Containment ability and groove depth design of U type protection ring

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Abstract High-energy rotor uncontained failure can cause catastrophic damage effects to aircraft systems if not addressed in design. In this paper, numerical simulations of three high-energy rotor disk fragments impacting on U type protection rings are carried out using LS-DYNA. Protection rings with the same mass and different groove depths are designed to study the influence of the groove depth. Simulation results including kinetic energy and impact force variation of single fragment are presented. It shows that the groove depth infects both the axial containment ability of the protection ring and the transfer process of energy. The depth of groove ought to be controlled to an appropriate value to meet both the requirement of axial containment and higher safety factor. Verification test on high-speed spin tester has been conducted and shows that protection ring with appropriate U structure can resist the impact of the disk burst fragments. The ring is inflated from a circular to an oval-triangle shape. The corresponding simulation shows good agreement with the test.

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1. Introduction

In turbine cooler of environment control system (ECS), auxiliary power unit (APU) and air turbine starter in aircraft, failed high speed rotor can be released as high-energy fragments, affecting flying performance in a number of direct and indirect ways and even leading to the loss of airplane.\textsuperscript{1} With a more stringent working condition of higher temperature and rotational velocity, degradation and burst failure are more likely to occur, especially on the critical disks. Even though disk burst accidents happen infrequently nowadays, they are not completely avoidable.\textsuperscript{2} Due to the catastrophic results, specific provisions are established for containment ability in both civil and military airplane specifications. Federal Aviation Administration (FAA) Federal Aviation Regulations (FARs) set requirements for equipment containing high-energy rotors of
2. Containment ability of different U geometries

With the aim of saving costs and improving efficiency of research, a series of numerical simulations is carried out to study the effect of U geometry to the containment ability using ANSYS/LS-DYNA.

2.1. Design objective

Containment ability is studied through the simulation of fan impeller disk fragments in air turbine cooler impacting on the protection casing. In practical situation, fan protection casing consists of three components, among which the pipe and the protection ring play a major role of protection. Thus, the model in simulation is built without the outer shell (see Fig. 1). The installation position of the protection ring is designed (see Fig. 2).

Referring to SAE Aerospace-ARP-85F12, the containment speed is defined 125% of the maximum speed resulting from normal operating condition. According to the design parameter of the air turbine cooler, the fan disk is supposed to burst with the speed of 70,069 r/min. The main design parameters are listed in Table 1. It should be noted that 2Cr13, the material of the protection ring, is a common material used in aerospace for its good corrosion resistance to the atmosphere. Available material parameters for simulation and fine machinability lead the choice.

2.2. Failure mode

According to FARs, it must be shown by test that high-energy rotor equipment can contain any failure of a high energy rotor that occurs at the highest speed obtainable with the normal speed control devices inoperative. TSO-C77b also puts forward provision that containment must be substantiated in accordance with the condition of hub containment in APU.

In advisory circular (AC) 20-128A of FAA, engine and APU failure model include single one-third disc fragment, intermediate fragment, fan blade fragment, etc. Before the test, the most dangerous bursting mode must be determined. In order to simplify the question, the impeller is assumed to be a disk with a radius of r. Therefore, the rotational kinetic energy (Ec) of the disk can be calculated as

\[
E_c = \frac{1}{2} J \omega^2 = \frac{1}{2} \left( \frac{1}{2} mr^2 \right) \omega^2
\]

where \( m \) is the total mass of the impeller and \( \omega \) the disk rotating/burst speed.

During the process of impacting, translational kinetic energy (\( E_t \)) plays a leading role among all the types of the energy of fragment. Assume the disk bursts into \( n \) equal parts. Thus, the centroid radius (\( r_m \)) and \( E_t \) of a fragment can be defined as

\[
r_m = \frac{2r \sin(\pi/n)}{3(\pi/n)}
\]

\[
E_t = \frac{1}{2} \frac{m}{n} v_m^2 = \frac{1}{2} \frac{m}{n} (\omega r_m)^2
\]

The ratio of \( E_t \) to \( E_c \) is presented as
\[ i = \frac{E_t}{E_c} = \frac{8n \sin^2(\pi/n)}{9\pi^2} \]  

Fig. 3 shows a drawing of energy ratio according to Eq. (4). It is possible to conclude that for a certain disk, the maximum translational kinetic energy of a single fragment occurs when the disk bursts into three parts.

2.3. Different U protection rings

Five protection rings with the same mass are studied in the simulation. The heights of rings are certain because of the overall structure. Fig. 4(a) presents four ring structures of different U-groove depths, among which Type I has the deepest U-groove of 17 mm, half height of the ring. U-groove depth is successively and uniformly decreased from Type I to Type IV. A straight cylinder is used in Type V for comparison with U geometries (see Fig. 4(b)). To obtain a more obvious contrast, thickness of Type II is set to approach a critical state.

It should be noted that the five rings are controlled to be of the same mass of 0.57 kg. The corresponding wall thicknesses are designed using UG, listed in Table 2.

2.4. Finite element model

To improve simulation efficiency, geometric characteristics that make few effects of containment are simplified. Finite element models are shown in Fig. 5. To capture the detailed behavior of the case, at least three elements through the thickness of the case are set. All elements are set to be 8-node solid element which can observe the failure mode through the thickness while other element types such as the shell element cannot easily obtain the message.14

Material model is a key factor affecting the accuracy of results from a nonlinear finite element simulation. In this paper, the Johnson–Cook (JC) model is chosen for the reason shown in Refs.9,15 and has already been described definitely.16,17 The material parameters used in this paper are listed in Table 3 and taken from Refs.18–20. In Table 3, \( A \) is the yield stress, \( B \) and \( n \) represent the effects of strain hardening, \( C \) is the strain rate constant and \( m \) represents the temperature constant in constitutive model.16 For fracture model, \( D_1, D_2, D_3, D_4, D_5 \) are failure constants determined by material tests.17

![Fig. 1 Geometric model of test components.](image1)

![Fig. 2 Schematic of fan components.](image2)

![Table 1 Main design parameters of components.](image3)

![Fig. 3 Ratio of translational kinetic energy (\( E_t \)) of the fragment to kinetic energy of the disk (\( E_c \)).](image4)

![Fig. 4 Five cross-sections of protection ring.](image5)
The elements of impeller fragments are given an initial angular velocity. Surface to surface contact between the disk fragment and the containment structure is modeled using a kinematic contact algorithm. The contact stiffness scale factor is defined as 1.0 and the friction coefficient is defined as typical values of 0.15. 9

2.5. Comparison and analysis

Fig. 6 shows the simulation results of different protection rings. It can be observed that Type I protection ring is torn by one fragment and a piece of breach appears. Fragments are contained within Type II. Since the outside surface of the ring damaged slightly, it can be defined as a critical state. For Types III–V, damage of the rings does not occur, but the fragments fly out in axial direction.

It is shown that smaller depth of the groove leads to less obvious deformation of the protection ring. However, the fragments are more likely to run out of the covered range of ring and fragments flying along axial-direction may cause damage to other components. High energy disk fragments containment should be defined to capture the fragments within the ring, so Type II protection ring, which successfully contains the fragments in both radial and axial direction, shows greater fitness.

From the forgoing it follows that U structure performs better than straight cylinder in containing the fragments. Under the condition of a constant mass of ring, greater depth of the groove leads to smaller thickness of the impacting zone, which indicates the reduction of safety factor of the protection ring. As shown in Fig. 6(a), ring penetration happens. When designing protection rings, the depth of groove ought to be controlled to an appropriate value.

The above analysis shows that U-groove depth plays an essential role for containment. In addition, it has influence on other aspects. On the one hand, the protection ring requires sufficient stiffness which is directly related to the groove depth. On the other hand, U-groove depth has an effect on the energy transfer process between the fragment and ring. Fig. 7 and Table 4 show the kinetic energy variation of the fragments. With the groove depth decreasing, the residual kinetic energy (after impacting) of the fragments increases slightly. Axial

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**Table 2** Geometries of five protection rings.

<table>
<thead>
<tr>
<th>Type</th>
<th>U-groove depth (mm)</th>
<th>Wall thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>17</td>
<td>1.8</td>
</tr>
<tr>
<td>II</td>
<td>13</td>
<td>2.1</td>
</tr>
<tr>
<td>III</td>
<td>9</td>
<td>2.4</td>
</tr>
<tr>
<td>IV</td>
<td>5</td>
<td>2.8</td>
</tr>
<tr>
<td>V</td>
<td>0</td>
<td>3.6</td>
</tr>
</tbody>
</table>

**Table 3** J-C constitutive relation and fracture criterion constant of TC4, 2A12 and 2Cr13.

<table>
<thead>
<tr>
<th>Material</th>
<th>A (MPa)</th>
<th>B (MPa)</th>
<th>n</th>
<th>C</th>
<th>m</th>
<th>D1</th>
<th>D2</th>
<th>D3</th>
<th>D4</th>
<th>D5</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC4</td>
<td>1130</td>
<td>250</td>
<td>0.20</td>
<td>0.0320</td>
<td>1.1</td>
<td>−0.005</td>
<td>0.200</td>
<td>0.30</td>
<td>0.0040</td>
<td>3.900</td>
</tr>
<tr>
<td>2A12</td>
<td>369</td>
<td>684</td>
<td>0.73</td>
<td>0.0083</td>
<td>1.7</td>
<td>0.112</td>
<td>0.123</td>
<td>1.50</td>
<td>0.0070</td>
<td>0</td>
</tr>
<tr>
<td>2Cr13</td>
<td>674</td>
<td>288</td>
<td>0.52</td>
<td>0.0612</td>
<td>1.0</td>
<td>0.150</td>
<td>0.740</td>
<td>2.12</td>
<td>0.0002</td>
<td>0.061</td>
</tr>
</tbody>
</table>
deviation of fragments emerges due to the interaction of themselves, for they rebound from the casing with certain kinetic energy. It is shown that the impacting force of the fragments tends to have a lower maximum value and a longer duration with a deeper U-groove, as Fig. 8 presents. The maximum impact force is also carried backward as the groove depth increases.

It is possible to conclude that appropriate U-groove depth helps to buffer the impact of fragments, leading to an adequate interaction and energy transfer. Rebounding fragments with less kinetic energy and the obstruction of U-groove are conducive to axial containment. However, considering the requirement of less weight and volume, it is also unsuitable for an excessive depth. The present results serve to illustrate that Type II protection ring, with a more suitable U-groove depth, can meet both the requirement of axial containment and higher safety factor.

3. Verification test and results

Component level containment test using high-speed spin tester is an appropriate method to study the behavior of fragments/casing impact, penetration and perforation. Containment ability studied above was verified through a test. Since tests are relatively expensive, they were carried out only for once.

3.1. Test arrangement

Protection case used in the test includes a U type protection ring, a pipe and the outer shell. According to the analysis in Section 2, Type II protection ring, with a relatively suitable U-groove depth of 13 mm, was chosen to be tested. Considering the expected result of containment and the limited cost, thickness is redesigned to 2.3 mm, with a safety factor of 1.1.

The test was conducted on the ZUST1 rotor high-speed spin tester in High-Speed Rotating Machinery Laboratory in Zhejiang University. Parameters of this spin facility are presented in Ref.21. For the requirement of a fan disk burst in speed ranging from 70069 to (75069 ± 50) r/min, a speed increasing gear box with ratio of 4.07 is added to attain a secondary acceleration with a final output maximum speed up to 96000 r/min. The experiment was conducted at room temperature. Fig. 9 presents the sketch of the testing rig and pretest photo in testing chamber.

3.2. Impeller bursting method

Before test, the fan impeller is supposed to be notched along radial direction at three symmetrical positions circumferentially with the aim of bursting into 3 pieces at target speed range along the direction of presented crack (see Fig. 10). In Fig. 10(a), area without the section line is supposed to be cut, thus, represents the distance from center to terminal of the crack and is the remaining length along the crack direction. Fracture occurs in the notched cross-section at which the localized plastic zone expands with the increase of rotating speed. When the circumferential stress at the cross-section is beyond the ultimate tensile strength of the material, the impeller bursts with a certain kinetic energy. The average stress method is used to calculate the notched cross-section circumferential stress roughly and provides guidance for cutting. In order to be workable, the process of notching is supposed to be conducted in multiple steps.

3.3. Results and analysis

Conservatively, the initial remaining length of the impeller (L) was 9.5 mm and impeller burst did not occur at the highest speed, 75069 r/min. The same procedure was carried out until the remaining length reduced to 7.0 mm, with the burst speed of 75069 r/min which is in accordance with simulations.

The first testing site is presented in Fig. 11. It is shown that the casing can resist the impact of three high-energy disk fragments. Blades at three impacting points wore seriously and missed; the pipe was penetrated and the disk fragments were successfully contained within the protection ring. The U type protection ring deformed from a circular to an oval-triangle shape. The test result indicates that the analysis of U type protection ring is conductive.

4. Numerical simulation of test

Since the actual bursting speed is 5000 r/min more than that in the simulation before, numerical simulation of the test is

![Fig. 7 Kinetic energy variation of single fragment.](image)

![Fig. 8 Impact force variation of single fragment.](image)

| Table 4 Residual kinetic energy of single fragment. |
|---|---|---|---|---|---|
| Type of the ring | I | II | III | IV | V |
| Residual kinetic energy of single fragment (J) | 39 | 64 | 94 | 130 | 217 |
conducted with the aim of further verification and better understanding of the impact process.

Geometric configurations of the disk and the protection ring are the same as those used in the test. Simulation method follows that in Section 2.

Simulation results indicate that the main failure modes of blades include crispation, wear of main impact zone and fracture of the root. It is found that the fragments breach the pipe and cause dishing deformation on the ring. Bulge deformation occurs at the impact region of the protection ring, and because of the three impact points from the disks' fragments, the ring deformed from a circular to an oval-triangle shape.

The combined disk fragments of simulation show good agreement with the test. Comparison is shown in Fig. 12. Fig. 13(a) presents the whole containment components in the test. Pipe and protection ring in Figs. 13(b) and (c) also accurately reveal the failure characteristics. According to the high concordance between the simulation and the test in Section 3, the simulation method can be regarded reliable.

Fig. 14 shows the von Mises stress contour plots at 8 different time points. The fragments are released after they separate from each other. The blade tip firstly impacts the pipe and bends due to extrusion, and an impact force peak occurs at 0.06 ms (see Fig. 15). As a result, for each disk fragment, blades on one side are subjected to severe extrusion while slight impacts occur on the other side. The pipe is perforated firstly at the time of 0.21 ms, meanwhile the impact force reaches the maximum. Contact of the protection ring and the fragments occurs at 0.30 ms, at this point, the pipe is severely deformed and damaged. Hereafter, a part of the fragment proceeds to tear the pipe, and other part impacts the ring. The third impact force peak in Fig. 15 at time 0.39 ms is the result from the impact of the fragment and the protection ring. After
Fig. 13  Comparison between test and simulation of casing.

Fig. 14  Containment simulation results.
the time of 3 ms, most of the initial kinetic energy of the fragments is consumed.

5. Conclusions

In this paper, numerical simulations of high-energy rotor disk fragments impacting on different U-type protection ring are carried out using LS-DYNA. Verification test and the corresponding simulation were also performed. Comparisons between the experimental and the numerical results show that the numerical simulations are in fitness. Based on the simulation observations and test results presented, the following conclusions were drawn:

1. While containing fragment of 1/3 disk, the U structure performs better than straight cylinder in protection ring design. U-groove depth infects both the axial containment ability and the energy transfer process between fragments and rings. The depth of groove ought to be controlled to an appropriate value to meet both the requirement of axial containment and higher safety factor.

2. Containment test shows that the fragments perforate the pipe and cause inflation of the U type protection ring. The ring is inflated from a circular to an oval-triangle shape. The test result indicates that the numerical analysis of U type protection ring is conductive. Simulation shows good agreement with the test and the method can be regarded as reliable.

References


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