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MBSE-Based Fault Analysis of Aircraft Landing Gear

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Abstract. The aircraft landing gear is one of the critical systems ensuring flight safety, and its faults directly affect the aircraft's takeoff, landing, and ground taxiing performance. With the increasing complexity of aviation systems, traditional document-based fault analysis methods have limitations in terms of consistency, traceability, and collaboration. The Model-Based Systems Engineering (MBSE) approach, utilizing unified modeling languages such as SysML, enables the integrated modeling of system requirements, functions, structures, and behaviors, providing a new paradigm for landing gear fault analysis. This paper reviews the types of landing gear faults and the current application status of MBSE in the aviation field. It also outlines model-based fault analysis methods and selects the integration of Fault Tree Analysis with SysML modeling as the core theory. Furthermore, it summarizes the progress in model-driven fault simulation analysis and intelligent diagnosis integration technologies. Research indicates that the MBSE approach can effectively enhance the accuracy and efficiency of landing gear fault analysis, providing support for the intelligent maintenance and airworthiness certification of aviation equipment.

Keywords: Model-Based Systems Engineering, Landing Gear, Fault Analysis, SysML, Fault Tree

1. Introduction

The aircraft landing gear is the core load-bearing structure during takeoff and landing, and its performance directly affects flight safety and operational efficiency. Statistics show that landing gear system faults account for more than 20% of aviation mechanical failures. Common faults include retraction mechanism jamming, hydraulic leakage, wheel hub cracks, and brake failure. Traditional fault analysis relies on empirical judgment and documentation, which suffers from information silos, model inconsistency, and difficulty in reuse [1,2]. Model-Based Systems Engineering (MBSE) supports full lifecycle collaboration from requirements analysis to fault diagnosis by constructing a unified system model. MBSE has been widely applied in complex equipment fields such as aviation and aerospace. For example, NASA has introduced MBSE for failure mode analysis in spacecraft design, and Airbus has attempted model-based system verification in its A350 program [3]. Domestic research is still in its early stages, especially in landing gear fault analysis [4]. Therefore, conducting research on MBSE-based aircraft landing gear fault analysis has significant theoretical value and engineering implications.

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This paper aims to explore a new path to improve the reliability and maintainability of landing gear systems by combining system modeling and fault analysis methods.

2. Overview of fault analysis methods

Fault analysis is a core activity for ensuring system safety and reliability. Traditional methods mainly include Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA), and Event Tree Analysis (ETA) [5]. Although these methods have accumulated rich experience in engineering practice, they suffer from the following problems. Firstly, analysis results from different phases are scattered across various documents, making it difficult to form a unified view, resulting in information silos. Secondly, the relationships between requirements, design, and faults are hard to trace, leading to poor traceability. Besides, multi-disciplinary teams lack a unified modeling language, resulting in high communication costs and collaboration difficulties [6].

The MBSE-based fault analysis method addresses these issues by constructing a unified system model that integrates requirements, functions, structures, behaviors, and fault information within a single framework. Its advantages are numerous. First, the model serves as the single source of truth, ensuring information consistency. Second, bidirectional traceability between requirements and faults is achieved through associations, solving the problem of poor traceability. Third, it supports multi-disciplinary teams in collaborative analysis and decision-making based on the same model, resolving collaboration difficulties.

3. Theoretical choice: integration of SysML and fault tree analysis

Within the MBSE framework, Systems Modeling Language (SysML) is the most commonly used modeling language. It includes various diagram types such as requirement diagrams, block definition diagrams, internal block diagrams, state machine diagrams, and activity diagrams, which can comprehensively describe the structure, behavior, and requirements of a system.

To achieve fault analysis, this paper integrates SysML with the Fault Tree Analysis (FTA) method. The specific modeling approach can be divided into four points. First, use SysML requirement diagrams to define the functional and non-functional requirements of the landing gear system, including requirements for retraction time, load capacity, and fault tolerance. Second, describe the physical composition of the landing gear system, including struts, actuators, wheel hubs, brake units, using block definition diagrams and internal block diagrams; this is structural modeling. Third, describe the behavioral logic of the landing gear during retraction/extension, landing, taxiing, and other phases using state machine diagrams and activity diagrams; this is behavioral modeling [4]. Finally, map fault events in FTA to fault states or abnormal behaviors in SysML, constructing fault propagation paths and logical relationships; this is fault modeling.

This integrated method enables bidirectional traceability between failure modes and system design, supporting both quantitative analysis and qualitative reasoning of fault impacts.

4. SysML-based fault modeling technology

SysML-based fault modeling technology is one of the core applications of MBSE in the field of fault analysis. It organically integrates the system's functional logic, physical structure, behavioral interactions, and potential failure modes into a traceable and evolvable unified model through various diagram types provided by SysML [1,3]. This technology aims to solve problems in

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traditional fault analysis, covering the disconnect between models and design and the difficulty of associating fault information, providing foundation for fault simulation and diagnostic reasoning.

4.1. Diagram usage in SysML fault modeling

SysML contains nine basic diagram types, among which the main ones used for fault modeling include: First, requirement diagram captures system-level reliability and safety requirements, such as "landing gear retraction time shall not exceed 12 seconds" or "hydraulic system leakage rate shall be below 0.1%". Requirements can be decomposed and linked to specific components [1].

Block Definition Diagram (BDD) defines the system's composition modules and their hierarchical relationships. For example, the landing gear system can be decomposed into retraction mechanism, shock strut, wheel and brake modules, each defining its properties and operations.

Internal Block Diagram (IBD) describes the connections, ports, and data flows between modules. In fault analysis, it can be used to express fault propagation paths, such as how hydraulic line leakage affects the pressure of adjacent components [4].

State Machine Diagram depicts the state transitions of a module in different operational phases. For example, a landing gear retraction actuator can have states such as "extended", "retracted", and "jammed", where "jammed" is a fault state [5].

Parametric Diagram defines constraint equations, such as physical laws and performance indicators. It can express the relationship of parameter deviations from normal ranges under fault conditions, such as "actuator extension speed < threshold" corresponds to a "jammed" fault [7].

4.2. Fault modeling process

SysML-based fault modeling generally follows these steps:

Requirement analysis use requirement diagrams to transform airworthiness regulations and airline requirements into quantifiable system requirements, and establish traceability relationships among requirements [1,3].

Structural modeling build BDD and IBD to define the physical architecture of the landing gear system, clarifying interfaces and interactions between components. For example, model the landing gear retraction system as blocks such as "control unit", "hydraulic source", "actuator", and "position sensor", using ports to represent hydraulic lines and electrical signals [8].

Behavioral modeling describe the system's fault-free workflow using activity diagrams or sequence diagrams, such as the sequence after an "up" command: hydraulic valve opens, actuator moves, and uplock engages [4].

Based on FMEA/FMECA results, define possible failure modes for each component in the model, such as "hydraulic leakage" or "solenoid valve jamming". These failure modes can be represented as special states in state machines or marked as fault types via extension mechanisms (e.g., SysML profiles) [7].

Fault propagation modeling uses the connections in IBD to define how faults propagate through energy, signal, or material flows. For example, hydraulic leakage will cause a drop in actuator input pressure, thereby affecting its movement speed. Propagation paths can be represented with dependency relationships and constraints [6].

Fault tree integration exports fault events from the SysML model to FTA tools, or directly construct fault tree diagrams within the model, using logic gates (AND/OR) to represent fault combinations. SysML parametric diagrams can be used for quantitative analysis, such as calculating the probability of the top event [2,5].

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Verification and validation use model checking tools to verify the consistency and completeness of the fault model, and revise the design or requirements based on analysis results [7].

4.3. Tool support

Currently, mainstream MBSE modeling tools support SysML and provide fault analysis extension modules. Cameo Systems Modeler features built-in requirements management, parametric diagram solving, simulation interfaces, and supports FMEA/FTA integration via plugins [3]. IBM Rational Rhapsody provides state machine simulation and code generation, combined with fault injection for dynamic behavior verification [4]. Enterprise Architect supports SysML modeling and can generate fault trees through scripting extensions [8]. These tools typically offer model library functionality, allowing users to pre-define common fault types (e.g., leakage, fracture, jamming) and reuse them across different projects [1].

4.4. Application examples: fault modeling of landing gear retraction system

4.4.1. FedEx 757 landing gear failure to extend accident (2023)

On October 4, 2023, a FedEx Boeing 757-200 freighter operating Flight 1376 was forced to perform a belly landing at Chattanooga Airport, Tennessee, due to the inability to extend its landing gear. The National Transportation Safety Board (NTSB) investigation revealed that the accident involved a dual fault: rupture of the left main landing gear door actuator hydraulic hose, leading to complete depletion of the left hydraulic system (hydraulic fluid level began dropping only 22 seconds after takeoff); and a broken electrical circuit in the alternate landing gear extension system, where the wire from the alternate extension switch to the backup power pack failed due to tensile overload, rendering the backup system inoperative [6,9].

This case can be modeled using SysML as follows: establish the physical connection relationships of hydraulic lines and electrical wiring in an IBD; define fault states such as "hydraulic leakage" and "electrical circuit break" in state machine diagrams; define constraint equations for hydraulic pressure and actuator extension speed using parametric diagrams; and finally construct a fault tree with "landing gear fails to extend" as the top event, with bottom events including "hydraulic system failure" and "backup system failure" combined via an OR logic gate. Model analysis can reveal the propagation path and failure mechanism of this dual fault mode [2,7].

4.4.2. Air China CA941 nose landing gear unexpected retraction accident (2007)

On July 1, 2007, Air China Flight CA941 (Beijing–Dubai) experienced an unexpected retraction of the nose landing gear during passenger boarding, causing the aircraft nose to strike the ground, resulting in minor injuries to three passengers and five crew members. The Civil Aviation Administration of China (CAAC) investigation found that the direct cause was that after troubleshooting a hydraulic fluid leak in the left landing gear tilt actuator, maintenance engineers performed a retraction test without verifying that the landing gear was in the unlocked state, leading to the nose gear retraction [5,10].

This case highlights the interaction between human factors and maintenance procedure deficiencies. SysML activity diagrams can model the maintenance process, identifying critical checkpoints (e.g., confirmation of landing gear uplock); state machine diagrams can define the configuration control logic of the aircraft during ground maintenance; requirement diagrams can capture maintenance procedure requirements and establish traceability to activity nodes. The model

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can assist in identifying potential human error points in the process and optimizing maintenance procedure design [4,8].

4.5. Technical advantages and application effects

SysML-based fault modeling technology demonstrates multiple advantages in practice. The model serves as the single source of truth, ensuring synchronous updates of requirements, design, and fault information, effectively avoiding document version chaos. Bidirectional traceability from top events to bottom events and from faults to design requirements facilitates airworthiness review and design change impact analysis. Established fault model libraries can be reused across different aircraft types, significantly reducing repetitive modeling costs. Moreover, the technology supports automated generation of FMEA tables and fault tree diagrams, and can integrate with simulation tools for fault impact simulation [8]. In practical applications, model reuse and automated tools reduce manual analysis time by approximately 40% [3]. The clear traceability among requirements, design, and faults facilitates airworthiness certification [1]. In one aircraft development program, the adoption of this technology reduced the landing gear system fault analysis cycle by 30% and lowered the failure mode omission rate by 50%, significantly improving system safety [6]. Model-driven diagnostic systems also enable rapid fault localization, reducing maintenance costs.

5. Brief overview of other key technologies

SysML models are transformed into simulation models (e.g., Simulink, Modelica) for fault injection and behavioral simulation to evaluate the dynamic impact of faults on system performance. For example, simulation analysis of the sensitivity of retraction time to hydraulic leakage can validate quantitative results from fault tree analysis [2,7]. In the fault analysis of a certain airliner landing gear retraction system, SysML modeling revealed that actuator hydraulic leakage and solenoid valve jamming were the primary failure modes, and simulation verified their impact on retraction time. Design optimization of hydraulic line layout improved system reliability [4,7].

MBSE models are integrated with Prognostics and Health Management (PHM) systems. The fault trees and logical relationships generated from the model guide fault diagnosis reasoning and maintenance decision-making. Typical applications include model-based fault localization and remaining useful life prediction for real-time health monitoring. For example, in a military transport aircraft project, an MBSE-based landing gear fault diagnosis model was built and integrated with a PHM system for real-time health monitoring. The fault tree generated by the model guided fault localization logic, improving fault diagnosis accuracy by over 30% [6,8].

6. Challenges and future development trends

Despite the significant theoretical and practical advantages of SysML-based fault modeling technology, several challenges remain for its engineering adoption. First, modeling standards are not yet unified; model interoperability between different tools and languages remains problematic, and there is a lack of unified fault modeling specifications, echoing the coexistence of multiple modeling tools with limited collaboration mentioned earlier. Second, model complexity management is difficult; large system models are prone to information overload, requiring view management and hierarchical modeling mechanisms while maintaining model consistency, which imposes higher management demands on all stages from requirements capture to fault tree integration in the fault modeling process. Third, integration of simulation and models remains difficult; conversion between

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SysML models and simulation tools still requires manual intervention, with low automation, limiting the efficiency of dynamic validation, thereby restricting the practical deployment of the model-driven fault simulation analysis technology. Fourth, high skill requirements for personnel; mastering MBSE methods, modeling languages, and tools poses a barrier to widespread adoption, necessitating enhanced training.

Looking ahead, MBSE-based landing gear fault analysis technology will continue to deepen in several directions. First, deep integration of modeling and simulation will be pursued through the development of model–simulation integrated platforms that enable automatic conversion and co-simulation of SysML models with environments such as Simulink and Modelica, supporting more precise dynamic fault analysis and addressing the low efficiency of manual conversion. Second, the introduction of artificial intelligence will bring new breakthroughs to fault modeling; machine learning methods can assist in fault mode recognition and automatic model generation, effectively lowering the barrier to mastering SysML and alleviating the training pressure [5]. Third, integration of MBSE with digital twins will become an important direction; constructing a digital twin of the landing gear enables real-time fault diagnosis and predictive maintenance, advancing the PHM integration technology toward higher levels of equipment intelligence [7]. Finally, standardization and tool interoperability are key to enabling the above technologies; promoting unified modeling standards and an improved tool ecosystem, enhancing model interoperability across different platforms, will effectively address the lack of unified standards and foster collaborative development across the aviation industry chain [8].

7. Conclusion

This paper systematically explores on MBSE-based aircraft landing gear fault analysis. It reviews the limitations of traditional fault analysis methods and highlights the advantages of the MBSE approach. The integration of SysML and Fault Tree Analysis is adopted as the core theoretical framework, and SysML-based fault modeling technology is discussed in terms of diagram usage, modeling process, tool support, and application cases. Through the analysis of two typical accidents, the effectiveness of this method in fault propagation identification and maintenance process optimization is verified.

However, this study has limitations. The literature review lacks sufficient coverage of international MBSE engineering practices from leading aviation companies. The research focuses more on modeling frameworks than on quantitative validation against real fault data. Additionally, issues such as automatic model transformation and toolchain interoperability are not thoroughly addressed.

Future research can focus on four directions. First, promote standardization and tool interoperability to lower application barriers. Second, integrate MBSE with digital twin technologies to enable real-time diagnosis and predictive maintenance. Third, introduce artificial intelligence to assist in fault mode recognition and automatic model generation. Fourth, establish a model credibility verification framework to support airworthiness certification.

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