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Research on MBSE-Based Aero-Engine System Modeling and Fault Analysis for SPO Operating Environments

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Abstract

As aviation systems become more complex, the traditional document-driven development method in aviation development faces serious limitations in requirements management, system integration and fault analysis. Model-Based Systems Engineering (MBSE) has therefore become a research hotspot in aviation. On this background, the development of Single-Pilot Operations (SPO) concept imposes more requests for autonomous monitoring, fault detection and health management of engine systems in future passenger planes. Focusing on aero-engine systems, in this paper, literature review and inductive analysis are used to elaborate systematically on the state-of-the-art research of MBSE-based aero-engine system modeling and fault analysis. The theoretical foundation of MBSE, aero-engine systems and SPO are introduced. Then, it summarizes the application of MBSE to engine requirements analysis, system modeling and simulation verification, and reviews the main kinds of aero-engine fault analysis methods now. Based on this, the paper discusses the existing problems and issues, and proposed research thoughts and future directions of research for the SPO operating environments. Summarizing and analyzing previous related research work, this paper provides references for future research for the MBSE-based aero-engine system modeling and fault analysis.

Keywords

MBSE, aero-engine, fault Analysis, SPO

1. Introduction

1.1 Research Background and Problem Statement

With the development of air transport and the complexation of aviation systems, modern civil airplanes are heading toward greater intelligence and higher degrees of integration. Aero-engine is the heart of an airplane, and the performance and dependability of an aero-engine directly influence flight safety and operational effectiveness. For this reason, the design and management of aero-engine systems have always been a hot topic in aviation research [1, 2].

In recent years, Model-Based Systems Engineering (MBSE) has gradually become an important methodology to develop complex aviation systems. Compared with document-driven engineering, MBSE can

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use a unified model to link different requirements, functions, structures and verification methods, which helps to increase development efficiency and traceability in complex systems [1, 3].

At the same time, Single-Pilot Operations (SPO), as one important aspect of future civil aviation, has higher requirements for the autonomy and intelligence of the aircraft. In the SPO operating environment, the engine system not only needs to ensure power, but also needs to support fault diagnosis, system status awareness, and decision support [4, 5].

Currently, MBSE has generated numerous research results in the modeling and design of aviation systems. But the research on aero-engine fault analysis and its application in SPO operating environment is still limited. It is thus necessary to review relevant research in a systematic manner, summarize existing methods and problems, discuss prospects and development directions [6, 7].

1.2 Research Objectives and Significance

Recently, MBSE has attracted great attention in the design and development of aviation system, and has gradually been used in requirements analysis, system architecture, and safety analysis. However, there are quite scattered studies on aero-engine fault analysis compared with aircraft-level design and avionics system development; moreover, the various studies have different methods and emphases. At the same time, as SPO operating mode develops, the importance of engine system in fault monitoring, health management, and decision assistance is growing. This new application and research motivation has emerged for this topic [1, 6, 7].

Based on this background, this paper reviews and summarizes related studies about MBSE in aero-engine fault analysis. It identifies the main methods, technical routes and application characteristics of relevant studies, and identifies current problems and shortcomings; it discusses the potential value and future development of MBSE in engine fault management in view of the operating requirements of SPO, in order to provide references for future research [4, 5].

2. Industry Background

Recently, due to increasing complexity of aero-engine system, the traditional document-driven development approach already manifests limitations in requirements management, system integration, and interdiscipline of collaborative design. In order to enhance the efficiency of developing complex systems, MBSE has entered the aero-engine domain and is one of the popular research topics in recent years [1].

At present, the practical use of MBSE in the aero-engine field is only on the requirements analysis, system architecture design, functional model and simulation verification. Mostly Systems Modeling Language (SysML) is used to build the requirements model, the functional model and system architecture model, unifying the requirement management of system and design work [6]. On this basis, modeling and simulation software (Modelica and Simulink are popularly used) is used to analyze and verify the functional logic, control strategy and system's performance in the operation condition of an engine, to improve the reliability and efficiency of the system development [1].

With the development of digital design concepts, the scope of the application of MBSE gradually expands from system design to operation and maintenance stages. Some researchers started to combine MBSE with Prognostics and Health Management (PHM), digital twin and intelligent maintenance. Through the common model, information can be shared over the design, verification, operation and maintenance stages of the system, which supports monitoring, fault diagnosis and life prediction of the engine [2, 8].

Overall, MBSE can improve the efficiency of collaboration and traceability during the development of complex engine system design, and can provide a unified data platform for system design, verification and subsequent maintenance. At the same time, as aero-engines become more intelligent, the application of MBSE in fault analysis, health management, intelligent decision support, etc. attracts people's attention, laying a basis for future research [1, 4].

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3. Analysis of MBSE Application Methods in Aero-Engine Fault Analysis

3.1 Typical Research Process of MBSE in the Aero-Engine Field

Existing literature demonstrates that the application of MBSE in the development field of aero-engine usually goes through the whole process of system development and analysis. The general process of MBSE can be divided into system requirements analysis, system modeling, simulation verification, fault analysis, health management, etc. [1, 6].

The first step is the requirements analysis stage, in which the researchers build a requirements model based on the functional requirements, safety requirements and other technical performance indicators of the engine system, and show the connections between them. The objective of this stage is that system design realizes the requirements for the system thrust, safe operation, fault management, etc., and builds a traceable connection between requirements and system design [6, 9].

Second, in the system modeling stage, the modeling tools such as SysML are adopted to multiple model system, such as functional model and architecture model, for the unified description of the engine mechanical system, fuel system, control system and sensor system model. These models can clarify the information relationship and function relationship between subsystems, and provide the basis for subsequent analysis [1, 6].

After system modeling is finished, researchers often use the simulation tools such as Modelica and Simulink for simulation verification. They can validate system functional logic, control strategy and working performance of system. The simulation analysis can detect the design defects in advance, and lower the system development cost and risk [1].

For safety-critical systems, fault analysis is an important part of research work. Based on system models, researchers usually combine FMEA, FTA, MBSA and other methods, to conduct safety analysis and fault injection. System response analysis can be used to study fault propagation and its effects, to evaluate system safety and reliability [7, 10].

In recent years, with the development of PHM and digital twin technology, some work has introduced engine condition monitoring, fault diagnosis, and life prediction into the framework of MBSE, allowing life-cycle management from engine system design to running and maintenance [2, 8]. This model-based research way has gradually been the research approach in the aero-engine field.

3.2 SysML-Based Aero-Engine System Modeling Method

From a study case using SysML-based aero-engine system modeling, modeling is usually made for this system model in the sequence of the requirements layer, the functional layer, the structural layer and the interface layer. Firstly, at the requirements layer, an engine system requirements model is modeled. Requirements such as thrust control, safe operation, fault monitoring and health management are categorized and organized, and traceability links for the requirements are created between these requirements and following requirements functional modules. Thus, requirements are not made into just textual descriptions, and each system function can be traced to clear requirements in design [6].

Secondly, at the function layer, the engine operating process is deconstructed. The basic functions of aero-engine can be classified as air intake, compressing, combustion, turbine work output, fuel regulation, state monitoring and control feedback. The researcher describes the sequence and logic relationship among the basic functions with activity diagrams or functional chain model. For example, the fuel system adjusts fuel flow based on the control command, the combustion chamber achieves energy transformation, sensors gather related status information (such as engine rotation speed, temperature and pressure), and send these parameters back to control system for control. Functional modeling makes explicit the logic operating process of the engine in normal working condition.

Thirdly, at the structural level, a system architecture model is carried out. At this level, the aero-engine is normally separated into the mechanical subsystem, the fuel subsystem, the control subsystem, and the sensor subsystem. The block definition diagram and the internal block diagram are used to describe the composition and linkage relationship between the above subsystems. The mechanical subsystem mainly includes the

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compressor, combustion chamber and the turbine; the fuel subsystem includes the fuel pump, the fuel metering devices and the fuel lines; the control subsystem mainly includes the Full Authority Digital Engine Control (FADEC), the actuators and control laws; the sensor subsystem includes the device, which collecting the important parameters of the engine work. Through structure modeling, a relatively definite aero-engine system architecture can be formed.

Finally, at the interface layer, the information flow, energy flow and control flow of all subsystems are described. An aero-engine system is not a simple summation of components; it is a complex system combined by mechanical system, fuel system and control system. For example, sensors provide engine state information to FADEC. FADEC sends commands to the fuel metering device and actuators in accordance with control logic, and the variation of the fuel system changes the combustion state of the engine and its output characteristic. Interface modeling, therefore, is a crucial bridge between system structure and fault analysis. Through the modeling process mentioned above, the SysML models can provide the basis for a unified system description of subsequent fault propagation analysis, safety evaluation, and simulation verification [1, 6].

3.3 MBSE-Based Engine Fault Analysis Method

After system modeling, researchers usually use the defined system model to do system fault analysis. Compared with traditional fault analysis methods, MBSE-based fault analysis can use a unified model to describe the system's structural characteristics, functional characteristics and behavioral characteristics. Information sharing is achieved between system design and safety analysis. The consistency and traceability of analysis are improved as well [7].

For example, model-based systems engineering (MBSE) can be combined with Failure Mode and Effects Analysis (FMEA). Researchers analyze the key components and functional modules of the engine system on the system model first, then analyze possible fault modes and effects for each component. These relations among models can be used to analyze the effect scope of each fault on the whole system. Compared with manual analysis traditionally, models can make researchers find potential faults of the system systematically, and improve the efficiency of the analysis [10].

Another widely used method is to combine MBSE with Fault Tree Analysis (FTA). Researchers build a fault tree structure according to the system model and then use logical relationships to analyze the causal chain leading to system failure. As the system model itself describes the connection between subsystems, it can also more accurately reflect fault propagation and the dependency of the system [10].

In recent years, model-based safety analysis (MBSA) has gradually become a focus of research. MBSA performs safety analysis by using the model of the system directly, making requirements analysis, system design and safety evaluation, all as a whole [7]. The researches in this field usually use the fault injection and simulation analysis, injecting faults artificially in the model and observing system responding, judging the influence of faults on the system performance and safety. The analysis method not only improves the efficiency of analysis, but also can display complex fault flow path, which is hard to be found by using traditional methods.

For aero-engine systems, based on MBSE, fault analysis can simultaneously address the coupling influence between the mechanical system, fuel system, control system and sensor system, and consider fault propagation and evolution of risk at system level. MBSE is thus developing gradually into an important technical means of aero-engine fault analysis and safety evaluation, and provides a basis model for further engine health management and intelligent decision-making research [7, 10].

3.4 Engine Fault Management Requirements in the SPO Context

As research into the Single-Pilot Operations (SPO) expands, the upcoming civil aviation operation modes will approach higher level of automation and intelligence. In the traditional two-pilot operation mode, the flight deck crew can perform some tasks such as system monitoring, fault judgment, and emergency handling through coordination. But in the SPO operation environment, the pilot should undertake more monitoring and decision responsibilities by itself. So the onboard system requires more autonomy, perception and decision support capabilities [4, 11].

For aero-engine, the traditional fault management depends mainly on pilots to judge and deal with faults according to the instrument information and fault alerts. In an SPO environment, the time and space available

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to the pilot for analyzing the fault information and the fault response plan are, therefore, more restricted. Engine systems require, thus, higher-level fault diagnosis and fault management capabilities. The engine system should not only detect abnormal states in advance but also correctly diagnose a fault location and evaluate the potential consequences of the faults [5].

At the same time, with the development of the PHM technology, engine fault management starts to convert from the mode of engine fault discovery and management to the mode of predictive fault management. By monitoring the engine operating states online and historical operating data, the engine system will be able to analyze the possible risk of engine failure before failure occurs and maintenance or control measures can be carried out in advance and reduce the impact of sudden failures on flight safety [2].

In addition, under complex fault conditions, the engine system needs to provide a pilot more intuitive and effective decision support. For example, the engine system can automatically generate risk evaluation results, suggest the response plan, and predict the remaining engine available capability according to the type of fault, and assist pilot in completing the decision process quickly [4, 5]. This can reduce the workload of the pilot, and help to improve flight safety under abnormal situations.

Therefore, in the SPO context, the aero-engine system is gradually forming from a power system in traditional meaning to an intelligent aero-engine system that integrates a fault diagnosis for condition monitoring, health management, and decision support. How to use MBSE to establish a unified model and effectively integrate the fault analysis function, PHM function and decision-support function is an important direction for future aero-engine research.

4. Feasibility Analysis and Application Prospects of the Research Scheme

4.1 Application Prospects

As the complexity and degree of automation of aeronautical systems continue to increase, the application prospects of MBSE in the aero-engine field are very broad. In the future, MBSE not only can be applied to the design and development process of the engine system, but can also be applied to the operation-maintenance, fault management-maintenance and life cycle management of the system. With the creation of a common system model, information sharing among different requirements, design, verification, and maintenance stages, MBSE will further improve the efficiency of engine system development and maintenance reliability [3].

At the same time, the developments of technologies like digital twin. Artificial Intelligence combine with Prognostics and Health Management (PHM) open new aspects of application of MBSE. The future work can link up real-time operating data and system models to construct the aero-engine digital twin model and realize some functions of condition monitoring, fault prediction, and life assessment to further improve engine maintenance effectiveness and reduce engine running costs [2, 8].

In addition, with the development of SPO mode, the engine system will take more responsibilities of autonomous monitoring and decision support. To construct a unified system model through MBSE and combine some functions of fault analysis, health management and decision support is beneficial to increase the intelligence of engine system and ensure flight safety in the future single-pilot operating mode [4, 11].

Overall, MBSE is developing gradually from a method for system development into an important technique to support the life-cycle management of complex aviation systems. MBSE will be further connected with emerging research directions such as PHM, digital twins and SPO, and will be an important trend in future aero-engine research.

4.2 Existing Problems in Current Research

MBSE has lots of advantages in modeling for aero-engine system, fault analysis and safety evaluation, but related research still has the following limitations at present. Different research institutions and enterprises use different modeling tools, modeling standards and modeling data form. They have low compatibility and reusability among the models and narrow use range of MBSE in complex aviation systems [3, 12].

Most previous studies focus on the analysis of single subsystem, whereas research on complex coupling relations of the engine mechanical system, fuel system, control system and sensor system is not sufficient. In

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addition, the situation that the fault has spread under complex fault condition, and the scope of influencing fault still cannot be described completely and precisely [1, 7].

Furthermore, although MBSE can set up the information link between system design and safety analysis, deep integration of SysML models with safety analysis methods, such as FMEA, FTA and MBSA cannot work well in practical engineering practice, and many existing studies still need a great deal of manual participation, the degree of automation needs to be further enhanced [7, 10]. At last, as SPO research progresses, future aero-engine systems will have stronger autonomous fault management and decision-support capability. However, most existing studies are based on the existing two-pilot operation mode, and research on the diagnosis of engine fault, health management and decision support under SPO still lags behind [4, 5, 11]. Therefore, model reuse research work needs to be further deepened, multidisciplinary collaborative modeling needs to be strengthened, safety analysis automation needs to be improved, and research to meet SPO requirement would be important research direction for the further development of MBSE in aero-engine field.

4.3 Analysis of Future Research Directions

Future development of aero-engine fault management will not be confined to fault detection and fault diagnosis. Rather, it will gradually evolve to be intelligence, prediction and autonomy. In this process, the deep integration of MBSE with digital twin, artificial intelligence, PHM technologies will surely be an important research trend.

Firstly, the digital twin technology has made a virtual model for an aero-engine, which is consistent with the real system in real time. Future research can use MBSE to establish a unified architecture model for the engine system and associate engine data (for example, temperature, pressure, vibration, rotational speed) collected in the course of an engine operation with the digital twin model in real time, dynamically reflecting the engine state. Different from traditional fault analysis, digital twin models can not only show the current operational state, but also reflect the process of fault occurrence simulation and predict future operational state, upgrading the fault warning ability [8].

Secondly, AI technology will further improve engine fault management level. Deep learning and machine learning technology have already been used to research fault diagnosis; at this stage, most research still leans on historical data to train and has no support from system mechanisms. The future should combine the system model built from MBSE with artificial intelligence algorithm. The model provides the information of system structure and operating logic, artificial intelligence technology can make use of operating data to analyze, forming an analytical way of hybrid model-driven and data-driven method, not only improving the accuracy of fault diagnosis, but also improving the intelligibility of artificial intelligence algorithm models [2, 8].

Thirdly, the development of PHM technology will push fault management from post-event maintenance to forward prediction. Future research can utilize MBSE to achieve the integration of engine life-cycle management, which unifies the management of data generated by design, operation, and maintenance stage. Combined with artificial intelligence algorithms, life-cycle management model can support remaining useful life prediction and optimization of maintenance decision. This could help lower maintenance costs and improve the engine availability and reliability of use [2].

When it is an SPO environment, the combination of the above-mentioned technologies is even more important. For future engine systems, not only do they need to complete the fault detection and diagnosis tasks, but also they require system autonomy to provide decision support. For instance, when a fault occurs, the digital twin model of the engine system can predict the trend of the fault development, an AI system can infer the risk level, and the response suggestions can be automatically generated. The response recommendations can be fed back to the pilot through a human-machine interface. Such intelligent fault management, based on MBSE and combining digital twin, PHM, and AI, will be an important direction of future development in aero-engine system [4, 5, 11].

So, building an intelligent engine fault management system for SPO operational environment and promoting deep fusion of MBSE with digital twins, Intelligent and PHM technologies, it will be an important breakthrough direction for future aero-engine research and engineering application.

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5. Conclusion

The paper reviews the application of MBSE in aero-engine fault analysis. It introduces the development background of MBSE, aero-engine systems and SPO, and summarizes the research methods of aero-engine fault analysis and studies the current application of MBSE in system modeling, fault analysis and safety evaluation.

The summary demonstrates that MBSE can build information links among the requirements, design, verification and safety analysis stages and thus improve the development and management efficiency of complex aero-engine systems. At the same time, with the development of digital twins, PHM and artificial intelligence, engine fault management will gradually shift toward predictive maintenance and intelligent decision support.

In the future, as SPO operating environment continues to evolve, future intelligent engine fault management system taking MBSE, digital twin, PHM and AI, to be combined is a new direction of research. Research of related technologies will not only improve engine usage safety and maintain maintenance efficiency, but also make technical progress for highly automated air transportation in the future.

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Conflicts of Interest

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