Bird strike on an engine primary compressor with high rotating speed: Numerical simulations and parametric study

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Abstract

Bird ingestion by jet engines will lead to serious consequences such as power loss, aircraft fires, and high speed blades debris, which is catastrophic to aviation. The primary compressor is the most vulnerable component during the transient impact. The method of experiment and simulation usually was used to anti-bird strike design on blade. However, simulation and experiment on compressor under bird strike at high rotating speed was rarely carried out.

In present paper, the model of a compressor impacted by bird is established by using commercial explicit code PAM-CRASH. The bird is meshed with smooth particles hydrodynamic (SPH) method and Murnaghan equation of state is employed to describe the fluid behaviour of the bird under high speed impact. The bird model shows no sign of instability and accurately characterized the splashing particles of the bird. Simulation of compressor revolving at speed of 3000r/min and 8000r/min impacted by bird with mass of 250g is preformed according to the experiments. The results show a good agreement between simulation and test , which indicates that the SPH－FE method could provide a very powerful numerical model in predicting the transient dynamic responses of engine structures in bird impact events. Finally, a number of parametric studies are conducted including: influence of the failure stain, the bird impact location, and impact timing.

Keywords: Bird impact, Engine blades, SPH method, Constitutive model, Transient finite element analysis

Introduction

Just about one and a half years after the first airplane was invented, Wright Brothers recorded the first bird-strike on 7 September 1905 [1]. Nowadays, bird-strike puts almost every single flight in risk. According to Federal Aviation Administration (FAA) database [2], the number of reported wildlife strikes of civil aircraft increased dramatically from 1990 to 2013, as is shown in Fig.1. In America, 10,856 bird strikes occurred solely in the year of 2013 and 601 of them caused damage to aircraft components. Besides, over 50 planes of civil aviation have been destroyed and more than 220 people have died due to bird-impact accidents since 1912 [3].

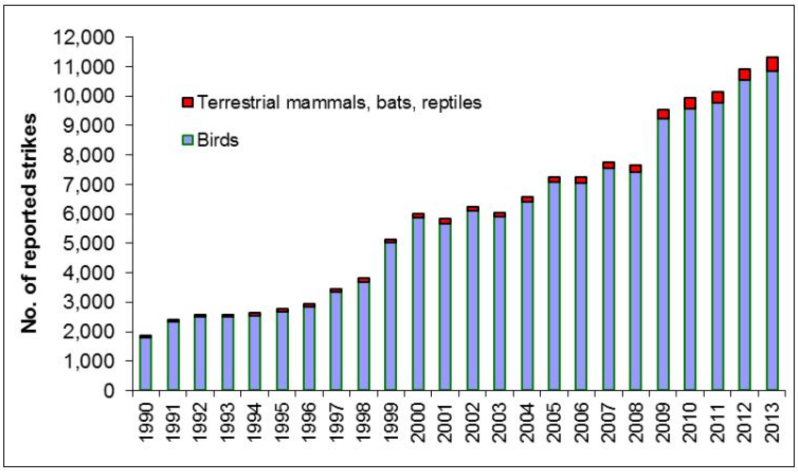


Figure 1. Number of reported wildlife strikes with civil aircraft, USA, 1990－2013.

Aircraft engines are most easily damaged by bird strikes (30 percent of all damaged components) compared with other components. They are particularly vulnerable while turning at a very high speed during the takeoff phase when the plane is at a low altitude where birds are commonly found. On 20th December, 2013, a Bombardier Challenger 300 hit 4 or 5 soaring turkey vultures at 1800 feet AGL while climbing from the Florida airport. Pilot declared an emergency and landed safely at an alternate airport. Repair costs for the engine and tail were over $800,000. The relevant airline closed down for 22 days. Fortunately, no one was injured in the accident.

Figure 2. The severely damaged engine

In bird ingestion tests, engines are required to demonstrate their ability to withstand bird ingestion and the following ingestion to produce enough trust as required by safety regulations. However, full scale of an aircraft engine testing is very expensive. In order to decrease this cost, a range of analysis methods applicable to bird strike simulation were developed. R.H.Mao et al. studied the nonlinear transient response of a bird striking a fan system using LS-DYNA. The bird is modeled as a fluid jet with a homogenized fluidic constitutive relation, using the Brockman hydrodynamics model [4]. They also analyzed the geometry effects of an artificial bird striking an aero engine fan blade, including hemispherical-ended cylinder, straight-ended cylinder, and ellipsoid [5]. Guan Yupu et al. set up a three-blade computational model of a fan rotor with shrouds. They compared the transient response curves from the simulation with that obtained from experiment and found that the variations in measured points and corresponding points of simulation agreed well[6,7]. Rade Vignjevic et al. carried out a number of parametric studies including: influence of the bird shape; the bird impact location and impact timing [8].

Rich experience has been obtained from the one or several engine blades tests subject to bird impacting. But simulations and experiments of bird strikes on the full scale of compressor rotating at high speed are rarely carried out. In the present paper, a 3D finite element compressor with a failure model is developed using commercial explicit code PAM-CRASH. The bird is modeled with smooth particles hydrodynamic (SPH) method and Murnaghan equation of state (EOS) is employed to describe the constitutive model. Simulations of the compressor rotating at different speeds (3300r/min and 8800r/min respectively) impacted by a 250g bird at velocity of 102 m/s were preformed to compare with the experimental results and analyze the influence of parameters used in the simulations. The flexible fan blades adopted in the present paper are typical metallic aero engine fan blades.

Test of bird impacting on primary compressor

Test methods and apparatus
The intention of the test is to obtain the dynamic responses of a primary compressor structure under a bird strike. The test results is used to compare with the numerical results presented in Section 3.

Fig.3 illustrates the arrangement of experimental apparatus during the test. The engine test-bed with high-speed rotation is placed in a vacuum box. The launching system accelerates the bird into the vacuum box through an air separation device and the bird will crash on the high-speed rotating blades.

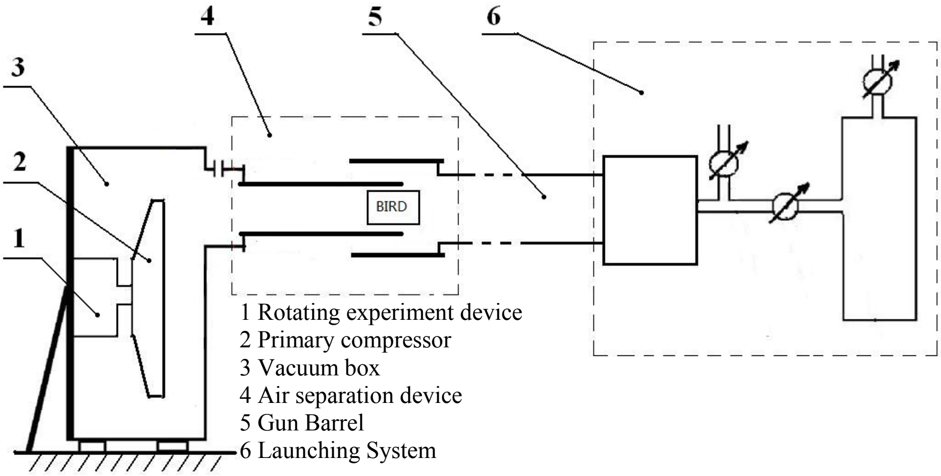


Figure 3. Experiment rig of bird impact on a rotating compressor

The geometry shape of the bird in present study is straight-ended cylinder. The ratio of length to diameter is 2 to 1. Gelatin is used to characterize the bird body due to its similarity with the real bird properties. The mass of the bird is 280g. The blades of engine is made of Ti6Al4V and the geometrical details of the primary compressor are showed in the following section.

Test results
Fig.4 displays the experimental results of a gelatin bird body impacting on a primary compressor in low rotating speed. The bird body is 280g and the velocity of the bird is 110m/s. The rotating speed of the blades ranges from 2900 to 3100r/min. The blades are visually inspected after the test. Slight plastic deformation of 3mm is found in one blade.

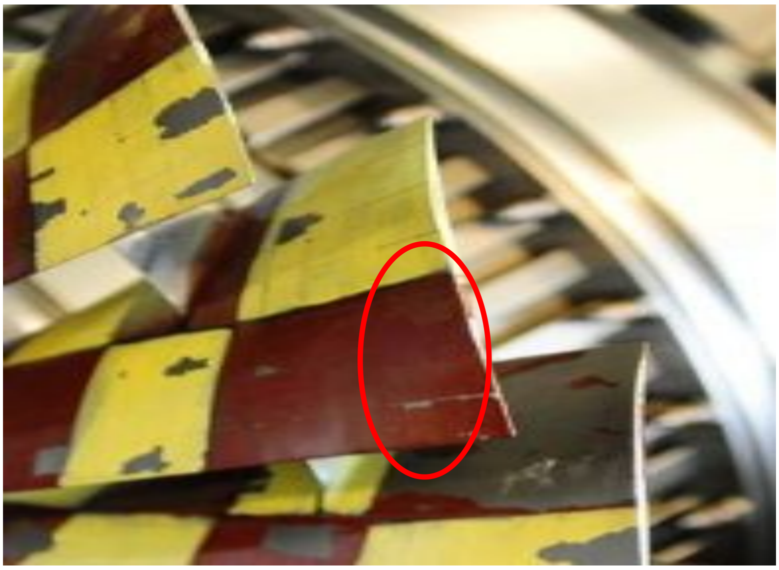
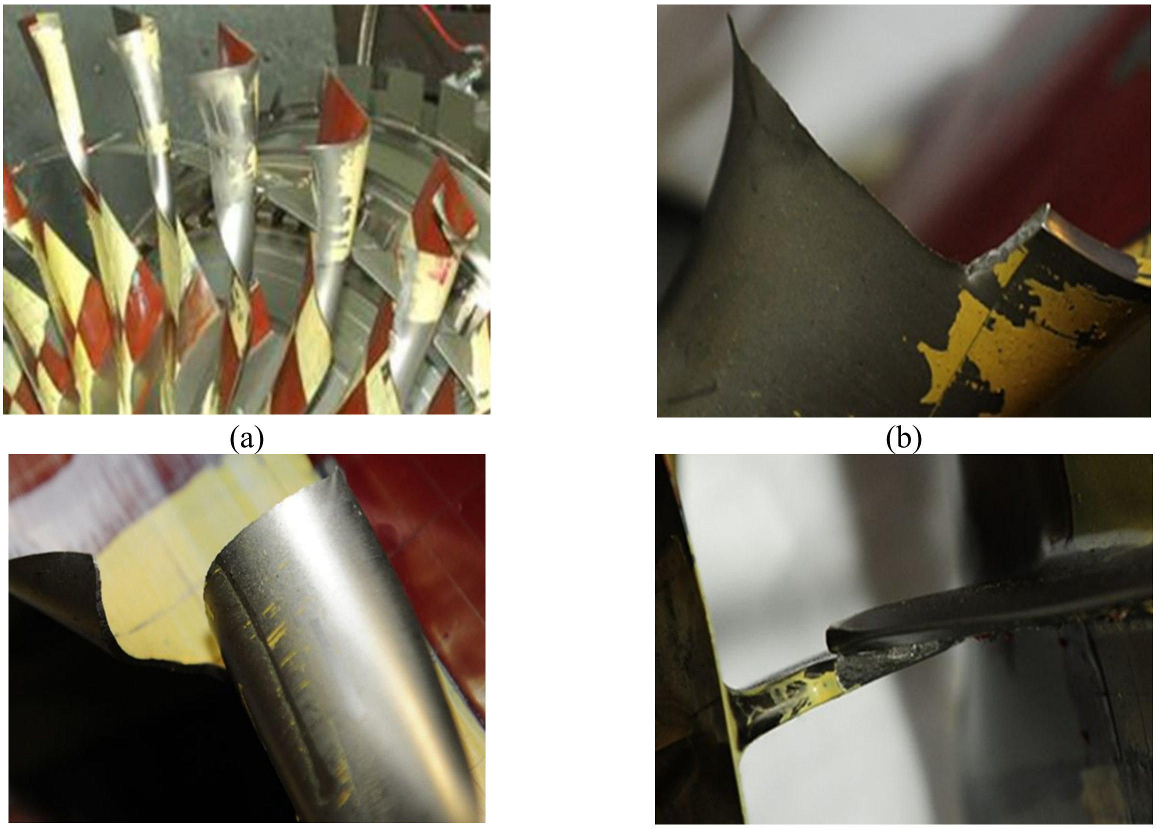


Figure 4. The deformation of blades after impact under low rotating speed

Fig. 5 shows the experimental results of bird body impacting on a primary compressor at high rotating speed. The actual mass and velocity of the bird is 280g and 110m/s respectively. The rotating speed varies from 7000 to 9000r/min. Severe plastic deformation are found in 7 blades, see Fig. 5(a). Fig. 5(b) shows a 40mm by 40mm block missing at a leading edge. A serious laceration is shown in Fig. 5(c). A shroud has a small dislocation accompanied by missing a small piece of block, which is shown in Fig. 5(d).



(a) (b)

(c) (d)

Figure 5. The deformation of blades after impact under high rotating speed

Numerical simulation

Bird modelling

During the impact at high velocity, the bird crushes into particles and splashes to all directions, which could be modeled by Smoothed Particle Hydrodynamics (SPH) method with the Murnaghan EOS for Solids.

SPH method

The SPH method is a grid-less Lagrange technique which allows for severe distortion. It is introduced by Lucy in the 1970s and first applied to solve hydrodynamic problems in astrophysical environment [9]. In terms of situation of high-velocity impact, the SPH method is very suitable for modeling problems associated with characterizing large displacements, strong discontinuities and complex interface geometries. This method has been implemented in PAM-CRASH [10].

A smooth particle is input like a 3-DOF (degree of freedom) solid element and defined by its center of mass, volume, part number, and domain of influence. It can be used with great advantage to model bulk materials with no cohesion (sand, liquid, gases) or in situations where perforation or mixing is expected. Note however that it can be much more time consuming for computational calculation than a classical solid element. Every smooth particle with its own shape function, which is similar to a finite element, is reconstructed at each iteration from its dynamic connectivity. Localization and information transmission from one particle to another are achieved through the notion of an interpolation distance called the smoothing length. Please see reference [11] for more detailed information.

Geometry and material model for bird

In order to match with the geometry shape of the bird used in the experiment, the straight-ended cylinder is adopted in the following simulation.

Five impact mechanics for solid materials is list by Wilbeck: elastic, plastic, hydrodynamic, sonic velocity and explosive. The hydrodynamic region shows to be suitable for characterizing the bird in a bird strike. In the case of a bird impacting, the yield stress of the bird is greatly exceeded due to its rapid deceleration and its inhomogeneity becomes increasingly negligible, so the bird can be considered as a homogeneous jet of fluid while impacting on a structure. The Murnaghan EOS implemented in PAM-CRASH (materials type 28) provides a powerful tool to simulate hydrodynamic behavior. The pressure for the Murnaghan EOS is given by:

$$p = p_0 + \mathrm{B}\left[\left(\frac{\rho}{\rho_0}\right)^{\gamma} - 1\right] \tag{1}$$

where p_0 is a reference pressure, p is the current pressure, ρ_0 and ρ are initial and current mass density respectively, and B and γ are the materials constants to be determined. B equals to128 MPa and γ equals to 7.9 in present paper.

Blade and rotor modelling

The blade disk assembly considered in this work comes from an aircraft jet engine. It consists of 27 equally spaced blades (Fig. 6) attached to the disk. The external radius is measured to the tip of the blade, the internal radius is measured to the root of the blade and the initial impact location is defined by the initial position of the bird’s center of mass.

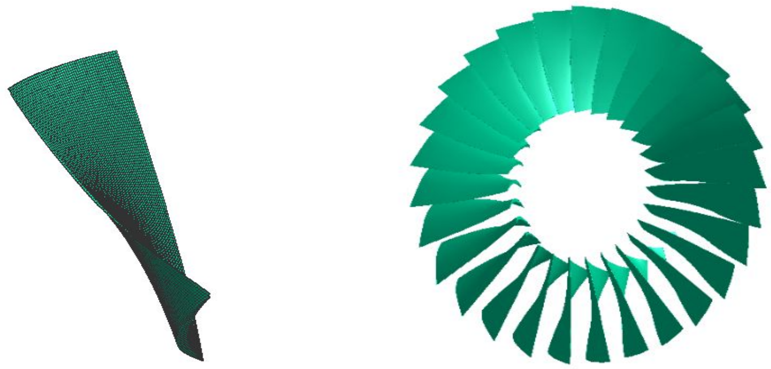


Figure 6. Finite element model of the blades

FE model of the disk and shrouds

The blades are meshed using Hypermesh software. Constant stress brick elements are used to mesh the blade and its attachment. Although plastic deformation due to in-plane and bending loads could be modelled by shell elements, the brick elements allows stress along the thickness and wave propagation to be taken into account, which is impossible using shell elements. A number of analyses are performed with different mesh densities, including increasing number of elements through the thickness. However, there is no considerable improvement of the results with the significant growth of the computational time. Hence, the blade is meshed with 21,400 elements: 107 elements along lengthwise, 50 elements width wise and 4 elements through the thickness, see Fig. 7. The disk is modelled as rigid body using tetrahedral elements and the shrouds are modelled using tetrahedral elements as well.

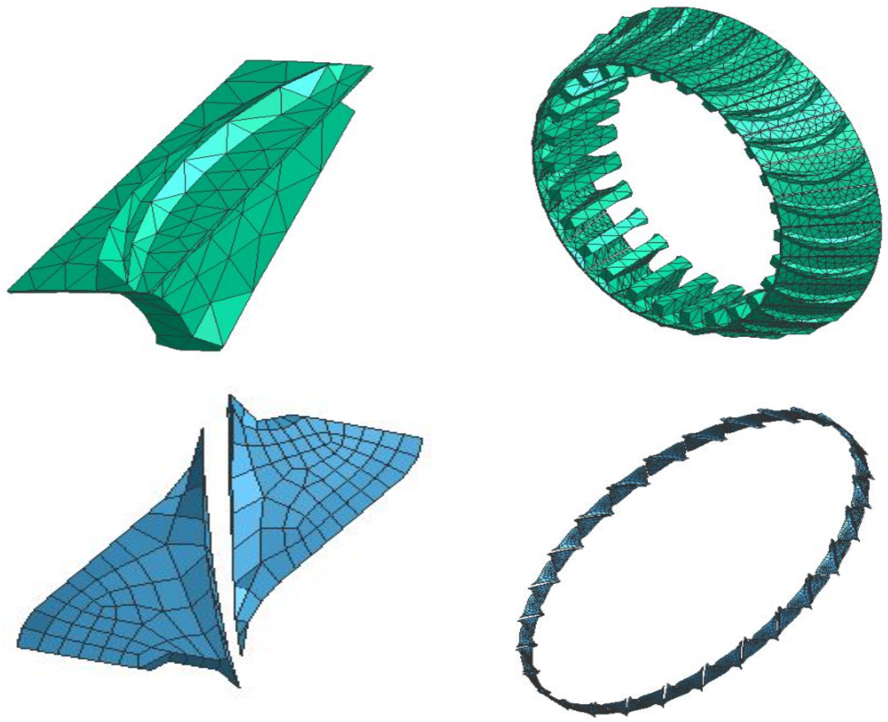


Figure 7. Finite element model of the disk and shrouds

Constitutive model of material

The disk is assigned with a rigid material, which is used to simulate a structure which is much stiffer than the regions of interest or experiences negligible deformations. In addition, the rigid material is computationally less expensive than other material models. The deformable blades are made of titanium alloy Ti-6Al-4V and the constitutive model used for this material is elastic-plastic solid with damage and failure which contains elastic behavior, elastic-plastic behavior, stain rate behavior, and damage behavior. The elastic behavior is described by the shear modulus and bulk modulus as follows:

$$\text{Shear Modulus:} \quad G = \frac{E}{2(1+\nu)} \tag{2}$$

$$\text{Bulk Modulus:} \quad K = \frac{E}{3(1-2\nu)} \tag{3}$$

The Johnson-Cook law is applied to describe elastic-plastic behavior and strain rate behavior, formulated as:

$$\sigma(\varepsilon,\dot{\varepsilon}) = \left[a + b(\varepsilon_p)^n\right]\left[1 + \frac{1}{p}\ln\left(\max\left(\frac{\dot{\varepsilon}}{D},1\right)\right)\right] \tag{4}$$

where $a + b(\varepsilon_p)^n$ denotes the basic elastic-plastic material curve; a, b and n are material constants which could be obtained by the test results of split Hopkinson bar; ε_p indicates the plastic strain; and p and D are the control parameters of strain rate which could be obtained by the stress-plastic strain curve results at different strain rates.

For damage and failure behavior, the isotropic damage law acts on the total element stresses in the formula:

$$\sigma = (1 - d(\varepsilon_p))\sigma_0 \tag{5}$$

where σ is damaged full tensor; ε_p is the isotropic function; σ_0 is the full stress tensor as calculated from the undamaged elastic-plastic material law. An element is failure as soon as one of the equivalent plastic strain values at its integration points reaches the specified limit of failure.
The blade material properties of titanium alloy Ti-6AL-4V are given in Table 1.

Table 1. Johnson Cook material properties for Tie6Ale4V

Parameter	Value
Density	4.4×10^3kg/m^3
Shear modulus	43GPa
Bulk modulus	110Gpa
Initial yield stress	1070MPa
Strain hardening modulus	850MPa
Strain hardening exponent	0.6
Strain rate dependence coefficient	0.01
Maximum plastic strain for element elimination	0.2

Calculation model

After establishing the fan FE model and the bird SPH model, the contact type 34 in software is applied to define the contact between the FE model and SPH model as well as between the two tips on adjacent blades. The rotation and displacement of the fan in y and z directions is fixed, and the displacement of the fan in x direction is fixed. Just rotation of the fan around x is free. The rotation speed 3300 r/min and 8880r/min are defined in the present simulation. At last, the bird velocity along negative x direction is set at 112 m/s and 114m/s respectively according to the experiment.

Simulation results
Fig. 8 illustrates the simulation results of bird impacting on the rotating blades of 3000r/min. As shown in the figure, slight plastic deformation take place on three blades' leading edges indicating that the blades are not severely damaged under low rotating speed situation, which shows a good agreement with the experimental results.

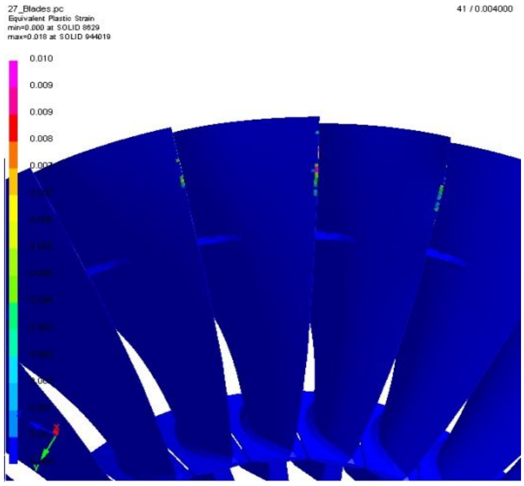
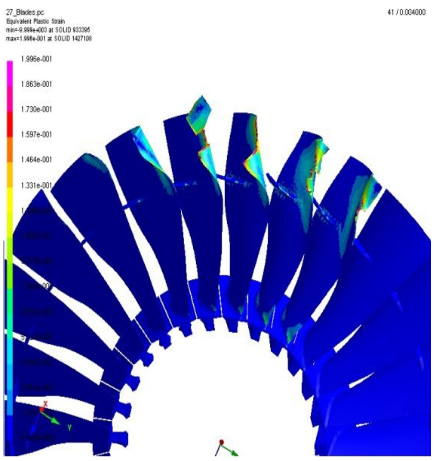
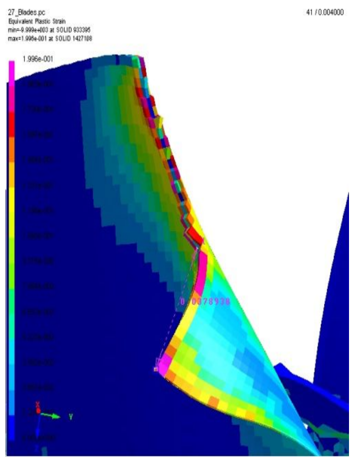


Figure 8. The deformation of blades after impact under low rotating speed

Fig. 9(a)-(d) are the simulation results of bird striking on high speed rotating blades. Fig. 9(a) shows that 6 blades yield large plastic deformation with 4 of them damaged. Fig. 9(b) shows that the leading edge of a blade is damaged severely with a block of 37mm by 58 mm missing. Fig .9(c) shows a serious laceration in another blade's leading edge. Fig. 9(d) shows dislocation occurred on two shrouds.



(a)



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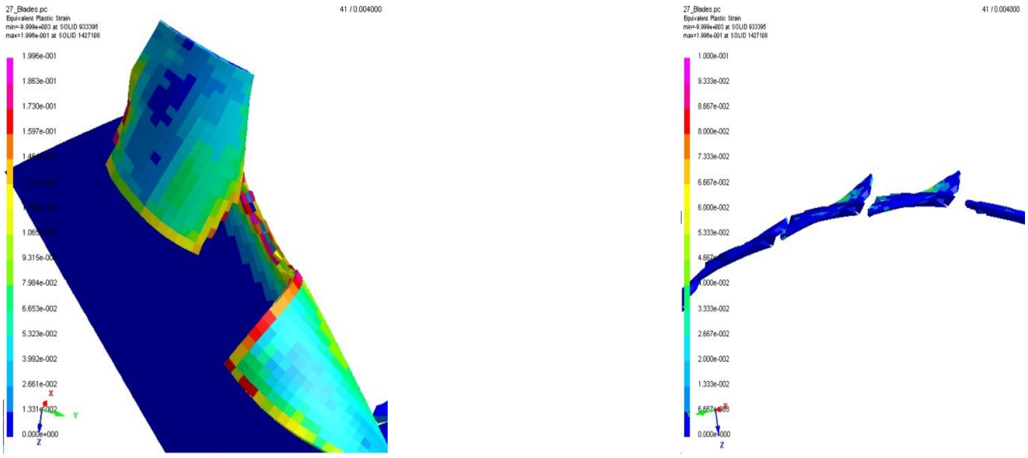


(c) (d)

Figure 9. The deformation of blades after impact under high rotating speed

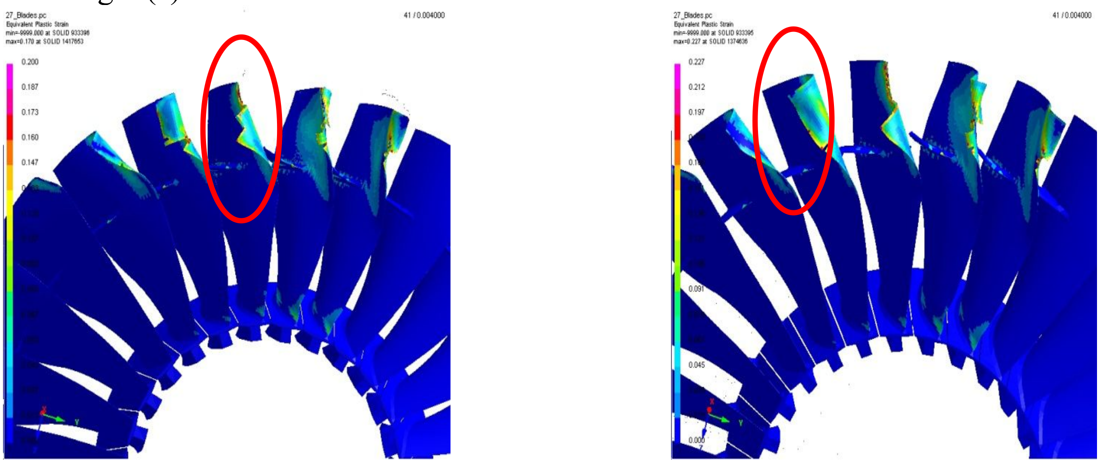
The good agreement of the simulation results and the experimental results suggests that the FE model with Murnaghan EOS for solid is quite suitable for soft body strike situation. This model can predicts the transient response of the blades under bird impact very well.

Parametric study

In order to study the influence of the parameters in the model intensively and analyze the stability, a number of parametric studies are performed to assess the influence of different impact conditions on the blade response.

Influence of the failure stain

The element elimination is determined by the failure stain. The maximum plastic strain for element elimination in the original model is 0.2. But in the actual situation, the value varies in a certain range. Fig. 10(a) and (b) gives the impacted results of model with different failure stain (0.17 and 0.23 respectively). Fig. 10(a) shows that the missing block area becomes larger than that in Fig. 9(a). Fig. 10(b) shows although the blade deforms a lot, the laceration of the blade is slight, while i the laceration n Fig. 9(c) is much more severe.

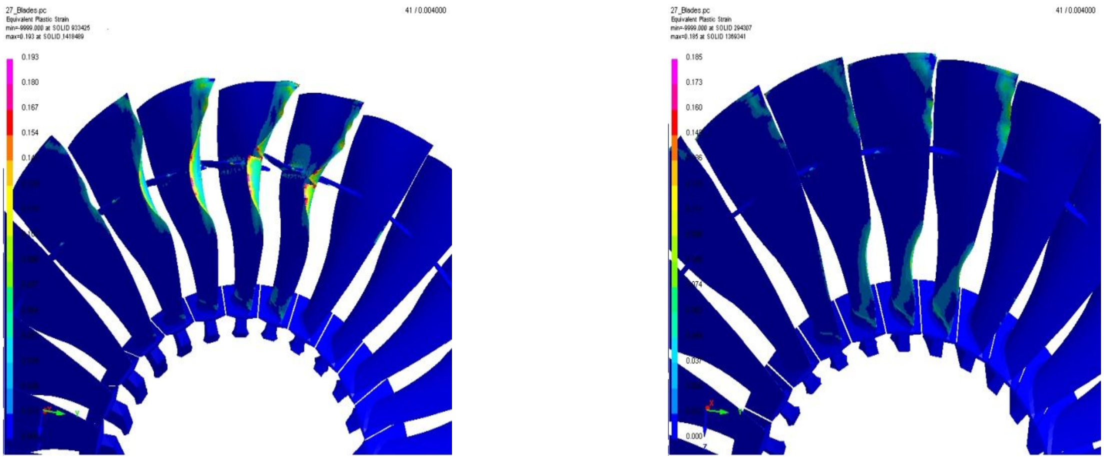


(a) (b)

Figure 10. Comparison of models with different failure stain

Bird impact location

In the actual situation, the bird may strike on almost anywhere of the compressor. To find the most vulnerable striking position is necessary. Fig. 11(a) and (b) show the deformation of blades of different impact locations (on middle and root of the blades). As shown in Fig. 11(a), 4 blades have large deformation and two of them have slight lacerations, while only a small extent of plastic deformation occurs in Fig. 11(b).

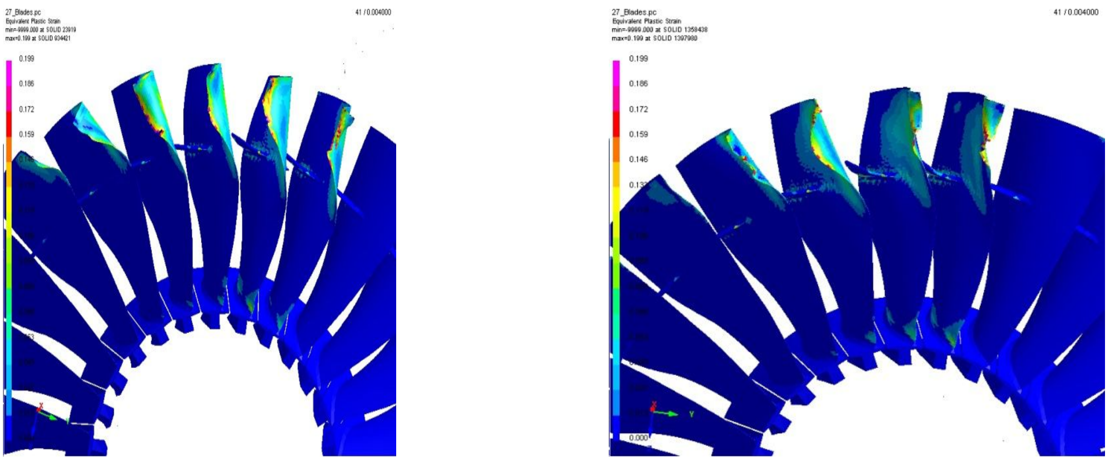


(a) (b)

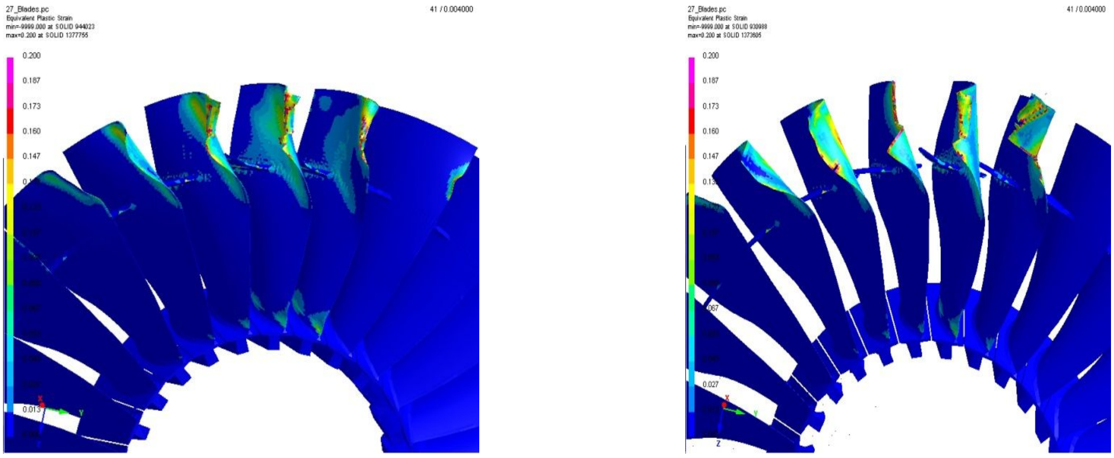
Figure 11. Comparison of models with different impact location

Impact timing

In the case of high rotating speed, the amount of bird sliced off by the blade in front of the leading blade is random. In this assessment impacts with different levels of interaction between the bird and the leading blade are considered. The impact timings considered are defined by varying initial location of the bird along the x axis and the amount of the bird which is removed from the analysis (from 5mm to 20mm). The distribution of plastic deformation on the blades varies a lot.



(a) (b)



(c) (d)

Figure 12. Comparison of models with different impact timing

Conclusions

The FE model accompanied with SPH method provides accurate predicative numerical tools for simulation. The SPH method can attain high accuracy in process the problems with large displacements and deformation. The numerical results are compared with the blade recovered from the physical experiment, indicating a good reliability of the numerical simulation method on this issue. The simulation indicates that the failure stain in the model somehow influences the result while there are strong dependences for the results on the bird impact timing and deformation location on the blade. This study shows the potential of the finite element method in predicting the deformation of engine primary compressor in bird strike events.

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