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Dynamic Modeling and Fault Diagnosis Technologies for Aircraft Landing Gear Systems: A Comprehensive Review

Zhuoran Cheng

School of Naval Architecture and Ocean Engineering, Dalian Maritime University, Dalian, China
czr06@qq.com

Abstract. Aircraft landing gear systems are characterized by strong nonlinearity, multi-physics coupling, and significant uncertainty. This paper reviews representative modeling approaches, including multibody dynamics, rigid–flexible coupling modeling, multi-domain unified modeling, co-simulation, and tire–runway coupled modeling. Furthermore, the applicability of fault tree analysis, bond graph-based diagnosis, data-driven diagnosis, and model-data fusion diagnosis is examined. The results indicate that physics-based models provide strong interpretability and support airworthiness verification; however, they involve high modeling costs and perform poorly in real time under complex operating environments and parameter uncertainties. Purely data-driven methods excel at extracting nonlinear features but are constrained by fault sample scarcity and the long-tail distribution of fault modes. Fusion diagnosis, digital twin technology, and hardware-in-the-loop (HIL) validation are regarded as promising solutions for balancing accuracy, interpretability, and engineering feasibility. Future research should focus on high-fidelity reduced-order modeling, intelligent diagnosis under limited samples, lifecycle-oriented digital twins, and airworthiness-oriented validation frameworks to support the design, health monitoring, and predictive maintenance of large civil aircraft landing gear systems.

Keywords: Landing Gear, Fault Diagnosis, Prognostics and Health Management (PHM), Digital Twin, Airworthiness Verification

1. Introduction

Aircraft landing gear serves as the primary load-bearing subsystem responsible for landing impact absorption and ground maneuvering. Its dynamic behavior directly affects aircraft safety, taxiing stability, and service life. As large civil aircraft performance continues to improve, stricter requirements have been placed on the design and validation of landing gear systems. Consequently, how to accurately characterize landing gear dynamics under complex operating conditions and achieve reliable fault identification and localization without sufficient fault references has become a major research focus.

Hou et al., Liu et al., and Wang demonstrated that the integration of multibody dynamics modeling and experimental validation can effectively support kinematic analysis and design verification of landing gear retraction mechanisms [1-3]. Wang et al. summarized common faults in hydraulic, mechanical, and locking subsystems from the perspectives of retraction system

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characteristics and typical failure modes . Their study further revealed that landing gear faults are often the result of coupled interactions among mechanical, hydraulic, and control subsystems [4]. However, most existing studies rely on isolated modeling approaches or individual fault detection techniques, lacking a comprehensive systems-engineering perspective. The intrinsic relationships among dynamic modeling, fault diagnosis, and airworthiness assessment have not been systematically investigated. Moreover, the trade-offs among diagnostic accuracy, response speed, and practical implementation feasibility have not been comprehensively reviewed or evaluated.

To address these limitations, this paper reviews representative studies published over the past decade from the perspectives of systems engineering and airworthiness requirements. A three-layer collaborative analytical framework comprising multi-physics modeling, intelligent diagnosis, and engineering validation is established for aircraft landing gear systems. In addition, a three-dimensional evaluation criterion involving accuracy, computational efficiency, and engineering applicability is proposed. The applicability boundaries of mechanism-driven, data-driven, and model, data fusion diagnostic approaches are systematically analyzed, and an integrated development roadmap for Digital Twin and Prognostics and Health Management (PHM) technologies is outlined.

2. Multi-physics coupling characteristics of aircraft landing gear systems

2.1. Mechanical–hydraulic–control coupling

The landing gear retraction/extension system consists of actuators, linkage mechanisms, locking devices, hydraulic pipelines, and control components. The subsystems interact strongly through hydraulic pressure, mechanical motion, and control signals. Changes in hydraulic pressure, valve response delays, mechanical clearances, or friction within locking mechanisms can cause extended or unstable retraction/extension, or incomplete locking [2, 4].

2.2. Thermo–fluid–structure coupling in oleo-pneumatic shock struts

Oleo-pneumatic shock struts absorb landing impact energy through gas compression and hydraulic oil throttling. During touchdown, gas compression, fluid flow, structural deformation, and seal friction occur together and jointly affect the shock absorption process. Under high-load conditions or repeated landing operations, rising oil temperatures alter fluid viscosity and flow characteristics, thereby affecting damping performance and restoring forces. Furthermore, drop-test investigations have demonstrated significant coupling effects among gas compression, hydraulic fluid flow, and structural responses within the shock strut system [5].

2.3. Tire–runway–structure coupling

Tire–runway contact forms the foundation for the analysis of taxiing, braking, and shimmy phenomena. Tire vertical deformation, cornering stiffness, relaxation length, friction coefficient, and runway contamination jointly affect structural loads on the landing gear. Models that incorporate tire relaxation and time-delay effects can more accurately characterize the lag relationship between lateral force generation and slip-angle deformation, thereby improving predictions of shimmy critical speed and stability boundaries [6, 7].

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3. Dynamic modeling methods of aircraft landing gear systems

Representative approaches for aircraft landing gear dynamic modeling include multibody dynamics modeling, rigid–flexible coupling modeling, multi-domain unified modeling, co-simulation, and tire–runway coupled modeling. These methods differ in modeling fidelity, computational efficiency, and applicability to engineering analysis.

3.1. Multibody dynamics modeling

In multibody dynamics (MBD) modeling, landing gear components are generally simplified as rigid bodies, while the motion of the entire mechanism is described through joint constraints, actuation forces, and external loads. Owing to its high computational efficiency and straightforward integration with CAD/CAE workflows, this approach is widely used for kinematic analysis and design optimization of landing gear retraction mechanisms [1, 8]. Nevertheless, because structural flexibility is neglected, multibody models cannot accurately capture high-frequency vibration characteristics and localized stress responses.

3.2. Rigid-flexible coupling modeling

Rigid-flexible coupling modeling includes flexible bodies in multibody dynamics to better represent the interaction between elastic deformation and overall motion. It is well suited for studying landing impact, taxiing vibrations, fatigue, and load transfer at critical connection interfaces [9, 10].

3.3. Multi-domain modeling and co-simulation

Multi-domain unified modeling approaches, such as Modelica and Simscape, employ equation-based formulations to describe energy exchanges among mechanical, hydraulic, electrical, and control subsystems within a unified framework. This modeling paradigm enables integrated analysis of the entire landing gear system on a single simulation platform. Previous studies have successfully applied this technique to the modeling of complete landing gear assemblies, retraction systems, and hydraulic control systems, thereby improving the efficiency, consistency, and maintainability of complex electro-hydro-mechanical system models [11].

To capture nonlinearities like friction and mechanical clearances, models such as LuGre are often used to reproduce complex frictional behavior in steering mechanisms, locking devices, and actuators [12]. As system complexity increases, co-simulation techniques have become increasingly popular, integrating specialized software platforms such as ADAMS, AMESim, and Simulink. By coupling mechanical, hydraulic, and control subsystems within a unified simulation environment, co-simulation enables more accurate prediction of the dynamic behavior of complex landing gear systems [13].

Furthermore, tire-runway interaction is also crucial for analyzing taxiing, braking, and shimmy behavior. Tire cornering stiffness, relaxation length, and friction characteristics directly affect the balance between lateral forces, braking forces, and structural loads. Several studies have demonstrated that incorporating tire nonlinearities and relaxation effects can significantly improve the accuracy of shimmy stability analysis and ground maneuvering behavior prediction, thereby enhancing the reliability of dynamic performance assessments [7, 8].

Overall, multi-domain modeling and co-simulation offer a useful framework for capturing the multidisciplinary coupling of aircraft landing gear systems. However, their reliability and predictive

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capability ultimately depend on accurate parameter identification and thorough experimental validation.

4. Fault diagnosis methods for aircraft landing gear systems

Dynamic models can support fault diagnosis by providing simulation data, residual signals, and physical constraints. For landing gear, the goal is to detect abnormal retraction/extension, locking failures, hydraulic issues, shock strut degradation, and tire or braking anomalies—all under complex conditions and limited sensor data. Diagnostic results also need to offer traceable evidence for maintenance, risk assessment, and airworthiness decisions. As a safety-critical system with extremely high reliability requirements, aircraft landing gear generates very few real severe fault samples, and the available data are often highly imbalanced. Furthermore, differences in aircraft types, mission profiles, and maintenance strategies result in inconsistent data distributions. Consequently, fault diagnosis methods should not be evaluated solely based on identification accuracy but should also consider physical interpretability, data requirements, real-time computational capability, and engineering validation feasibility. Existing approaches generally fall into three categories: mechanism-driven, data-driven, and model-data fusion.

4.1. Mechanism-driven diagnosis

Mechanism-driven diagnostic methods explicitly incorporate system structures, fault propagation mechanisms, and physical models into the diagnostic process. Fault Tree Analysis (FTA) is particularly suitable for fault scenarios with clear causal relationships, such as abnormal strain responses or locking failures [14]. In contrast, bond graph-based approaches focus on energy flow analysis and enable fault diagnosis across multiple engineering domains [15]. These approaches are physically interpretable and make fault mechanisms easier to understand; however, their diagnostic performance is highly dependent on model completeness and parameter accuracy.

4.2. Data-driven diagnosis

Data-driven diagnosis relies on sensor measurements such as pressure, displacement, vibration, strain, and temperature to extract representative system features, which are subsequently processed using machine learning or deep learning algorithms for fault identification. Commonly adopted approaches include Support Vector Machines (SVM), Random Forests (RF), Convolutional Neural Networks (CNN), and transfer learning techniques. Although these methods demonstrate excellent performance in extracting nonlinear fault characteristics, their performance is often limited by scarce fault samples and poor generalization across different operating conditions [16].

4.3. Model–data fusion diagnosis

Model–data fusion diagnosis combines the interpretability of physics-based models with the powerful feature-learning capability of data-driven approaches. By simulating fault samples, adding physical constraints, and using techniques like Physics-Informed Neural Networks (PINNs), it can improve diagnostic accuracy even with limited fault data. In addition, explainable artificial intelligence methods, such as SHAP (SHapley Additive exPlanations), can visualize the relationships between diagnostic outcomes and critical physical variables, thereby enhancing the practicality and credibility of diagnostic results in engineering applications. Nevertheless, this field still lacks standardized datasets and comprehensive validation frameworks. Future research should

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therefore focus on the development of standardized testing platforms and HIL validation technologies to facilitate the engineering deployment of fusion diagnostic systems.

5. Engineering challenges and future development trends

Despite the continuous advancement of dynamic modeling and fault diagnosis research, the practical deployment of Prognostics and Health Management (PHM) technologies for aircraft landing gear systems still faces multiple challenges. Beyond diagnostic performance, future PHM systems must also handle model credibility, data availability, algorithm interpretability, and airworthiness certification compliance. These factors collectively determine the feasibility of engineering implementation and large-scale industrial application.

5.1. Major challenges in current research

5.1.1. Balancing modeling accuracy and real-time performance

High-fidelity models can significantly improve the prediction accuracy of loads, stresses, and fault propagation processes. However, their extensive computational requirements and high modeling costs often prevent direct deployment in onboard computing platforms or edge-computing environments. Accurate landing gear modeling must account for structural flexibility, hydraulic transients, nonlinear friction, and tire-ground interaction. As model complexity increases, the number of parameters grows rapidly, resulting in substantial computational burdens. Conversely, excessive simplification may reduce the capability of the model to predict extreme operating conditions and fault evolution accurately. Therefore, achieving an appropriate balance between predictive accuracy and real-time computational performance remains one of the most critical challenges for online fault diagnosis and real-time PHM applications.

5.1.2. Airworthiness verification and standardization

For practical engineering applications, PHM algorithms need to deliver reliable fault identification while also meeting requirements for traceability, verifiability, and long-term maintainability. However, the black-box nature of many deep learning models conflicts with the chain-of-evidence requirements imposed by airworthiness certification procedures. Furthermore, no universally accepted evaluation framework currently exists for landing gear PHM systems, and standardized public datasets as well as systematic model lifecycle management procedures remain largely unavailable. These gaps seriously limit the adoption and certification of intelligent fault diagnosis in aerospace.

5.2. Future research directions

5.2.1. Development of high-fidelity reduced-order real-time dynamic models

Future research should integrate model reduction, parameter identification, sensitivity analysis, and uncertainty quantification. High-dimensional finite element and multibody dynamic models should be reduced to meet real-time computational requirements. Shimmy and brake-induced vibration still require further validation and testing. Hierarchical modeling architectures should be established for major subsystems, including retraction mechanisms, shock struts, and tire, ground interfaces. High-fidelity models can be used in design and verification, while simplified reduced-order models are

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suitable for online monitoring and diagnosis. This multi-level strategy balances reliability and real-time performance [17].

5.2.2. Establishment of experimental and simulation databases for complex environments

To support the development of advanced diagnostic methods, comprehensive experimental and simulation databases should be established to cover diverse operating environments, including dry runways, wet surfaces, and contaminated runway conditions. Such databases would provide reliable data resources for various model-data fusion diagnostic algorithms and facilitate robust algorithm training and validation. In addition, standardized data annotation protocols and evaluation criteria should be developed to improve the comparability, reproducibility, and credibility of research outcomes across different studies and institutions.

5.2.3. Establishment of airworthiness-oriented validation standards and fusion diagnostic frameworks

Future studies should establish a unified framework that simultaneously addresses integrated fault diagnosis and airworthiness verification requirements. Critical information on landing gear kinematics, load responses, and structural constraints should be incorporated into diagnostic decisions. Diagnostic conclusions should be derived from both data-driven features and physical principles. Explainable methods should link model outputs to physical variables such as pressure, displacement, vibration, and locking states, enabling maintenance personnel to interpret and act on the results. A hierarchical verification procedure should be developed, including simulation, bench testing, HIL validation, and comparison with operational data. Standardized evaluation metrics, such as accuracy, false alarm rate, missed detection rate, response time, and interpretability, should be established. Standardized data governance, model version management, and verification evidence retention can enhance credibility and certification readiness, making systems more suitable for airworthiness assessment and deployment.

6. Conclusions

This paper reviews dynamic modeling and fault diagnosis technologies for aircraft landing gear systems. It covers three types of coupling, mechanical-hydraulic-control, thermo-fluid-structure, and tire-runway-structure, and compares modeling approaches such as multibody dynamics, rigid-flexible coupling, multi-domain unified modeling, co-simulation, and tire-runway coupling. It also evaluates mechanism-driven, data-driven, and model-data fusion methods in terms of modeling capability, diagnostic performance, and engineering applicability.The review indicates that physics-based models provide strong interpretability and a solid foundation for airworthiness verification; however, they are costly to build and slow for real-time use in complex conditions. Data-driven approaches demonstrate superior capability in extracting nonlinear characteristics but are constrained by the scarcity of fault samples and limited generalization capability across different operating conditions. Emerging technologies, including model–data fusion diagnosis, digital twins, and HIL validation, are seen as promising for making PHM systems more practical and deployable.

Due to limited public literature, experimental data, and standardized criteria, a rigorous quantitative comparison among existing approaches could not be fully achieved in this review. Future research should focus on establishing standardized fault datasets and comprehensive airworthiness-oriented validation frameworks, thereby facilitating the engineering implementation and industrial adoption of advanced fusion diagnostic technologies.

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