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Distributed Architecture Optimal Design for Aircraft Thrust Management System with Safety Method

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Abstract. In order to ensure the safety and reliability of aircraft thrust management system design and reduce the risk of engineering development, the distributed optimization architecture design based on the aircraft safety method for thrust management system has been put forward in this paper. First, the thrust management function requirement is analysed; second, the distributed architecture design method for thrust management is presented by following the SAE ARP4754 and ARP4761; then the automatic take-off thrust control system function which is not available in Airbus and Boeing civil aircraft thrust management architecture is designed by using this method. The results show that the method proposed in this paper is feasible and effective. The usage efficiency of airborne computer is improved and the aircraft weight is decreased, which greatly enhanced the safety and reliability of aircraft thrust management system.

1. Introduction

Thrust management technology is generated based on aircraft performance optimization. In different flight phases such as take-off, climb, cruise, approach and landing etc, Thrust management system controls aircraft fly along an optimized flight profile by calculating right engine thrust target in order to reduce operating costs.

Thrust management was first adopted by Boeing Aircraft Corporation in the 1970s and successfully applied to its commercial airplanes such as the B737 and B747. In the late 1970s, thrust management technology was applied by US Department of Defense (DOD) to its large aircraft such as bombers, tankers, and transport planes. Later, DOD also tried to use this technology to the fighters [1-2]. The Airbus aircraft company in Europe has also adopted thrust management technology for the A300, A310, A320 and other series of aircraft. In recent years, many domestic scholars have also analyzed and studied the thrust management functions and architecture [3-8], but they did not discuss how to design the thrust management system.

Being one of the aircraft systems, thrust management system architecture should be built at the beginning of the design phase. Modern civil aircraft systems designs are generally more complicated. If the mature safety method can be applied, the thrust management system architecture design will be more reasonable and safe, and the risk of aircraft development will be reduced effectively. In order to decrease the system design weight on the condition of safety guaranteed, we design the thrust



management system based on requirement by using the safety method and the distributed optimization architecture.

2. Function design based on requirement

2.1. Requirement Analysis

The function design of the thrust management system is mainly to meet three aspects of aircraft requirements: (1) Reduce the operation and maintenance cost; (2) Automatic control engine thrust during the flight phase (including the automatic take-off thrust control system, ATTCS); (3) Fan speed(N1) synchronous for noise reduction.

The main factors considered in the requirement analysis are:

(1) Flight phase

The function requirements for thrust management are vary from one flight phase to another flight phase. In the take-off phase, it is mainly considered that the take-off thrust cannot exceed the engine thrust limit. If there is one engine inoperative(OEI), it is necessary to automatically increase the remaining engine thrust to the emergency take-off state (ATTCS function); in the cruise phase, thrust management mainly synchronize fan speed for noise reduction, and control speed or thrust automatically by moving throttle for auto-navigation.

(2) Cost-effectiveness

The derated thrust technology in thrust management can extend engine life and reduce maintenance costs, but it needs to be considered comprehensively for different sizes of aircraft design. The large aircraft has more high efficiency in reducing thrust, and would generally design multiple take-off thrust levels, but the corresponding technical cost is also high. However, the small aircraft has only one take-off thrust level for less benefit.

2.2. Function design

The thrust management system function is designed according to the requirements of the aircraft. It is closely related to the flight management system, automatic flight control system, engine control system as well as the airborne computer importance level and safety index. Different aircraft have different thrust management system architectures, but functions are basically the same, which mainly include the thrust level / thrust limit / target thrust calculation, automatic throttle control, and engine N1 synchronization, and automatic take-off thrust control.

2.2.1. Thrust level / thrust limit / target thrust calculation. According to the different thrust requirements on different flight phase, the thrust level in an aero-engine such as take-off, maximum continuous, climb and cruise usually are designed. In order to fly along the optimal flight profile every time, the thrust management system needs to calculate the required thrust level and target thrust according to the flight phase and cost index, while also giving real-time thrust limits to prevent undesired engine thrust response.

2.2.2. Automatic throttle control. The automatic throttle control includes the thrust control mode and speed control mode, different flight phase has different mode. In the climb phase, thrust control mode is selected to keep the thrust target; When in the cruise phase, the speed control mode is selected to hold the airspeed or Mach number which chosen by the pilot using the automatic flight control unit or given by the flight management computer; During the landing phase, the automatic throttle holds a certain safe speed or enters the idle state.

2.2.3. Engine N1 synchronization. The radiated noise for high bypass engine mainly comes from the discrete single-tone noise of the fan components. When the multiple working engines N1 are close, it is easy to generate acoustic wave interference called beating noise in cabin. In order to eliminate the beating noise effect, the engine N1 will be adjusted automatically to keep consistent. Engine N1

synchronization is only valid during the cruise phase and invalid during take-off, climb or idle engine state. Because this function is mainly to eliminate the beating noise, the engine N1 synchronization can not significantly affect the aircraft three-axis motion, so the N1 speed adjustment values need to be limited in a small range.

2.2.4. Automatic take-off thrust control system (ATTCS). The take-off thrust level plays an important role during aircraft safety take-off. Most of civil commercial aircraft have the OEI take-off capability (after the decision velocity). Some aircrafts may not have sufficient OEI take-off thrust under full load, the ATTCS function in the thrust management system is triggered when an OEI has happened. Aircraft may have two or four engines, each engine thrust control is independent and cannot communicate each other, when the OEI has happened, the ATTCS function cannot be triggered by themselves. So this function requires the aircraft system to transfer the OEI signal from one engine control systems to the other in order to trigger the ATTCS.

3. Safety design method

In the modern aircraft design process, the safety design for complex systems need to follow the SAE ARP4754A and ARP4761 standards. Otherwise the aircraft can not obtain the airworthiness certification issued by the FAA and EASA [9-10].

The ARP4754A establishes a compliance demonstration method for airworthiness regulation to ensure the development process. This SAE standard distinguishes the aircraft system function development assurance level (FDAL) and item development assurance level (IDAL) in detail, and stipulates the system FDAL needs to be implemented by the corresponding IDAL, or formed with the non-similar redundancy architecture by the degraded IDAL. The ARP4761 describes the safety analysis process including Function Hazard Analysis (FHA), Preliminary System Safety Analysis (PSSA), System Safety Analysis (SSA), and Common Cause Analysis (CCA). The main safety analysis methods include Fault Tree Analysis (FTA), Failure Mode and effect Analysis (FMEA) and etc (Table 1). This paper mainly uses the FTA method when optimizing the thrust management architecture.

The top system function in Figure 1 can be composed of multiple sub-functions. If any one sub-function fails, the top system function is considered invalid. For function 1, since the non-similar devices 1A and 1B form redundancy architecture, so the item assurance level of devices 1A and 1B can be lower than that of function 1; for function 2, there is no other device to form redundancy architecture, and then device 2 item development assurance level must be at least the same as the function 2.

Table 1. System architecture development assurance level allocation requirements.

Top-level failure	Failure probability	Corresponding FDAL	Function failure sets with members	
			option 1	option 2
Catastrophic (I)	Less than 10E-9	FDAL A	At least one member should reach IDAL A	At least two members should reach IDAL B
Hazardous (II)	Less than 10E-7	FDAL B	At least one member should reach IDAL B	At least two members should reach IDAL C
Major(III)	Less than 10E-5	FDAL C	At least one member should reach IDAL C	At least two members should reach IDAL D
Minor(IV)	Less than 10E-3	FDAL D	At least one member should reach IDAL D	
No safety effect(V)	More than 10E-3	FDAL E	IDAL E	

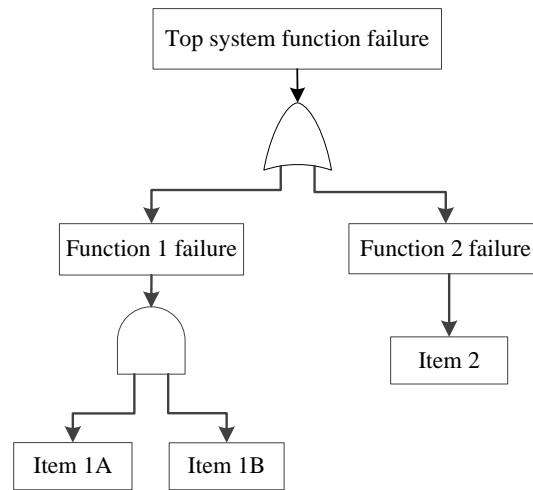


Figure 1. Fault tree analysis for FDAL and IDAL.

4. Application

Different types of aircraft have different thrust management system architectures because of their differences in functions and airborne computers. However, the safety and reliability should be considered in a better thrust management system architecture design.

4.1. Current mainstream thrust management architecture

Although the thrust management functions of Boeing and Airbus aircraft are basically same (except ATTCS), their architectures are quite different. Boeing aircraft has an independent thrust management system; Airbus aircraft's thrust management function is embedded in flight management system.

4.1.1. Boeing series aircraft thrust management architecture. The Boeing series aircrafts have the thrust management system (TMCS) concept (figure 2), which includes automatic throttle (AT) control law, N1 trimming, thrust limit calculation and so on. When the high integrated system design is popular, TMCS' hardware is often integrated with the flight management system (FMS) in order to conveniently visit the FMS database information. The FMS function includes navigation, performance, and guidance modules, where the performance module refers to calculating the aircraft's most economical speed, optimal flight altitude and top decent point for the whole flight profile, and the FMS needs to calculate the thrust limits Value (N1 limits) and thrust target value (N1 targets) for each flight phase. On Boeing's early airplanes, the thrust limit calculation was done by the FMS; while on later airplanes, the thrust limit calculation was handled by the TMCS.

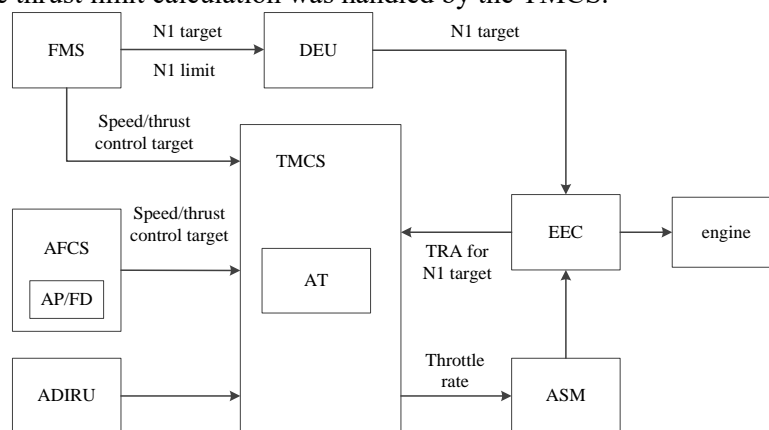


Figure 2. Boeing typical airplanes thrust management architecture diagram.

The Boeing 787 integrates all thrust management functions into an integrated modular avionics (IMA), which also integrates the flight management system and the automated flight system, and will help to interact deeply and reduce aircraft system weight. The Boeing 787 thrust management with more perfect function includes automatic throttle control laws as well as thrust levels, thrust electronic trim and thrust monitoring. The thrust level calculates the data such as the reduced take-off and the reduced climb. The electronic trim thrust completes fan speed trimming and small thrust adjustment without moving the throttle.

4.1.2. Airbus series aircraft thrust management architecture. Airbus series aircraft does not have an independent thrust management system, which is included in the flight management guidance envelope computer (FMGEC). The engine electronic controller (EEC) has also played an important role in the thrust management function realization (figure 3). FMGEC includes flight management, flight guidance and flight envelope protection modules. The automatic flight control and automatic throttle are integrated in the flight guidance module. Therefore, FMGEC only provides automatic control thrust target, thrust level and thrust limit value to EEC. The automatic throttle commands connect or disconnect is placed in the EEC. The FMGEC provides data to EEC needs to pass through the flight control computer (FCU) and the engine Interface vibration monitoring unit (EIVMU).

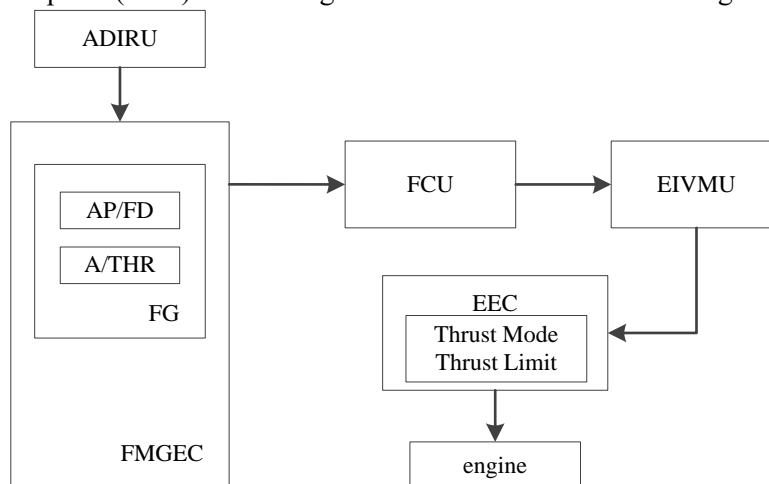


Figure 3. Airbus typical airplane thrust management architecture diagram.

4.2. Thrust management architecture design process

4.2.1. Function hazard analysis. The FHA of the thrust management function is analyzed by referring Table 1, and the results are shown in table 2.

Table 2. Function hazard analysis.

No.	Function hazard	Level
1	Loss of thrust level / thrust limit / thrust target calculation capacity	III
2	Automatic throttle control failure	III
3	Engine N1 synchronization failure	IV
4	ATTCS failure	I

4.2.2. Safety assessment analysis. Each function hazard item in Table 2 is analysed by using FTA method, and take No.4 ATTCS failure as example. Generally, the flight management system (FMS) can reach FDAL III, and the automatic flight control system (AFCS) can reach FDAL II, but the No.4 function FHA is the level I, single aircraft system cannot meet the safety requirement. According to

SAE ARP4754, the question can be solved by adding a new IDAL I item, or by optimizing the design based on the existing item. The later is selected in this paper.

4.2.3. Distributed architecture design. ATTCS function failures include engine control system failure and OEI signal transferring failure, both of them can lead to ATTCS function failure. The engine control system can reach FDAL I, and the OEI signal transferring failure also needs to reach FDAL I. According to the ARP4754, the FDAL I can be formed by two different systems or devices with FDAL II, so the architecture can be designed by using dual engine interface unit (EIU) and AFCS for transferring the OEI signal, especially there is no common mode fault between them. The fault tree analysis is shown in Figure 4.

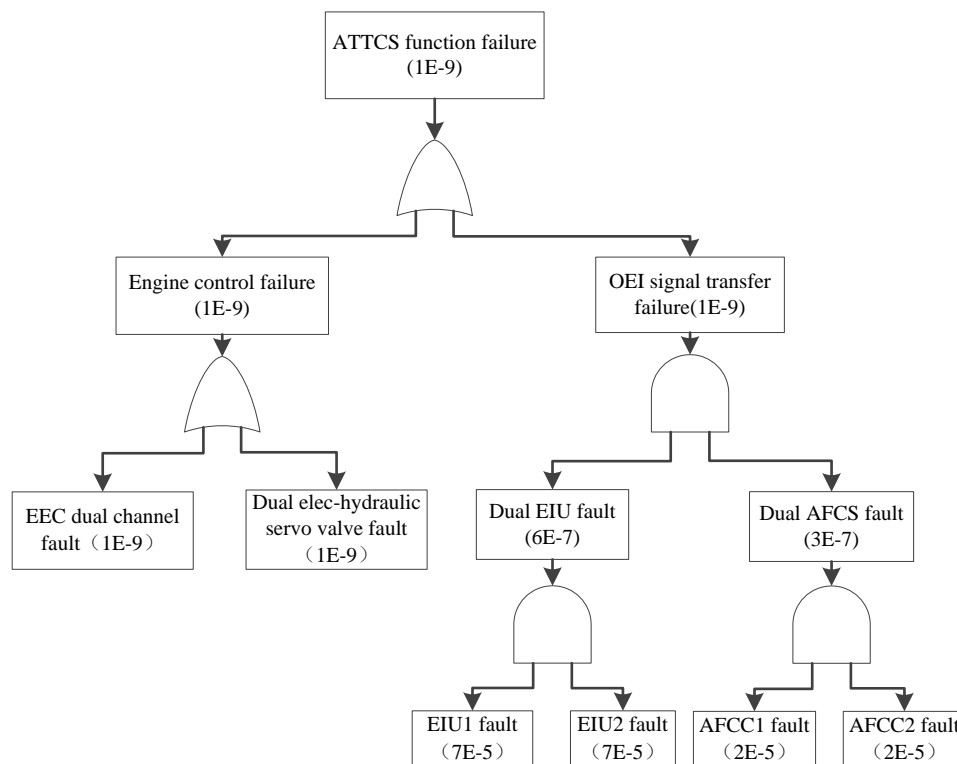


Figure 4. ATTCS fault tree analysis.

4.2.4. Optimized design. Weight is an important index in the aircraft design. The numbers of airborne computer decrease not only reduce the equipment's weight, but also reduce aircraft cable's weight. Although the Boeing aircraft's independent thrust management system can enhance system functions and the Airbus aircraft's thrust management system embedded in FMGEC can easily visit the flight guidance data, the distributed thrust management architecture has the advantage of saving resources and decreasing aircraft weight. In this paper, aircraft design weight can be decreased by 18.7kg by using distributed design method for the ATTCS function (Table 3).

The distributed thrust management architecture is optimized without increasing the new development equipment, which will significantly improve the efficiency of airborne computer.

Table 3. Aircraft weight optimization analysis for ATTCS function.

Solution	Equipment Weight	Cable Weight	Total Weight
Increase new development equipment	8.7kg	15kg	23.7kg
Optimize system architecture	0kg	5kg	5kg

5. Conclusion

In this paper, a new distributed thrust management system architecture design method is presented during the aircraft design. This method includes function requirement analysis and architecture safety design, it can realize complex thrust management system function design. The ATTCS function which is not available in Airbus and Boeing civil aircraft thrust management architecture is simulated by using this method, and the results show that the aircraft design weight can be decreased by 18.7kg. Meanwhile, the safety and reliability of the thrust management system can be guaranteed in the design stage. Therefore, the decreased weights will have the benefits for aircraft loading and extended-range operations.

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