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Application of GO methodology in reliability analysis of aircraft flap hydraulic system

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ABSTRACT

The Goal-Oriented methodology (GO methodology) is an effective method for the reliability analysis of complex systems. It is especially suitable for the reliability analysis of multi-state complex systems containing the actual logistics, such as current, airflow and liquid flow. In order to solve the limitation that the GO methodology is not suitable for the reliability analysis of the system with feedback loop, the Boolean algebra idea is introduced to construct the Boolean operation formula of the feedback loop. In this paper, a certain type of civil aircraft flap hydraulic system with feedback loop is taken as the research object. According to the structural schematic diagram of the flap hydraulic system, the GO model of the flap hydraulic system is established. Next, the GO calculation is carried out to obtain the reliability of the flap hydraulic system. The comparison between the system reliability without feedback loop and that with feedback loop proves that the GO methodology with feedback loop is more accurate. The reliability of the system is analyzed by using the fault tree analysis (FTA) method, and the GO methodology with feedback loop is compared with the FTA method to verify the availability and correctness of the GO methodology in the reliability analysis and safety evaluation of aircraft flap hydraulic system.

Keywords: flap hydraulic system; reliability analysis; GO methodology; FTA

NOMENCLATURE

A	digital controller
$A_{rj}(i)$	state cumulative probability of the output signal when the output signal of jth operator is i
B	power module
B'	velocity feedback
C	hydraulic pump
D	hydraulic valve

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E	actuator module
E'	position feedback
E''	pressure feedback
F_1	main oil circuit fault
F_2	operating system fault
F_3	return oil circuit fault
F_4	control system fault
F_5	flow fault
F_6	left flap fault
F_7	right flap fault
F_8	shell oil return fault
F_9	drive component fault
F_{10}	EDP flow fault
F_{11}	EMP flow fault
P_k	occurrence probability of the kth minimum path set
$P_{cj}(i)$	operator state probability when the state value of jth operator is i
$P_{rj}(i)$	output signal state probability when the output signal of jth operator is i
Q_k	kth minimum path set
T	the fault of the aircraft flap hydraulic system
q_i	occurrence probability of the ith bottom event
X	output signal of power module
x_i	the ith bottom event
Y	the output signal of actuator module
λ	the fault rate

1.0 INTRODUCTION

The aircraft flap hydraulic system is an important part of the aircraft, which is controlled by two identical and independent channels, and each channel has multiple control, feedback and monitoring components. At present, the aircraft flap hydraulic system is developing towards high pressure (35 MPa), intelligent, modular, etc. Although some research results have been achieved, how to design a high-reliability hydraulic system to reduce pressure pulsation, temperature rise, and the influence of adverse factors such as oil pollution on the working conditions of hydraulic system is still an urgent problem to be solved in the development of aircraft hydraulic technology[1,2].

The normal operation of aircraft flap hydraulic system is an important prerequisite to ensure the safety of aircraft flight, and its reliability is an important index to measure the reliability of aircraft, and an important factor to determine the efficiency and service life of aircraft. The reliability of aircraft flap hydraulic system has always been concerned by the developers and users, especially in the context of the rapid development of the new generation of large civil and military aircraft, and the research on the reliability of aircraft flap hydraulic system has been of great significance.

The aircraft flap hydraulic system belongs to the aviation hydraulic system. Up to now, there is few literature on reliability analysis of aviation hydraulic system. Kai[3] analyzed the reliability of civil aircraft hydraulic system with Weibull distribution method; Jun[4] analyzed the reliability of aviation hydraulic system with fault tree method; Mihalčová[5] analyzed the reliability of aircraft engine hydraulic system with the method of hydraulic fluid characteristic monitoring. Christian[6] proposed the developed methods that integrate safety and reliability analysis with multi-domain object-oriented modelling and simulation to improve the aircraft systems development process. However, the above research only analyzes the reliability based on the situation of series and parallel connection of each component within the system, without considering the feedback loop existing in the system. Therefore, the reliability of the system cannot be comprehensively and effectively analyzed.

The GO methodology was first proposed by the US military in the 1960s as an effective method to analyze the reliability of weapon systems[7]. It is particularly suitable for the reliability analysis of multi-state complex systems containing actual logistics, such as current, airflow and liquid flow, and more suitable for the analysis of complex and time-series systems[8–10]. It can effectively avoid construction difficulties and poor modeling consistency when using FTA[11] method to analyze the complex system reliability. Shen[12] proposed the supplementary algorithm of GO methodology for repairable system and analyzed the reliability of the water injection system. Jiang[13] put forward the improved method of GO methodology based on probability matrix and analyzed the reliability of a device drive system. The existing GO methodology is suitable for open-loop system, and it is not suitable for the reliability analysis of the system with feedback loop, which is due to its inherent limitation. In the existing GO methodology, the feedback loop is usually ignored or split into several parts, simply using a signal generator to replace the feedback signal without considering the internal feedback characteristics, which often leads to inaccuracy for reliability analysis of systems with feedback loop. By creating a new function operator and corresponding quantification formulas, Yi[14–16] presented an improved method of GO methodology to conduct the reliability analysis for two-input feedback system, multi-input feedback system, and two-input feedback system considering shutdown correlation, respectively.

In our study, a reliability analysis method for the systems with feedback loop is proposed by introducing Boolean algebra into the GO methodology. As the research object, the reliability analysis of a certain type of civil aircraft flap hydraulic system is conducted. The solution of the feedback loop of the flap hydraulic system is given. The GO model of the aircraft hydraulic system with feedback loop is built. The quantitative analysis of the results compared with GO methodology presented by Yi[14–16] and FTA verified the availability and correctness of GO methodology in the reliability analysis of the aircraft flap hydraulic system.

2.0 PRINCIPLE OF AIRCRAFT FLAP HYDRAULIC SYSTEM

The flap hydraulic system generally consists of the following components: self-pressurized oil tank, filter, priority valve, accumulator, power drive assembly, safety valve, digital control assembly, flap screw actuator, etc. Figure 1 shows the schematic diagram of a certain type of civil aircraft flap hydraulic system. The pressure feedback of the self-pressurized oil tank through the high-pressure pipeline increases the oil suction pressure of the pump source and prevents the air suction of the pump source. The filter is mainly used to filter the solid particles and other harmful substances in the oil of the system, to ensure the pollution degree of oil within the tolerance limit of the key hydraulic components, so as to improve the reliability of

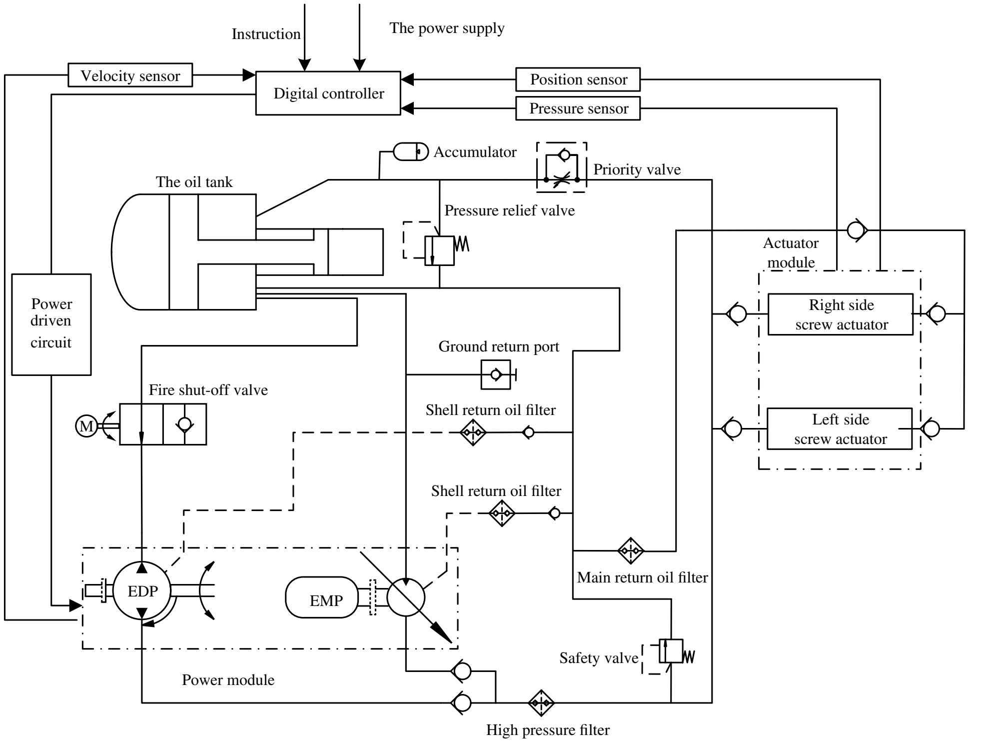

Figure 1. Schematic diagram of flap hydraulic system of a certain aircraft[18].

the hydraulic system and extend the life of the components. When the system is under low pressure, the priority valve should ensure the oil supply and work of the key actuator to ensure flight safety. The accumulator is mainly used to reduce system pulsation, and to supply system flow in short time and large flow occasions such as interrupted takeoff, flyback and landing to ensure system work. The flap power drive assembly consists of an Engine Driven Pump (EDP) and an Electrical Motor Pump (EMP). A safety valve is installed between the EDP and the fuel tank. When the hydraulic system is extremely hot or the engine is fired, the fire shut-off valve is automatically opened; the EDP suction line is disconnected; the EDP pump is no longer working, and the possibility of engine ignition is reduced. The digital control component conducts the flap screw actuator control according to the motion command and the position feedback signal[17].

3.0 GO METHODOLOGY ANALYSIS OF AIRCRAFT FLAP HYDRAULIC SYSTEM RELIABILITY

The main analysis process of GO methodology includes establishment of GO model and completion of quantitative calculation. The corresponding modules of aircraft flap hydraulic system operate normally in accordance with the requirements of control instructions, so that the system as a whole works normally. The success probability of the system is calculated by combining the GO model diagram and the operation rules.

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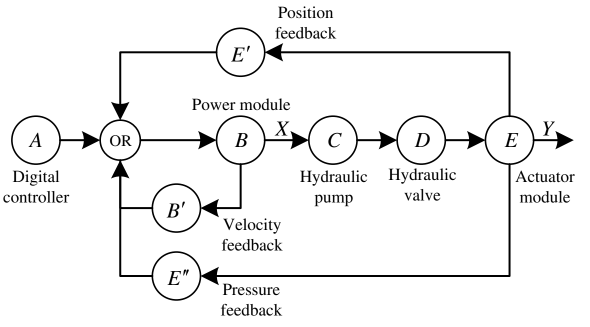

Figure 2. Structure diagram of aircraft flap hydraulic system with feedback loop(19).

3.1 Solving the feedback loop of the aircraft flap hydraulic system

In system reliability analysis, the feedback loop is an important part of the aircraft flap hydraulic system, which provides real-time and accurate control and monitoring of the system. If the feedback loop cannot be effectively processed, the reliability of the system cannot be accurately evaluated, and ultimately the system performance cannot be effectively evaluated. The current practice is to split the feedback loop into several parts, and simply replace the feedback signal with a signal generator, or just ignore it, but this kind of method will inevitably bring errors and affect the calculation of reliability. In this paper, the idea of Boolean algebra is used to represent the feedback loop of the system in the form of Boolean equation, which can accurately represent the feedback signal of the aircraft hydraulic system, and improve the accuracy of reliability analysis. A schematic diagram of the feedback loop structure of the aircraft flap hydraulic system is shown in Fig. 2.

Taking component A as an example, the set of events successfully output is represented as $A_{\mathrm{v}}\, A_{\mathrm{w}}$, where A_{v} represents the set of events successfully run by component A; A_{w} represents the set of all states of component A, and the representation method of other components is the same as that of component A, then the Boolean relation can be expressed as:

$$Y = C_v C_w D_v D_w E_v E_w X \qquad \ldots (1)$$

As can be seen from Fig. 2, the input signal of B' is X; the input signal of E' and E'' is Y; the input signal of or gate is A, B, E', E'' so the expression of X is:

$$\begin{aligned} X = [&A_v A_w + B_v{}' B_w{}' X \\ &+ (E_v{}' E_w{}' + E_v{}'' E_w{}'')Y\,] B_v B_w \end{aligned} \qquad \ldots (2)$$

Simplify (1) and (2):

$$\begin{aligned} X = &A_v A_w B_v B_w + B_v B_w B'_v B'_w X \\ &+ B_v B_w C_v C_w D_v D_w E_v E_w (E'_v E'_w + E''_v E''_w) X \end{aligned} \qquad \ldots (3)$$

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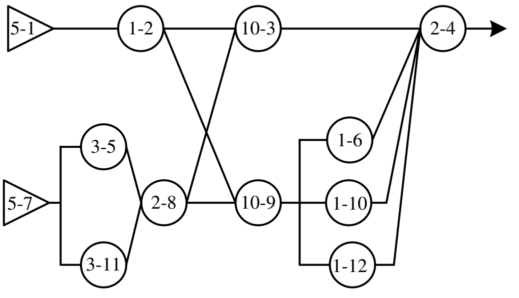

Figure 3. Feedback loop GO model.

According to the Boolean algebra set operation $A_s A_s = A_s$, $1 + A_s = 1$, solve the Boolean Equation (3):

$$X = A_v A_w B_v B_w + m_1 B_v B_w B'_v B'_w X + m_2 B_v B_w C_v C_w D_v D_w E_v E_w (E'_v E'_w + E''_v E''_w) \quad \ldots (4)$$

Where: m_1 and m_2 are arbitrary Boolean elements.

The GO methodology is based on system success, assuming all components of the system are successfully started, so there is:

$$A_w = B_w = C_w = D_w = E_w = B'_w = E'_w = E''_w = 1$$

And so there is

$$X = A_v B_v + m_1 B_v B'_v + m_2 B_v C_v D_v E_v (E'_v + E''_v) \quad \ldots (5)$$

Figure 2 can directly derive the expression (6) of X after E is successfully output.

$$X = A_v B_v + A_v B_v B'_v + A_v B_v C_v D_v E_v (E'_v + E''_v) \quad \ldots (6)$$

Comparing (5) and (6), we can see that $m_1 = A_v$, $m_2 = A_v$, so the expressions for X and Y successfully output are respectively:

$$Y = A_v B_v C_v D_v E_v + A_v B_v B'_v C_v D_v E_v + A_v B_v C_v D_v E_v (E'_v + E''_v) \quad \ldots (7)$$

In Equation (8): the first term represents the main path; the second term represents the ring $B - B'$ structure; the third term represents $B - C - D - E - E'$ and $B - C - D - E - E''$, translated into the GO model as shown in Fig. 3.

3.2 Constructing GO model of aircraft flap hydraulic system

The GO model is mainly composed of operators and signal streams[7]. Combined with the schematic diagram of the aircraft flap hydraulic system and the GO signal of the feedback signal, the GO model of the aircraft flap hydraulic system is established as shown in Fig. 4.

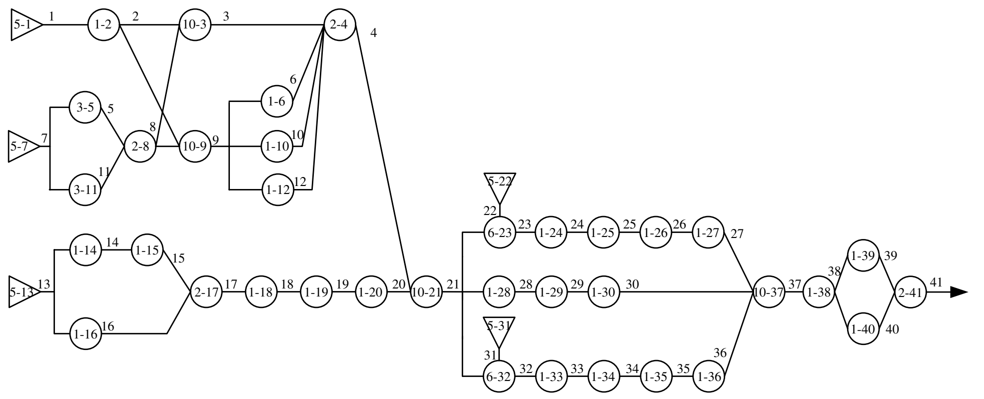

Figure 4. GO diagram of aircraft flap hydraulic system.

Power signals, control signals, oil tanks, etc. can be represented by the type 5 signal generator operator. Controllers, sensors, hydraulic valves, hydraulic cylinders, aviation high-pressure piston pumps, etc. are considered as two-state units and can be represented by type 1 operators. The motor and the engine may have an early output signal due to an undesired external stimulus such as a short circuit of the power supply, and thus may be represented by a type 3 trigger generator. The correspondence among all components in the Fig. 4 and the GO method operator is listed in Table 1.

In Table 1, the state value 0 indicates that the unit is in an advanced state; the state value 1 indicates that the unit is in a successful state; the state value 2 indicates that the unit is in a fault state, and the probability that the unit is in a fault state is the unit failure rate λ, meaning the probability of failure of the unit in unit time; the probability that the unit is in the advanced state is P_{p}, that is, the probability that the unit will cause the output signal to occur in advance due to external factors.

3.3 GO methodology reliability operation

According to the probability analysis formula of the GO methodology, the expression of the key signal flow in the Fig. 4 is calculated as follows:

(1) Signal stream 8

The input signal stream of signal stream 8 is signal stream 5 and signal stream 11. Since signal stream 5 and signal stream 11 both contain signal stream 7, signal stream 7 is the common signal of signal stream 8, which needs to be corrected [9].

$$
\begin{aligned}
&A_{R8}(0) = P_{c5}(0) + P_{c11}(0) + \\
&P_{c5}(1)A_{r7}(0) + P_{c11}(1)A_{r7}(0) \\
&- P_{c5}(0)P_{c11}(0) - P_{c5}(0)P_{c11}(1)A_{r7}(0) \\
&- P_{c11}(0)P_{c5}(1)A_{r7}(0) - P_{c5}(1)P_{c11}(1)A_{r7}(0)
\end{aligned}
$$

$$
\begin{aligned}
&A_{R8}(1) = P_{c5}(0) + P_{c11}(0) + \\
&P_{c5}(1)A_{r7}(1) + P_{c11}(1)A_{r7}(1)
\end{aligned}
$$

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Table 1
Aircraft flap hydraulic system operator data

Number	Type	Meaning	State probability ($\times 10^{-6}$)		
			state 0	state 1	state 2
1	5	Power signal	0	1-λ	26.0321
2	1	Controller	0	1-λ	2.1332
3, 9 21, 37	10	And gate			
4, 8, 17, 41	2	Or gate			
5	3	Engine	6.0361	1-λ-P_p	15.9873
6	1	Speed sensor	0	1-λ	3.5121
7	5	Drive control signal	0	1-λ	11.0765
10	1	Positon sensor	0	1-λ	3.5121
11	3	Electric motor	7.9642	1-λ-P_p	17.4771
12	1	Pressure Sensor	0	1-λ	3.5121
13	5	Oil tank	0	1-λ	38.1373
14	1	Fire shut-off valve	0	1-λ	16.9856
15	1	EDP	0	1-λ	48.0083
16	1	EMP	0	1-λ	48.0083
18, 25, 34	1	Overflow valve	0	1-λ	71.9410
19, 24, 27, 33, 36	1	Check valve	0	1-λ	12.5001
20	1	High pressure filter	0	1-λ	23.9032
22, 31	5	Power supply for electro-hydraulic reversing valve power supply	0	1-λ	10.8731
23, 32	6	Electro-hydraulic directional valve	0	1-λ	43.7201
26	1	Left side spiral actuator	0	1-λ	24.4171
28	1	Priority valve	0	1-λ	15.7197
29	1	Accumulator	0	1-λ	120.2504
30	1	Pressure relief valve	0	1-λ	39.9821
35	1	Right side spiral actuator	0	1-λ	24.4171
38	1	Main oil return filter	0	1-λ	12.2826
39, 40	1	Shell return oil filter	0	1-λ	16.4326

$$- P_{c5}(0)P_{c11}(0) - P_{c5}(0)P_{c11}(1)A_{r7}(1)$$
$$- P_{c11}(0)P_{c5}(1)A_{r7}(1) - P_{c5}(1)P_{c11}(1)A_{r7}(1)$$

$$A_{R8}(2) = 1$$
$$P_{r8}(0) = A_{r8}(0)$$
$$P_{r8}(1) = A_{r8}(1) - A_{r8}(0)$$
$$P_{r8}(2) = A_{r8}(2) - A_{r8}(1)$$

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(2) Signal stream 4

The signal stream 4 has a plurality of input signal streams, and each signal stream exists only on the premise of the existence of the signal stream 2 and the signal stream 8, so the signal stream 2 and the signal stream 8 are the common signals of the signal stream 4, and the common signal is corrected:

$$a = 1 - [1 - P_{c6}(0)][1 - P_{c10}(0)][1 - P_{c12}(0)]$$
$$b = 1 - [1 - P_{c6}(1)][1 - P_{c10}(1)][1 - P_{c12}(1)]$$
$$A_{r4}(0) = aA_{r9}(0) + A_{r3}(0) - aA_{r3}(0)/A_{r2}(0)A_{r8}(0)$$
$$A_{r4}(1) = bA_{r9}(1) + A_{r3}(1) - bA_{r3}(1)/A_{r2}(1)A_{r8}(1)$$
$$A_{r4}(2) = 1$$
$$P_{r4}(0) = A_{r4}(0)$$
$$P_{r4}(1) = A_{r4}(1) - A_{r4}(0)$$
$$P_{r4}(2) = A_{r4}(2) - A_{r4}(1)$$

(3) Signal stream 21

$$A_{r21}(0) = A_{r4}(0)A_{r20}(0)$$
$$A_{r21}(1) = A_{r4}(1)A_{r20}(1)$$
$$A_{r4}(2) = 1$$
$$P_{r21}(0) = A_{r21}(0)$$
$$P_{r21}(1) = A_{r21}(1) - A_{r21}(0)$$
$$P_{r21}(2) = 1 - A_{r21}(1)$$

(4) Signal stream 37

The signal stream 37 has a plurality of input signal streams, each of which contains a signal stream 21, so the signal stream 21 is a common signal of the signal stream 37, and the common signal is corrected:

$$A_{r37}(0) = A_{r27}(0)A_{r30}(0)A_{r36}(0)/A_{r21}(0)^2$$
$$A_{r37}(1) = A_{r27}(1)A_{r30}(1)A_{r36}(1)/A_{r21}(1)^2$$
$$P_{r37}(0) = A_{r37}(0)$$
$$P_{r37}(1) = A_{r37}(1) - A_{r37}(0)$$
$$P_{r37}(2) = 1 - A_{r37}(1)$$

(5) Signal stream 41

The signal stream 41 includes the signal stream 39 and the signal stream 40. Since both the signal stream 39 and the signal stream 40 contain the signal stream 38, the signal stream 41 needs to be corrected when calculating.

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Table 2
Feedback loop and system output probability

Name	State 0	Stat 1	Stat 2
Feedback output probability	0	0.999983	0.000017
System output probability (without feedback loop)	0	0.999314	0.000686
System output probability (with feedback loop)	0	0.999297	0.000703

$$A_{r41}(0) = A_{r39}(0) + A_{r40}(0) - A_{r39}(0)A_{r40}(0)/A_{r38}(0)$$
$$A_{r41}(1) = A_{r39}(1) + A_{r40}(1) - A_{r39}(1)A_{r40}(1)/A_{r38}(1)$$
$$P_{r41}(0) = A_{r41}(0)$$
$$P_{r41}(1) = A_{r41}(1) - A_{r41}(0)$$

Where, $A_{rj}(i)$ is the state cumulative probability of the output signal when the output signal of jth operator is i; $P_{rj}(i)$ is the operator state probability when the state value of jth operator is i; $P_{rj}(i)$ is the state probability of the output signal when the output signal of jth operator is i. Combined with the data in Table 1, the calculation results are shown in Table 2.

According to the Table 2, it is concluded that the probability of successful system output calculated by the GO model of the system with feedback loop is small, indicating that the feedback loop is more reliable to the system and considering the feedback loop of the system can accurately calculate the system reliability and effectively evaluate the system performance.

4.0 RELIABILITY ANALYSIS OF AIRCRAFT FLAP HYDRAULIC SYSTEM BASED ON FTA

The FTA method is used to analyze the aircraft flap hydraulic system mentioned above, and the fault of the aircraft flap hydraulic system is used as the top event. The fault tree is built as shown in Fig. 5.

In Fig. 5, F_1 is the main oil circuit fault; F_2 is the operating system fault; F_3 is the return oil circuit fault; F_4 is the control system fault; F_5 is the flow fault; F_6 is the left flap fault; F_7 is the right flap fault; F_8 is the shell oil return fault; F_9 is the drive component fault; F_{10} is the EDP flow fault; F_{11} is the EMP flow fault. The bottom event data is shown in Table 3.

Due to the large number of minimum cut sets of the fault tree shown in Fig. 5, this paper uses the minimum path set to analyze the reliability of the fault tree.

The minimum path set indicates that the top event can be prevented when all bottom events contained in a minimum path set do not occur. It can be seen that each minimal path set is a condition to ensure the failure tree top event does not occur, and a way to prevent accidents. In this sense, the minimal path set represents the security of the system. Therefore, this paper uses the probability that none of the bottom events in the minimum path set occur to calculate the reliability of the whole system in normal operation. The calculation formula is:

$$P_k = \prod_{x_i \in Q_k} (1 - q_i)$$

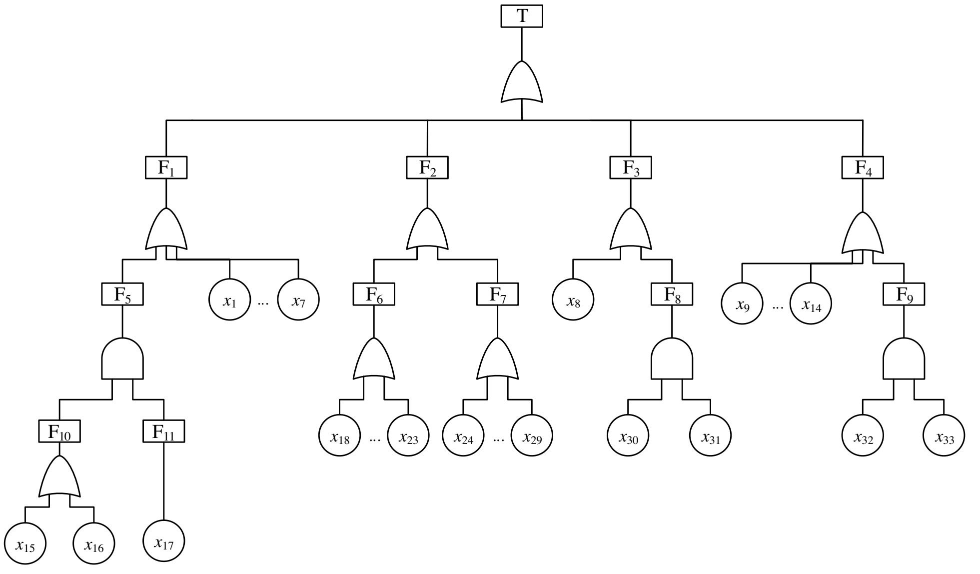

Figure 5. Fault tree of aircraft flap hydraulic system.

Where P_k represents the occurrence probability of the kth minimum path set ($k = 1, 2, \ldots,$ 8), namely, the system reliability; $x_i \in Q_k$ represents the ith bottom event belonging to the kth minimum path set; q_i represents the occurrence probability of the ith bottom event.

According to the duality principle and the optimization idea of reliability engineering, the minimum path set with the lowest reliability is selected in all of the minimum path sets with the same number of bottom events. Also, in the minimum path sets with the closest reliability, the path set with more bottom events is selected(20,21). Therefore, the minimum path set k of the fault tree is obtained:

$$\{x_1, \ldots, x_{14}, x_{15}, x_{16}, x_{18}, \ldots, x_{29}, x_{30}, x_{32}\}$$

After calculation, $P_k = 0.999165$, which can be taken as the lower limit of success probability of the system.

5.0 COMPARISON OF METHODS

In order to verify the correctness and effectiveness of the proposed method, the results of the proposed method in our study, the FTA method and the methods proposed in Refs 14–16 are represented in Table 4.

According to the above calculation method of FTA, the analysis result of FTA can be considered as the lower limit of system's success probability. As Table 4 shows, the quantitative calculation result of the proposed method in our study is very close to the result of FTA, and a little greater than it, as well as the reliability results calculated by both methods are in the same order of magnitude, which shows that the proposed method is correct.

According to the comparison results of different GO methods dealing with feedback loop in Table 4, the result of the proposed method is same as the method presented by Yi(14–16), which shows the proposed GO methodology is feasible. But the methods presented by Yi(14–16) with

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Table 3
Data of each bottom event

Serial number	Bottom event	Incidence probability ($\times 10^{-6}$)	Serial number	event	Incidence probability ($\times 10^{-6}$)
x_1	Tank failure	38.1373	x_{13}	Controller failure	2.1332
x_2, x_{21}, x_{27}	Overflow valve failure	71.9410	x_{14}	Control signal failure	11.0675
x_3, x_{20} x_{23} x_{26}, x_{29}	Check valve failure	12.5001	x_{15}	Fire shut-off valve failure	16.9856
x_4	High pressure oil filter failure	23.9032	x_{16}	EDP failure	48.0083
$x_{5,}$	Priority valve failure	15.7107	x_{17}	EMP failure	48.0083
x_6	Accumulator failure	120.2504	x_{22}	Left side spiral actuator failure	24.4171
x_7	Pressure relief valve failure	39.9821	x_{28}	Right side spiral actuator failure	24.4171
x_8	Main oil return failure	12.2826	x_{30}, x_{31}	Shell return filter failure	16.4326
x_9	Speed sensor failure	3.5121	x_{32}	Motor failure	17.4771
x_{10}	Position sensor failure	3.5121	x_{33}	Engine failure	15.9873
x_{11}	Pressure sensor failure	3.5121	x_{18} x_{24}	Electro-hydraulic reversing valve power failure	10.8731
x_{12}	Electricity failure	26.0321	x_{19}, x_{25}	Electro-hydraulic reversing valve failure	43.7201

Table 4
Comparison of system output probability of different GO methods and FTA

Methods	State 0	State 1	State 2
The proposed method	0	0.999297	0.000703
The method in Ref 14	0	0.999297	0.000703
The method in Ref 15	0	0.999297	0.000703
The method in Ref 16	0	0.999297	0.000703
The FTA method	0	0.999165	0.000835

creating the new function operator and formulas to deal with the feedback loop in system increase the complexity of GO methodology, and may be inconvenient for engineers and researchers to use.

The comparison analysis above shows that the proposed GO method is effective and correct. However, the calculation results of the GO methods and FTA are not completely equal, because the basic concepts and algorithms of the two methods are different. Firstly, the GO methodology is a success-oriented method for reliability analysis of complex systems and includes many operators which can represent various units, while FTA is a fault-oriented method using multi-level logic chart to represent the relationship of different fault events with limited logic gate. Secondly, GO model is developed from system functional diagram and system structure diagram, reflecting the original appearance of system and the process of operation, so it can avoid the influence of engineer experience for reliability analysis while FTA is subjective and its inferences are affected by the knowledge and abilities of engineers establishing the fault tree. Moreover, the quantitative analysis of FTA is mostly based on computing minimal cut sets of the system, and computing the success(failure) probability of complex systems based on minimal cut sets is NP-hard. Therefore, the calculation results of the two methods are not equal exactly and the relative error between the proposed method and FTA is 0.0132%.

6.0 Conclusion

(1) Boolean algebra is introduced to solve the limitation that GO methodology cannot analyze the reliability of the system with feedback loop. The reliability of the flap hydraulic system of a certain type of civil aircraft is studied, and the solution of the flap hydraulic system with feedback loop is given.

(2) The GO methodology with feedback loop is compared with the GO methodology without feedback loop, the FTA method, and the GO methodology with creating new operator respectively, which verifies the effectiveness and accuracy of using Boolean algebra to solve the limitation that GO methodology cannot analyze the reliability of the system with feedback loop.

(3) According to the research results of this paper, the feedback loop has a great influence on the system reliability. Considering the feedback loop of the system, the system reliability can be accurately calculated and the system performance can be effectively evaluated. The research results of this paper can provide an important theoretical basis for the reliability research of aviation hydraulic system.

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