Research on Probabilistic Safety Analysis Approach of Flight Control System based on Bayesian Network

Chen Kang\textsuperscript{a}, Lu Zhong\textsuperscript{a,*}, Zeng Haijun\textsuperscript{a,b}

\textsuperscript{a}College of Civil Aviation, Nanjing University of Aeronautics & Astronautics, Nanjing, 211106, China
\textsuperscript{b}Research and Development Center, AVIC COMMERCIAL AIRCRAFT ENGINEERING CO., LTD, Shanghai, 201108, China

Abstract

Traditional probabilistic safety analysis methods are not suitable for modern flight control system with multi-state probability. In this paper a Bayesian Network based probabilistic safety model is built according to the state relationship between flight control system and its constituting components. A safety probability algorithm is proposed by using Universal Generating Function (UGF) combined with Clique Tree Propagation. The probability of system top failure condition and the importance of each constituting component are acquired efficiently, the safety level of the flight control system can be asessed and the role of each component in the system safety can be determined. The probabilistic safety analysis approach based on Bayesian Network provide a simple and intuitive measure to deal with the safety analysis of flight control system with multi-state property, which overcome the deficiencies of traditional approach.

1. Introduction

Safety analysis is an important method to demonstrate compliance with airworthiness requirement in type certification. At present, Fault Tree Analysis, Markov Analysis and Dependence Diagram Analysis are the most widely-used methods of probabilistic safety analysis for civil airborne system [1]. All these methods are based on
traditional binary model allowing for only two possible states for a system and its components: perfect functionality and complete failure. However, flight control system of modern civil aircraft is a typical integrated and complex system that consists of mechanical, electronic, electrical, and hydraulic components; and the diversity of these constituting components cause the system to have different performance levels and several failure modes with various effects on the entire system performance. Therefore, all of the above mentioned probabilistic safety analysis methods are not suitable for modern flight control system. The probabilistic safety analysis approach proposed herein can be applied to the safety analysis of flight control system with multi-state property.

We will establish a probabilistic safety model based on Bayesian Network to describe the multi-state property of modern flight control system [2]; and then, in terms of the model, we will present a safety probability algorithm which can be used to calculate the probability of system top failure condition and importance of each component constituting the system.

2. General architecture and failure feature of flight control system

The flight control system is commonly composed of three types of subsystem: Sensor subsystem, control computer subsystem and actuator subsystem. In the Fig. 1, the general architecture of flight control system is shown.

- Sensors collect the signals that are available to the flight control progress and provide these signals to the control computers. The failure features of sensors can be divided two modes: mistake signals output and the function of output signals get failed.
- Control computers receive the output signals of sensors and output the control signals to the actuators to the flight control surface. The failure feature of control computers can be divided two modes: mistake signals output and computing control signals function fail. While failure feature of the control computers’ power is that providing power function fail.
- Actuators receive the signals from control computer and move the surfaces to the corresponding position. The failure feature of actuators can be divided two modes: part of actuating function lost, full actuating function lost. While the failure features of hydraulic pressure system that provide hydraulic pressure to the actuators can be divided two modes: part of providing pressure function fail, full providing pressure function fail.

3. Bayesian Network based probabilistic safety model of flight control system

In this paper UGF is used to describe the multi-states and series-parallel structures to build the Conditional Probability Table (CPT) of the Bayesian network. The UGF polynomial expression of the multi-state units or systems like [3,4]:

\[ U_{s}(z) = \sum_{i=0}^{k} p_{s_{i}}z^{s_{i}} \]  

(1)
In this formula, $s$ is the number of units or systems, $j_i$ is the state of $s$ unit or system, $k_s$ express the state number of $s$ state, $g_{sj_i}$ is the state value of the $j_i$ state in $s$ unit or system, $p_{sj_i}$ is the probability of the $j_i$ state in $s$ unit or system, $z$ is auxiliary variable.

If the units or systems in series, the probability mass functions (p.m.f) of system composed of $n$ units or systems like this:

$$U_s(z) = \min(U_1(z), U_2(z) \cdots U_n(z))$$

$$= \sum_{j_1=0}^{k_1} \sum_{j_2=0}^{k_2} \cdots \sum_{j_n=0}^{k_n} \prod_{s=0}^{n} p_{sj_i} z^{\min(g_{s1}, g_{s2}, \cdots, g_{sn})}$$

(2)

If the units or systems in parallel, the p.m.f of system composed of $n$ units or systems like this:

$$U_s(z) = \max(U_1(z), U_2(z) \cdots U_n(z))$$

$$= \sum_{j_1=0}^{k_1} \sum_{j_2=0}^{k_2} \cdots \sum_{j_n=0}^{k_n} \prod_{s=0}^{n} p_{sj_i} z^{\max(g_{s1}, g_{s2}, \cdots, g_{sn})}$$

(3)

Assume that $X_1$, $X_2$, $X_3$ and $X_4$ respectively represents the electronic, mechanical, power, and hydraulic units and systems. $\theta$ express that event gets failed, $\theta^0$ express that output mistake, $m$ express that part of function get failed, and $l$ express that event is normal. Through the formula (1), get the UGF polynomial of the $X_1$, $X_2$, $X_3$ and $X_4$. Through the formula (2) (3), the p.m.f of different type units and systems in series-parallel can be got. Get the states probability from the p.m.f of the units and systems to establish the CPT of the Bayesian network.

4. Safety probability algorithm based on Clique Tree Propagation and Universal Generating Function

The clique tree algorithm is currently the most practical inference method for Bayesian networks. Based on the clique tree, the posterior probability of units and systems can be computed in five steps [5,6].

- Initialize the clique tree through the probability function of the Bayesian network. For each variable $X$ belong the $N$ clique, $P(X|\text{parent}(X))$ is stored into the $N$ clique.
- Set the evidence $\{E=e\}$.
- Chose a clique $C_Q$ including query variable $Q$ and other variable $L$ and $R$ as the hub node, we will compute the $P(Q|E=e)$.
- Get the function information $\varphi_1(X), \varphi_2(X), \cdots \varphi_n(X)$ from the adjacent nodes $C_1, C_2, \cdots C_n$ of the $C_Q$ to clique $C_Q$. The function information stored in the CPT of Bayesian network, we can get it from the UGF easily.
- Multiply the function information and function $\varphi_Q(X)$ stored in the $C_Q$ and get the function $H(C_Q) = \varphi_1(X)\varphi_2(X)\cdots\varphi_n(X)\varphi_Q(X) = H(Q, L, R)$, then remove the variable except $Q$ in the $H(C_Q)$ and the result normalization, lastly the posterior probability $P(Q|E=e)$ is received.

$$P(Q | E = e) = \frac{\sum_{L,R} H(Q, L, R)}{\sum_{Q,L,R} H(Q, L, R)}$$

(4)

Assume that $Q$ is top event, and $\theta$ express that the event get failed, $X_i$ and $Y_i$ represent the different state value of the events, so the inference of top event failure probability like this:
\[ P(Q = 0) = \sum_{X_i, Y_i} H(Q = 0, L = X_i, R = Y_i) \]

5. Case Study

Aileron control system accomplishes the roll operation of the civil aircraft; if the aileron control system gets failed, the spoiler control system will replace it to accomplish the roll operation. So the failure of aileron control system reduces the operation ability and safety redundancy of the airplane. Thus based on the Preliminary System Safety Assessment (PSSA), the failure probability of aileron control system is $10^{-5}$ to $10^{-7}$ per hour. The function figure of aileron control system like this:

![Function figure of the aileron control system](image1)

The sensors send control signals to the ELAC, then ELAC compute these signals and send control signals to the aileron servo-control. Then the aileron surfaces are moved. Based on the different function of the sensors, define the sensors into three types: feedback sensors (surface position sensors, servo-valve position sensor, servo-actuator mode sensor), flight law computing sensors (LGCIUs, accelerometers, ADIRSs, radio altimeters), flight control signals output sensors (side stick order transducers, FMGCs). Confirm the structure and function logic relationship of the units and systems, get the Bayesian network model topology structure (Fig. 3) of the aileron control system.

![Bayesian network model topology structure of the aileron control system](image2)

Based on the failure modes and affect of the units and systems, then combined with the bottom events failure probability in the table 3 and assume the operating time is $10^5$ h, then Bayesian Network based probabilistic safety model of aileron control system is established. Then the failure probability of aileron control system and the
posterior probability of bottom events are computed (Table 1). Through the inference, we get the top event failure probability is $0.63 \times 10^{-5}$/h, this result satisfy the safety requirement of aileron control system.

| Bottom events                                      | Failure probability($10^{-6}$/h) | Posterior probability |
|----------------------------------------------------|----------------------------------|-----------------------|
| Power 1 function fail                              | 0.4                              | 0.04                  |
| Power 2 function fail                              | 0.4                              | 0.04                  |
| Feedback transducer function fail/mistake          | 1.5/1.1                          | 0.42/0.05             |
| Flight law computing transducer function fail/mistake | 1.2/0.6                          | 0.32/0.05             |
| Flight control signals output transducers function fail/mistake | 1.3/0.8                          | 0.37/0.04             |
| Blue hydraulic part of function fail/full function fail | 3.3/1.2                          | 0.32/0.14             |
| Green hydraulic part of function fail/full function fail | 3.3/1.2                          | 0.32/0.14             |

Through the posterior probability value (Table 1), we can find the importance of feedback sensors is more important than other bottom events. Thus the reliability of the feedback sensors should be improved to assure the safety of flight control system.

6. Conclusions

In this paper, to solve the multi-state property of flight control system in the system safety analysis, a Bayesian Network based probabilistic safety model is built according to the state relationship between flight control system and its constituting components. A safety probability algorithm is proposed by using UGF combined with Clique Tree Propagation. The probability safety assessment of aileron control system is shown to prove this method is effective.

Acknowledgements

The authors would like to express their sincere appreciation to the support from National Natural Science Foundation of China(U1333118), Natural Science Foundation of Jiangsu Province(BK20130811), and Fundamental Research Funds for the Central Universities (NZ2012118).

References

[1] SAE ARP4761 Guideline and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment, SAE, 1996.12
[2] A. Lisnianski, I. Frenkel, Y. Ding. Multi-state System Reliability Analysis and Optimization for Engineers and Industrial Managers, Springer, London, 2010.
[3] H. Pham. The Universal Generating Function in Reliability Analysis and Optimization, Springer, London, 2005.
[4] GaoPeng. Reliability Analysis of Multi-state Systems Based on Improved Universal Generating Function, ACTA AERONAUTICA ET ASTRONAUTICA SINICA, 5(2010) 935–939.
[5] T. Koski, John M. Noble. Bayesian Networks An Introduction, WILEY, Chichester, 2009.
[6] A. Becker, D. Geiger. A sufficiently fast algorithm for finding close to optimal clique trees, Artificial Intelligence. 125 (2001) 3–17.