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Yanfeng Li, Hong-Zhong Huang*, Shun-Peng Zhu, Yu Liu and Ning-Cong Xiao

An Application of Fuzzy Fault Tree Analysis to Uncontained Events of an Areo-Engine Rotor

Abstract: Fault tree analysis is an important tool for system reliability analysis. Fuzzy fault tree analysis of uncontained events for aero-engine rotor is performed in this article. In addition, a new methodology based on fuzzy set theory is also used in fault tree analysis to quantify the failure probabilities of basic events. The theory of fuzzy fault tree is introduced firstly. Then the fault tree for uncontained events of an aero-engine rotor is established, in which the descending method is used to determine the minimal cut sets. Furthermore, the interval representation and calculation strategy is presented by using the symmetrical *L-R* type fuzzy number to describe the failure probability, and the resulting fault tree is analyzed quantitatively in the case study.

Keywords: uncontained event, fuzzy, reliability, fuzzy fault tree, aero-engine rotor

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Yanfeng Li: School of Mechatronics Engineering, University of Electronic Science and Technology of China, No. 2006, Xiyuan Avenue, West Hi-Tech Zone, Chengdu, Sichuan, 611731, P. R. China
***Corresponding author: Hong-Zhong Huang:** School of Mechatronics Engineering, University of Electronic Science and Technology of China, No. 2006, Xiyuan Avenue, West Hi-Tech Zone, Chengdu, Sichuan, 611731, P. R. China
E-mail: hzhuang@uestc.edu.cn
Shun-Peng Zhu: School of Mechatronics Engineering, University of Electronic Science and Technology of China, No. 2006, Xiyuan Avenue, West Hi-Tech Zone, Chengdu, Sichuan, 611731, P. R. China
Yu Liu: School of Mechatronics Engineering, University of Electronic Science and Technology of China, No. 2006, Xiyuan Avenue, West Hi-Tech Zone, Chengdu, Sichuan, 611731, P. R. China
Ning-Cong Xiao: School of Mechatronics Engineering, University of Electronic Science and Technology of China, No. 2006, Xiyuan Avenue, West Hi-Tech Zone, Chengdu, Sichuan, 611731, P. R. China

1 Introduction

The rotor of an aero-engine rotates with high speed in its service. If any part, such as chip off-falling of vanes, chip of tympanic ring, counterweight or coupling screws of disk, pins, falls from a high-speed rotating rotor, the tremendous centrifugal force will make them thrown out with great energy and high speed. The part out event cannot be avoided even in modern advanced aero-engines. This event is also named as "uncontained event", which is a significant safety event that initiates from an uncontained release of debris from a rotating component malfunction (blade, disk, spacer, impeller, and/or drum/spool) [1]. In general, uncontained rotor failures can be caused by various reasons including fatigue and internal and external foreign object debris. They will lead to considerable damage to aircraft structures. This is because failed rotating components can be released as high-energy fragments, which could perforate the engine cowling and damage fuel tanks, auxiliary power units and other accessories, affecting engine performance in a number of direct and indirect ways and even leading to hundreds of passenger fatalities and the loss of the airplane. The impact process of failed rotating parts on containment structures, especially the casing, is very complex, involving high-energy, high-speed interactions of numerous locally and remotely located engine components. For example, serious accidents, in which the ruptured vanes of compressor penetrate the powerbrake to cause fire and prang, happened several times in early JT&D engines. According to the statistics of the international civil aviation department in 10 years from 1966 to 1975, the number of accidents that debris thrown by the rotor penetrated engine powerbrake and the nacelle were about 246 times. On average, this happened about 25 times annually, which affects the flight safety seriously. Uncontained engine failures were briefly reviewed in [15]. He et al. [16] investigated an experimental and numerical study of an aero-engine fan blade/casing impact process. Noted that if there is no through-thickness crack in the bulge when the maximum interaction force arrives, the released blade will be contained within the casing. Otherwise, the released blade will be uncontained. Although the uncontained events of aero-engine have been investigated extensively, it cannot reveal its reliability and causes analysis for the possible failure patterns.

The conventional fault tree analysis (FTA) based on probabilistic approach has been used extensively in the past decades. For the components such as aero-engine rotors, it is difficult to estimate precise failure probabilities of individual components or failure events due to the insufficient available data and the variation in the estimated values. Fuzzy methods might be the only resort when very limited quantitative information is available for determining the parameters [16–18]. Fuzzy FTA has been used to predict reliability of the complex system in many fields [19–20], such as nuclear reactor, aerospace, petrochemical industry, pipelines, and so on. Singer [10] developed a fuzzy set approach to represent the relative frequencies of the basic events and then there were some approaches about fuzzy fault tree analysis introduced by Refs. [17, 21–23].

In design, it must therefore ensure the parts falling from the rotor being contained in power brake or the nacelles so as to avoid second damage (which is also named as contain [1]) when they are thrown out. According to the reliability analysis of these uncontained events of aero-engine rotor, research shows that the conventional fault tree analysis using probabilities has been found to be inadequate to handle the imprecision of input failure data and the uncertainties associated with the modeling particularly in relation to dependency of failures. To overcome these problems, the fuzzy sets theory is applied to model the fuzzy system structure, and a new procedure along with a new importance index is proposed to calculate the system reliability of an aero-engine rotor.

This paper consists of 4 sections. In the rest sections, the basic concepts of fuzzy fault tree are briefly introduced in Section 2. The concepts of the proposed fuzzy FTA analysis approach are presented and exemplified in Section 3, and it is followed by a brief conclusion in Section 5.

2 Theory of fuzzy fault tree analysis

2.1 Fault tree analysis

Fault tree analysis (FTA) is a logical and diagrammatic method which has been extensively used to evaluate the probability of an accident resulting from sequences and combinations of faults and failure events [3–5]. A typical fault tree consists of the top event, the basic events, and the logic gates. Gates reflect relationships between events. During the design process of system, the logic diagram (fault tree) is drawn to analyze the potential factors (hardware, software, environment, human factor) leading to a system failure. The probability of system failure is calculated based on the known combinations and probabilities of basic events. Corresponding corrective actions are made to improve the system reliability [6]. Thus, the fault tree is useful for understanding logically the mode of occurrence of an accident. In conventional FTA, the failure probabilities of components are treated as exact values. It is often difficult to evaluate the failure probabilities of components from past occurrences, because the environments of the systems change.

2.2 Fuzzy number

It is difficult to determine the exact failure probability or relationship between events. According to the fuzzy set theory proposed by Zadeh [7], fuzzy numbers are used to handle the imprecise information and represent the possibilities of events and relationship of events. Fuzzy sets theory provides a useful tool for directly working with linguistic expression in reliability analyses. Its basic idea is to view the absolute membership of the elements as a set based on classic set theory. The membership of the element x to set A is not defined as 0 or 1, but is valued between 0 and 1, which reflects the membership of the element x to set A. Thus, it is well suited for handling ambiguous and imprecise information obtained in system safety engineering.

Definition 1: If L satisfies [8]:

$$L(x) = L(-x); \quad L(0) = 1;$$

where $L(x)$ is a non-increasing and piecewise continuous function in the interval $[0, +\infty]$, then L is called the reference function of a fuzzy number.

Definition 2: Supposed that L, R are the reference functions of a fuzzy number, if

$$\mu_A(x) = \begin{cases} L[(m-x)/\alpha], & x \le m, \alpha > 0 \\ R[(x-m)/\beta], & x > m, \beta > 0 \end{cases} \tag{1}$$

then the fuzzy number is called L-R type fuzzy number, $\tilde{A} = (m, \alpha, \beta)_{LR}$, where m is the mean value of $\tilde{A}$, α, β are the confidence upper and lower bounds, respectively. When α, β are 0, $\tilde{A}$ is not a fuzzy number but a crisp number. $\tilde{A}$ is more fuzzy with a bigger α and β.

There are many forms of reference functions to represent the linguistic values, also for the forms of membership functions of L-R type fuzzy numbers. The common used L-R type fuzzy numbers are the triangular fuzzy number, the normal fuzzy number, and the cusp type fuzzy number, which can be depicted as shown in Fig. 1. The shape of membership functions of a fuzzy number affects their final results.

The reference function of a triangular fuzzy number is illustrated as:

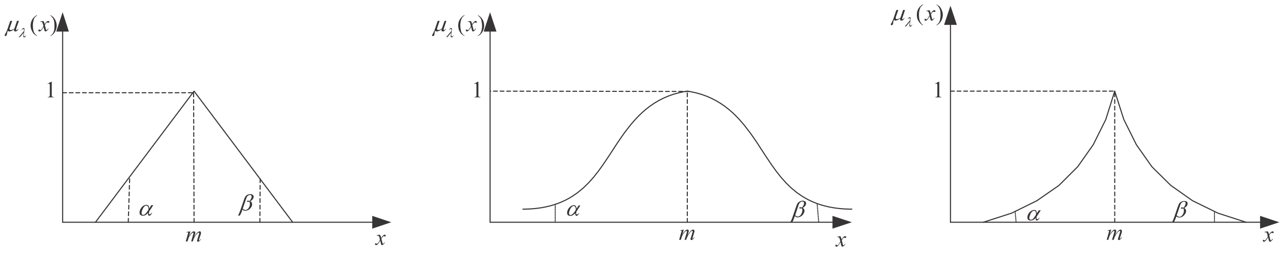

Fig. 1: Kinds of fuzzy numbers

$$\begin{cases} L[(m-x)/\alpha] = \max\{0, 1-(m-x/\alpha)\}, & x \le m, \alpha > 0 \\ R[(x-m)/\beta] = \max\{0, 1-(x-m/\beta)\}, & x > m, \beta > 0 \end{cases} \tag{2}$$

Similarly, the reference function of a normal fuzzy number is:

$$\begin{cases} L[(m-x)/\alpha] = \exp[-((m-x)/\alpha)^2], & x \le m, \alpha > 0 \\ R[(x-m)/\beta] = \exp[-((x-m)/\beta)^2], & x > m, \beta > 0 \end{cases} \tag{3}$$

And the reference function of a cusp type fuzzy number is:

$$\begin{cases} L[(m-x)/\alpha] = 1/[1+(m-x)/\alpha], & x \le m, \alpha > 0 \\ R[(x-m)/\beta] = 1/[1+(x-m)/\beta], & x > m, \beta > 0 \end{cases} \tag{4}$$

It is noteworthy that the type and parameters of the fuzzy linguistic variables will be determined on the basis of the experts' perception of the subjective terms. For example, an expert could be asked what his perception is of the term "probability of fracture of a specific fan blade", and his response could be "the probability is somewhere between 0.15 and 0.18". These sorts of judgments can be collected and represented by fuzzy numbers [24].

To obtain the possibilities of the top event, the possibilities of sub events using the possibilities of the fuzzy gates and basic events need to be computed. The algorithms of fuzzy numbers and the calculation symbols are listed as follows [7]:

Addition ⊕

$$(m,\alpha,\beta)_{LR} \oplus (n,\gamma,\delta)_{LR} = (m+n, \alpha+\gamma, \beta+\delta)_{LR} \tag{5}$$

Subtraction –

$$(m,\alpha,\beta)_{LR} - (n,\gamma,\delta)_{LR} = (m-n, \alpha+\delta, \beta+\gamma)_{LR} \tag{6}$$

Multiplication ⊗

$$(m,\alpha,\beta)_{LR} \otimes (n,\gamma,\delta)_{LR} \simeq (mn, m\gamma+n\alpha, m\delta+n\beta)_{LR} \tag{7}$$

Division ÷

$$(m,\alpha,\beta)_{LR} \div (n,\gamma,\delta)_{LR} \simeq \left(\frac{m}{n}, \frac{m\delta+n\alpha}{n^2}, \frac{m\gamma+n\beta}{n^2}\right)_{LR} \tag{8}$$

2.3 Fuzzy operators of fault tree analysis

In order to obtain the probability of the top event in traditional fault tree analysis, the probabilities of basic events are calculated via logic gate operators. The probability of the top event is determined by the probabilities of basic events and the structure function. Meanwhile, during the fuzzy fault tree analysis, the probabilities of basic events are described as fuzzy numbers $F(\sim)_i$, and the traditional logic gate operators are replaced by fuzzy logic gate operators to obtain the fuzzy probability of the top event.

The AND fuzzy operator and the OR fuzzy operators are defined as follows [8]:

AND operator

$$\begin{aligned} \tilde{F}_s^{\text{and}} &= \prod_{i=1}^{n} \tilde{F}_i = \tilde{F}_1 \bullet \tilde{F}_2 \bullet \cdots \bullet \tilde{F}_n \\ &= (m_s, \alpha_s, \beta_s)_{LR} \\ &= (m_1, \alpha_1, \beta_1)_{LR} \bullet (m_2, \alpha_2, \beta_2)_{LR} \bullet \cdots \bullet (m_n, \alpha_n, \beta_n)_{LR} \\ &= (m_{s_{i-1}} m_i, m_{s_{i-1}} \alpha_i + m_i \alpha_{s_{i-1}}, m_{s_{i-1}} \beta_i + m_i \beta_{s_{i-1}})_{LR} \\ &= (m_{s_i}, \alpha_{s_i}, \beta_{s_i})_{LR} \end{aligned} \tag{9}$$

where $m_{s_i}, \alpha_{s_i}, \beta_{s_i}$ $(i = 1, 2, \ldots, n)$ are defined respectively as follows

$$\begin{aligned} & m_{s_1} = m_1, m_{s_2} = m_1 m_2, m_{s_3} = m_{s_2} m_3, \ldots, \\ & m_{s_i} = m_{s_{i-1}} m_i \\ & \alpha_{s_1} = \alpha_1, \alpha_{s_2} = m_1 \alpha_2 + m_2 \alpha_1, \alpha_{s_3} = m_{s_2} \alpha_3 + m_3 \alpha_{s_2}, \ldots, \\ & \alpha_{s_i} = m_{s_{i-1}} \alpha_i + m_i \alpha_{s_{i-1}} \\ & \beta_{s_1} = \beta_1, \beta_{s_2} = m_1 \beta_2 + m_2 \beta_1, \beta_{s_3} = m_{s_2} \beta_3 + m_3 \beta_{s_2}, \ldots, \\ & \beta_{s_i} = m_{s_{i-1}} \beta_i + m_i \beta_{s_{i-1}} \end{aligned} \tag{10}$$

OR operator

$$\begin{aligned}\tilde{F}_s^{or} &= 1-\prod_{i=1}^{n}(1-\tilde{F}_i)\\ &=(1,0,0)_{LR}-\{[(1,0,0)_{LR}-(m_1,\alpha_1,\beta_1)_{LR}]\\ &\quad\bullet[(1,0,0)_{LR}-(m_2,\alpha_2,\beta_2)_{LR}]\\ &\quad\bullet\cdots\bullet[(1,0,0)_{LR}-(m_n,\alpha_n,\beta_n)_{LR}]\}\end{aligned} \tag{11}$$

Eq. (11) can be rewritten in recursive form as

$$\begin{aligned}\tilde{F}_s^{or} &=(m_s,\alpha_s,\beta_s)_{LR}\\ &=(1,0,0)_{LR}-[m_{s_{i-1}}(1-m_i),m_{s_{i-1}}\alpha_i+(1-m_i)\alpha_{s_{i-1}}m_{s_{i-1}}\beta_i\\ &\quad+(1-m_i)\beta_{s_{i-1}}]_{LR}\\ &=(1,0,0)_{LR}-(m_{s_i},\alpha_{s_i},\beta_{s_i})_{LR}\end{aligned} \tag{12}$$

where $m_{s_i},\alpha_{s_i},\beta_{s_i}$ $(i=1,2,\ldots,n)$ are defined respectively

$$\begin{aligned}&m_{s_1}=m_1,m_{s_2}=(1-m_1)(1-m_2),\\ &m_{s_3}=m_{s_2}(1-m_3),\ldots,m_{s_i}=m_{s_{i-1}}(1-m_i)\\ &\alpha_{s_1}=\alpha_1,\alpha_{s_2}=(1-m_1)\alpha_2+(1-m_2)\alpha_1,\\ &\alpha_{s_3}=m_{s_2}\alpha_3+(1-m_3)\alpha_{s_2},\ldots,\alpha_{s_i}=m_{s_{i-1}}\alpha_i+(1-m_i)\alpha_{s_{i-1}}\\ &\beta_{s_1}=\beta_1,\beta_{s_2}=(1-m_1)\beta_2+(1-m_2)\beta_1,\\ &\beta_{s_3}=m_{s_2}\beta_3+(1-m_3)\beta_{s_2},\ldots,\beta_{s_i}=m_{s_{i-1}}\beta_i+(1-m_i)\beta_{s_{i-1}}\end{aligned} \tag{13}$$

The fuzzy fault tree analysis extends traditional fault tree analysis by removing the assumption that probabilities of failure event must be represented by a set of crisp values and/or the operation and failure states can be obviously identified. Fuzzy fault tree analysis can be applied when [20]: (1) There are no clear boundaries between failure and success states of the system; (2) The probability of system failure can not be calculated precisely due to the lack of sufficient data; (3) Subjective information, like natural language expressions, is collected from experts and analysts.

3 Fuzzy fault tree analysis of uncontained events of aero-engine rotor

3.1 Fault tree of uncontained events of aero-engine rotor

According to the fault tree analysis, "uncontained event of rotor" is chosen as the top event of the fault tree. The fault tree is built with the "deductive method", as shown in Fig. 4–Fig. 7.

3.2 Qualitative analysis of the fault tree

The purpose of qualitative analysis of fault tree is to achieve all potential sets of basic events that leading to the top event of fault tree occur (system failure), i.e. to achieve all minimal cut sets (MCS). Minimal cut sets are obtained using descending method (Fussell-Vesely method) [9].

By using Fussell-Vesely method, following the principles "AND gate adding, OR gate multiplication":

$$\begin{gathered}T=M_1+M_2+M_3+M_4\\ M_1=M_5+M_6+M_7+M_8\\ M_2=M_9+M_{10}+M_{11}+M_{12}\\ M_3=M_{13}+M_{14}\\ M_4=M_{15}+M_{16}\\ M_5=x_1+x_2+\cdots+x_8\\ M_6=M_7=\cdots=M_{12}=x_9+x_{10}+\cdots+x_{14}\\ M_{13}=M_{14}=M_{15}=M_{16}=x_{15}+x_{16}+\cdots+x_{22}\end{gathered}$$

Then the representation is obtained as below:

$$\begin{aligned}T&=M_1+M_2+M_3+M_4\\ &=x_1+x_2+\cdots+x_{22}\end{aligned}$$

In general, the less the order of MCS is, the higher is its occurrence frequency. The MCSs of the fault tree are obtained as: $\{x_1\}$, $\{x_2\}$, $\{x_3\}$, . . . , $\{x_{20}\}$, $\{x_{21}\}$, $\{x_{22}\}$. Given failure probability of basic events, effect of basic events on the probability of top event could be assessed quantitatively.

3.3 Quantitative analysis of the fault tree

Quantitative analysis includes evaluation of failure probability of the top event and the basic events. If all the MCSs and probabilities of the basic events are obtained, the failure probability of the top event can be achieved. To evaluate failure probability of the top event, probabilities of the basic events must be known in advance. The probabilities of basic events with fuzzy number are described by the reference function as follows:

Event codes	Basic events	Mean *m*	Upper and lower bounds α,β
x_1	Level 1 fan blades with high-cycle fatigue fracture	1×10^{-5}	5.56×10^{-7}
x_2	Level 1 fan blades with low-cycle fatigue fracture	1×10^{-6}	5.56×10^{-8}
x_3	The material of level 1 fan blades is inappropriate	1×10^{-6}	5.56×10^{-8}
x_4	The load of level 1 fan blades increases	1×10^{-6}	5.56×10^{-8}
x_5	The machining of level 1 fan blades is defective	1×10^{-6}	5.56×10^{-8}
x_6	The corrosion of level 1 fan blades is serious	1×10^{-6}	5.56×10^{-8}
x_7	The material of level 1 fan blades is defective	1×10^{-6}	5.56×10^{-8}
x_8	Inhale foreign objects	1×10^{-6}	5.56×10^{-8}
x_9	All levels of disks & shafts of fans, all levels of disks of compressors, and labyrinth disks, shafts high-cycle fatigue fracture	1×10^{-6}	5.56×10^{-8}
x_{10}	All levels of disks & shafts of fans, all levels of disks of compressors, and labyrinth disks, shafts low-cycle fatigue fracture	1×10^{-6}	5.56×10^{-8}
x_{11}	The material of all levels of disks & shafts of fans, all levels of disks of compressors, and labyrinth disks, shafts is inappropriate	1×10^{-6}	5.56×10^{-8}
x_{12}	The load of all levels of disks & shafts of fans, all levels of disks of compressors, and labyrinth disks, shafts increases	1×10^{-6}	5.56×10^{-8}
x_{13}	The machining of all levels of disks & shafts of fans, all levels of disks of compressors, and labyrinth disks, shafts is defective	1×10^{-6}	5.56×10^{-8}
x_{14}	The material of all levels of disks & shafts of fans, all levels of disks of compressors, and labyrinth disks, shafts is defective	1×10^{-6}	5.56×10^{-8}
x_{15}	High-pressure turbine disks, labyrinth disks, shafts, all levels of low vortex turbine disks and shafts high-cycle fatigue fracture	1×10^{-6}	5.56×10^{-8}
x_{16}	High-pressure turbine disks, labyrinth disks, shafts, all levels of low vortex turbine disks and shafts low-cycle fatigue fracture	1×10^{-6}	5.56×10^{-8}
x_{17}	High-pressure turbine disks, labyrinth disks, shafts, all levels of low vortex turbine disks and shafts creep fatigue fracture	1×10^{-6}	5.56×10^{-8}
x_{18}	The material of high-pressure turbine disks, labyrinth disks, shafts, all levels of low vortex turbine disks and shafts is inappropriate	1×10^{-6}	5.56×10^{-8}
x_{19}	The load of high-pressure turbine disks, labyrinth disks, shafts, all levels of low vortex turbine disks and shafts increases	1×10^{-6}	5.56×10^{-8}
x_{20}	The machining of high-pressure turbine disks, labyrinth disks, shafts, all levels of low vortex turbine disks and shafts is defective	1×10^{-6}	5.56×10^{-8}
x_{21}	The local temperature of high-pressure turbine disks, labyrinth disks, shafts, all levels of low vortex turbine disks and shafts increases	1×10^{-6}	5.56×10^{-8}
x_{22}	The material of high-pressure turbine disks, labyrinth disks, shafts, all levels of low vortex turbine disks and shafts is defective	1×10^{-6}	5.56×10^{-8}

Table 1: The basic events code table [6]

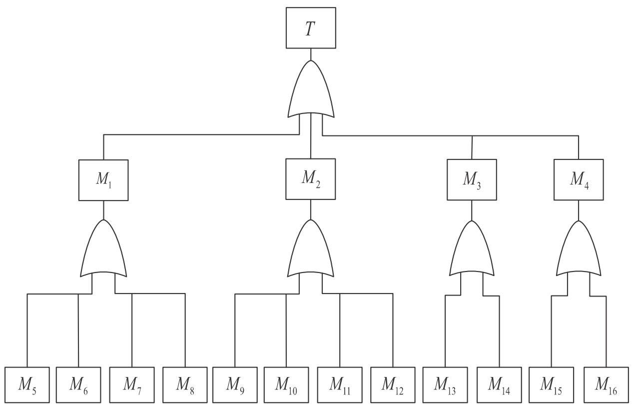

Fig. 2: The fault tree of uncontained event of an aero-engine rotor (I)

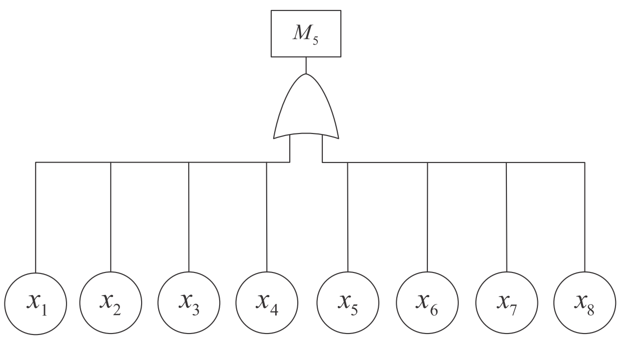

Fig. 3: The fault tree of uncontained event of an aero-engine rotor (II)

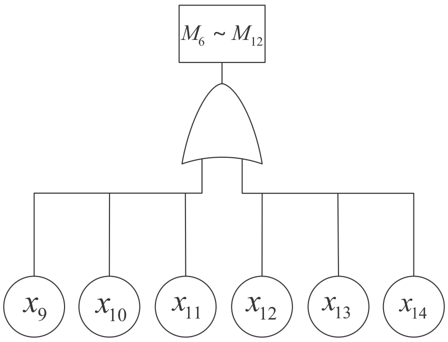

Fig. 4: The fault tree of uncontained event of an aero-engine rotor (III)

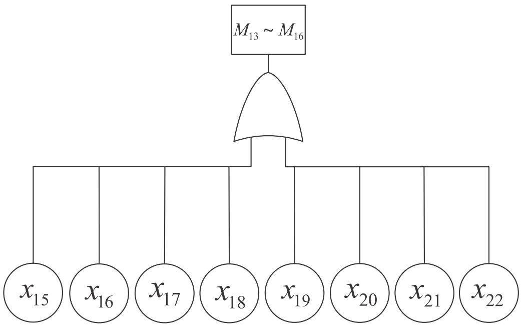

Fig. 5: The fault tree of uncontained event of an aero-engine rotor (IV)

$$\tilde{F}_i(x) = \begin{cases} L[(m-x)/\alpha] = 1/[1+(m-x)/\alpha], & x \le m, \alpha > 0 \\ R[(x-m)/\beta] = 1/[1+(x-m)/\beta], & x > m, \beta > 0 \end{cases} \quad (14)$$

According to the basic event data in [8] and the grading description on ranks of failure modes probability in [13], the means of basic events m are calculated as listed in Table 1.

Supposed that the membership function of fuzzy number $F(\sim)_i$ is symmetrical, and the membership is 0.1 at x differing by ±50% with mean m_i

$$\alpha_i = \beta_i$$
$$1/[1+(m-x)/\alpha] = \alpha/(\alpha+0.5m) = 0.1$$

Then $\alpha_i = \beta_i = 0.0556 m_i$. The upper and lower bounds α, β can be solved based on this relationship, which is listed in Table 1.

The intermediate event M_5 is obtained as

$$\tilde{F}_s^{or}(M_5) = \mathrm{OR}(x_1, x_2, \ldots, x_8) = (1,0,0)_{LR} - (m_{s_i}, \alpha_{s_i}, \beta_{s_i})_{LR}$$

The values of $m_i, m_{s_i}, \alpha_{s_i}, \beta_{s_i}$ are calculated according to recurrence formula in Eq. (13). The results are listed in Table 2.

The mean, left and right bounds of the intermediate event M_5 are calculated using the data in Table 2 as follows

$$m_{M_5} = 1 - m_{s_8} = 1 - 9.999830 \times 10^{-1} = 1.69999 \times 10^{-5}$$
$$\alpha_{M_5} = \beta_{M_5} = 9.451899 \times 10^{-7}$$

The fuzzy probability of the intermediate event M_5 is

$$\tilde{F}(M_5) = (1.699991 \times 10^{-5}, 9.451899 \times 10^{-7}, 9.451899 \times 10^{-7})$$

In summary, it is worth noting that during the process of fuzzy fault tree analysis, it is possible to calculate the subjective reliability of the corresponding system by giving a fault tree structure and information about the reliability of the system components in linguistic terms. The fuzzy sets express the subjective possibility of failure of the system by mapping each linguistic value to a range of subjective failure possibilities through membership function of a fuzzy set.

Event code	m_i	$(1 - m_i)$	m_{s_i}	α_i, β_i	$\alpha_{s_i}, \beta_{s_i}$
x_1	1.000000E-05	9.999900E-01	1.000000E-05	5.560000E-07	5.560000E-07
x_2	1.000000E-06	9.999990E-01	9.999890E-01	5.560000E-08	6.115989E-07
x_3	1.000000E-06	9.999990E-01	9.999880E-01	5.560000E-08	6.671977E-07
x_4	1.000000E-06	9.999990E-01	9.999870E-01	5.560000E-08	7.227963E-07
x_5	1.000000E-06	9.999990E-01	9.999860E-01	5.560000E-08	7.783949E-07
x_6	1.000000E-06	9.999990E-01	9.999850E-01	5.560000E-08	8.339933E-07
x_7	1.000000E-06	9.999990E-01	9.999840E-01	5.560000E-08	8.895917E-07
x_8	1.000000E-06	9.999990E-01	9.999830E-01	5.560000E-08	9.451899E-07

Table 2: The results of the intermediate event M5

4 Conclusion

FTA is an effective method to assess safety and reliability of complex system. The reliability of uncontained event of an aero-engine rotor was analyzed. Based on the theory of fuzzy fault tree analysis, the fuzzy fault tree of uncontained events of an aero-engine rotor was established and analyzed qualitatively and quantitatively. The symmetrical *L-R* type membership function was used to analyze the uncontained event of an aero-engine rotor. The future work of this study will focus on the joint dependent failures and common cause failures of mechanical components, including material properties, operation restrictions and environmental effects.

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References

[1] S. Seng, J. Manion, and C. Frankenberger. Uncontained engine debris analysis using the uncontained engine debris damage assessment model. Federal Aviation Administration, Report No. DOT/FAA/AR-04/16, September 2004.
[2] C. Liu and M. Deng, Structure Analysis of Aircraft Engine. Xi'an: Northwestern Polytechnical University Press, 2006.
[3] Y. F. Li, H. Z. Huang, Y. Liu, N. Xiao, H. Li, "A new fault tree analysis method: Fuzzy dynamic fault tree analysis," Eksploatacja i Niezawodnosc – Maintenance and Reliability, vol. 14, no. 3, pp. 208–215, 2012.
[4] H. Z. Huang, H. Zhang, Y. Li, "A new ordering method of basic events in fault tree analysis," Quality and Reliability Engineering International, vol. 28, no. 3, pp. 297–305, 2012.
[5] H. Z. Huang, X. Tong, M. J. Zuo, "Posbist fault tree analysis of coherent systems," Reliability Engineering and System Safety, vol. 84, no. 2, pp. 141–148, 2004.
[6] Q. Mei and J. Liao, The Basis of System Reliability Engineering. Beijing: Science Press, 1987.
[7] L. A. Zadeh, "Fuzzy sets," Information and Control, vol. 8, pp. 338–353, 1965.
[8] H. Z. Huang, "A new fuzzy set approach to mechanical system fault tree analysis," Mechanical Science and Technology, no. 1, pp. 1–7, 1994.
[9] J. B. Fussell, E. B. Henry and N. H. Marshall, MOCUS-A Computer Program to Obtain Minimal Sets from Fault Trees. Idaho Falls: Aerojet Nuclear Company, 1974.
[10] D. Singer, "A Fuzzy set approach to fault tree and reliability analysis," Fuzzy Sets and Systems, vol. 34, pp. 145–155, 1990.
[11] Q. Huang, L. Zhang, R. Kong, C. Liu, H. Liu and W. Shi, "Safety analysis of the uncontained event for aero-engine," In: Proceedings of 11th Annual Conference of Scientific Committee of Reliability Engineering of Chinese Society of Aeronautics and Astronautics, pp. 142–147, 2008.
[12] Y. Zhao and W. Gong, "Fuzzy fault tree analysis and its application," China Safety Science Journal, vol. 12, no. 6, pp. 81–87, 2001.
[13] D. Dubois and H. Prade, Fuzzy Sets and Systems-Theory and Application. New York: Academic Press, 1980.
[14] Q. Gong, Model Reliability Engineering Manual. Beijing: National Industry Press, 2007.
[15] N. A. Moussa, M. D. Whale, D. E. Groszmann, X. J. Zhang, The potential for fuel tank fire and hydrodynamic ram from uncontained aircraft engine debris, Federal Aviation Administration, Report No. DOT/FAA/AR-96/95, January 1997.
[16] Q. He, H. Xuan, L. Liu, W. Hong, R. Wu, Perforation of aero-engine fan casing by a single rotating blade, Aerospace Science and Technology, in press, doi:10.1016/j.ast.2012.01.010, 2012.
[17] P. V. Suresh, A. K. Babar, V. Venkat Raj. Uncertainty in fault tree analysis: A fuzzy approach. Fuzzy Sets and Systems, vol. 83, no. 2, pp. 135–141, 1996.
[18] H. Tanaka, L. T. Fan, F. S. Lai, K. Toguchi. Fault-Tree Analysis by Fuzzy Probability. IEEE Transcations on Reliability, 1983, vol. 32, no. 5, pp. 453–457, 1983.
[19] Y. H. Dong, D. T. Yu. Estimation of failure probability of oil and gas transmission pipelines by fuzzy fault tree analysis. Journal of Loss Prevention in the Process Industries, vol. 18, pp. 83–88, 2005.
[20] I. M. Dokas, D. A. Karras, D. C. Panagiotakopoulos. Fault tree analysis and fuzzy expert systems: Early warning and emergency response of landfill operations. Environmental Modelling & Software, vol. 24, pp. 8–25, 2009.
[21] A. C. F. Guimarẽes, N. F. F. Ebecken. Fuzzy FTA: A fuzzy fault tree system for uncertainty analysis. Annals of Nuclear Energy, vol. 26, pp. 523–532, 1999.
[22] M. Kumar, S. P. Yadav. The weakest t-norm based intuitionistic fuzzy fault-tree analysis to evaluate system reliability. ISA Transactions, vol. 51, pp. 531–538, 2012.
[23] A. Mentes, I. H. Helvacioglu. An application of fuzzy fault tree analysis for spread mooring systems. Ocean Engineering, vol. 38, pp. 285–294, 2011.
[24] S. Gupta, J. Bhattacharya. Reliability Analysis of a conveyor system using hybrid data. Quality and Reliability Engineering International, vol. 23, no. 7, pp. 867–882, 2007.