Reliability Analysis on electric propulsion System Combining GO-FLOW Methodology with Multi-Valued Decision Diagrams

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Abstract. The electric propulsion system of an electric aircraft is the core power of the whole aircraft, which provides assurance for the safe flight of the aircraft. There are multiple stages in the flight process of electric aircraft, as well as different failure behaviors of system components at different stages. The electric motor system is a k-out-of-n system. Therefore, it is not possible to accurately describe the electric motor system with the existing operators when using the GO-FLOW method for electric propulsion system reliability calculations. In order to solve this problem, this paper models the electric motor system using the multi-valued decision diagram method (MDD method), based on which a new operator 43 is proposed to simulate the electric motor system, and then builds the GO-FLOW model and calculates the overall reliability based on the distributed electric propulsion system schematic. The example results show that the method can calculate the reliability of the distributed electric propulsion system more realistically.

Keywords: Distributed Electric Propulsion System; Phased Mission System; k-out-of-n System; GO-FLOW Methodology; Multi-Valued Decision Diagrams (MDD).

1. Introduction

The distributed electric propulsion system consists of multiple motor-driven propellers distributed across the wings to provide the primary power for the electric airplane. Distributed electric propulsion systems are typical Phased-Mission System (PMS) due to the multi-stage nature of electric aircraft in flight. There is a stage dependency in the operating state of the components of PMS, the initial state of the components in the latter stage is the same as the final state in the former stage. The dynamics and correlation between the system structure and component failures bring great challenges to the reliability analysis of PMS. Currently, the main methods for analyzing the reliability of PMS are Monte Carlo (MC) method[1], Petri-net method[2], Multi-Valued Decision Diagram (MDD)[3], and Bayesian Network (BN) [4].

Among the many system reliability assessment methods, the GO-FLOW method is success-oriented and is suitable for reliability analysis of complex systems such as those whose state changes over time or have staged tasks[5]. The GO-FLOW method is commonly used in system reliability analysis in aerospace[6] due to its intuitiveness and simplicity. However, the GO-FLOW method has its limitations, as the GO-FLOW method only considers the steady state reliability of the system and cannot perform dynamic reliability analysis of the system. Researchers combined the GO-FLOW method with other reliability analysis methods to solve this problem[7]. The motor system[8] operates in different states during different phases of the flight of an electric airplane. The GO-FLOW method does not have a suitable operator to model the motor system.

Multi-valued Decision Diagramming (MDD) is an extension of Binary Decision Diagramming (BDD) to the multi-valued case for reliability modeling of multi-phased dynamic systems[9]. Many scholars have conducted a lot of research in recent years. For the unrepairable cold reserve system, Zeng[10] proposed a conditional event-based MDD analysis method, which solved the problem of dynamic modeling that could not be solved by the traditional MDD method; and Wang[11] proposed an efficient reliability analysis method based on the MDD method, which optimized the modeling process of the k-out-of-n system, and improved the ability of the MDD method to analyze large-scale systems.

In this paper, the MDD method is introduced to analyze the k-out-of-n motor system and a new GO-FLOW operator is proposed to simulate the motor system. On the one hand, the GO-FLOW method solves the problem that the GO-FLOW method cannot solve the problem that there are phased differences in the failure modes of the electric motor system components at different phased; on the other hand, the MDD method solves the problem of dependence between the components of the multi-phased system. The GO-FLOW method is then used to assess the reliability of the whole system, which improves the computational accuracy of the system.

2. Motor system reliability modeling

2.1 Electric aircraft motor system

The structural principle of a distributed electric propulsion system for an electric airplane is shown in Fig. 1. The motor system of an electric airplane is a k-out-of-n system as shown in the motor system in Fig. 1. Four motors are uniformly distributed on the wing and have equal power. In different stages of the flight of an electric airplane, the power requirement of the motor system is different, so the working status of the motor system is different in different stages. In the take-off stage of the electric airplane, the motor system on the wing needs at least three motors to work normally, and the system structure is 3-out-of-4; in the cruise stage of the electric airplane, the motor system on the wing needs at least two motors to work normally, and the system structure is 2-out-of-4; in the landing stage of the downward slide of the electric airplane, the motor system on the wing needs at least one motor to work normally, and the system structure is 1-out-of-4; the motor system on the wing needs at least one motor to work normally, and the system structure is 1-out-of-4; the motor system on the wing needs at least one motor to work normally, and the system structure is 1-out-of-4. In the downward landing phase of the electric airplane, the electric motor system on the wing needs at least one electric motor to work properly, and the system structure is 1-out-of-4.

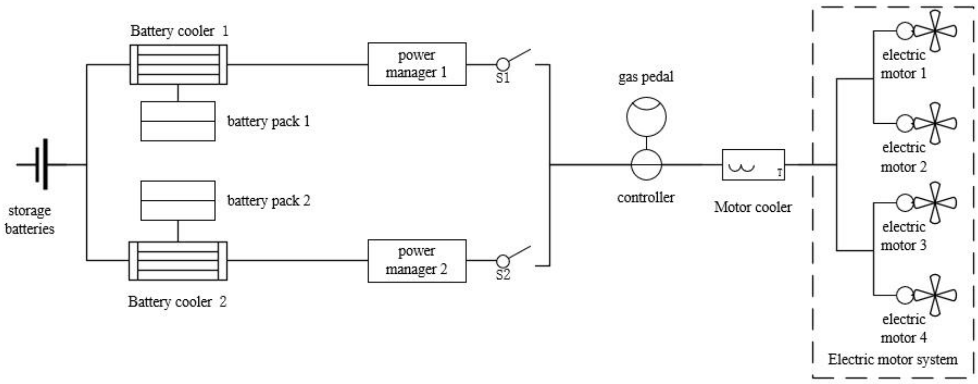

Fig. 1 The Distributed Electric Propulsion System for a certain type of Electric Aircraft

In Fig. 2, the FTA model is used to describe the motor system. In the motor system FTA model, there are 13 intermediate events and 4 bottom events.

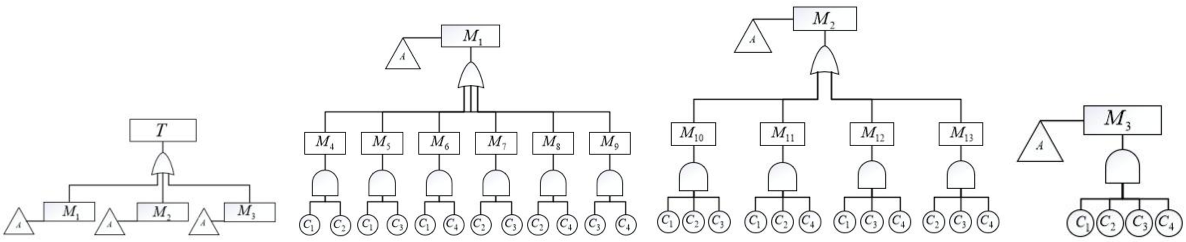

Fig. 2 Fault Tree Analysis of Electric Motor System

2.2 Motor system analysis based on MDD model

The construction of the MDD model is described in the following three steps.

Step 1: Code the variables in the system.

The MDD consists of a non-aggregation node and two aggregation nodes, which are labeled as "0" and "1" to indicate system success and failure, respectively. In a system with n phases, the two-state components C1,...,Cn are represented by n multivalued variables x1, . . xn. Non-converging nodes contain a multivalued variable, and each non-converging node associated with xi has H+1 outward directed edges; the 0th edge indicates that the component Ci does not fail in all H stages (xi = 0), while the jth edge (1 ≤ j ≤ H) indicates that the component Ci fails in stage j.

According to the characteristics of the multi-stage task system, which is not repairable or maintainable, if the component Ci is in a failed state in one stage, it will remain in a failed state in all the subsequent stages, and the corresponding MDDs of the components in the three stages are shown in Figure 3, which are derived from Figure 2.

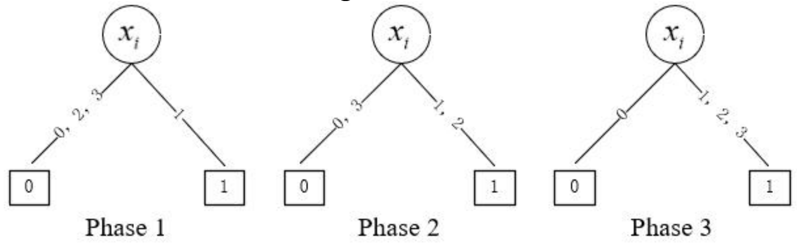

Fig. 3 MDD Structures of Basic Events in a Three-Stage PMS

Step 2: Order the input variables.

Before the generation of a multivalued decision diagram, the variables of the basic events need to be ranked. In this paper, DFLM is used to order the multivalued variables of different components in PMS and the variable ordering used to generate MDD is x1<x2<x3<x4.

Step 3: Generate the MDD.

Each non-convergent node encoding in the MDD is represented as a Boolean function in case format:

$$\begin{aligned} E &= case(x_i, E_0, E_1, \cdots, E_H) = (x_i = 0)E_{(x_i=0)} \\ &+(x_i = 1)E_{(x_i=1)} + \cdots + (x_i = H)E_{(x_i=H)} \end{aligned} \quad (1)$$

$$\begin{aligned} F &= case(x_j, F_0, F_1, \cdots, F_H) = (x_j = 0)F_{(x_j=0)} \\ &+(x_j = 1)F_{(x_j=1)} + \cdots + (x_j = H)F_{(x_j=H)} \end{aligned} \quad (2)$$

$$\begin{aligned} & E \Diamond F \\ &= case(x_i, E_0, E_1, \cdots, E_H) \Diamond case(x_j, F_0, F_1, \cdots, F_H) \\ &= \begin{cases} case(x_i, E_0 \Diamond F_0, E_1 \Diamond F_1, \\ \cdots, E_H \Diamond F_H) & index(x_i) = index(x_j) \\ case(x_i, E_0 \Diamond F, E_1 \Diamond F, \\ \cdots, E_H \Diamond F) & index(x_i) < index(x_j) \\ case(x_j, E \Diamond F_0, E \Diamond F_1, \\ \cdots, E \Diamond F_H) & index(x_i) > index(x_j) \end{cases} \end{aligned} \quad (3)$$

In Eqs. (1)-(3), ◊ denotes the logical operation AND (•) or OR (+) operation, *index* denotes variable ordering, *E* and *F* denote two Boolean expressions corresponding to the sub-fault tree, and E_{xi} ($0 \le i \le H$) and F_{xj} ($0 \le j \le H$) are sub-expressions of *E* and *F*, respectively.

The final MDD is given in Fig. 4. Each path from the root node to node "0" or "1" represents a combination of states in which the PMS disconnected components succeed or fail. Therefore, the sum of the probabilities of all paths yields the unreliability (reliability). The probability of each path is the product of the probabilities of each edge.

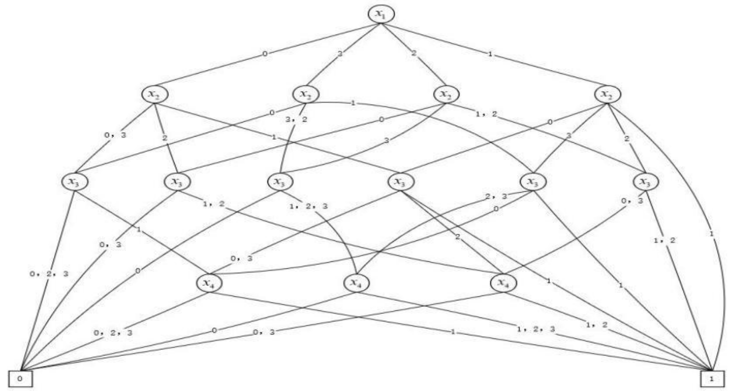

Fig. 4 Final MDD

2.3 Motor system operator

The GO-FLOW method is a success-oriented approach to system reliability analysis that consists of 14 standard operators categorized as functional, logical, and generator operators.

By using the MDD diagram of the motor system in Fig. 4, the unreliability of the motor system of a certain type of electric flight is obtained as: UR_{PMS}.

Then the reliability of the electric airplane motor system is expressed as:

$$A=1-UR_{PMS} \quad (4)$$

The operator 43 is given to simulate the motor system as shown in Fig. 5, where A is the output signal.

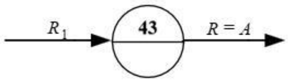

Fig. 5 Diagram of the type-43 operator

3 Reliability assessment of distributed electric propulsion systems

3.1 GO-FLOW model construction

To construct the GO-FLOW model of the distributed electric propulsion system, the operator 43 proposed in this paper is used to simulate the electric motor system. Through operator selection and system signal flow analysis, the GO-FLOW model of the distributed electric propulsion system of the electric aircraft shown in Fig. 6 is obtained.

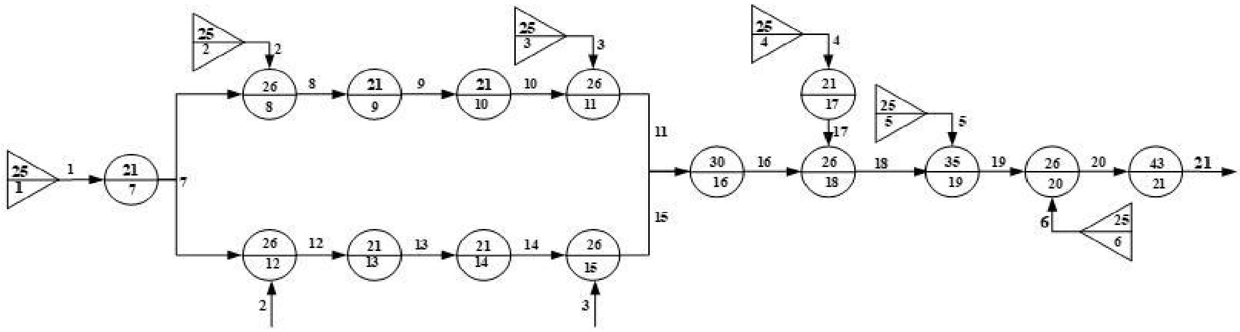

Fig. 6 GO-FLOW Model for Distributed Electric Propulsion Systems in Electric Aircraft

In order to analyze the reliability of distributed electric propulsion systems for electric aircraft in various stages, seven points in time when the electric propulsion system is in operation are defined:

(1) Time point 1 is the initial time point, the system is not working.

(2) Time point 2 battery on.

(3) Time point 3 is the moment when the battery cooler starts working.

(4) Time point 4 is the moment when the switch is closed.

(5) Time point 5 is the moment when the throttle starts working.

(6) Time point 6 is the moment when the motor cooler starts working.

(7) Time point 7 is 4 hours after time point 6.

The types of operators and the data of each component of the GO-FLOW model of the distributed electric propulsion system of the electric airplane are shown in Table 1.

Table 1 Operator Data for Distributed Electric Propulsion Systems

Number	Typology	Parametric	Connotation
1	25	$R(1)=0$, $R(t)=1(t\neq 1)$	Switch on the signal generator of battery
2	25	$R(3)=1$, $R(t)=0(t\neq 3)$	Signal generator for battery cooler work
3	25	$R(4)=1$, $R(t)=0(t\neq 4)$	Signal generator with switch closed
4	25	$R(5)=1$, $R(t)=0(t\neq 5)$	Signal generator for throttle operation
5	25	$R(6)=1$, $R(t)=0(t\neq 6)$	Motor cooler operating signal generator
6	25	$R(7)=4h$, $R(t)=0(t\neq 7)$	Signal generator indicating time intervals
7	21	$P_{g(7)}=0.999987$	storage batteries
8、12	26	$P_{p(8)}=P_{p(12)}=0.000023$ $P_{g(8)}=P_{g(12)}=0.999935$	Battery cooler
9、13	21	$P_{g(9)}=P_{g(13)}=0.999973$	battery pack
10、14	21	$P_{g(10)}=P_{g(14)}=0.999944$	power manager
11、15	26	$P_{p(11)}=P_{p(15)}=0.000015$ $P_{g(11)}=P_{g(15)}=0.999986$	switchgear
16	30		AND gate
17	21	$P_{g(17)}=0.999952$	gas pedal
18、19	26、35	$P_{p(18)}=0.000018$ $P_{g(18)}=0.999964$ $\lambda=0.0001/h$	controllers
20	26	$P_{p(20)}=0.000026$ $P_{g(20)}=0.999935$	Motor cooler
21	43	$P_{g(21)}{}'=A_{(\mathrm{A})}$	Motor system

3.2 Motor system reliability calculation

Since the motor power is different in different stages, the motor is subjected to different stresses in different stages, and the higher the stress the more likely it is to fail. When the motor works in different stages, the longer the duration of the stage, the higher the probability of motor failure, Table 2 gives the probability of motor failure in the three stages and the duration of each stage.

Table 2 Duration of Phase and Failure probability of Electric Motors

	Phase 1	Phase 2	Phase 3
Duration	0.5h	3h	0.5h
Motor Failure Probability	0.0008	0.0035	0.0004

The reliability of the motor system of the electric airplane was obtained by calculating the output signal strength of the motor system as:

$$A_{(\mathrm{A})}=1-UR_{\mathrm{PMS}}=0.99919 \tag{5}$$

3.3 Distributed electric propulsion system reliability calculations

The change in reliability of the propulsion system at different points in time is shown in Fig. 7.

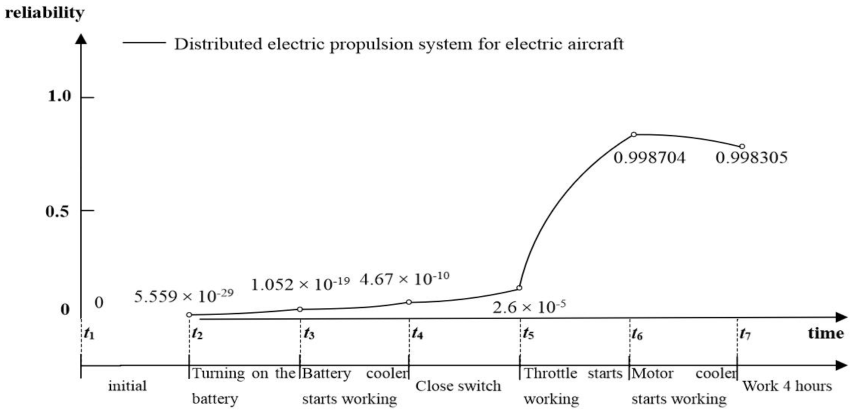

Fig. 7 Reliability Growth Plot for Distributed Electric Propulsion Systems

4 Summary

In this paper, reliability calculations have been performed for a k-out-of-n motor system using the MDD method, which does not need to deal with stage dependencies, is given as a computational procedure.A new GO-FLOW operator No.43 is proposed to address the reliability assessment of propulsion systems.The calculation results of the examples show that the method proposed in this paper is closer to the real reliability of the system in the process of multi-stage task system reliability calculation due to the consideration of stage dependency.

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