

CAUSALITY DIAGRAM BASED SAFETY ANALYSIS OF MICRO TURBOJET ENGINE

Ding Shuiting, Bao Mengyao

(School of Jet Propulsion, Beijing University of Aeronautics and Astronautics, Beijing, 100191, P. R. China)

Abstract: An improved safety analysis based on the causality diagram for the complex system of micro aero-engines is presented. The study is examined by using the causality diagram in analytical failure cases due to rupture or penetration in the receiver of micro turbojet engine casing, and the comparisons are also made with the results from the traditional fault tree analysis. Experimental results show two main advantages: (1) Quantitative analysis which is more reliable for the failure analysis in jet engines can be produced by the causality diagram analysis; (2) Graphical representation of causality diagram is easier to apply in real test cases and more effective for the safety assessment.

Key words: micro turbojet engines; safety analysis; causality diagram; fault tree analysis; failure

CLC number: V235.1 **Document code:** A **Article ID:** 1005-1120(2011)03-0262-07

INTRODUCTION

Recent studies of micro turbojet engines draw increasing interests due to their tiny designed sizes and special purposes. However, the study in this field is not trivial because of the consideration in the design step of extreme high rotating speed and small body size requirements. Furthermore, the complex working environment causes quite a few issues, such as shorter life cycle, difficulty in maintenance, as well as high cost for the damage. Since applications for the micro turbojet engines are extended, the difficulties in the structural design, the failure modes and the connections among these failure modes increase a lot, which require more considerations in the design and manufacture process. All of these lead to a more detailed study requirement of safety analysis of aero engines. In addition, there is no study approach is generated for the use in micro turbojet engines while most of the current methods are generated for the usual jet engines. For the reasons mentioned above, the lacking in complete understanding in this area drives more attention and research in the safety analysis of micro turbo-

jet engines^[1-2].

The safety analyses of civil aerospace system and equipments are described in Ref. [3]. Based on this reference, the traditional methods such as FTA, RBD and Markov, are not quite excellent fit into the micro turbojet engines and the main disadvantages are reviewed as below. Firstly, for the complex analytical cases, the CPU requirement for the calculation grows high and relations are still difficult to achieve. Moreover, for the coupling causes of the safety issues, the results might not be reliable enough. In addition, the relation consideration of time and conditional probabilities is neglected in these approaches. The causal diagram introduced in this paper is a loop directed graph, which introduces logic gates into the network and dynamic characteristics into topology. The results show that this diagram can give effective corrections for the disadvantages mentioned above.

This paper presents an improved safety analysis approach based on the causality diagram, which is verified by test case, such as rupture or penetration of receiver of micro turbojet engine casing. With the description of the analytical pro-

cess, the comparisons are also made with the results produced from the traditional FTA method.

1 HAZARD OF MICRO TURBOJET ENGINE

In this paper, a certain turbojet engine with a structure assembling integral guiding vanes and turbines as a whole component is researched as a case. The vanes also serve as stator casing. The structure sketch is shown in Fig. 1. In the design process of components of micro turbojet engine turbine, turbine rotor is the key component for safety analysis which determines the failure mode "rupture or penetration" of turbojet engine casings (noncontainment). This failure mode is one of the most hazardous failures, thus it should be eliminated during design process. Therefore, the safety analysis for turbine casing must be conducted. In the following sections, the causal graph theory for safety analysis is applied.

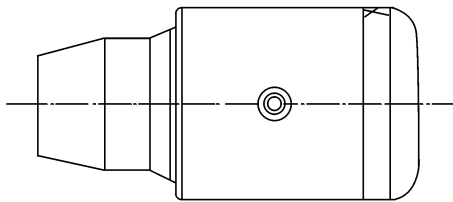


Fig. 1 Structure of micro turbojet engine

2 CAUSALITY DIAGRAM THEORY

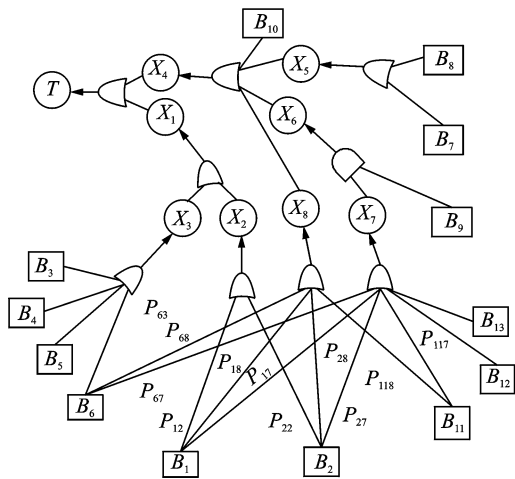
2.1 Basic concept of causality diagram theory

Firstly, the causality diagram^[4-6] is based on the probability theory, which is a solid theoretical foundation including Boolean logic operation and has no restriction for network topology. Hence the causality diagram^[2,4] can establish network according to actual situation. Secondly, the causality diagram introduces logic into network and implies straight causal level rather than conditional probability to avoid related issues at the given time. Thirdly, the causality diagram approach is also a kind of flexible deductive analysis, which obtains the causes from results and results from reasons, thus solving causes mixing problems^[5-8].

Therefore, for turbojet engines, this approach is consistent with the practical requirements of complex systems^[9], and effectively simulates the actual failure modes.

2.2 Models of causal graph theory

In order to conduct the safety analysis for noncontainment of micro turbojet engine casings, a causality diagram for the "rupture or penetration of turbojet engine casings" is established and shown in Fig. 2. According to the causal graph-structure, reasons for rupture or penetration, their internal relations, and the correlations between failures are clearly illustrated.



T : Rupture or penetration of turbine casing; X_1 : Burst of turbine components casing; X_2 : Exceeding material strength limit; X_3 : Stress increasing; X_4 : Casing burst caused by uncontained rotor; X_5 : Bearing failure; X_6 : Dangerous fragment puncture casing; X_7 : Dangerous fragment of turbine disk; X_8 : Turbine disk-shaft failure; B_1 : High and low cycle fatigue rupture; B_2 : High temperature creep rupture; B_3 : Rotor casing stress increasing burst caused by manufacturing defects; B_4 : Mechanical wear caused by small radial clearance to penetrate casing; B_5 : Rotor casing stress increasing burst caused by maneuvering flight; B_6 : Rotor casing stress increasing burst caused by high gradient of local temperature; B_7 : Bearing wear caused by lack of oil in bearing chamber causes; B_8 : High-temperature gas into bearing chamber, so that bearing over-temperature; B_9 : Sufficient energy for dangerous fragment to penetrate a casing; B_{10} : Manufacturing defect; B_{11} : Failure by rotor excess revolution; B_{12} : Blade failure by over temperature damage; B_{13} : Blade root rupture, blade loss; P_{ij} : Linkage event between cause event i and result event j ; \triangleleft : OR gate; \square : AND gate; \circ : Node event; \square : Basic event

Fig. 2 Causality diagram of rupture or penetration of turbojet engine casings

2.3 Reasoning process in causality diagram

The calculation process in the causality diagram is divided into following four steps:

(1) Calculation of the first-order cut set expressions of node events.

Definition 1 The cut set C_i is defined as a set of events (including basic events B_i , node events X_i , logic events G_i , and linkage events P_{ij}) combined with logic relation "AND". The relation between different cut sets is logic relation "OR". The cut set which is comprised merely by events adjacent to a certain node event is defined as the first-order cut set.

(2) Calculation of the final cut set expression of node events.

Definition 2 The cut set which is expressed merely by basic events and connected events is called the cut set of node events.

(3) Calculation of the nonintersect cut sets of node events.

Definition 3 $X = \bigcup_{i=1}^m C_i$, where $C_i = \bigcap_{j=1}^{n_j} V_{ij}$,

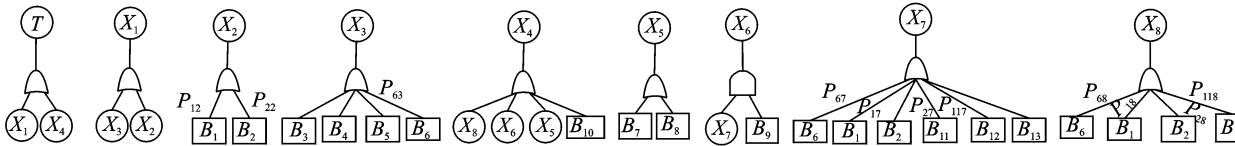


Fig. 3 Micro causal trees

The whole causality diagram is shown in Fig. 4 corresponding to the micro causal trees, from which the relationships among reasons of failures can be determined clearly.

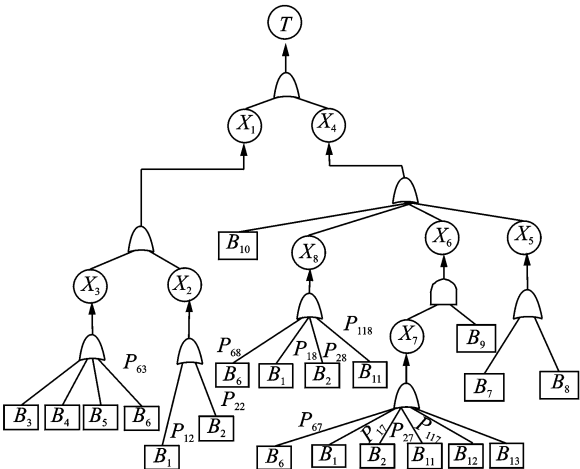


Fig. 4 Whole causal tree

the nonintersect cut set can be expressed as: $T = C_1 \oplus C_2 \overline{C_1} \oplus C_3 \overline{C_1} \overline{C_2} \oplus \dots \oplus C_m \overline{C_1} \overline{C_2} \dots \overline{C_{m-1}}$, in which, \oplus represents exclusive, T is the top event and C_i the cut set variable indexed by i .

(4) Calculation of the probability of top event $P(T)$ and corresponding quantitative calculation.

2.4 Model calculations in causality diagram theory

As a kind of the equivalent expression of the causality diagram, causal trees (based on events or variables) can be used to calculate the occurrence probability of top events. Therefore, the causality diagram shown in Fig. 2 can be simplified to the micro causal trees illustrated in Fig. 3. Each node event (or variable) in the causality diagram corresponds to a micro causal tree. The root of each micro causal tree is the corresponding node event (or variable). Essentially, for the causal trees, node events are roots, while the adjacent node events are input events.

(1) Calculation of the first-order cut set of node events.

From the micro causal trees, the reasoning processes can be expressed as follows

$$\begin{aligned}
 X_1 &= X_3 \cup X_2 \\
 X_2 &= P_{12}B_1 \cup B_2 \\
 X_3 &= B_3 \cup B_4 \cup B_5 \cup P_{63}B_6 \\
 X_4 &= X_8 \cup X_5 \cup B_{10} \cup X_6 \\
 X_5 &= B_7 \cup B_8 \\
 X_6 &= X_7B_9 \\
 X_7 &= P_{67}B_6 \cup P_{17}B_1 \cup P_{27}B_2 \cup P_{117}B_{11} \cup B_{12} \cup B_{13} \\
 X_8 &= P_{68}B_6 \cup P_{18}B_1 \cup P_{28}B_2 \cup P_{118}B_{11} \\
 T &= X_1 \cup X_4
 \end{aligned}
 \tag{1}$$

(2) Calculation of the final cut set of node event.

$$X_1 = X_3 \cup X_2 = B_3 \cup B_4 \cup B_5 \cup P_{63}B_6 \cup P_{12}B_1 \cup B_2$$

top event is 0.020 2, thus the difference of probability between the causality diagram result and the experiment result is 3×10^{-5} .

The minimum cut set refers to the least number of occurring failures and a set of the most necessary basic events. Therefore, discovering the minimum cut set is crucial to finding out reasons of failures. According to Eq. (5), the minimum cut sets triggering the top event are

$$\{B_3\}, \{B_4\}, \{B_5\}, \{B_6\}, \{B_1\}, \{B_2\}, \{B_{11}\}, \{B_7\}, \{B_8\}, \{B_{10}\}, \{B_9B_6\}, \{B_9B_1\}, \{B_9B_2\}, \{B_9B_{11}\}, \{B_9B_{12}\}, \{B_9B_{13}\}$$

Among these 16 minimum cut sets, if one of them happens, then the top event happens. Because the minimum cut sets represent failure modes, the importance of minimum cut sets (IMCS), which is the importance level of the minimum cut sets, can represent impacts of each failure mode on the top event.

Definition 4 Set $P_T^M = \frac{P_M}{P_T}$, where P_T^M is the importance of minimum cut sets, P_M the probability of minimum cut sets, P_T the occurrence probability of the top event. The results of IMCS are shown in Table 2.

Table 2 Importance of minimum cut sets

| MCS | IMCS | MCS | IMCS | MCS | IMCS |
|-------|----------|----------|----------|-------------|-----------------------|
| B_3 | 0.095 55 | B_{11} | 0.038 22 | B_9B_2 | 0.000 12 |
| B_4 | 0.114 66 | B_7 | 0.038 22 | B_9B_{11} | 5.83×10^{-5} |
| B_5 | 0.095 55 | B_8 | 0.133 77 | B_9B_{12} | 8.84×10^{-5} |
| B_6 | 0.095 55 | B_{10} | 0.114 66 | B_9B_{13} | 2.95×10^{-5} |
| B_1 | 0.114 66 | B_9B_6 | 0.000 15 | | |
| B_2 | 0.076 44 | B_9B_1 | 0.000 18 | | |

According to the data analysis in Table 2, B_8, B_4, B_1 , and B_{10} are the most significant failure modes for the top event. Thus they are the key factors. Therefore, following situations must be prevented and some promotion measures must be implemented to avoid these problems.

First of all, the hot gas ingested into bearing chamber must be prevented in order to avoid overheating problem of bearings (i. e. B_8). In terms of micro turbojet engines, because of the short engine diameter, high rotor speed, heavy load-

bearing of shafts, and limitation of shaft, the number of failures of shafts is large. The impact of hot gas on shafts can be prevented by reasonable design, such as installing cooling channel and heat shield at the hot part to cut off the influence of high temperature gas on the bearing.

Then, mechanical friction, which is caused by small radical clearances, must be prevented (i. e. B_4). In design process, the small clearances between blades, which lead to hydrodynamics excitation to rub damage of rotors and stators, must be avoided. In addition, during assembling process, nonconcentricity between rotors and case, imperfect alignment and high disturbance degree of rotors must be avoided. If the friction still exists, some experiments must be used to ensure that it cannot penetrate the casing.

Finally, high-low cycle fatigue rupture (i. e. B_1) and manufacturing defects (i. e. B_{10}) must be prevented. Because rotor speed and centrifugal effect are as high as $(1.0-1.6) \times 10^6$ r/min, the stress concentration must be avoided. In addition, because working rotor speed is high and support stiffness of rotors has a great impact on the critical speed, appropriate support stiffness about $(2.0-3.0) \times 10^7$ N/m is required. For micro turbojet engine, the dynamic balance of flexible rotor is required to reduce shake.

In addition, it is clear that B_{11}, B_{12} and B_{13} have few influences on the top event, thus they can be neglected.

In conclusion, the causality diagram can discover reasons of failures, obtain the minimum cut sets, and then achieve the goal of failure diagnosis. Meanwhile, the key to reduce probability of top event is reducing the occurrence probability of events at high importance level within the minimum cut set. Through analysis of related failures, correct methods must be implemented to eliminate potential risks and limit impacts within the minimum range.

3 COMPARE ANALYSIS

3.1 Result of fault tree analysis

Referring to Ref. [10], as shown in Fig. 5,

the occurrence probability of the top event is

$$P_T = \sum_{i=1}^8 X_i + X_{15} \sum_{j=9}^{14} X_j + \sum_{k=16}^{20} X_k = 0.01417,$$

thus the difference between the result of fault tree and actual probability is $0.00603 \approx 6 \times 10^{-3}$.

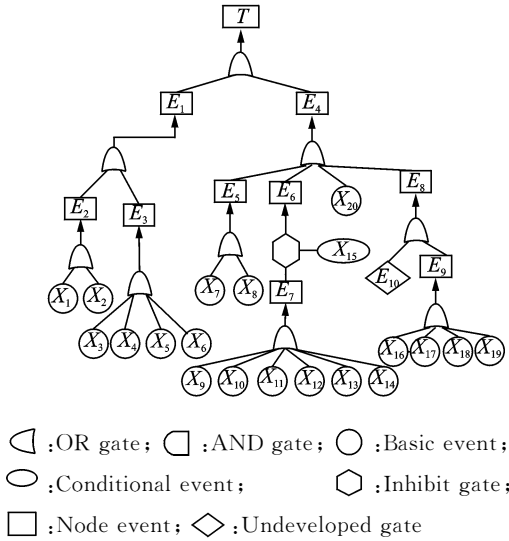


Fig. 5 Fault trees

3.2 Variance analysis

According to the experimental data, the actual probability of the top event is 0.0202. The probability of failure occurrence produced by the causality diagram is 0.02017. Compared with the FTA result 0.01417, it is closer to the reality.

Through establishing the model of top event T and the method simplification, the reasons of difference between the causality diagram and fault tree can be figured out: As shown in Figs. 2-5, the causality diagram overcomes the problems of correlation in nonindependence among the reasons of failures, lack of systematic and comprehensive consideration of failures, and lack of diagnosis information. Therefore, for the high-precision complex system with more basic events and correlations, the matrix of nonintersect cut sets can improve calculation speed and reduce calculating amount.

The fault tree approach is based on the component connections and the analysis of failure modes. It decomposes reasons of systematic faults into middle events and basic events in order to obtain the quantitative index such as occur-

rence probability of top event if basic events are dependent and the occurrence probabilities are known. In the safety analysis of reasons for failures, because of the problem of correlation in nonindependence, it is incorrect to divide reasons into completely independent basic events in the decomposing process. However, the accurate results of fault tree analysis are seriously depended on the information completeness. Therefore, the application of the fault tree analysis has certain limitations and results in a larger error compared with the true value.

In addition, through the calculation of causality diagram and an investigation of difference with fault tree analysis, it is clear that the causality diagram can be used for failure diagnosis and identification of malfunction causes. It can calculate the occurrence probability of specified events of failure in order to carry out safety analysis and assessment. For the safety analysis of micro turbojet engines, compared with the fault tree analysis, the causality diagram is more suitable for actual system operations and failure conditions of complex systems of aero-engines, and can improve the failure diagnosis accuracy.

4 CONCLUSION

The outcomes of this research demonstrate that: Initially, aiming to the characteristics of complex systems of micro turbojet engines, the application of causality diagram during process of safety analysis can successfully solve the issues of correlation in nonindependence and the lack of diagnosis information; Moreover, the implementation of nonintersect cut set matrix can excellently improve calculation speed and simplify calculation amount; Furthermore, compared with the fault tree analysis, the causality diagram is more effective for failure diagnosis, qualitative and quantitative safety analysis, identifying possible failure modes, and analyzing impacts of each events on the "rupture or penetration" failure; Finally, the causality diagram shortens development length and reduces potential risks.

Therefore, the causality diagram approach

for safety analysis can satisfy practical requirements of high-precision complex systems of aero-engines. There are two main advantages are concluded: (1) Quantitative analysis which is more reliable for the failure analysis in aero engines can be produced by the causality diagram analysis; (2) Graphical representation of causality diagram is easier to apply in real test cases and more effective for the safety assessment.

References:

- [1] Merrill W C, DeLaat J C, Abdelwahab M. Turbo-fan engine demonstration of sensor failure detection [J]. Journal of Guidance, Control & Dynamics, 1991, 14(2):337-349.
- [2] Kappas J. Review of risk and reliability methods for aircraft gas turbine engines [R]. DSTO-TR-1306, 2002:1-53.
- [3] ARP 4761. Guidelines and methods for conducting the safety assessment process on civil airborne systems and equipment[S]. SAE, 1996.
- [4] Zhang Qin. Probabilistic reasoning based on dynamic causality tree/diagrams [J]. Safety Engineering and System Safety, 1994, 46(6):209-220.
- [5] Liang Xinyuan, Shi Qingxi, Zhang Qin. Application

of causality diagram in system safety analysis [J]. Journal of Chongqing University: English Edition, 2005, 4(3):158-163.

- [6] Paska J, Oleksy A. Safety issues in power systems with DG [C]//Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century. Pittsburgh:[s.n.], 2008:17.
- [7] Plattner H, Siemens A G. A new component concept for fault trees [C]//The 8th Australian Workshop on Safety Critical Systems and Software. Canberra: Australian Computer Society, 2003:33.
- [8] Leveson N G, Dulac N. Safety risk-driven design in complex systems of systems [C]//The 1st Space Exploration Conference: Continuing the Voyage of Discovery. Florida: American Institute of Aeronautics and Astronautic, 2005: AIAA 2005-2558.
- [9] Fan Xinghua, Sun Maosong. A reasoning algorithm of applying causality diagram to fault diagnosis of complex hybrid systems [C]//The 5th World Congress on Intelligent Control and Automation. Hangzhou, China:[s.n.], 2004: 1741-1745.
- [10] Bao Mengyao, Zhou Yanpei, Ding Shuiting. Safety analysis on micro-turbojet engine for airworthiness [C]//The 1st International Symposium on Aircraft Airworthiness. Beijing, China:[s.n.], 2009.

基于因果图的微小型涡喷发动机安全性分析

丁水汀 鲍梦瑶

(北京航空航天大学能源与动力工程学院, 北京, 100191, 中国)

摘要:针对复杂的航空发动机系统,提出一种基于因果图的方法对其进行安全性分析。以微小型涡喷发动机机匣破裂或被击穿失效为例,对因果图在安全性分析中的应用进行了研究,并与传统的故障树分析结果进行了对比和分析。研究表明,基于因果图的方法一方面可以找出导致航空发动机系统失效的原因之间的复杂因果关系,给出定量

分析,符合客观实际;另一方面图形化的推理方法易于安全评估和工程应用。

关键词:微小型涡喷发动机;安全性分析;因果图;故障树;失效

中图分类号:V235.1

(Executive editor: Zhang Huangqun)