led to cupping of all damaged blades (Figure 7a). On the contrary, application of a wider AR 1.5 bird resulted in severe global deformation of 1 or 2 blades, which then shielded the following blades from the bird (Figure 7b). These results are in line with the conclusions drawn regarding the use of different EOS, and re-emphasize the influence of the bird diameter and internal pressure or density distribution on the damage sustained by the fan blades during a bird strike. Overall, fan damage predicted by simulations involving AR 1.5 bird matched well with the available test data. Thus far, modeling a bird as an SPH cylinder with hemispherical ends and an aspect ratio of 1.5 shows potential to adequately capture the impact dynamics involved in the problem; however, additional work is necessary to confirm these results.

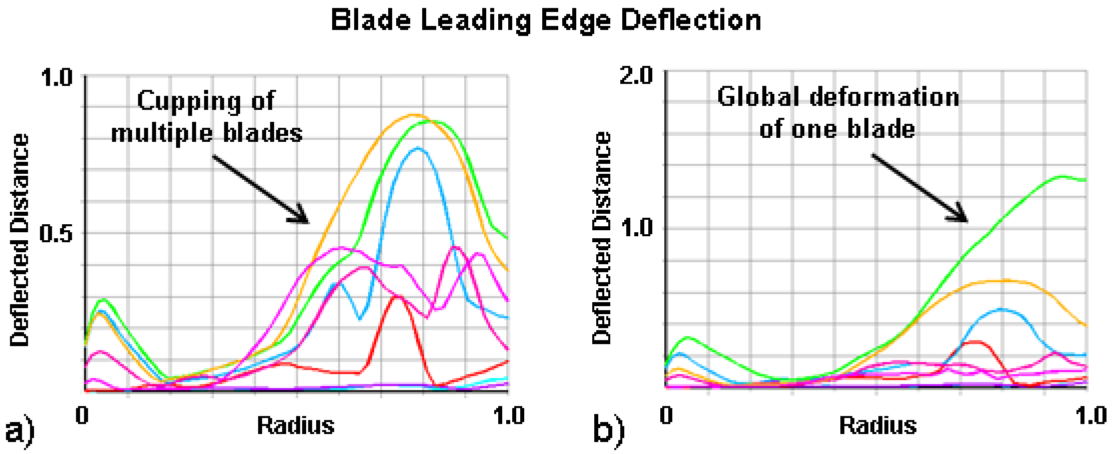
Blade Leading Edge Deflection

Figure 7, Blade deformation plots for a bird with a) AR 2 and b) AR 1.5
[Values are relatively scaled]

4 Conclusions

LS-DYNA was used to simulate a bird strike on an engine and to investigate the effect of bird related parameters on the damage sustained by fan blades. Through numerous simulations it was found that the geometry of the bird and its hydrodynamic properties incorporated into the model strongly influence the bird-blade interaction during the impact, due to the coupled effect of impact and slicing. Overall, blade deformations attained while using an AR 1.5 bird in combination with EOS 10 agreed well with the results of the previously conducted bird strike tests. The present study has further shown the potential of the SPH based impact models to capture damage sustained by the fan blades during a bird strike. Future work will encompass application of the SPH method to bird strike analysis on other Pratt and Whitney engines.

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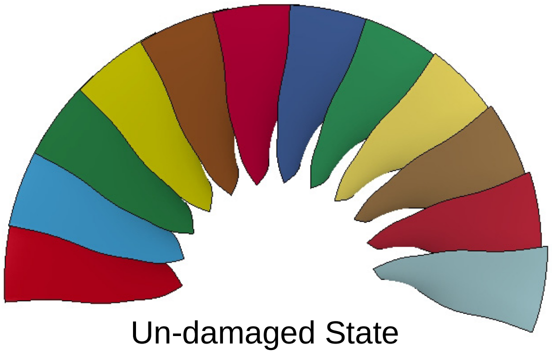
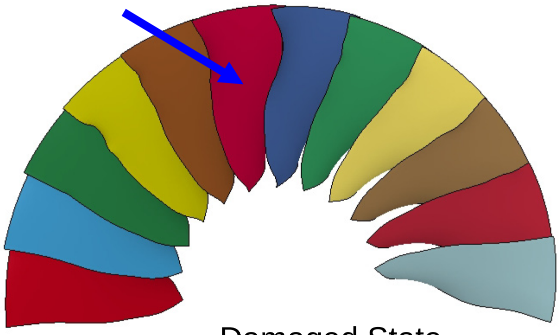
Appendix


Un-damaged State



Damaged State

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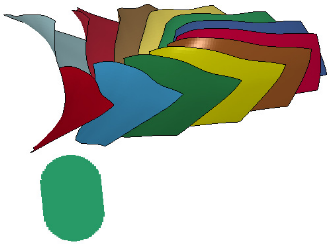

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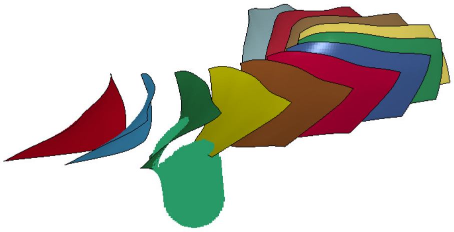
Time 0.6 ms



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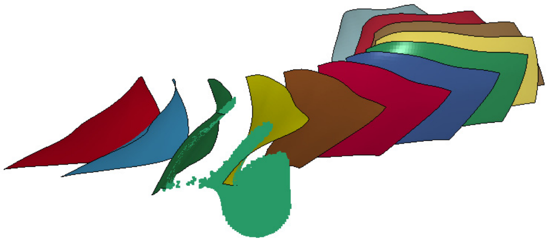

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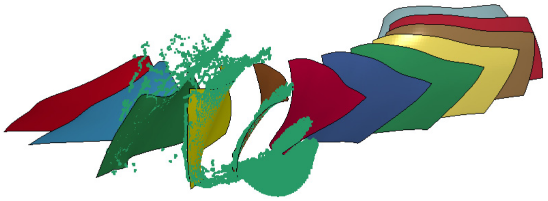

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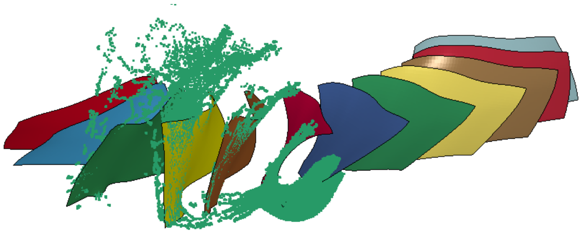

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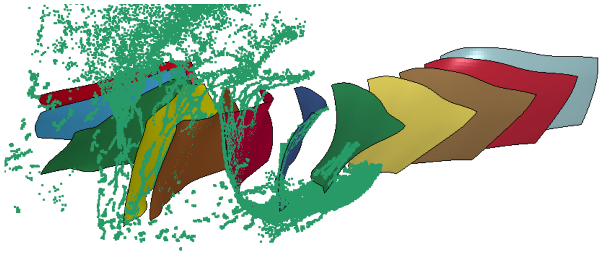

Final deformed shape (damped out)