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A Novel Mission Reliability Assessment Approach Based on System Performance Simulation under Multi-Mission Profiles

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Traditional reliability assessment methods often fail to adequately address the complexities posed by diverse and dynamic mission profiles, thereby limiting their ability to accurately represent system reliability in real-world, variable environments. In response to this challenge, the present study introduces an innovative reliability assessment approach grounded in performance simulation tailored for multi-mission scenarios. Centered on fault analysis, this approach integrates reliability evaluation with high-fidelity system performance simulation in a comprehensive manner. Initially, a performance simulation model is developed using the Modelica language, designed to precisely capture the system's physical characteristics, functional logic, and control strategies. Subsequently, representative mission profiles are delineated, encompassing various mission phases, environmental loads, operational modes, and fault conditions. The performance simulation model is then executed under these diverse mission profiles, generating trajectories that depict the system's performance evolution amid the influences of multi-mission operational conditions and multiple fault modes. Finally, by establishing mission success criteria, the method determines the outcome of each mission simulation, thereby facilitating a quantitative assessment of mission reliability. A case study involving an aero-engine system was performed to validate the proposed method. The findings demonstrate that this approach effectively addresses the shortcomings of conventional reliability assessment techniques and substantially enhances both the accuracy and practical applicability of reliability evaluations for complex systems operating under multi-mission and multi-fault mode scenarios.

Keywords: Reliability assessment, Multi-mission profile, Performance simulation, Modelica language.

1. Introduction

The precision of mission reliability assessment for complex systems, when grounded in performance simulations, is fundamentally contingent upon the extent to which various operational modes and environmental load conditions are accurately modelled. Conventional approaches typically rely on assumptions of standard operating conditions or typical mission durations, often presuming that environmental loads remain constant throughout. In contrast, actual operational environments exhibit a wide range of environmental loads corresponding to distinct mission phases, accompanied by multiple potential fault modes. This complexity results in intricate patterns of performance degradation under the influence of multi-mission scenarios and diverse fault mechanisms, thereby presenting significant challenges to current reliability assessment methods.

Currently, in the context of multi-mission profiles for complex systems, Hao J et al.(2025) have developed a mission reliability assessment approach for multi-stage data, which integrates fault data from diverse mission profiles through the use of equivalent conversion coefficients. Wang W et al.(2024) proposed a reliability analysis model tailored for modular phased-mission systems, wherein complex systems comprising multiple K/N redundant subsystems are decomposed into modules, enabling flexible adaptation to variations in subsystem configurations and mission reliability requirements across different stages within multi-mission profiles. Rani S et al.(2025) introduced a time-varying Copula model to effectively capture the dynamic correlations among components under multi-mission conditions. Additionally, Cao D et al.(2020) presented an integrated design framework addressing both multi-mission performance and reliability, establishing a performance-reliability mapping model that incorporates the multi-condition adaptability characteristic of variable cycle aeroengines. Nevertheless, these studies have largely overlooked the diverse fault characteristics of the system's internal components.

Meanwhile, numerous scholars have also carried out relevant research on multi-fault modes of systems. Lu S et al.(2001) proposed a technology for real-time prediction of system performance reliability by considering various fault modes. Gai J et al.(2025) conducted a multi-fault analysis for the reliability of turbojet engines. Tang M et al.(2023) presented a cross-stage competitive fault analysis framework, which quantifies the competitive relationships between fault modes across different mission stages for the first time. Du X et al.(2023) proposed a fusion method of multi-fault mode tree and multi-state multi-valued decision diagram, realizing the reliability assessment of phased-mission systems (PMS) across levels (fault mode-component-system) and scales (single-stage-multi-stage). Xie G et al.(2021) developed a Copula Bayesian network model to solve the modelling of nonlinear relationships among multiple faults, revealing the impacts of Copula functions with different fault types and different parameters on system reliability, and laying a theoretical foundation for the parallel analysis of multi-fault modes under multi-mission profiles. Nevertheless, these investigations seldom incorporate the coupling characteristics between the parameters and performance of the system's internal components.

To address the above problems, this paper proposes a mission reliability assessment method based on system performance simulation under multi-mission profiles. The main innovations of this paper are as follows:

(i) Considering the coupling relationships among parameters across device models in various domains, a system performance model using Modelica language is developed. Based on which, a time-sequential and correlated multi-mission profile is constructed.

(ii) Considering the impacts of external environmental conditions under multi-mission profiles, this paper analyses the performance degradation trajectory of the system under the disturbance of multi-fault modes to realize the system reliability assessment.

2. Description of Method Principles

This section elaborates on the theoretical basis of the proposed assessment method, covering the construction of the system's multi-domain coupling performance model, the definition of multi-mission profiles, and the simulation of performance degradation under multi-mission profiles.

2.1. Construction of Multi-Domain Coupling Performance Model for Complex Systems

Within complex systems, interaction mechanisms typically exist among excitation sources originating from diverse physical domains. To further construct a high-fidelity system performance simulation model and achieve accurate analysis of system performance, it is necessary to build the model in a multi-domain integration manner based on the Modelica language.

First, it is essential to clarify the system composition and the exchange logic of physical quantities between various devices inside the system, and establish a cross-domain parameter conversion method between devices. Second, by integrating the key parameters of internal components with external environmental conditions, a multi-domain coupling performance model of the complex system is constructed by virtue of the cross-domain parameter conversion. This performance model allows for the definition of internal parameters according to the mission profile, and realize high-fidelity simulation of the system through the conversion and transmission of physical quantities within the model. This process is illustrated in Fig. 1.

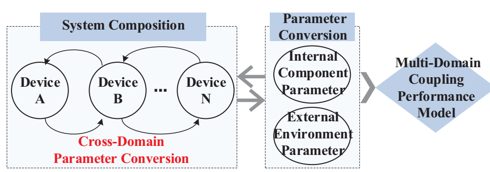

Fig. 1. Performance Model Construction Process

2.2. Definition of Multi-Mission Profiles

The definition of internal parameters for the system's multi-domain coupling performance model must be carried out based on mission profiles. This study proposes a method for defining multi-mission profiles that encapsulate both temporal sequencing and inter-mission correlations. To characterize the system's dynamic behavior across its entire life cycle, mission profiles are modeled as stochastic processes that evolve temporally.

Define the mission state sequence as

$$S=\{S_1,S_2,\ldots,S_T\} \quad (1)$$

where $S_t=\{s^{(1)},s^{(2)},\ldots,s^{(m)}\}$ represents the specific mission phase executed by the system at time *t*.

Define the associated environmental stress sequence as

$$E=\{E_1,E_2,\ldots,E_T\} \quad (2)$$

where $E_t=\{e_{1,t},e_{2,t},\ldots,e_{k,t}\}$ represents the multi-dimensional stress vector observed under this mission phase (e.g., temperature, vibration load, etc.).

The temporal dimension of missions is manifested in the one-to-one mapping between each element S_i and E_i in the sequences and time t throughout the life cycle, which depicts the dynamic evolution of the mission phases executed by the system and also reflects the real-time fluctuations of environmental loads as the mission progresses.

The correlation of missions is in two primary dimensions: Firstly, the pronounced association between missions and the environment, wherein the mission state S_i at any given moment corresponds to an environmental stress vector E_i ; Secondly, there exists a coupling relationship between the transition of mission phases and the system performance degradation, specifically, the switching of mission phase induces interactions among the core internal parameters of complex systems.

2.3. Simulation of Performance Degradation under Multi-Mission Profiles

Taking the time-sequential multi-mission profiles as inputs, this method governs the operation of the system's multi-domain coupling performance model. Fault parameters are introduced into each phase of the profiles to develop a multi-fault model of the system. Through Monte Carlo simulation, the synergistic effect of multi-fault disturbances under multi-mission profiles is analysed, the evolution law of core performance parameters is tracked, and the performance degradation of the system is more comprehensively captured. Finally, reliability assessment is carried out. This process is illustrated in Fig. 2.

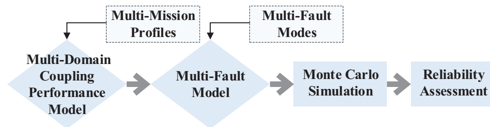

Fig. 2.Simulation Flow Chart

3. Overall Analytical Procedures

According to the methodological principles described in Section 2, this paper proposes a mission reliability assessment method grounded in system performance simulation under multi-mission profiles, with the specific steps of the method detailed as follows. An analytical flowchart depicting this process is presented in Fig. 3.

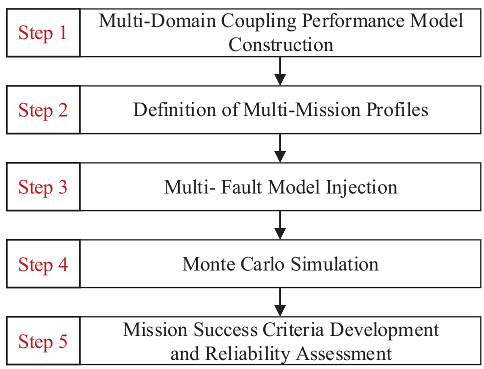

Fig. 3.Analysis Flow Chart

Step 1: A system multi-domain coupling performance model is developed by adopting the system component integration. This model is constructed based on the logical interrelationships and critical parameters among components of various domains, and it incorporates the external environmental conditions;

Step 2: Define a multi-mission profile that includes different phases, environmental loads, etc., characterized by both temporal dynamics and interdependencies;

Step 3: The time-sequential parameters of multi-mission profiles are taken as input to govern the operation of the performance model. Subsequently, fault parameters are injected into the model to develop a multi- fault model;

Step 4: Combined with the Monte Carlo simulation method, the synergistic effect of multi-fault disturbances under multi-mission scenarios is investigated, and the time-sequential evolution law of core performance parameters is tracked;

Step 5: Develop success criteria for the design mission, evaluate the results of the mission simulation, and consequently conduct a reliability assessment of the system.

4. Case Study

4.1. Aero-engine System Model

4.1.1. Multi-Domain Coupling Performance Model Establishment

The aero-engine system consists of six modules: the control system, air intake system, exhaust system, fuel supply system, combustion chamber system, and power output and transmission system. Drawing on the MVEM engine mean-value model in the model library of MWorks. Sysplorer, the system composition was improved, and the interface transmission relationships among the various subsystems of the aero-engine have been refined., and finally a multi-domain coupling performance model of the aero-engine system is established, as illustrated in Fig. 4.

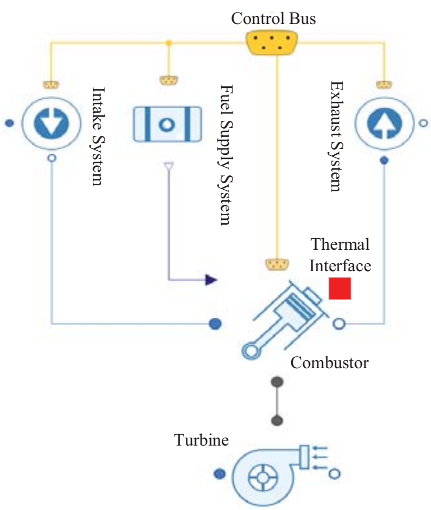

Fig. 4.Multi-domain Coupling Performance Model

The yellow icon labeled “Control Bus” serves as the control system, providing centralized control signals to the air intake system, fuel supply system, exhaust system and combustion chamber system. This arrangement facilitates time-sequenced coordination and state transitions among the various subsystems.

The blue spherical icons represent material flow interfaces, and the red square-shaped icons denote thermal interfaces. The air intake system draws in the working medium through the designated interface, which is subsequently combined with the fuel supplied by the fuel supply system before being delivered to the Combustor system. The high-temperature gases generated by combustion in the Combustor is fed into the exhaust system through the blue pipelines and finally discharged. Heat generated in the Combustor is transferred outward through the thermal interfaces, concurrently transmitting mechanical power produced by combustion to the transmission system located below. This system receives mechanical power through the mechanical interface and, following internal conversion processes, outputs shaft power externally through interfaces situated at both ends. Detailed parameters are provided in Table 1.

Table 1.Subsystem Parameters

Subsystem	Parameter	Value
Fuel Supply	Fuel Flow Rate (kg/s)	8
	Fuel Supply Pressure (MPa)	3
Combustor	Pressure Loss Coefficient	0.03
	Gas Temperature Outlet (K)	1800
	Combustion Efficiency	0.98
Power Output and Transmission	Total Moment of Inertia of Shaft System (kg·m^2)	0.42
	Mechanical Friction Torque of Shaft System (N·m)	75
	Turbine Design Rotational Speed (rad/s)	523.3
Air Intake System	Outlet Pressure (MPa)	0.85
	Mass Flow Rate (kg/s)	87.3
Exhaust System	Outlet Back Pressure (kPa)	30
	Outlet Temperature (K)	1100

4.1.2. Definition of Multi-mission Profile

According to the multi-mission profile definition method outlined in Section 2.2, the missions of the aero-engine from pre-takeoff preparation to mission completion is initially segmented into typical time-sequential phases, including ground idle, takeoff acceleration, boosted climb, cruise stabilization, and shutdown deceleration.

Subsequently, by utilizing the input-output interface relationships among the various subsystems of the aero-engine system, the climb and cruise phases are ultimately identified. These phases not only satisfy the mission's functional requirements but also align with the temporal sequence of actual operating conditions and possess clearly identifiable characteristics.

Within the multi-mission profile of the aero-engine, the climb and cruise phases are closely linked continuous operating conditions that exhibit dynamic correlations and smooth temporal transitions. Focusing on two principal observable variables — total fuel injection quantity and crankshaft rotational speed—there exists a pronounced here exists a pronounced coupling relationship whereby the initial state of each subsequent phase is determined by the preceding phase, and the steady state of the subsequent phase reacts on the regulation precision of the preceding phase.

Specifically, fuel injection quantity and rotational speed demonstrate a strongly coupled, positively correlated relationship. As shown in Fig. 5. At the initial stage of the climb phase, the fuel injection quantity is matched to 100% rated rotational speed to maintain peak supply. As the rotational speed is gradually reduced, the total fuel injection quantity decreases linearly to ensure stable combustion efficiency. When entering the cruise phase, the fuel injection quantity stabilizes synchronously at approximately 80% of the peak value with the stabilization of rotational speed, and maintains this steady-state level throughout the cruise phase.

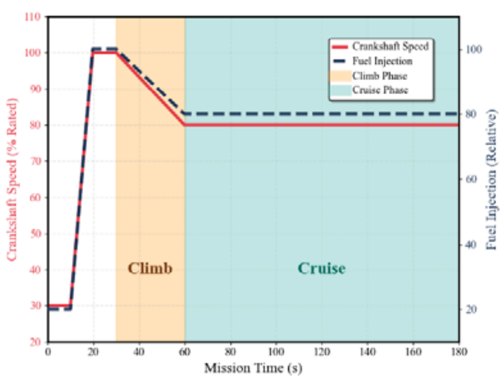

Fig. 5. Rotational Speed and Total Fuel Injection Quantity Curve

4.2. Performance Degradation Simulation Under Multi-Mission Profiles

4.2.1. Multi-Fault Injection

Drawing upon the two mission profiles—the climb phase and the cruise phase, a fault library for the aero-engine system was developed. This library was constructed by integrating historical data with the established aero-engine multi-domain coupling model, as presented in Table 2.

Table 2 .System Fault Library

Mission	Fault	Reasons
Climb	Shaft wear	High acceleration results in friction power consumption
Cruise	High-temperature coking	Fuel quality issues or poor combustion conditions

The fault distributions and parameters are shown in Table 3.

Table 3 .Fault Distributions and Parameters

Fault	Distribution	Parameters
Shaft wear	Weibull distribution	$\beta_1 = 3.2$, $\eta_1 = 100$
High-temperature coking	Log-normal distribution	$\mu_2 = 5.298$, $\sigma_2 = 0.5$

To facilitate fault injection, the subsystems are integrated into a single unified entity, represented by an engine icon. An additional thermal interface is connected to the Combustor fault module, while a supplementary mechanical interface is linked to the shaft system wear fault module; both interfaces are managed through time-series control. Moreover, two dark blue spherical boundaries are attached to the material flow interfaces of the intake and exhaust systems to simulate environmental loading conditions. Finally, a scheduling mechanism is employed to control the shaft system wear fault module and the Combustor fault module, thereby enabling fault injection across multiple mission profiles and establishing a comprehensive multi-fault model, as illustrated in Fig. 6.

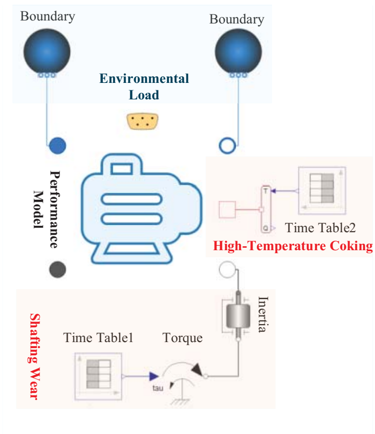

Fig. 6.Multi- fault Model

4.2.2. Mission Reliability Assessment

In this case, the total fuel injection quantity of the aero-engine system is selected as a critical performance parameter, given its strong correlation with the engine's rotational speed, thrust output, and heat exchange efficiency. During the transition of the aero-engine system from the climb phase to the cruise phase a comparative analysis is performed to examine the performance degradation under both single-mission and multi-mission profiles, as depicted in Fig. 7. According to the time settings, the interval from 25 seconds to 50 seconds is designated as the climb phase, and the period from 50 seconds to 100 seconds is defined as the cruise phase.

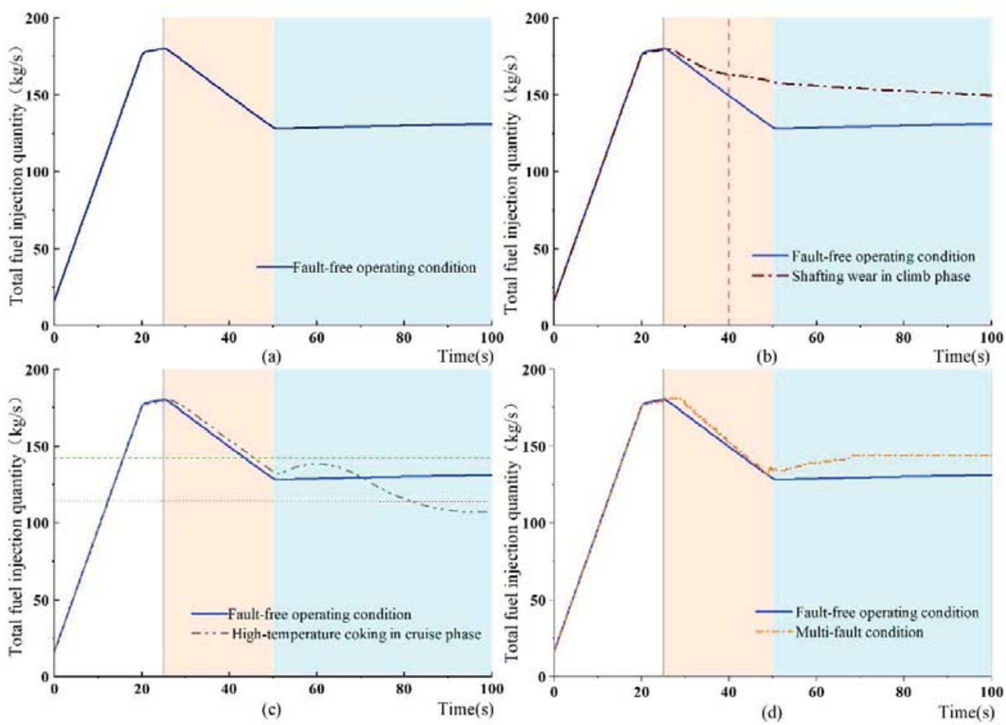

Fig.7.Simulation of Performance Degradation

Fig. 7 (a): Fault-free Operating Condition. This figure illustrates the trend of the total fuel injection quantity of the aeroengine during normal operation in the climb and cruise phases.

Fig. 7 (b): Shaft Wear Fault Injection Condition. During the climb phase, the aero-engine system encountered a shaft wear fault. Specifically, at 40 seconds, the total fuel injection quantity measured 149 kg/s under normal operating conditions, whereas it increased to 163 kg/s in the presence of the shaft wear fault. This variation in total fuel injection quantity, exceeding 6%, is indicative of a system fault.

Fig. 7 (c): High-Temperature Coking Fault Injection Condition. It is evident that the aero-engine system undergoes a high-temperature coking fault within the combustion chamber during the cruise phase. Specifically, at 80 seconds into the cruise phase, the total fuel injection quantity decreases to 115 kg/s, accompanied by fluctuations exceeding 8%. Consequently, it is determined that the engine fails to deliver the necessary thrust for the cruise phase, thereby constituting a system fault.

Fig. 7 (d): Multi-Fault Injection Condition. Given that the multi-mission profile exhibits time-sequential characteristics the fault criteria are established as follows: if the fluctuation of the total fuel injection quantity during the climb phase ranges between 3% to 5%, and the increase in the total fuel injection quantity during the cruise phase exceeds 6%, the condition is classified as a composite fault. The results indicate that the fluctuation of the total fuel injection quantity of the aeroengine is between 3% and 5% during the climb phase (25–50 seconds), and the fluctuation is no less than 6% during the cruise phase (50–100 seconds), which demonstrates that the aeroengine is unable to complete the entire climb-cruise mission.

The above results indicate that single-phase faults feature a single fault characteristic with prominent fault phenomena, making them easy to identify; composite faults involve the superposition of fault characteristics with strong fault concealment, which tends to result in missed judgments.

To assess the mission reliability of the system, 2000 Monte Carlo simulations were conducted on the aero-engine model. Following this, Python was employed to identify and extract the number of samples in which the system successfully completed the mission without any faults, based on the multi-mission profile fault criteria. This measure corresponds to the mission reliability under multiple mission profiles. Additionally, four categories of sample outcomes were recorded: mission success, fault during the climb phase, fault during the cruise phase, and overall fault, as depicted in Fig. 8.

Finally, the mission reliability of the aero-engine system performance simulation under the multi-mission profile is obtained as 74.1%. Among the four fault modes, the cruise-phase coking fault (12.8%) has the highest occurrence rate, followed by the climb-phase wear fault (10.9%), and then the compound fault (2.2%).

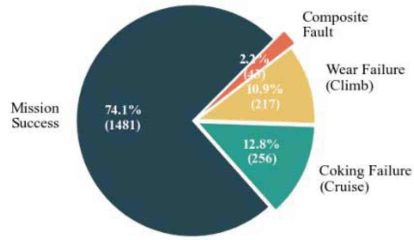

Fig. 8.Statistical Chart of System Mission Reliability

5. Conclusion

This study introduces a method for assessing mission reliability through system performance simulation under multiple mission profiles. The approach developed a performance simulation model in the Modelica language, which effectively integrates multi-domain interactions among various physical fields within each subsystem, and captures the system's physical properties, functional logic, and control strategies. Subsequently, a multi-mission profile characterized by temporal sequencing and interrelated features is constructed. the synergistic effects of multiple fault disturbances across the multi-mission profile are examined through simulation analysis. This enables the tracking of the temporal evolution of critical performance parameters, thereby providing a more comprehensive understanding of system reliability under the influence of multiple fault modes during multi-mission operational scenarios.

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