Identification and quantification of hazards caused by uncontained engine rotor failure

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Abstract

One approach based on AC20-128A is presented in order to assess the risk caused by uncontained engine rotor failure (UERF). In this approach, the risk assessment procedure includes hazard identification and hazard quantification. In the step of hazard identification, the catastrophic functional hazards, derived from the functional hazard analysis (FHA) results for the airplane, are used as the top events to construct the fault trees. The minimal cut sets (MSCs) of the fault trees are the hazards to be identified exactly. In the step of hazard quantification, the probability of one hazard triggered by some uncontained debris is evaluated. After the probabilities of all the identified hazards are quantified, the risk assessment of the airplane is completed. And the assessment result is compared with the design specifications to show compliance with the safety design. A small example is introduced to illustrate the rationality and accuracy of the aforementioned method.

Keywords: airplane; engine; uncontained engine rotor failure; airplane safety

1. Introduction

Some catastrophic accidents may be caused by the uncontained debris of engine or auxiliary power unit (APU) rotor failures. Therefore, the method and model for the analysis of rotor failure must be presented in order to show the compliance with FARs. AC20-128A lay base for safety assessment of uncontained rotor failure[1]. However, the
Some related works have been completed by Federal Aviation Administration[2]. One safety assessment method for uncontained rotor failure is presented in[3]. And the computer simulation of the penetration of broken blade is developed in[4]. The events of the rotor failure are discussed in[5]. By refs[3] and[5], we can determine the top events, and then build failure model for each top event by using fault tree, and find the rotor failure modes which can trigger the minimum cut sets of the fault tree finally. This method is straightforward and effective. However, its quantitative aspect is a little problematic and should be improved.

In this paper, one method for assess the safety of the airplane caused by the uncontained rotor failure is presented based on AC20-128A. The method can be divided into qualitative and quantitative part. In the qualitative part, the hazards caused by the uncontained rotor failure are identified, and the probabilities of the hazards are evaluated in the quantitative part. The emphasis of the paper is on the latter rather than on the former.

2. Identification of hazards caused by uncontained rotor failure

The goal of safety assessment of uncontained rotor failure is identification and quantification of the hazards. Hazards identification includes hazards modeling and triggering analysis, and hazards quantification includes probability evaluation, sensitivity analysis and uncertainty analysis. If the assessment results cannot be satisfied with the requirements, the design scheme must be revised in order to reduce the risk caused by the uncontained rotor failure. Therefore, the safety assessment must be developed as early as possible. The basic process of the safety assessment is shown as Fig. 1.

![Fig. 1. The process of the safety assessment of uncontained rotor failure.](image-url)
A method for hazards identification is presented in ref [3], in which the hazards is identified based on aircraft functional hazard assessment (FHA) results. The top events of the uncontained rotor failure are picked out from the results, and are decomposed into hazards by using fault tree. The method includes five steps as follows.

1. Picking out the catastrophic functional hazards from the aircraft FHA results, such as loss of thrust, loss of flight control function or fire.
2. Building fault tree for each top level hazard.
3. Finding the minimum cut set of the fault tree, which is the minimal combination of hazards causing catastrophic accident.
4. Analysis of impact area of intermediate fragment, single one-third disc fragment, and triple one-third disc fragments respectively.
5. Triggering analysis of minimum cut set. If some minimum cut set lies in the impact area of the fragment(s), it is triggered. It means that this impact area can cause catastrophic accident.

The so called hazards identification is finding the intersection of impact area of some fragment(s) and the minimum cut set. For example, the spread angle for the single one-third disc fragment is ±5°, and we have get the minimum cut sets of one fault tree are \{A failure\} and \{B failure, C failure\}. A, B and C are located as Fig. 2. Obviously, the set \{A failure\} can be triggered by the single fragment, and \{B failure, C failure\} cannot be triggered because B is not covered by the impact area of the single fragment.

3. Modeling and quantification of hazards caused by uncontained rotor failure

3.1. Model of uncontained fragment and some assumptions

There are six models for all the uncontained fragments, which are single one-third disc fragment, intermediate fragment, alternative model, small fragment, fan blade fragment and APU failure model. The small fragment has less effects on the airplane. Only single and triple one-third disc fragment and intermediate fragment are considered when the hazards caused by uncontained rotor failure are assessed.

1. Single one-third disc fragment

The one-third disc fragment has the maximum dimension corresponding to one-third of the disc with one-third blade height, as shown in Fig. 3. And its spread angle is ±3° and one-third of the bladed disc mass and energy.

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**Fig. 2. Hazard triggering by the intermediate fragment.**

**Fig. 3. Single one-third disc fragment.**
(2) Intermediate fragment

The intermediate fragment has a maximum dimension corresponding to one-third of the bladed disc radius shown as Fig. 4. And it has a spread angle of ±5°. Its mass is 1/30 of the bladed disc mass.

There are some assumptions for the hazards assessment of uncontained rotor failure.

(1) The occurring probability of the event of uncontained rotor failure is 100%. And it is the premise of the safety assessment.

(2) For one engine, the probability of uncontained rotor failure for each level is identical. For different engines located on one airplane, the probabilities of uncontained rotor failures are identical.

(3) The fact that two or more than two levels of rotors failed at the same time is not considered. And the fact that the uncontained failures occurred in the two or more than two engines on the same airplane is not considered also. There is no possibility of the uncontained rotor failure of one engine causing the same failure of another one.

(4) The probability of release of debris within the maximum spread angle is uniformly distributed over all directions. All the unprotected component lying on the flight path of the debris will be destroyed and the flight path will not be changed.

(5) There is no possibility of independent failure of other critical component of the airplane and the uncontained rotor failure occurring at the same time.

(6) Uncontained events involving in-flight penetration of fuel tanks will not result in fuel tank explosion.

(7) Unpowered flight and off-airport landings, including ditching, may be assumed to be not catastrophic to the extent validated by accident statistics or other accepted factors.

3.2. Impact area analysis of the fragment

The airplane can be impacted by the fragment in the radial or axial direction. Therefore, the impact area is classified as radial and axial area. The former is the intersection of maximum spread angle and airframe. The area surrounded by bold lines in Fig. 5 is axial area, and the shadow part is the location of one engine. Obviously, the axial area is dependent on the maximum spread angle and the location of the engine.
The rotor fragment can be liberated from the engine case in any direction covered from 0 to 360 degree. Then the radial impact area is the intersection of airframe and axial impact area (see Fig. 6).

3.3. Quantification of hazard caused by uncontained rotor failure

From Fig. 5 and 6, we can see that the rotor fragment impacts the airplane in a probabilistic manner. When the minimal cut sets have been acquired, we need analyze how much the likelihoods of the minimal cut sets being triggered by the fragment(s) is.

3.3.1. Case 1: Single rotor and single fragment

(1) The minimal cut set with order 1.
It means that the number of the elements in the minimal cut set is 1 exactly, namely, the top event can be caused by the failure of the component. If the component is installed in the impact area of the fragment, then the probability of component failure can be evaluated by using the following formula.

\[
P = \frac{\text{Degree of the translational risk angle}}{360} \times \frac{\text{Degree of the spread risk angle}}{\text{Degree of the spread angle}}
\]

(1)

The translational risk angle and spread risk angle are shown in Fig. 7. The spread angle is \(\Psi\) and the translational angle is \(\Phi\), and more details about them can be found in ref [3]. What should be point out is that if the spread risk angle is greater than the spread angle, the fragment must hit the component and the second term of formula (1) should be set to be 1.

(2) The minimal cut set with order \(n\).
It means that the top event is caused by two or more than two components’ failure. If the \(n\) components are covered by the flight path of the fragment, then the minimal cut set is triggered. And the probability of all the components being covered by the flight path on the spread plane is
where $\Psi'_i$ and $\Psi''_i$ are the initial and final spread angles for the component $i$, respectively. And $\Psi_i$ and $\Psi''_i$ are the upper and lower bounds of the fragment’s spread angle.

In the similar way, the probability of the components are being covered by the fragment swept path on the translational plane is

$$P_2 = \frac{\min\{\phi'_1, \phi'^2, \ldots, \phi'^n\} - \max\{\phi''_1, \phi''^2, \ldots, \phi''^n\}}{360} \quad \text{(3)}$$

where $\phi'_i$ and $\phi''_i$ are the final and initial translation angles for the component $i$, respectively.

From above, we can get the probability of the top event caused by the uncontained fragment as follows.

$$P = P_1P_2 \quad \text{(4)}$$

### 3.3.2. Case 2: single rotor and multiple fragments

It is subtle to assess the hazards caused by the uncontained fragments because there are a lot of combinations of the fragment types. According to AC20-128A, only one combination, namely the combination of triple one-third disc fragments should be considered. Then the complexity of the problem is reduced to a great extent.

(1) The minimal number of swept paths is 1.

It means that anyone of the three disc fragments can trigger the top event independently. Therefore, the triggering probability of the top event is

$$P_M = 1 - (1 - P)^3 \quad \text{(5)}$$

The probability can be evaluated by using formula (1) or (4).

(2) The minimal number of swept paths is greater than 1.

It means that only if more than one components are covered by the swept paths of different fragments, the top event will be triggered. Let $L$ denote the minimal number of the swept paths. Obviously, $L \leq 3$ holds because the maximum number of the fragments is 3.

If all the three disc fragments are combined to trigger the top event, then $L$ is equal to 3 exactly. For example, there are three fragments $A$, $B$ and $C$, and the minimal cut set is $\{T_1, T_2, T_3\}$. $L$ is equal to 3 if and only if anyone of the three fragments must trigger only one component and none or any two of them can trigger more than one components simultaneously. Therefore, we can get the probability of the minimal cut set being triggered.

$$P_M = C_1^3 C_1^3 P(L_1)P(L_2)P(L_3) = 6P(L_1)P(L_2)P(L_3) \quad \text{(6)}$$

where $P(L_1), P(L_2)$ and $P(L_3)$ are the probabilities of the three swept paths which can be evaluated by using formula (1) or (4).

If only one or two fragments are enough to trigger the minimal cut set, $L$ will be 1 or 2. If $L=1$, the probability is evaluated by using formula (5). If we assume that fragments $L=2$, the probability is

$$P_M = 6P(L_1)P(L_2)[1 - P(L_1) - P(L_2)] + 3P(L_1)^2P(L_2)^2 + 3P(L_1)^2P(L_2) \quad \text{(7)}$$

where $P(L_1), P(L_2)$ are the probabilities of the two swept paths.

Finally, according to AC20-128A, the probability of the catastrophic accident caused by uncontained rotor failure should be averaged for all disks or rotor stage on all engines across a nominal flight profile. More details can be found in AC20-128A.
4. Example

One example in ref[3] is reintroduced here to demonstrate the usability of the aforementioned method. The risk angle for the one-third disc fragment of one-stage rotor is shown in Table 5.9 of ref[3]. For simplicity, we only extract a part of the table, to see Table 1. It should be noted that the risk angles in Table 1 are measured from one true airplane.

Table 1. Risk angle.

<table>
<thead>
<tr>
<th>No.</th>
<th>Minimal cut set</th>
<th>Components</th>
<th>Fragment types</th>
<th>Risk Angle (RA)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Initial spread RA</td>
</tr>
<tr>
<td>1</td>
<td>{A2, A4}</td>
<td>A2</td>
<td>one-third disc fragment</td>
<td>87°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A4</td>
<td>one-third disc fragment</td>
<td>267°</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Only when A2 and A4 are covered simultaneously, the minimal cut set will be triggered. Therefore, the minimal number of the swept paths is \(L=2\). It means only triple one-third disc fragments can trigger the minimal cut set. Because \(L<3\), then the probability can be quantified by using formula (7).

Let \(P(A2)\) and \(P(A4)\) denote the probabilities of the swept paths covering A2 and A4 respectively, which can be calculated by formula (1). We have

\[
P(A2) = P(A4) = 0.025
\]

By substituting them into (7), we get the probability \(P_M\)

\[
P_M = 0.0037
\]

The airplane is designed as single engine which has 13 rotor stages. Then we get the final probability of \(2.8125 \times 10^{-4}\) by averaging \(P_M\) over all the 13 stages. The results of ref[3] is \(0.34 \times 10^{-4}\), and it means that the approximate formula in ref[3] underestimates the risk of the uncontained rotor failure.

5. Conclusions

One method for safety assessment of the uncontained rotor failure is designed based on AC20-128A, which can be divided into qualitative and quantitative part. The qualitative part is borrowed from AC20-128A and ref[3]. The focus is the quantitative part. The quantification topic is discussed under two cases, which are single fragment and triple one-third fragments. Compared with the existing approximate formula, the aforementioned method can get more accurate result which is helpful to the safety of airplane.

References


